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Introduction

In October 2017, Ultrafast Optics (UFO) celebrated its 11th conference and 20th year. Keeping with the long tradition of hosting UFO in special locations, the conference was held in Jackson, Wyoming, gateway to Yellowstone and Grand Teton National Parks, with 160 attendees from 18 countries.

The field of ultrafast science expanded significantly in the 1990s strongly boosted by the development of chirped pulse amplification and Ti:sapphire based ultrafast lasers. Commercially available laser systems enabled researchers around the world to make rapid advances in ultrafast research in physics, chemistry, materials science, biology, electronics, engineering, and medicine. Conferences such as CLEO and Ultrafast Phenomena were the natural forum for discussion of the science and application of these new sources. SPIE hosted a meeting as part of Photonics West that covered some of the technology aspects of ultrafast laser sources, but there was no dedicated conference focused on the science and technology of the generation, manipulation, and measurement of ultrafast laser pulses. It was, however, the sense of the community that the topic was of sufficient interest and breadth to justify a dedicated, stand-alone topical meeting.

The planners of the first UFO conference in Monterey, California self-organized all aspects of the conference, counting on active engagement from the international community of ultrafast laser research groups and the financial support of several laser and optical component manufacturers. The conference operated as a week-long, single session meeting to enable full participation of all attendees for every presentation. The sense of community was enhanced by social activities and excursions to enable casual interactions among the attendees. The success of this original formula has been duplicated over the past two decades, with the conference switching between locations in North America, Europe, and Asia.

In 2017, the field of ultrafast optics continues to show rapid fundamental and technological development with significant achievements reported in numerous areas including petawatt lasers, coherent combination of multiple sources, X-ray free electron lasers, thin-disk lasers, fiber systems, precision timing and synchronization, ultrafast metrology, attosecond science, optical parametric amplifiers, and continuous development of related technologies and applications; these topics were the focus of UFO XI in fifteen oral sessions and two poster sessions.

This is the first UFO conference for which an electronic summary of abstracts will be published online in a searchable digital library, and the organizers are grateful to SPIE for their enthusiastic support of this effort. Furthermore, a large fraction of the presenters of UFO XI permitted copies of their presentations and posters to be distributed to the attendees at the end of the conference, and we are grateful to the authors for their generosity and trust in their colleagues to share their research in this uncommonly open manner.

UFO continues to be organized by the individual efforts of the general chairs and program chairs, with guidance from an executive committee of previous UFO chairs. We believe that the small size (typically 150-200 attendees), single session format, strong support and engagement from exhibitors, memorable locations, and deliberate efforts to engage participants will continue to build and support the international ultrafast optics community for many years to come.

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Nuclear Photonics with Ultrabright Lasers and Gamma Beams

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Nuclear Photonics, i.e. pursuit of photon-based nuclear or isotopic science and applications is a new field of study that is being enabled by the rapid emergence of ultra-bright, quasi-mono-energetic gamma-ray sources based on laser-Compton scattering and by the creation of relativistic electro-magnetic fields with ultrahigh intensity laser systems. The first international topical meeting on Nuclear Photonics was held in October 2016 with more than 120 talks and posters presented by experts in gamma-ray source and intense laser development and experts from a variety of disciplines for which these sources may enable new scientific, industrial and medical opportunities. This talk will introduce Nuclear Photonics from the perspective of advanced laser-Compton sources and provide a look toward the future of this exciting new field.

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MeV x-rays from intense laser interaction with solids

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Abstract: Here we present MeV x-ray generation from intense laser-solid interactions both from the pitcher-catcher setup (electrons from a thin foil impinging on a thick converter foil) and direct laser interaction with thick solid targets.

I. INTRODUCTION

Compact x-ray sources with photon energies reaching MeV level have several applications such as nuclear photonics, radiography, dynamics studies, and nuclear security and nonproliferation. High power lasers generate multi-MeV electron beams, which could be used to generate compact MeV x-rays via Bremsstrahlung radiation. Here we show results from recent experiments at the Trident laser facility (80J, 0.6ps) at the Los Alamos National Laboratory generating MeV x-rays from intense laser-solid interactions.

A vast amount of research has been done in the past on laser-based x-ray generation both in the KeV and MeV range[1,2]. Typically an intense laser interacts with a thick (10's of microns to mm) high-Z target driving an energetic electron beam into the high-Z target generating Bremsstrahlung x-rays. Recent simulations suggested that generating electrons from thin (a tenth of a micron) low-Z target in the relativistic transparency regime - where otherwise opaque overdense plasmas become transparent to laser light due to relativistic electron mass increase[3] - and impinging those electrons on a separate thick high-Z converter target could generate efficient x-rays[4]. Here we explore these two x-ray generation schemes and compare the results.

II. RESULTS

We have performed MeV x-rays generation experiments at the Trident laser facility both in the pitcher-catcher setup and in the traditional thick target setup. The laser was focused onto the target with f/3 off-axis-parabola to a peak intensity of 2×10^{20} W/cm^2. In the pitcher-catcher setup, the Trident laser was incident on a 100nm thick aluminum foil. The accelerated electrons from the thin foil impinged on a 1mm thick tantalum converter foil that was 50μm to 300μm away from the first foil. This setup produced a maximum of 1.6×10^{13} photons/steradian with a temperature of 4.8 MeV. However, the shot-to-shot x-ray yield varied by more than a factor of 10 compared to the maximum yield of 1.6×10^{13} photons/steradian. The x-ray source size also varied from 125μm to 800μm from shot-to-shot.

We have also performed experiments where the Trident laser was incident straight on a 1mm thick tantalum foil. This setup produced 2-5 $\times 10^{13}$ photons/steradian with a temperature of 1.7 MeV. The shot-to-shot variation from this setup is roughly within a factor of 2. We also added 1ns pedestal before the main laser pulse from 10^{-5} to 10^{-7} levels, which did not have significant effect on the x-ray yields. The x-ray source size in this setup was measured to be ~150 microns.

III. CONCLUSION

In conclusion, both the pitcher-catcher setup and in the traditional thick target setup generates comparable MeV x-ray yields (2-5 $\times 10^{13}$ photons/steradian). However, the traditional setup yields much better shot-to-shot reproducibility, which is also not sensitive to the laser contrast.

ACKNOWLEDGMENTS

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Realizing the temporal resolution of electron dynamics in UEM

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Abstract: We demonstrate more than an order of magnitude enhancement in the UEM temporal resolution by generating isolated ~ 30 fs electron pulses via optical-gating, with sufficient intensity for efficiently probing the electronic dynamics of matter.

I. Introduction

Ultrafast Electron Microscopy (UEM) has been demonstrated to be an effective table-top technique for imaging the atomic motion in real time and space[1]. However, imaging the faster motion of electron dynamics has remained beyond reach due to the lack of temporal resolution. Here, we demonstrate the generating isolated ~ 30 fs electron pulses, accelerated at 200 keV, in UEM via the optical-gating approach, with sufficient intensity for imaging the electronic dynamics of matter in real time[2].

II. Optical gating of electron pulse

This approach is based on (PINEM)[3] in which the optical photon-electron coupling takes place in the presence of nanostructures when the energy-momentum conservation condition is satisfied. This coupling leads to gain/loss of photon quanta by some of the electrons in the electron packets, which can be resolved in the electron energy spectrum consisting of discrete peaks, spectrally separated by multiples of photon energy ($n\hbar\omega$), on both sides of the zero loss peak (ZLP), as shown in Fig 1a. Since, the electrons can gain or lose energy due to the coupling only in the presence of photons, the optical laser pulse acts as a "temporal gate" of these electrons. These gated electrons emulate the temporal profile of the gating laser pulse and it can be filtered out, providing a dramatic enhancement of the temporal resolution in UEM for exploring ultrafast dynamics of matter triggered by another ultrashort laser pulse in different UEM modes[2]. In this work, we generate isolated gated 30 fs electron pulse by optical gating utilizing ultrashort visible laser pulse. Then, the temporal profile of this pulse was characterized by the means of the cross correlation

II.A. Temporal characterization of the isolated 30 fs electron pulse

In these measurements, NIR pulse (~33fs) is scanned across the "gated" and "original" electron pulses and can couple to both of them as a function of temporal overlap. The temporal profile of "gated" electron pulse can be retrieved from the coupling cross-correlation temporal profile between the "gated" electron and the NIR pulse given the fact the pulse duration of the NIR pulse is known[2].

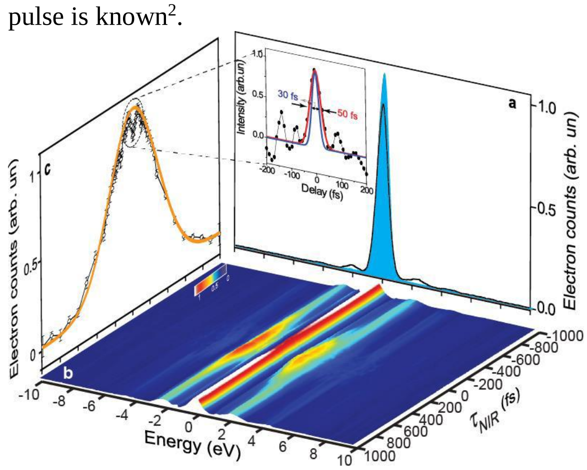

Fig. 1. (a) The electron energy spectra represent the original electron pulse (ZLP) (blue shaded curve) and the coupling between "original" electron pulse and "gating" visible pulse (30 fs) (black line). (c) The cross-correlation electron energy spectrogram of the electron-photon coupling between the NIR laser pulse and both "original" and "gated" electron pulses. (d) The cross-correlation temporal profile retrieved from the measured spectrogram in (c). Left inset in (b) shows the cross-correlation of the "gated" electron and NIR pulse.

III. CONCLUSIONS

The demonstrated 30 fs electron pulses by optical gating approach enhance the temporal resolution in UEM and permits the imaging of ultrafast electronic dynamics as surface plasmon, electron-electron and electron-phonon scattering in real time.

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High-harmonic generation driven by single-cycle mid-infrared pulses in solids

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Abstract: We have demonstrated high-harmonic generation (HHG) from a silicon thin crystal by using single-cycle mid-infrared pulses. The carrier-envelope phase dependence of the HHG spectrum was clearly observed.

In recent years, high-harmonic generation (HHG) in solids is attracting a lot of attention in the field of ultrafast science. Controlling such nonperturbative phenomena in condensed matter systems within a single-cycle time scale would be a key technology to realize a compact solid-state attosecond pulse generator and PHz electronics [1]. Naturally, experimental study with single- or sub-cycle pulses with well-characterized waveforms is one of the most straightforward approaches to investigate single-cycle ultrafast phenomena. In this contribution, we show experimental demonstration of HHG in solids by the use of single-cycle mid-infrared (MIR) pulses.

The light source was based on a Ti:Sapphire multi-pass amplifier (800 nm, 30 fs, 0.85 mJ, at 1 kHz, Femtopower compactPro, FEMTOLASERS). Carrier-envelope phase (CEP) stable single-cycle MIR pulses (15 fs, 450 nJ, 4.3 μm) were generated through two-color filamentation in air [2]. The pulses were focused into a silicon thin crystal (t=200 nm, SUF1054D, Norcada) by using an off-axis parabolic mirror (f=100 mm). The HHG spectra were recorded with a spectral analyzer (AQ6373, YOKOGAWA) and an EMCCD camera (SP-2358 with ProEM+1600, Princeton Instruments).

Figure 1 (a) shows the waveforms of single-cycle MIR pulses used for HHG. The two waveforms with different CEPs were measured by using FROG-CEP technique [3]. The phases at 4.3 μm are 0.14π and -0.68π, respectively. HHG spectra from the silicon thin crystal driven by each of the single-cycle MIR pulses are shown in Fig. 1 (b). The HHG spectra caused by the Bragg reflection within the crystal spread to higher frequencies than 800 THz, and the CEP dependence of the structures are clearly observed.

To investigate the complex structure and CEP dependence of the HHG spectrum, we performed numerical simulations based on the semiconductor Bloch equations (SBE). The structure and CEP dependence of the HHG spectrum is very well reproduced when we use the experimentally measured waveform as a fundamental field at the numerical simulation. We have noticed that the HHG spectrum is very sensitive to the shape of the fundamental field. Complete waveform characterization is very important for the investigation of such highly nonlinear processes with single-cycle pulses.

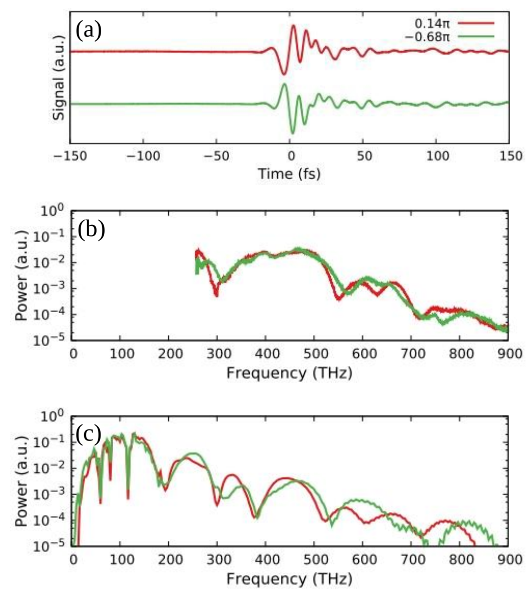

Fig. 1. (a) Temporal waveforms of the single cycle MIR pulses used for the HHG. (b) HHG spectra from silicon thin crystal driven by the single-cycle MIR pulses. (c) Simulated HHG spectra.

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Kilowatt-Class, Application-Enabling Petawatt Laser Technology

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Abstract: The HAPLS laser system has been commissioned to its first integrated performance milestone, delivering laser pulses with 16J sub-30fs duration at a 3⅓Hz repetition rate. This first all-diode-pumped petawatt-class laser offers the average powers required for secondary source applications.

Large laser systems that deliver optical pulses with peak powers exceeding one Petawatt (PW) have been constructed at dozens of research facilities worldwide and have fostered research in High-Energy-Density (HED) Science, High-Field and nonlinear physics. Furthermore, the high intensities exceeding 10^{18}W/cm^2 allow for efficiently driving secondary sources that inherit some of the properties of the laser pulse, e.g. pulse duration, spatial and/or divergence characteristics. The feasibility of numerous applications with transformational character has been demonstrated, such as proton radiography of HED targets, particle beam generation, and coherent and incoherent x-ray sources, and many others. For the most part, these experiments have necessarily been conducted at single shot repetition rate to allow for thermal cool-down and recovery of the laser driver. Hence, the brightness of secondary sources, the precision, reliability and repeatability of experiments, and the number of experiments accessible to users has been limited. Further, today's PW lasers mainly rely on flashlamp pumped laser technology, and have therefore been constrained to access commercial, and industrial applications that require average power levels of typically kilowatt and beyond, or exploratory research that requires highest pulse fidelity and repeatability. Furthermore, achieving highest intensities, controlling pulse shape in space and time, correcting for drift, and carrier envelope phase stabilization for shortest pulse, require feed-back and closed-loop control. High-peak power laser systems –a new generation of high intensity laser systems– with innovative technologies for thermal management, new optical materials and pulse compressor gratings and advanced computer controls are required to enter the new regimes. Current pulsed laser systems typically deliver <10 MJ/day, with two high energy laser systems pushing beyond that barrier: The high energy DiPOLE100 laser system designed and developed for the Czech HiLASE center by the UK's Science and Technology Facilities Council, Rutherford Appleton Laboratory, relies on amplification in cyro-cooled Yb:YAG and recently demonstrated delivery of nanosecond laser pulses at 1kW of average power and 10Hz repetition rate; and the High-repetition-rate Advanced Petawatt Laser System (HAPLS) developed by the Lawrence Livermore National Laboratory and delivered to the European Extreme Light Infrastructure (ELI) Project in the Czech Republic recently demonstrated continuous delivery of laser pulses with energy exceeding 16J, pulse duration 28fs, at 3.3Hz – equivalent to a peak power of ~0.5 PetaWatt/pulse delivered at rep rate, setting a new world-record for diode pumped short pulse high energy lasers. HAPLS is pumped by a kW-class, gas-cooled Nd:glass laser system that delivers at rep rate pulses with 100-200J, programmable pulse shape and up to 20nanoseconds pulse duration. After installation at the ELI facility and ramped to its final design performance HAPLS will be the world's highest average power Petawatt laser system. HAPLS is designed to provide a flexible experimental platform to ELI users for extended data collection sessions that enable today's proof-of-principle experiments to be pushed towards high fidelity data acquisition, including reduction to practice of commercial secondary source applications.

We will discuss how high-precision experiments and nearly all real-world applications of high intensity lasers require higher average powers than the current state-of-the-art systems and report on the technology development path for the next generation high intensity laser systems with even higher average powers.

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Demonstration of a Petawatt-class multi-Hz repetition rate laser

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Abstract: A Ti:sapphire laser system pumped by high-repetition-rate frequency-doubled Nd:glass slab amplifiers was demonstrated. 33 J pulses were generated at a record at 3.3 Hz and compressed to 33fs, corresponding to 0.77 Petawatt.

Several Petawatt (PW) power lasers have been demonstrated or are under development in laboratories world-wide. 10 PW systems are under development. To date, most PW laser system have been developed with Ti:Sapphire (Ti:Sa) as gain medium, which can provide broad bandwidth, very short pulse duration and compact size. However their repetition rate has been limited to 1 Hz [1], and is typically significantly less. A diode-pumped Nd:glass PW laser designed to operate at 10 Hz is under development, and has demonstrated 16 J pulses before compression at 3.3 Hz repetition rate, 53 W average power [2]. Here we report the demonstration of a PW-class laser designed to operate at repetition rates of up to 5 Hz based on Nd:glass slab amplifiers that is currently producing 33.1 J pulses before compression at 3.3 Hz repetition rate, a record > 100 W average power. Single pulses were compressed to 30 fs, generating 0.77 PW.

This chirped pulsed amplification (CPA) Ti:Sa laser system has a conventional front end that includes an acousto-optics programmable dispersive filter to control the spectrum, producing 200 mJ pulses. These seed pulses are amplified into three multi-pass high power Ti:Sa amplifiers (25 mm, 60 mm, and 90 mm diameter) pumped by frequency doubled Nd:glass slab laser amplifiers. The front end of the pump laser consists of a Q-switched 1053 nm Nd:YLF oscillator followed by several Nd:YLF amplifiers, which output is split to feed two flashlamp pumped Nd:glass slab amplifiers that in turn feed 8 arms of identical Nd:glass slab amplifiers. Each arm of the beam is amplified in two passes through the 400 mm long Nd:glass slab amplifiers in zig-zag to generate pulses of 18 J energy at 1053 nm. The beams are reshaped and are frequency doubled in LBO crystals to obtain a total pump energy of ~ 88 J at 527 nm. The average energy before compression at 3.3 Hz repetition rate is 33.1 J.

The output pulses are compressed in a four gratings compressor. With transmission efficiency of ~ 70%, the output energy is 23.2 J. The spatial profile of the output beam is close to homogeneous flattop. The final spectral bandwidth after the compressor is ~50 nm. The measured compressed pulse duration is 30 fs, giving a peak power of ~ 0.77 Petawatt.

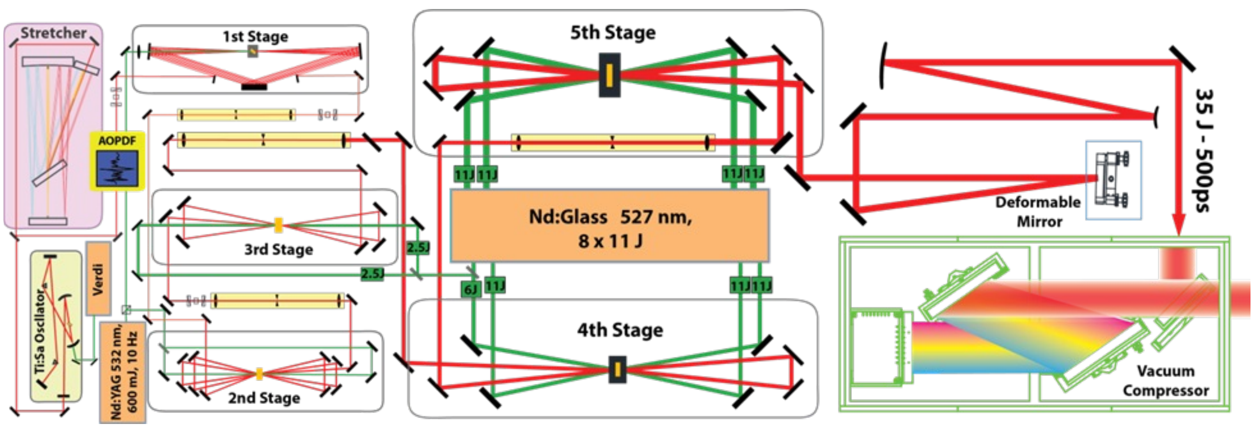

Fig.1. Schematic diagram of the Petawatt-class high repetition rate CPA Ti:Sa laser.

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BELLA PW – The Laser Facility with High Repetition Rate PW Pulses for Particle Acceleration Research

Csaba Toth, Kei Nakamura, Anthony J. Gonsalves, Hann-Shin Mao, Sven Steinke, Art M. Magana, Joe R. Riley, Joost Daniels, Chris V. Pieronek, Don L. Syversrud, Nathan M. Ybarrolaza, and Wim P. Leemans

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Abstract: Well-characterized 33 femtosecond pulses were delivered at 1 Hz into radiation shielded and monitored target area for laser-plasma-driven electron and ion acceleration research. Operational experience and latest results by “users" of the facility is described.

I. BASELINE AND PERFORMANCE

The Berkeley Lab Laser Accelerator (BELLA) is currently the world’s highest repetition rate (1 Hz) PW-scale regularly operating laser facility dedicated for laser plasma acceleration (LPA) research. After early test operations [1], the Ti:sapphire and Chirped Pulse Amplifications (CPA) based system quickly produced cutting edge results in high-peak-power laser-plasma interaction and LPA studies [2,3]. The facility now routinely provides high quality focused laser pulses (controllable spatial distribution in focus, exceptional beam pointing stability, shot-to-shot energy and pulse duration stability) for high precision experiments, including the use of gas-jet and capillary discharge based LPAs [4].

II. PATH FORWARD AND CHALLENGES

In preparation for a transition towards a collaborative research facility, that can offer a variety of experimental arrangements and diagnostics (for laser beams, plasma and target parameters, electrons and other particles, and secondary radiation), the facility is laying the groundwork in areas of enhanced operational and safety training, experiment planning and implementation, standardized data acquisition, data analysis, and data archiving systems. Latest results achieved in ongoing experiments with gas jets and capillary discharges for electron acceleration; and in the first thin-foil target experiments with loosely focused PW beams for ion acceleration will also be discussed.

ACKNOWLEDGMENTS

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TABLE I. Key parameters of the PW laser system

Parameter	Value	Notes
Wavelength	815±10 nm	Ti:sapphire
Bandwidth	>40 nm	supports <40 fs
Energy	>40 J	on target
Pulse duration	<40 fs	controllable 30-500 fs
Repetition rate	1 Hz	Shot on demand, too
Peak power	>1 PW	@ 1 Hz
Contrast @1 ns and at 5 ps	$>10^9$, $>10^6$	critical for solid target experiments
Pointing stability	<1.5 µrad	r.m.s.
Strehl in focus	~0.9	w/deformable mirror
Fluctuation - tau	<5%	r.m.s.
Fluctuation - E	<2.5%	r.m.s.

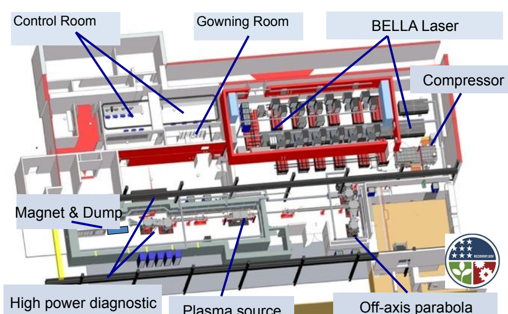

Fig. 1. Layout of the BELLA PW LPA Facility with the Laser, Target and Diagnostics rooms.

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PENELOPE – amplifier benchmarks and 10 J performance

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Abstract: We present the status of the PENELOPE laser, especially the performance of the second to the last amplifier, boosting the available energy to the 10 Joule-level, while benchmarking the performance of the whole last two amplifier sections.

I. INTRODUCTION

Diode-pumped solid state laser (DPSSL) systems using trivalent Ytterbium (Yb^{3+}) showed major interest in recent years. Most notable nanosecond laser systems are Lucia Refs. 1, GENBU (using TRAM) Refs. 2, PFS Refs. 3 and Dipole Refs. 4. Yb^{3+}-doped YAG crystals or ceramics tend to be first choice due to their high small signal gain and good thermo-optical properties. The second type of afore mentioned DPSSL systems aim at direct ultrashort chirped pulse amplification (CPA), e.g. Polaris Refs. 5 and PENELOPE (Petawatt, ENergy-Efficient Laser for Optical Plasma Experiments) Refs. 6.

In order to keep the necessary bandwidth, choices for a direct diode-pumped laser system doped with Yb^{3+} are relatively limited to a few selected materials besides glasses. One of the most promising candidates is Yb^{3+}:CaF_2 Refs. 7.

II. PENELOPE SYSTEM OVERVIEW

The PENELOPE project, a fully and directly diode-pumped laser system under development at the Helmholtz-Zentrum Dresden-Rossendorf, Germany, aims at 150 fs long pulses with energies of up to 150 J at repetition rates of up to 1 Hz.
The system consist of an oscillator generating pulses of ~60 fs, which are stretched by ~200 ps/nm and a hardclip of 50 nm. Subsequent amplification in several stages (RA I to MPA II) increases the energy to the sub-J level. The last two amplification stages (MPA III and IV) are designed to increase the energy to 200 J before final compression takes place. The peak power is foreseen to reach 1 PW.
With increasing energy, concepts for amplification change mainly due to the drastic increase in required pump power. While first amplification stages rely on an active-mirror approach, the last two amplifiers work in transmission with several He-gas cooled gain medium slabs.

III. EXPERIMENTAL RESULTS MPA III

One of the main uncertainties lies in the energetic performance of the amplifiers due to the very low gain cross section of Yb^{3+}:CaF_2. As MPA III and IV show in total 2x12 passes, we set up MPA III in a double-pass scheme using polarization coupling to simulate both final stages.

The 10 J operation of MPA III is shown by injecting only ~30 mJ (see Figure 1, gain of ~340) with about 5 nm of bandwidth. Here, RA I and MPA I were taken as seed source providing cavity-dumped, 6 ns long pulses. As the first 12 passes of MPA III don't exhibit gain saturation, it is safe to assume a similar energetic performance for 12 passes with about 600 mJ of input energy.

In order to compensate for further reduction in gain due to a higher bandwidth of about 20 nm, MPA II with an output pulse energy of 1 J will be inserted in the amplifier chain.

As pump performance at MPA IV is designed to perform better than MPA III, we can consequently estimate to meet the target performance of up to 200 J for MPA IV.

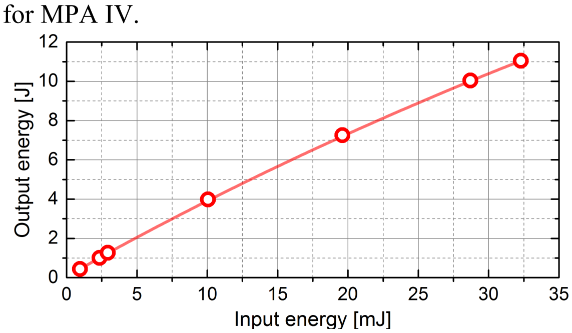

Fig. 1. Energetic performance using 2×12 passes at MPA III surpassing 10 J of output energy.

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The performance of a 5 Hz, joule-level OPCPA front-end for a 10 PW high repetition rate laser system

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Abstract: We present the latest results on the joule-level OPCPA front-end for a 10 PW laser system. The OPCPA chain operates at a 5 Hz repetition rate and features control over the pump pulse shape at the individual amplification stages.

I. INTRODUCTION

A multi-petawatt system that will be installed at ELI-Beamlines in the Czech Republic is currently being developed at National Energetics (Austin, TX, USA). It will produce 1.5 kJ pulses compressed to 150 fs, resulting in 10 PW peak power pulses delivered once a minute. The latest results for the OPCPA-based front-end of the system are presented, covering the general layout, energetics, spectrum shaping and pulse contrast enhancement techniques.

II. SYSTEM OVERVIEW

The argument for the hybrid design of the beamline is defined by the requirements of both relatively broadband amplification and high energy output. The OPCPA provides high gain and supports the bandwidth required for femtosecond compression. The Nd:glass amplifiers are a proven technology capable of kJ pulse amplification and the mixed glass design allows the amplification of a broad bandwidth in case of relatively low gain. Therefore, an approach similar to that used by the Texas Petawatt system[1] was chosen for the ELI-Beamlines 10 PW system.

The laser system is designed to operate near 1057 nm and consists of a picosecond front-end, nanosecond OPCPA chain and finally Nd:glass amplifiers. The picosecond front-end is OPCPA-based and is seeded by a broadband, femtosecond Yb:doped fiber oscillator. A portion of the oscillator pulse is used to seed a picosecond Nd:YAG laser, which provides up to 250 mJ energy for the picosecond OPCPA pump at 532 nm. The remaining portion of the broadband pulse is amplified in three stages of picosecond OPCPA, undergoes contrast enhancement, is stretched in a grating stretcher and then amplified in 5 stages of nanosecond OPCPA, pumped by Nd:YAG lasers with a controlled output pulse shape. After that, the pulse will be further amplified in flashlamp-pumped silicate and phosphate Nd:glass amplifiers to the kJ energy level and will be compressed using grating compressor to ~150 fs pulse duration.

III. NANOSECOND OPCPA CHAIN

The nanosecond part of the front-end consists of five OPCPA stages. The first stage is seeded by the stretched sub-mJ pulse and pumped by ~1 J at 532 nm. A combination of two BBO crystals is used here allowing for the optimum nonlinear media length. Four subsequent OPCPA stages utilize LBO crystals and are each pumped at 532 nm using individual pulse shape controlled Nd:YAG lasers (Ekspla, Ltd.). All OPCPA stages are operating in Type I configuration with a slight non-collinear angle for idler beam separation. The stages are operated close to saturation, therefore the pump pulse shape is partially imprinted on the broadband chirped pulse shape and on its spectrum. This, together with the variation of the pump pulses' delays, provides a programmable control over the pulse spectrum at the output of the OPCPA chain.

IV. CONCLUSIONS

A detailed design and achieved performance parameters of the nanosecond OPCPA amplifiers are presented and optimization criteria are discussed.

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Development and applications of a 20 fs, 4 PW Laser at CoReLS

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Abstract: A high-contrast 4 PW, 20 fs Ti:sapphire laser with a repetition rate of 0.1 Hz was developed and applied for the exploration of superintense laser-matter interactions.

I. Introduction

Petawatt (10^{15} W) lasers have been developed in a number of institutes around the world for exploring superintense laser-matter interactions. As the focused laser intensity with such lasers can easily exceed 10^{18} W/cm^2, relativistic plasmas can be produced and utilized for investigating superintense laser-matter interactions, such as laser-driven electron/ion acceleration[1,2]. A multi-GeV electron beam can be produced from a He gas target driven by a PW laser, and the GeV electron source can be used for Compton backscattering to produce MeV gamma rays. The development of ultrahigh power lasers, thus, offers new generation of particle and radiation sources, which can initiate another new challenging physics in astrophysics and nuclear physics as well as in plasma physics. Here we present the development of the 4 PW laser and applications to high field physics.

II. 20 fs, 4 PW Ti:Sapphire Laser

At Center for Relativistic Laser Science of Institute for Basic Science, two PW laser beamlines with outputs of 1.0 PW and 1.5 PW at 30 fs were utilized for research on laser-driven particle acceleration since 2012[3,4]. One of the PW beamlines was recently upgraded to a 4 PW beamline[5]. For the upgrade, we shortened the pulse duration while increasing pulse energy. We adopted the cross-polarized wave generation (XPW) and the optical parametric chirped-pulse amplification (OPCPA) techniques in order to compensate for gain narrowing and gain depletion effects and were able to obtain laser pulses with broad amplified spectrum.

For the increase of the output energy, a final double-pass booster amplifier was added. The double-pass booster amplifier was pumped with the second harmonic of Q-switched Nd:glass lasers with a total energy of 170 J in green at 0.1 Hz. After the pulse compressor consisting of four gratings, we obtained compressed laser pulses with an energy of 83 J and the pulse duration of 19.4 fs, producing 4.2-PW laser pulses with the low energy fluctuation of 1.5% (rms). Consequently, we successfully upgraded one of the PW laser beamlines to the 4 PW, 20 fs beamline.

III. Applications

With the PW lasers laser wakefield acceleration (LWFA) has been investigated to produce quasi-mono-energetic GeV electron beams in a centimeter-scale acceleration length. We succeeded in controlling the acceleration process by manipulating the temporal structure of PW laser pulses, generating stable multi-GeV electron beams. We plan to carry out the Compton backscattering to generate MeV gamma-rays from the interaction of a GeV electron beam and another laser beam. Furthermore, the newly upgraded 4-PW laser can offer opportunities to produce a 10-GeV electron beam and multi-MeV gamma rays. Consequently, the development of high energy electron beam and ultrafast gamma-ray sources with multi-PW lasers will open a route to explore QED effects and photo-nuclear physics.

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Sub-Femtosecond, Large-Scale, Long-Term Stable, Pulsed Optical Timing Distribution

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Abstract: Sub-femtosecond synchronization of lasers and RF-sources over a 4.7-km fiber network is demonstrated. This work enables clocking of photon-science facilities with sub-atomic spatial and now also attosecond temporal resolution.

I. TIMING IN PHOTON SCIENCE FACILITIES

Photon-science facilities such as X-ray free-electron lasers (XFELs)[1] and intense-laser and attoscience beamline facilities[2] are emerging world-wide with some of them producing sub-fs X-ray. These facilities are in need of a high-precision timing distribution system[3], which can synchronize various microwave and optical sub-sources across multi-km distances as required for seeded FELs and attosecond pump-probe experiments. Recently, we reported on a synchronous laser-microwave network that permits attosecond precision across such long distances. [4] This was achieved developing new ultrafast timing metrology devices and carefully balancing the fiber nonlinearities and fundamental noise contributions in the system.

II. SUB-FEMTOSECOND PERFORMANCE

Demonstration of sub-femtosecond timing distribution was achieved with the laser-microwave network shown in Fig. 1a. The timing signal from the master laser is distributed through a network that contains two independent fiber links of 1.2-km and 3.5-km length operated in parallel. The link outputs

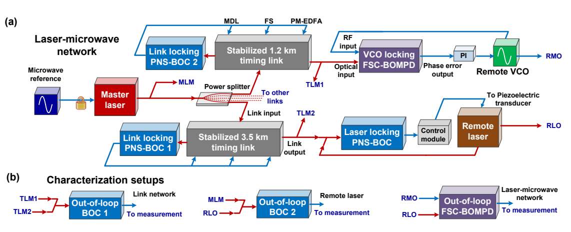

Fig. 1 (a) Laser-microwave network (VCO, voltage-controlled oscillator); (b) Out-of-loop characterization setups[4].

are used to synchronize a remote laser (e.g., serving as a pump-probe laser at the FEL end station) and a voltage-controlled oscillator (VCO) (e.g., serving as a microwave reference of the FEL linear accelerator) simultaneously. New *polarization-noise-suppressed BOCs* (PNS-BOC) and *free-space-coupled balanced optical-microwave phase detectors* (FSC-BOMPD) for improved noise performance have been and implemented. Residual second- and third-order dispersion links are carefully compensated with additional dispersion-compensating fiber to suppress link-induced Gordon-Haus jitter and to minimize output pulse duration; the link power is stabilized to minimize the nonlinearity-induced jitter as well as to maximize the SNR for BOC locking. Characterization setups are shown in Fig. 1b, to evaluate the performance of the link network, as shown in Fig. 2.

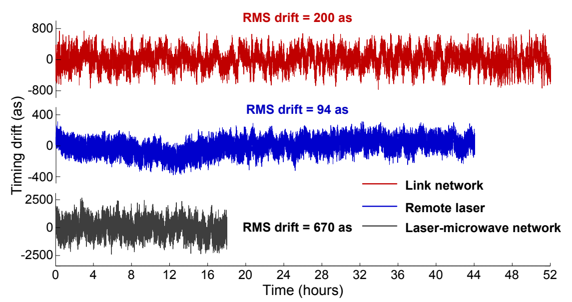

Fig. 2. Long-term timing drift results for the laser-microwave network[4].

The residual timing drift between links below 1 Hz is only 200 as RMS (red), and the total integrated timing jitter from 6 μHz to 1 MHz is 580 as (red). Remote laser synchronization over 44 hours without interruption is within 100 as RMS (blue). Overall, an unprecedented long-term precision of 670 as RMS out-of-loop drift over 18 hours (black).

III. CONCLUSIONS

A sub-femtosecond laser-microwave network has been demonstrated using novel timing devices.

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In-situ arrival time measurement during liquid-phase chemical experiments at X-ray free-electron laser sources

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Abstract: We report a novel background-free interferometric method for in-situ determination of the relative arrival time between X-ray and optical pulses with fs time resolution by measuring their cross-correlation signal in a few-µm thin, flat liquid jet used for studying chemical dynamics simultaneously.

At modern X-ray free-electron lasers (XFEL), a timing jitter of only a few tens of fs between X-ray pulses and an external optical laser can be achieved by careful synchronization of all subsystems of the facility [1]. However, for the highest time resolution in pump-probe experiments, an independent measurement is of utmost importance. We applied an improved technique to measure the relative arrival time at an XFEL facility, which is an interferometric extension of the spectral encoding technique routinely used at the Linac Coherent Light Source (LCLS) [2,3]. In our approach, we measure the timing jitter in a flat-sheet liquid jet, which is simultaneously used to deliver solvated molecules for chemical dynamics experiments. In contrast to the spectral encoding scheme with a fixed target, we measure an X-ray induced optical phase change in a fast flowing liquid. A supercontinuum pulse is split into two orthogonally polarized replica by passing through an a-cut BBO whose optical axis is rotated 45° with respect to the optical polarization. The supercontinuum pulses are spatially overlapped with the X-ray pulses in the liquid jet, consequently probing the X-ray induced refractive index change in the jet at different time delays. Both supercontinuum pulses are then temporarily combined with a second a-cut BBO and finally interfere in a polarization analyzer. The residual spectral-dependent intensity carries the relative arrival time information.

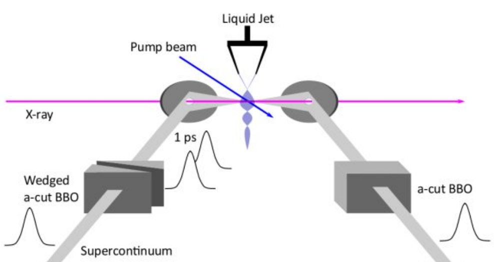

Fig. 1. Schematic experimental setup illustrating the different beam paths for X-rays, interferometric timing tool as well as the optical pump beam to study chemical dynamics in the liquid phase.

This scheme should particularly work well for upcoming high-repetition rate XFEL sources where available timing tool techniques could suffer damage from the potentially high heat load deposited by the X-ray pulses. We stress that the presented technique allows for in-situ arrival time monitoring, ensuring that the extracted timing information originates from the very same X-ray sample interaction volume, where a possible experiment would takes place.
The scheme discussed was successfully implemented in a proof-of-principle experiment at LCLS, yielding a robust timing signal with 30 fs accuracy in a 15 µm thick flat sheet jet.

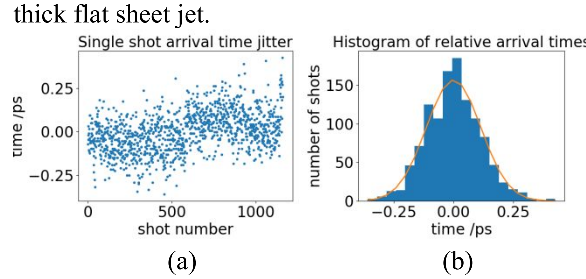

Fig. 2. (a) Relative arrival times of 1142 consecutive single X-ray pulses measured in a 15 µm liquid flat sheet water jet. The distribution (b) of these arrival times has width of 230 fs FWHM.

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Ultrafast imaging and X-ray diffraction of materials under dynamic compression

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Abstract: An outstanding challenge in multiphase physics problems is the ability to effectively capture dynamic processes. Here we demonstrate the use of brilliant X-ray pulses at the LCLS to study the material phase and dynamics.

I. Introduction

The possibility of improvement in the majority of our current technological capabilities is limited by material properties. There is a need to understand how materials behave under extreme conditions and how they ultimately fail across many industries and applications in order to improve current materials. For example, high strength steels for the automotive industry, damage resistant lightweight metals for military applications, and corrosion/temperature tolerant materials for the energy industry.

Being able to probe materials in extreme conditions at the inherent nanometer and ultrafast time scale is critical in order to validate materials damage and fluid models, especially where defects and instabilities initiate larger scale phenomena. Here we demonstrate the use the brilliant X-rays at the Linac Coherent Light Source Materials in Extreme Conditions hutch (LCLS-MEC) to study the material phase and dynamics using simultaneous wide angle X-ray diffraction (XRD) and Phase Contrast Imaging (XRD).

Two recent dynamic compression experiments utilizing combined XRD and PCI at LCLS-MEC will be described: (1) shock wave and void collapse dynamics in the molecular crystal PETN and (2) jet formation and breakup from free surfaces in shock loaded copper (Fig. 1). Single shot ultrafast pulses from the LCLS X-ray free electron laser (XFEL) capture PCI imaging and wide angle XRD. Planar shock waves were driven into the samples perpendicularly to the XFEL beam with the MEC nanosecond laser. Up to 32 J of 532 nm doubled YAG laser beam with a variable pulse length (nominally 20 ns) drove the shocks up to 10 GPa.

II. CONCLUSIONS

We performed the first concurrent imaging and diffraction from jets being ejected from shocked free surfaces and of void collapse under shock loading using the Linac Coherent Light Source.

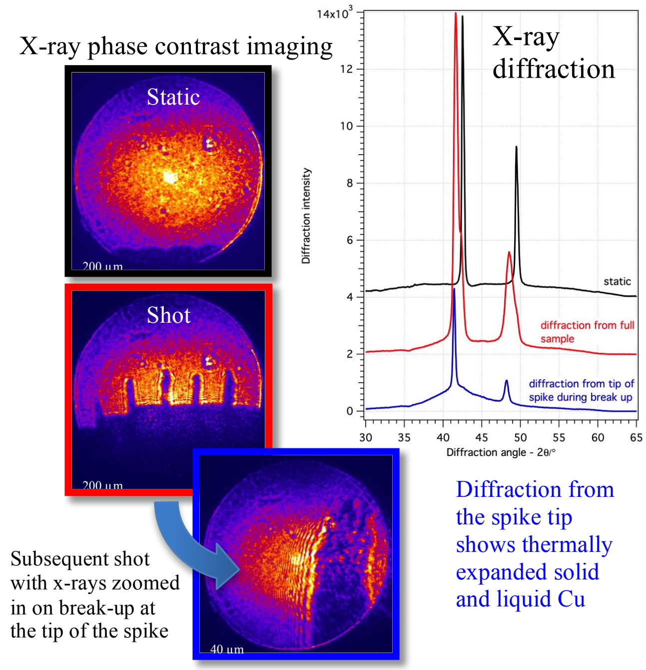

Fig. 1. Concurrent PCI and XRD of materials jets off of a free surface in shock loaded copper conducted at the LCLS-MEC.

The diffraction data yield measurements of the crystalline or liquid phases of the shocked material and will be used to improve materials dynamic materials models in or.

ACKNOWLEDGMENTS

This work was performed at the: 1. Matter at Extreme Conditions (MEC) instrument of LCLS, supported by the U.S. DOE Office of Science, Fusion Energy Science under contract No. SF00515, and was supported by LCLS, a National User Facility operated by Stanford University on behalf of DOE-BES

A review of OPCPA technology applied to free-electron lasers (FEL)

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Abstract: A review of OPCPA applied to future developments of FELs will be presented. Because OPCPAs can be compact, stable, wavelength tunable and scalable to hundreds of watts, they find application as high repetition rate seeding and pump-probe lasers, and in FEL pulse metrology.

I. Introduction

High repetition rate free-electron lasers (FEL), for example, at FLASH and XFEL (Hamburg Germany), and the future upgrade of LCLS (Menlo Park, USA), require high power lasers for various applications, including FEL seeding and pump-probe experiments, as well as electron beam injectors. White light seeded optical parametric chirped-pulse amplifiers (OPCPA) are well suited to meet these needs compared to traditional technologies, such as Ti:sapphire oscillators and amplifiers. OPCPAs are wavelength tunable from MID-IR down to UV, and in the NIR the bandwidths are capable of supporting sub-7 fs. Additionally, white light seeded OPCPAs can be scalable to many hundreds of watts [1, 2]. For user facilities, 24/7 operation and reliability are also important factors and in combination with stable commercial Yb-based pump technologies, the long term performance of OPCPAs can be guaranteed [3]. In this presentation, we review a 112 W burst mode OPCPA, designed and tested for seeding FLASH2 (Hamburg, Germany) [3]; as well as a compact OPCPA designed for pulse metrology to characterize the seeded FEL at FERMI (Trieste, Italy) [4].

II. Burst mode seeding laser for FLASH2

A tunable, 112 W (burst mode) OPCPA is demonstrated with center frequencies ranging from 720–900 nm, pulse energies up to 1.12 mJ and a pulse duration of 30 fs at a repetition rate of 100 kHz [3]. Furthermore, third and fourth harmonic generation experiments are performed and the results are used to simulate a seeded FEL with high gain harmonic generation.

III. Pulse duration measurements at the seeded FEL FERMI

We measured the temporal pulse shape of an XUV externally seeded FEL operating in the high gain harmonic generation mode using cross-correlation of the FEL pulses with an external optical laser [4]. Essential to this experiment was a compact tunable OPCPA. The results allowed a direct observation of the pulse lengthening and splitting at saturation (as an example, see Fig. 1), in agreement with the proposed theory.

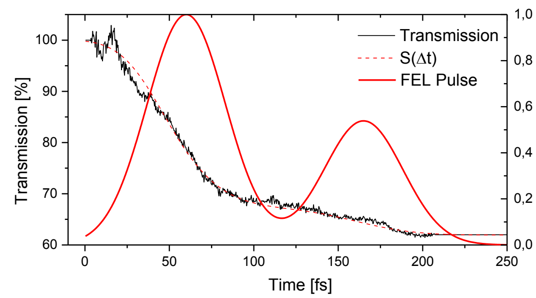

Fig. 1. An example of a time-resolved optical transmission signal from a seeded FEL with a detuned R_{56} (solid black line) and the resulting fit ($S(\Delta t)$, dashed red line). From the fit, the temporal structure of the FEL pulse is reconstructed (solid red line). For more experimental details see [4].

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Progress of time-resolved studies using an arrival-timing monitor in a diagnostic branch of SACLA

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Abstract: We developed an arrival-timing monitor between XFEL and optical laser pulses with a dedicated diagnostic branch at SACLA. This tool based on XFEL induced optical change enables us to improve the time resolution below several ten femtoseconds.

I. INTRODUCTION

X-ray Free electron laser (XFEL) of SPring-8 Angstrom Compact free-electron LAser (SACLA)[1] with a femtosecond pulse duration have promoted researches of ultrafast dynamics, often being combined with femtosecond optical lasers for pump-probe technique. Although these optical lasers are synchronized to the RF signal of the XFEL accelerator via a phase-locking system, some error sources produce sub-ps timing jitters between XFEL and optical laser pulses. In order to utilize the ultrashort-pulse property for time resolved experiment, shot-to-shot diagnostics on the relative arrival time between these pulses are absolutely essential.

Recently we have developed an arrival-timing monitor using X-ray induced optical change in gallium arsenide (GaAs) [2,3] and constructed a dedicated diagnostic branch for this monitoring system in hard X-ray beamline BL3 in SACLA. We also have developed software for quick analysis during experiment.

II. EXPERIMENT AND RESULT

Figure 1 shows the schematic design of the diagnostic branch in BL3[3]. The XFEL beam is split with one-dimensional transmission gratings fabricated on thin silicon membranes by electron-beam lithography. A 500-nm period grating diffracts the incident beam to produce +1st-order and -1st-order branches in the vertical plane by an angle of 0.248 mrad at 10 keV. The -1st-order beam is horizontally reflected with a plane mirror (M1) to be further separated from the 0th-order beam. An elliptical mirror (M3) reflects the -1st-order beam vertically to make a line-focused spot on a 5-µm-thick GaAs crystal. An incidence angle to the crystal is 45°, which allows spatial decoding of the relative arrival time of the XFEL pulse with respect to the optical pulse. Transient change in optical transmittance of GaAs crystal is probed with optical laser pulses with 40-fs duration and 800-nm wavelength. The optical laser beam is provided by a synchronized Ti:sapphire chirped pulse amplification system and line-focused on the GaAs target by using a cylindrical lens with a 0.4-m focal length. The transparent images on the target are taken with a long-work-distance microscope and a CCD detector on a shot-to-shot basis. Figure 2(a) shows a single shot image captured by the CCD detector. We determined a conversion factor as 2.6 fs/pixel from the spatial decoding geometry. The XFEL irradiated area in the image is observed as a black spot. The edge (shown in Fig. 2(a) bottom), which indicates the point of temporal coincidence of XFEL and optical-laser pulses, fluctuates shot-to-shot because of jitter.

We have developed an analyzing tool in order to provide shot-to-shot jitter values measured by the arrival-timing monitor for user experiment. We determined the edge position with both differential and fitting methods from the projection trace of the image. Figure 2(b) shows the distribution of the edge positions of 2000 traces recorded at 30 Hz in a shot-by-shot manner. We evaluated the jitter value to be 289 fs (rms) from the histogram. Users also can obtain data of the relative arrival timing of individual shots through the data acquisition system of SACLA.

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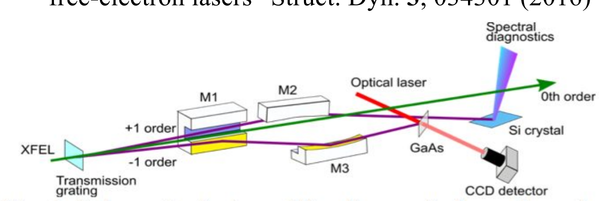

Fig. 1, Schematic design of the diagnostic beam branch

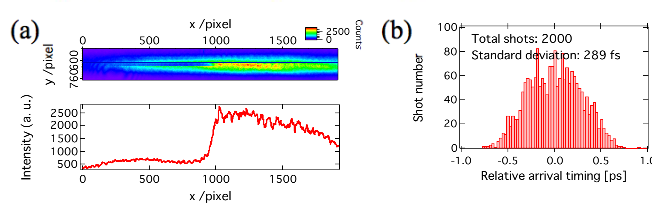

Fig. 2, (a): CCD detector image (top) and horizontal line profile (bottom) of the arrival timing monitor, (b): Histogram of edge variation

Ultrafast laser development driven by accelerator and xray FEL research

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X-ray FEL facilities place challenging demands on the stability and configuration of ultrafast optical lasers for the FEL electron source and for pump-probe experiments; future facilities will push the frontiers for high peak and average power, precision timing, and stability and reliability of ultrafast lasers.

SPIDER, 20 Years of Arachnophilia

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Abstract: Spectral interferometry has proven to be a spectacularly successful technique in ultrafast optics, enabling the complete characterization of light pulses from atto- to nano-seconds, with pulse energies ranging from mJ to single photons.

I. Ultrafast pulse characterization

The study and control of dynamical phenomena occurring at the molecular and atomic time scale prompted, over the last few decades, the development of new techniques for manipulating ultrashort light pulses. The ability to measure the electric field of such pulses is crucial both as a diagnostic tool and as a means for acquiring signals in experiments. Advanced methods for the characterization of broadband pulsed optical fields have developed at a rapid pace. Among these techniques, interferometry has proven to be perhaps the most fruitful, since it provides direct access to the electric fields that are primary entities of any optical signal.[1,2] The technologies that enable experimental characterization of short electromagnetic pulses using interferometry, have advanced rapidly over the past two decades, and both new devices and new algorithms have greatly enhanced the range of application of these methods.

2. Spectral Interferometry

Interferometry provides a very sensitive and accurate means to measure the phase of an optical field. The conversion of phase to amplitude information that is the hallmark of interferometric measurement allows robust and reliable extraction of the phase from the measured data. The general principle of spectral shearing interferometry is that the spectrum of two interfering pulses with spectrally shifted (or sheared) fields is measured. If the reference field is known, then the shear may be set to zero, and it is straightforward to extract the amplitude and phase of test field by means of a simple Fourier transformation and filtering algorithm. In the case that the reference field is a replica of the test field, then it is still possible to extract the test field by means of a modified version of the same algorithm, in which the derivative of the spectral phase of the pulse is estimated. Together with a measurement of the pulse spectrum, which may be made simultaneously, this provides a complete characterization of single pulses.[3]

Finally in the case when the reference field is unknown and not a replica of the test field, it remains possible to extract both test and reference fields when the signal is available for several values of the shear.[4] This multishear approach is a powerful extension to the arsenal of imaging, including holography, and at extreme wavelength ranges.

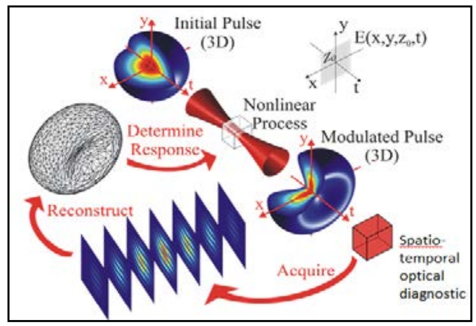

Fig. 1. Conceptual utilization of pulse characterization as an experimental tool. Estimation of the pulsed field before and after the interaction enable full characterization of the system itself.

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Spatio-temporal metrology at the focus of ultra-intense femtosecond lasers

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Abstract: We propose a new technique for the spatio-temporal characterization of femtosecond lasers, and demonstrate it on a 100 TW system. The measurement is performed around the beam focus, right where laser-matter experiments take place.

I. Importance of spatio-temporal couplings

Femtosecond lasers can now deliver ultrahigh intensities at focus, making it possible to induce relativistic motion of charged particles with light and opening the way to new generations of compact particle accelerators and X-ray sources. With diameters of up to tens of centimeters, ultra-intense laser beams tend to suffer from spatiotemporal distortions, that is, a spatial dependence of their temporal properties that can dramatically reduce their peak intensity. Until recently[1], however, these intense electromagnetic fields were characterized and optimized in space and time separately. Here, we present the first complete spatiotemporal experimental reconstruction of the field $\mathbf{E}(\mathbf{x},\mathbf{y},\mathbf{t})$ for a 100 TW peak-power laser <u>at focus</u>, and reveal the spatiotemporal distortions that can affect such beams, precisely where the laser-matter interaction takes place. This new measurement capability opens the way to in-depth characterization and optimization of ultra-intense lasers at focus and ultimately to the advanced control of relativistic motion of matter with femtosecond laser beams structured in space–time.

II. Complete E-field reconstruction

In this work, we demonstrate a new technique of spatio-temporal measurement based on a multispectral phase retrieval algorithm. Compared to the previous implementation of this general idea[2], our measurement scheme provides information on the two transverse dimensions of the beam, and thus requires no assumption on its properties. The data collection is performed near the laser focus of the attenuated beam, and provides a complete reconstruction of the space-time, or equivalently space-frequency couplings of the laser beam at focus, that is at the laser-matter interaction position. This technique will be highly complementary to the recently-demonstrated TERMITES, which applies to collimated beams.

The technique has been applied and validated on a 100 TW peak-power laser. Figure 1a shows the amplitude of the E-field in the space-frequency domain at focus. This representation reveals a significant and non-linear drift of the focus position with frequency, especially in the x-direction. As the technique provides spatio-spectral amplitude and phase profile, we can also numerically propagate it away from the focus. Fig 1b shows the real part of the E-field in the space-time domain, after propagation over a distance of about $4z_R$ (z_R is the Rayleigh length at central frequency) away from best focus.

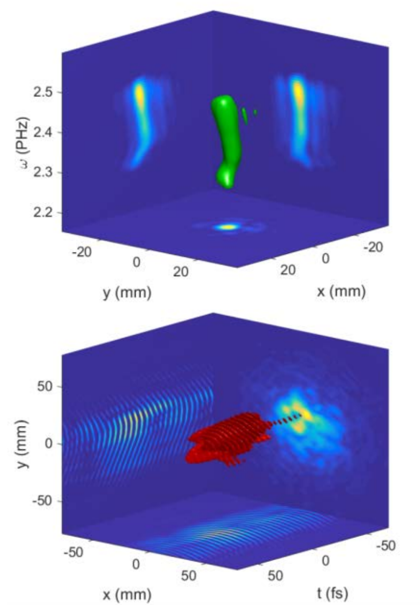

Fig. 1. Reconstructed spatio-spectral amplitude profile (top), reconstructed spatio-temporal electric field, slightly after focus (bottom).

III. Conclusions

This technique gives for the first time a complete reconstruction of the laser field at focus, i.e. precisely where the laser-matter interaction takes place. It will provide new insights for the optimization and understanding of high-intensity laser-matter interactions.

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Generation and in-situ measurement of the full electric field of near-single-cycle light pulses by CEP dispersion-scan

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Abstract: We demonstrate the generation and in-situ measurement of the electric field and CEP of intense near-single-cycle laser pulses using the new optical technique of CEP dispersion-scan.

The reproducible generation and measurement of intense CEP-stable single-cycle pulses is highly desirable for attoscience. The f-to-2f technique provides access to the pulse CEP stability, but not to its absolute value on target. Full characterization of a single-cycle optical pulse in-situ, including its absolute CEP, is a very powerful tool for interpreting experiments and for their simulation, which has been achieved with attosecond streaking [1], but so far no analogous optical method has been developed. Nomura *et al.* [2] demonstrated a method for measuring the intensity and phase of ultrashort laser pulses, as well as their absolute CEP, which combines FROG with electro-optic sampling, but this technique does not provide on-target measurements and has not yet been demonstrated in the VIS-NIR spectral region.

We previously used the dispersion-scan (d-scan) technique [2] to successfully generate CEP-stable 3.2 fs, 1.4-cycle pulses from a single d-scan device [3]. In this work, we describe the in-situ optical measurement of the complete electric field – including the absolute CEP – of intense near-single-cycle pulses, with the new technique of CEP dispersion-scan. The setup uses a hollow-core fiber (HCF) compressor filled with Ar at 1 atm, pumped by sub-25 fs, 500 μJ pulses from a Ti:Sapphire CPA. The HCF output is sent to an ultra-broadband (450-1000 nm) chirped mirror compressor (UltraFast Innovations GmbH), which is part of a single-cycle d-scan system (Sphere Ultrafast Photonics, SA) that further comprises a pair of fused silica wedges and a BBO crystal cut for type-I SHG. The resulting octave-spanning spectrum – see Fig. 1 (top) – has a Fourier limit of 2.1 fs and produces CEP-dependent fringes directly in the measured trace due to spectral overlap between the fundamental and the second-harmonic above 400 nm, as shown in Fig. 1 (bottom). An adapted d-scan algorithm [2] that takes into account the CEP dependence in the trace enables retrieving the complete electric field of the pulses in-situ with high precision, including their absolute CEP, reveals the generation of intense CEP-stable single-cycle pulses with 2.5 fs (FWHM) and a peak power of approximately 40 GW.

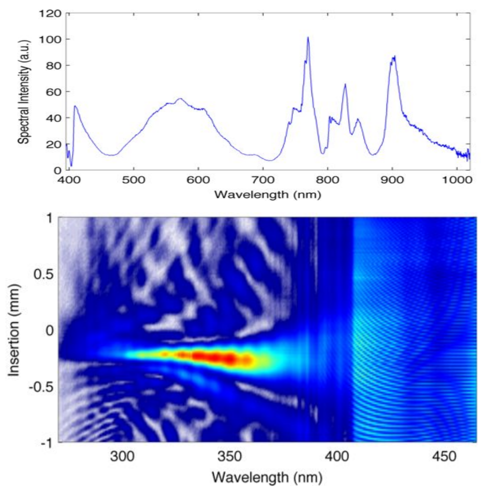

Fig. 1. HCF spectrum (top) and CEP d-scan trace.

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Characterization of Ultrashort Laser Pulses using Tunneling Ionization

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Abstract: We demonstrate that an arbitrary time-dependent laser field can be directly measured using tunneling ionization in a gaseous medium or in air. The light field is converted directly into an electric current.

I. DIRECT MEASUREMENT OF LASER FIELD

An arbitrary laser field can be measured using attosecond pulses (1) or sub-cycle electron dynamics (2) in HHG. These techniques require a complicated apparatus for the generation and detection of the attosecond x-ray pulse in vacuum. In this work, we show that the arbitrary laser field can be sampled directly into an electric current.

I.A. TIPTOE Method

In our approach, called the Tunneling Ionization with a Perturbation for the Time-domain Observation of an Electric field (TIPTOE) method, the tunneling ionization is used as a temporal gate to measure the laser field waveform. When an atom is exposed to a strong main laser pulse, the tunneling ionization occurs. The weak signal pulse to be measured is superposed on the strong laser field to perturb the process of the tunneling ionization. As we change the time delay τ between two laser pulses, the ionization yield modulates as shown in Fig. 1. It can be shown that the modulation of the ionization yield is proportional to the additional signal field as

$$\delta N(\tau) \propto E_S(\tau). \qquad (1)$$

Consequently, the direct sampling of the laser field waveform can be accomplished by measuring the modulation of the total ionization yield.

I.B. Measurement in Air

Since we measure the ionization yield, the experiment can be performed in air. The ionization yield is measured using biased metal plates and a current amplifies. We show both theoretically and experimentally that the TIPTOE measurement accurately reproduces the original signal field including the carrier envelope phase (CEP) of the pulse.

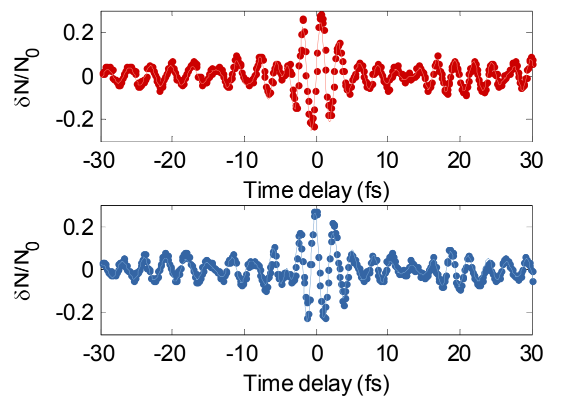

Fig. 1. Few cycle laser pulses measured by the TIPTOE method are shown. The modulation of the ionization yield δN/N is measured at different CEPs.

II. CONCLUSIONS

We demonstrated the TIPTOE method that can convert an arbitrary laser field directly into an electric current using tunneling ionization in a gaseous medium or in air.

ACKNOWLEDGMENTS

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CEP stability of high-power few-cycle fiber lasers

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Abstract: We characterize the carrier-envelope phase noise of the ELI-ALPS HR1 laser system emitting 100 W of average power, 1 mJ of pulse energy and <7 fs pulses. Contributions of individual components and technological solutions to carrier-envelope phase noise are analyzed.

In the last years the progress in fiber-laser technology has allowed for reaching kilowatt-level average powers with multi-mJ pulse energies and low amplitude noise[1] by employing coherent beam combining (CBC, Ref. 2) with a possibility to apply nonlinear compression for generating few-cycle pulses[3]. Recently, an Yb:fiber chirped-pulse amplifier delivering µJ-level pulses compressed to ~30 fs with an excellent carrier-envelope phase (CEP) stability of 100 mrad up to 400 kHz has been demonstrated[4].

We are pursuing the task of achieving a similar level of CEP stability in a chirped-pulse amplifier system reaching the average power of 100 W and 1 mJ energy of 7 fs pulses. The system will be employed as the HR1 laser at the ELI-ALPS research facility in Szeged, Hungary and is described in detail elsewhere[3,5].

A series of experiments was performed to characterize the CEP noise of the system. Fig. 1a depicts the noise measured in a single-channel regime with a single-shot stereo-ATI. The integrated CEP noise of few-cycle pulses estimates to 0.6 rad in the frequency range of 10 Hz to 50 kHz. The noise in the acoustic range will be corrected by a feedback loop from the stereo-ATI using a Dazzler-based phase shaper[6]. In order to achieve the highest CEP stability we study the contributions of individual components of the system by removing them or alternating their parameters one at a time.

Pulse picking with two acousto-optical modulators (AOM) in the amplifier chain was analyzed by an f-to-2f interferometer capable of measuring the noise of the pulse trains with non-zero carrier-envelope offset (CEO) frequencies. Analysis of a tandem AOM setup – two AOMs with complementary diffraction orders connected in series – as an alternative to synchronous picking[7] is shown in Fig. 1b. Employing several AOMs seem to introduce high-frequency contributions presumably due to spectral leakage through the device.

The CEO noise with CBC of two channels is shown in Fig. 1c. The spectrum has a good correlation with the result obtained by stereo-ATI. Remarkably, the CBC technology affects only the cutoff frequency of acoustic noise contributions without a penalty on the integrated phase noise (IPN).

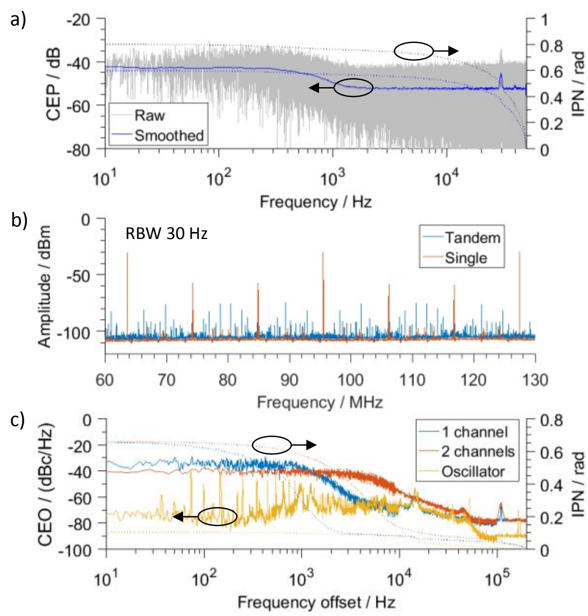

Fig. 1. (a) Single-shot stereo-ATI measurement in a single-channel regime. (b) Tandem AOMs as pulse pickers, picking factor 2. (c) CEO noise of the CPA

The CEP noise of the ELI-ALPS HR1 laser is characterized by a stereo-ATI phase meter and an f-to-2f interferometer. Contributions of individual components are studied in detail. The work on reducing the reported CEP noise of 0.6 rad in the frequency range of 10 Hz to 50 kHz by a feedback loop is in progress.

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Intrapulse coherence as a limiting factor in interferometric carrier-envelope phase measurements

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Abstract: Carrier-envelope phase stabilization of millijoule pulses is still a very challenging task that often results in several hundred milliradian residual jitters. Here we discuss a loss of spectral coherence as the origin of this limitation.

Carrier-envelope phase (CEP) stabilization plays a decisive role for attosecond pulse generation and in precision frequency metrology. While residual phase jitters of 20 mrad have been reported for the stabilization of oscillator systems, best reported values for amplifiers are about one order of magnitude larger. Moreover, self-stabilization schemes based on parametric amplification often exhibit rather disappointing residual CEP jitters of several hundred milliradian. Here we discuss that one previously unrecognized source of these fluctuations lies in a loss of spectral intrapulse coherence in the supercontinuum process, which is always an integral part of the CEP measurement scheme.

Coherence in optics is traditionally defined via the temporal correlation $\Gamma(\tau)=\int E(t)E^*(t-\tau)\mathrm{d}t$. For a HeNe laser, e.g., Γ drops by 1/e of the maximum for a delay of a few hundred nanoseconds. The above definition becomes ambiguous on application to mode-locked lasers. Formally, the coherence time of a mode-locked laser is given by its inverse spectral bandwidth and has sometimes been confused as the pulse duration in autocorrelation measurements of unstable pulses. However, two successive pulses from a mode-locked laser can typically also interfere with large fringe contrast, which gives rise to a second coherence time scale that is similar to the coherence seen in continuous wave operation of the same laser. Supercontinuum generation in photonic crystal fibers often destroys the interpulse coherence. Successive pulses in such a supercontinuum do not interfere anymore and can consequently not be compressed anymore. However, despite the apparent loss of interpulse coherence, such supercontinua can still be exploited in frequency metrology, i.e., there must be a remaining coherence between different Fourier components within the individual pulse. To evaluate this intrapulse coherence, we suggest a new definition of coherence, namely $\Gamma^{(\mathrm{CEP})}=E^2(f)E^*(2f)$ as it is relevant for f-$2f$ interferometry, which is typically used for measurements of the CEP.

In order to illustrate the development of $\Gamma^{(\mathrm{CEP})}$ during supercontinuum generation, we investigated two fundamentally different processes. Restricting ourselves to the leading nonlinearity, we computed $\Gamma^{(\mathrm{CEP})}$ for pure self-phase modulation and for multiphoton-absorption driven plasma generation as it dominates filamentation. In the former case, spectral broadening is symmetric, and one initially observes a steady increase of the figure-of-merit, i.e., the modulus of $\Gamma^{(\mathrm{CEP})}$ until the first and global maximum is reached for a B-integral slightly above 2π. Simulating an ensemble with 1% rms pulse energy variation, one observes a small resulting amplitude jitter in the f-$2f$ heterodyne signal and tolerable phase jitters in the few ten milliradian range when operating at the sweet spot. Redoing the same simulation for filamentation in sapphire dramatically changes this beneficial behavior. Operation at the global optimum results in $\sim\pi$ phase jitters and prohibitive amplitude fluctuations. Restriction to the first local maximum is still accompanied by a 200 mrad phase jitter.

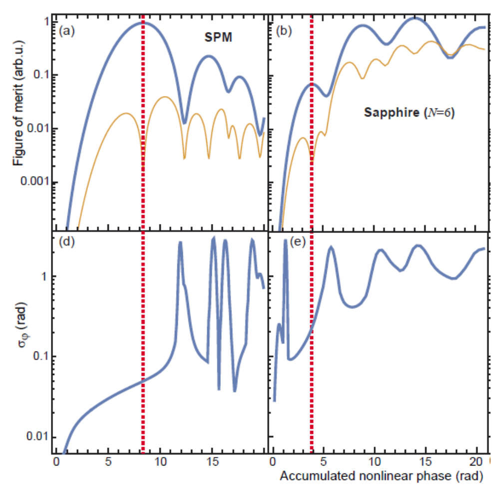

Fig. 1: Numerically simulated figure-of-merit and amplitude and phase variation of the heterodyne signal in the f-$2f$ interferometer. Left column: symmetric spectral broadening due to self-phase modulation. Right column: asymmetric broadening due to filamentation.

We will present further experimental and theoretical results on the optimum choice of the nonlinear material in the broadening process. In conclusion, we believe that the concept of intrapulse coherence plays a decisive role for further progress in the generation of CEP-stabilized millijoule pulses and may also affect frequency comb spectroscopy.

Applications of ultrafast laser for biomedical imaging

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Abstract: The desirable characteristics of ultrafast lasers for imaging deep into scattering tissue will be discussed, and recent advances in multiphoton microscopy for mouse brain imaging that are enabled by new ultrafast sources will be presented.

Optical imaging plays a major role in both basic biological research and clinical diagnostics, providing non-invasive or minimally invasive microscopic imaging capability to investigate biological tissues. Optical image acquisition through significant depths of biological tissues, however, presents a major challenge since tissue is extremely heterogeneous and the strong scattering of the various tissue components has restricted high-resolution optical imaging to superficial layers. Multiphoton microscopy (MPM), because of its 3D excitation confinement and long wavelength excitation, has significantly extended the penetration depth of high-resolution optical imaging, particularly for in vivo brain imaging. Over the last two decades, multiphoton microscopy has created a renaissance in the brain imaging community. It has changed how we visualize neurons by providing high-resolution, non-invasive imaging capability deep within intact brain tissue. Multiphoton imaging will likely play an essential role in understanding how the brain works at the level of neural circuits, which will provide a bridge between microscopic interactions at the neuronal level and the macroscopic structures that perform complex computations.

Multiphoton imaging critically depends on a variety of optical technologies, particularly ultrafast lasers for the nonlinear excitation. In this talk, we will discuss the desirable characteristics of ultrafast lasers for imaging deep into scattering tissue, such as the mouse brain. We will review the recent advances in MPM for mouse brain imaging that are enabled by new, energetic femtosecond sources, particular on the long wavelength and 3-photon excitation approach [1-5]. Large scale volumetric imaging, with high spatial and temporal resolution, deep within the scattering mouse brain remains a major challenge for neuroscience. We will discuss the opportunities and possible future directions for ultrafast technology development to address this important application.

ACKNOWLEDGMENTS

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Valley-resolved Electronic Coherences in Silicon Observed by Attosecond Transient Absorption Spectroscopy

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Abstract: Electronic coherences are observed in silicon by attosecond transient absorption spectroscopy. Various sub-4 fs oscillations across the conduction band reveal complex couplings between valence-conduction and conduction-conduction bands indicating pathways for coherent preparation of highly excited electrons.

I. INTRODUCTION

Understanding the absorption of light and subsequent carrier dynamics in semiconductors plays a crucial role for optimizing next-generation photonic devices for increasingly faster performance. However, a direct access of dynamics during carrier excitation for a multitude of possible band transitions when using broadband light remains challenging.

Here, attosecond transient absorption spectroscopy is employed for studying band couplings, i.e. electronic coherences, in single crystalline silicon during excitation by an intense 5-fs optical pulse (1×10^{13} W/cm²).

II. RESULTS & CONCLUSION

Transient absorption changes in the conduction band (CB) of silicon are monitored by an attosecond pulse at the silicon $L_{2,3}$-edge (~99.8 eV). The recorded transient (Fig. 1a) features a multitude of oscillations across the CB. In a frequency-over-energy Fourier analysis in comparison to the band structure, couplings can be identified by lines with unit slope (Fig. 1b & c). Besides observing 2ω oscillations consistent with previous observations of the NIR field driving electrons across the band gap, the data suggests that the optical pulse can coherently couple the valence band (VB) and CB at the L and Γ points by a multiphoton process (black dashed lines and circles). However, some newly observed features, can be assigned to CB-CB coherences (purple dashed lines), notably between the L_1/L_3, $\Gamma_{15}/\Gamma_{2'}$ and K_3/K_1 critical points, with K_3/K_1 requiring two photons. A possible path for creating CB-CB coherences can be understood by the leading edge of the pulse first indirectly exciting carriers into the Δ_1 valley via the indirect gap excitation and subsequently the main pulse initiating the coupling among the conduction band density of states. The time domain measurement allows measuring lifetimes of these coherences as well as their sequence of generation. Detailed time-domain analysis and supporting TDSE simulations will be presented.

In conclusion, the results provide insight into complex couplings between bands that take place during excitation with broadband ultrashort laser pulses, an effect that should be general for most semiconductor materials. Specifically, couplings between CBs expose pathways for generating highly excited electrons in semiconductors. Monitoring electronic coherences valley-resolved opens prospects for control of hot carrier generation by electric field engineering.

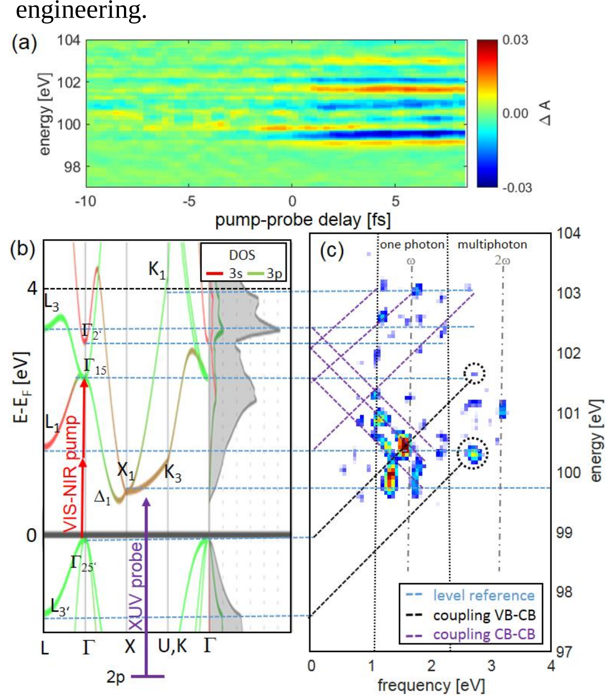

Fig. 1. (a) Transient absorption changes at the silicon $L_{2,3}$-edge. (b) Si band structure and density of states (DOS) indicating critical points and the pump-probe scheme. (c) Fourier analysis of (a) revealing various VB-CB and CB-CB electronic coherences. Only one possible excitation pathway is indicated (b) for clarity.

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Field-Resolved Spectroscopy of Molecular Vibrations

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Abstract: We record the electric fields emitted by impulsively excited molecular vibrations as the most fundamental ensemble-averaged physical measurable of coherently oscillating microscopic electric dipoles. This background-free, time-domain detection of molecular fingerprints offers high detection sensitivities.

The ability to generate and precisely control optical electric fields with strengths on the order of the atomic Coulomb field, uniquely afforded by carrier-envelope phase (CEP) stabilized pulses of modelocked lasers, constitutes the basis for the real-time observation – and control – of optical polarization in matter on its native sub-cycle time scale. This was first achieved with THz technology, where ultrashort pulses are used both for the generation of phase-stable transients and for sampling their electric fields [1]. With the emergence of lasers emitting high-energy CEP-stabilized few-cycle visible-near-infrared pulses, attosecond metrology provided the tools (high-order harmonic generation and attosecond streaking) for time-resolved studies of polarization in matter with frequencies into the PHz range [2]. Nowadays, these techniques – summarized under the term "field-resolved spectroscopy" (FRS) – are rapidly developing towards a broad spectral coverage [3,4], becoming indispensable tools for fundamental studies of light-matter interactions and in the quest for novel ultrafast technologies.

Here, we use FRS techniques to directly measure the electric fields emitted by impulsively excited molecular vibrations. Resonant vibrational excitation is provided by few-cycle, phase-stable 10-µm pulses [3]. The electric fields emitted at frequencies specific to the molecular sample represent the most fundamental ensemble-averaged physical measurable of coherently oscillating microscopic electric dipoles. We measure these fields with electro-optical sampling [3,4], demonstrating a unique potential of field-resolved vibrational spectroscopy for molecular fingerprinting. In our proof-of-concept study, we dissolve organic molecules (glucose) in water and show that impulsive excitation allows for a good temporal separation of the coherent vibrational fingerprint from the instantaneous (non-resonant) sample response, rendering the detection sensitivity of FRS immune to source intensity noise. This is in sharp contrast to traditional frequency-domain methods, where fingerprints of the sample-specific polarization are detected by evaluating the change of the source intensity for each spectral element.

The decay of vibrational response of glucose is measured with FRS in the band from 8 to 11 µm (see Fig.1a) using the system described in [3], and the power absorption spectrum of the same samples is measured with a state-of-the-art Fourier-transform spectrometer (FTIR) (Bruker Vertex 70). To determine the concentration of glucose in water, we fit suitable ab-initio models to the measurements. The results (Fig.1b) reveal similar limits of detection (LOD) for FTIR and FRS if for the latter the superposition of the two parts of the response without temporal separation is considered. However, when filtering out the instantaneous sample response carrying the source's relative intensity noise (RIN), and evaluating only the resonant fingerprint response, a concentration lower by one order of magnitude is detected with FRS owing to the background-free measurement.

With compact electro-optic sampling devices enabling field-resolved detection over the entire IR range [4], FRS becomes a powerful tool for studying ultrafast polarization in matter with an unparalleled dynamic range.

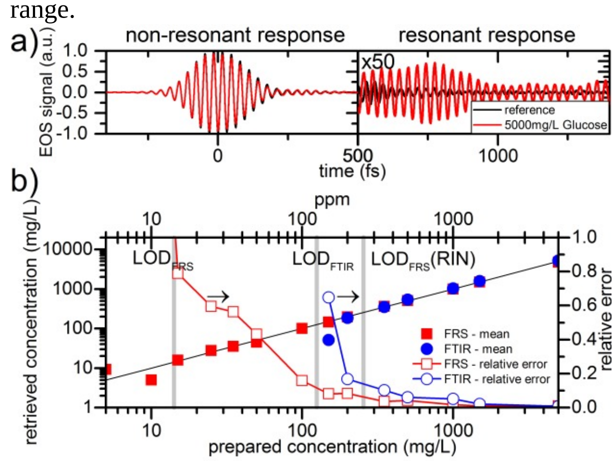

Fig. 1. a) FRS trace of a reference (water, black) and sample measurement (5000 mg/L glucose, red). b) Glucose dilution series: FTIR (blue), FRS (red). The LOD is defined as the concentration at which the relative standard deviation of the retrieved value is 100%.

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Linear and nonlinear Fourier-Transform Spectroscopy in the vibrational Fingerprint Region with a birefringent Interferometer

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Abstract: We introduce a birefringent interferometer for linear and non-linear Fourier-transform spectroscopy in the vibrational fingerprint region. Our interferometer employs the highly-birefringent calomel crystal, is compact, guarantees excellent long-term stability and resolution better than 3 wavenumbers.

Fourier transform (FT) spectroscopy[1] is a powerful technique to measure spectra in the time domain. FT spectrometers have higher signal to noise ratio and optical throughput than frequency-domain spectrometers, and allow to set the frequency resolution. FT spectroscopy is advantageous in the mid-infrared (mid-IR) fingerprint region[2] (1000-2000 cm^{-1}), where array detectors for spectrometers are noisy and expensive. FT spectroscopy requires two field replicas whose delay is scanned with accuracy of a fraction of the optical cycle. The replicas are typically generated by robust, feedback-compensated Michelson interferometers. As an alternative, in birefringent interferometers[3] two cross-polarized fields travel a common optical path, and hence have high long-term stability. We recently demonstrated a birefringent interferometer for FT spectroscopy[4] based on the Translating-Wedge-based Identical pulses eNcoding System (TWINS)[5] with substrates transparent in the near-IR.

In this work we extend the TWINS interferometer to the fingerprint region by using mercurous chloride (Hg_2Cl_2, calomel)[6]. This crystal combines a large birefringence ($\Delta n \approx 0.55$) with transparency ranging from 400 nm to 20 µm. Our calomel TWINS generates pulses with static delay fluctuation of 1/4000th of the optical cycle at 6µm, and maximum achievable delay of 7.5 ps, corresponding to a frequency resolution of 2 cm^{-1}.

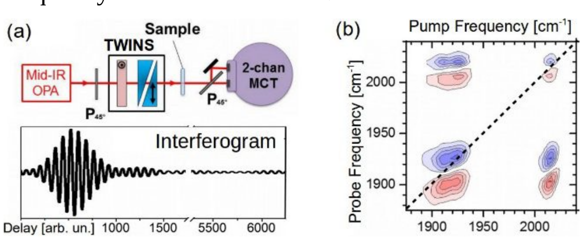

Fig. 1. (a) Scheme of the TWINS-FTIR setup and interferogram of a 6-µm pulse measured at 30% humidity. (b) 2D-IR spectra of the Rhenium carbonyl complex at 0.5 ps delay.

We tested the calomel TWINS using 2-µJ-pulses from an OPA tunable between 2.6 and 10 µm (1000-3800 cm^{-1}). Figure 1(a) shows our FT infrared (FTIR) spectrometer and a typical interferogram. We applied our spectrometer to measure the absorption spectrum of water vapor and to perform 2D spectroscopy in the mid-IR, in the partially collinear pump-probe geometry[7]. We measured Rhenium carbonyl complex in dimethyl sulfoxide. A 2D map at 0.5ps delay is provided in Fig. 1(b): it clearly shows the symmetric mode at 2019 cm^{-1}, two asymmetric ones near 1921 cm^{-1}, and the cross peaks, which reflect the strong coupling between these modes. These measurements confirm that calomel TWINS translates to the mid-IR the advantages of its versions in the visible[5,7].

ACKNOWLEDGMENTS

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Towards the Generation of Isolated Attosecond Pulses with Femtosecond Enhancement Cavities

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Abstract: We demonstrate a power-scalable high-finesse enhancement cavity with integrated half-sided delay masks. This presents a milestone towards an intracavity attosecond lighthouse via wave-front rotation for the production of isolated attosecond pulses at multi-MHz repetition rates.

Isolated XUV attosecond pulses (IAPs) obtained by high-order harmonic generation (HHG) are instrumental for the investigation of ultrafast dynamics in atoms, molecules, solids and plasmas. While current sources operate well below 1 MHz, increasing the repetition rate would, amongst others, benefit experiments involving charged particles, where the desired number of particles per shot is limited by space charge effects, e.g., time-resolved microscopy of nano-plasmonic fields [1].

So far, the most successful technique for HHG at multi-MHz repetition rates is to coherently stack a femtosecond laser in a passive enhancement cavity (EC) to reach the required intensities. Bandwidth limitations of the EC mirrors [2] make it necessary to apply a gating scheme to generate IAPs. We evaluated various methods [3] and identified *transverse mode gating*, a new scheme based on non-collinear gating [4], as most promising in terms of efficiency and robustness for implementation in ECs: Using half-sided delay masks, a delay to one of the lobes of a TEM_{01} mode is first introduced and, after the focus, compensated for (Fig. 1a). An on-axis maximum in the focus is obtained by choosing the delay as N+1/2 cycles [5]. Assuming seeding pulses with parameters readily reachable with Yb-based lasers (0.7-µJ, phase-stable 5-cycle pulses centered at 1.04 µm) and a state-of-the-art EC [2], thorough simulations show that it is possible to generate IAPs with an intensity contrast ratio better than 7 and photon energies around 100 eV at a photon flux of 10^8 photons/s, with repetition rates of 10 MHz and higher [3].

To demonstrate the concept, we fabricated delay mirrors by depositing 2.34 µm material onto one half of a plane mirror substrate before applying a highly reflective coating, and used them in a 3.92-m-long empty EC (Fig. 1b), corresponding to a repetition rate of 76 MHz. The delay is chosen for optimum generation of IAPs as described in [3]. We seeded the EC with a (slightly offset) TEM_{00} mode of a 1064-nm CW laser. The achieved finesse was 652 at an input coupler reflectivity of 99.4%, corresponding to a round-trip loss of 0.36%, or an enhancement of 259 for optimal mode matching. Fig. 1c shows the mode on one plane mirror (imaged in transmission). We also imaged the focus region via reflection off a Brewster plate close to the focus (Fig. 1d), where a clear on-axis maximum is observed [3,5].

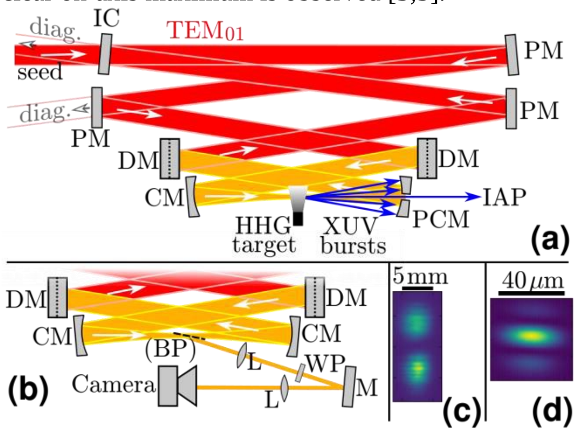

Fig. 1. *a)* Suggested setup for TMG as in [3]. IC: input coupler, diag.: diagnostics, PM: plane highly reflective (HR) mirror, DM: HR delay mirror, CM: curved HR mirror, PCM: pierced curved HR mirror, IAP: isolated attsecond pulse *b)* proof-of-principle experiment. BP: Brewster plate, L: lens, WP: wire-grid polarizer, M: mirror *c)* intensity of the measured mode on the plane mirror and in the focus.

These results demonstrate that the production of delay mirrors with sufficient surface quality is possible and that a cavity with integrated delay mirrors can still feature a high enhancement, even when operated with a large enough mode on the mirrors to allow for high peak powers. With a pulsed seed and broadband cavity mirrors, such an EC will enable wave-front rotation in the focus and, thus, an efficient IAP gating mechanism.

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Direct diode pumped Ti:Sapphire (DDPTS) : The Next Ultrafast Revolution

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Abstract: We report on direct diode pumping of Ti:sapphire (DDPTS) in oscillators and amplifiers with GaN based laser diodes from 445nm to 520nm. While this technology is in its infancy, higher power single emitter laser diodes, and bars promise a revolution in high power ultrafast lasers in the 20fs regime. DDPTS promises new life for the most-widely used ultrafast technology for basic science research, as well as for the bio-medicine and micro-machining.

I. Introduction

Ti:sapphire has been the workhorse gain medium for a myriad of applications in research and industry. However, Ti:sapphire amplifier systems have not yet found broad use outside basic research despite the exceptional performance of the material. This stems from the fact that Ti:sapphire amplifier systems use complex and expensive intracavity-doubled lasers for pumping. Yb-based ultrafast lasers, on the other hand, compromise ultrafast pulse performance for the low cost, practicality and increased reliability allowed by direct diode pumping[1-3].

II. DDPTS

With the commercial availability of high-power blue and green laser diodes based on GaN, direct diode pumping for low-power CW and modelocked lasers has been demonstrated, including for full kerr-lens modelocked ~10 fs ultrafast lasers. However, the real potential for direct diode pumping is in scaling-up power to demonstrate new capabilities beyond simply replacing the pump source. Luckily, the lighting industry (in the form of projection units, headlights, TVs, etc..) are leading the charge in producing ever high powers from single emitters, currently at 4W near 450nm. These devices are also ~4% the price \$/W of conventional intracavity CW 532nm lasers. Figure 1 illustrates this with a 250kHz ultrafast amplifier system using a total of 15W of diode lasers, costing a total of \$260 for the lasers themselves, and \$2000 for the power supplies and chillers. This is in comparison to the nearly \$60,000 it would cost for the same 15W (CW) of 532nm lasers commercially available. We will discuss the challenges and outlook for this technology, for the next generation of ultrafast lasers and amplifiers.

Figure 1. First of its kind, Ti:sapphire oscillator /amplifier pumped with 465nm laser diodes . 3.1 W in the oscillator, and 12W in the cryogenically cooled amplifier producing 3W of amplified power.

III. Future

We believe this technology will revolutionize ultrafast lasers, especially with pulse durations <100fs, energies >1mJ and very high 100kHz repetition rates.

ACKNOWLEDGMENTS

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Relativistic-intensity near-single-cycle laser pulses at 1kHz

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Abstract: We generate high-temporal-contrast 1.3-optical-cycle laser pulses with TW peak power at 1 kHz from a stretched hollow-fiber compressor, which are then used to drive relativistic laser-plasma experiments.

CEP-stable few-cycle light pulses find numerous applications in attosecond science, most notably the production of isolated attosecond pulses for studying ultrafast electronic processes in matter [1]. Scaling up the pulse energy of few-cycle pulses could extend the scope of applications to even higher intensity processes, such as attosecond dynamics of relativistic plasma mirrors [2,3].

Hollow fiber compressors are widely used to produce few-cycle pulses with excellent spatiotemporal quality [4], where octave-spanning broadened spectra can be temporally compressed to sub-2-cycle duration [5,6]. Several tricks help increase the output energy: using circularly polarized light [7,8], applying a pressure gradient along the fiber [9] or even temporal multiplexing [10]. The highest pulse energy of 5 mJ at 5 fs pulse duration was achieved by using a hollow fiber in pressure gradient mode [11] but in this case no CEP stabilization was achieved, which is crucial for most applications of few-cycle pulses. Nevertheless, it did show that in order to scale up the peak power, the effective length and area mode of the fiber had to be increased proportionally, thereby requiring the use of longer waveguides with larger apertures. Thanks to an innovative design utilizing stretched flexible capillaries [12], we recently demonstrated the generation CEP-stable sub-4fs pulses with multi-mJ energy using a 2m length 450mm bore hollow fiber in pressure gradient mode [13].

Here, we show that a stretched hollow-fiber compressor operated in pressure gradient mode can generate relativistic intensity pulses with continuously tunable waveform down to almost a single cycle. The pulses are characterized online using an integrated d-scan device directly under vacuum [14]. At optimal compression, we generate 3.5fs pulses (1.3 cycle at 750nm central wavelength) with 3.5mJ energy, corresponding to 1TW peak power. While the pulse shape is tuned, all other pulse characteristics, such as energy, pointing stability and focal distribution remain the same on target, making it possible to explore relativistic laser-plasma interactions in the few-cycle regime at kHz repetition rate [15].

ACKNOWLEDGMENTS

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Generation of mid-infrared supercontinuum in cascaded fluoride and chalcogenide glass fibers pumped with Tm-based femtosecond amplifier

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Abstract: We have demonstrated mid-infrared (MIR) sequential supercontinuum (SC) generation in fluoride and chalcogenide glass fibers pumped with a Thrium based master oscillator power amplifier. The spectrum of the SC reached up to 10μm.

Broadband mid-infrared (MIR) coherent supercontinuum (SC) is very useful for dramatic improvement of advanced MIR spectroscopy. Pursuit of high energy MIR optical parametric amplifiers (OPA) for use in high harmonic generation lead to development of 2 μm lasers. Such lasers offer promising prospects for MIR SCG in a new scheme, i.e., cascaded SC generation (SCG). A 2 μm lasers can be used for SCG reaching 4 μm with a fluoride glass (ZBLAN) fiber, and a portion of the generated light in the vicinity of 4 μm is subsequently sent to a chalcogenide fiber, which would extend SC even further into the MIR region. The cascaded SCG was proposed in theoretical work a few years ago [1], and two experimental works have been reported with a cascaded fiber system pumped by a 1.55 μm nanosecond laser. In both the works, the spectrum of the final output does not extend beyond 7 μm [2,3].

In this contribution, we have experimentally demonstrated cascaded SCG in fluoride and chalcogenide glass fibers pumped with a thulium (Tm) based femtosecond regenerative amplifier.

The light source of 2 μm pulses was a chirped pulse amplification (CPA) system based on a Tm:YAP solid state regenerative amplifier, which consisted of a Tm:ZBLAN fiber oscillator [4], a grating stretcher, a ring-cavity regenerative amplifier and a grating compressor. We limited the output pulse energy to 10 μJ by reducing the pump power and increasing the repetition rate to 10 kHz.

ZBLAN has low dispersion around 2 μm. Therefore, a simple single-mode fiber can have the zero dispersion wavelength (ZDW) around 2 μm. The output beam from the regenerative amplifier was focused into a ZBLAN fiber with the core diameter of 8 μm, numerical aperture (NA) of 0.2, and length of 1 m. It generates SC that reached 4 μm. The power of the 4μm beam was 3.1 mW (310 nJ) when we pumped the ZBLAN fiber at 20 mW. We focused the ZBLAN output into a tapered chalcogenide fiber. The chalcogenide fiber (SelenOptics) is basically a single-mode fiber made of $Ge_{10}As_{22}Se_{68}$ (core diameter is 11.6 μm; ZDW is 5 μm).

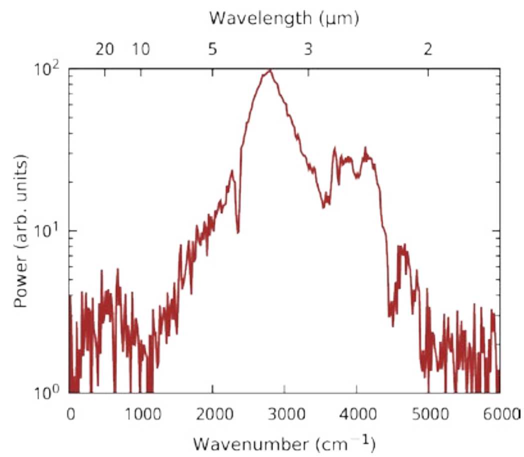

Fig.1. The spectrum of the output from the tapered GeAsSe fiber pumped at 3 mW (300 nJ).

The spectrum of the output beam from the tapered chalcogenide fiber, which is pumped by the SC from the ZBLAN fiber, is shown in Fig. 1. The spectrum extends up to 10 μm (1000 cm^{-1}). As a result, the SC spans more than two octaves (2-10 μm). The broadness of the spectrum is almost the same as that shown in the theoretical paper [1]. The sharp dip at 4.3 μm (2300 cm^{-1}) comes from the absorption of carbon dioxide.

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Few-cycle near-infrared pulses from a narrowband cw injection-seeded femtosecond optical parametric amplifier

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Abstract: We demonstrated for the first time pulse coherent synthesis of a sub-nanometer-linewidth cw injection seeded femtosecond OPA. Pulse durations as short as 19.2 fs (3.9-cycle) at 1.47 μm are readily obtained.

There is keen interest in the generation of few-cycle light due to its potential applications in arbitrary optical waveform generation, high resolution direct comb spectroscopy, as well as asynchronous optical sampling. OPA designs for kilohertz repetition rate pump sources are available delivering pulses with few-optical-cycle pulse duration (Ref. 1). However, achieving short pulses operating at high repetition rate remains particularly challenging, because the peak power utilizing to drive nonlinear effects are reduced as the pulse repetition rate increases. On the other hand, injection seeding of a femtosecond OPA by a sub-nanometer linewidth cw diode laser exhibits superior both the long term and the pulse-to-pulse stability (Ref. 2). In this presentation, a nearly transform-limited (TL) 19.2 fs duration (3.9 cycles at 1470 nm) synthesized pulse is obtained at 53 MHz, which is based on a sub nanometer linewidth cw injection seeded femtosecond OPA.

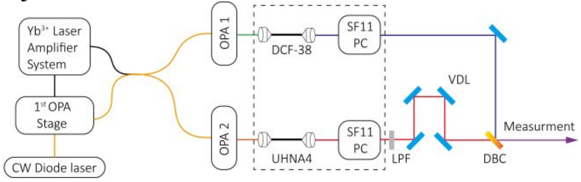

Fig. 1. Schematic diagram of the experimental setup.

The system is outlined in Fig.1. The pump source is a home-made Yb^{3+} amplifier system delivering up to 6 W average power at 53 MHz. The output pulse is 100 fs at FWHM, with a central wavelength of 1040 nm. It is directly followed by a narrow linewidth cw-seeded OPA stage. Then, the generated pulse feeds two further parallel secondary OPA stages. Additionally, in order to generate tailored broadband spectra pulses, each output beam is coupled into a commercial high nonlinear fiber. Finally, a dichroic beam combiner is used to synthesize the output pulses.

In branch 1, we select a commercial dispersion fiber to generate a broadband wave with a FWHM bandwidth of 175 nm centered at a wavelength of λc=1405 nm. For branch 2, a HNF fiber is adopted to produce another broadband spectra at λc=1590 nm, resulting in a bandwidth of 120 nm. Therefore, the combined spectrum extends from 1250 nm to 1670 nm (see Fig. 2(a)).By optimizing the intensity ratio between the two channels, a modified pulse profile is obtained. Fig. 2(b) shows the interferometric two-photon autocorrelation traces of the synthesized pulse, which presents a 19.2 fs Gaussian pulse (close to a transform-limited pulse duration of 16 fs), corresponding to 3.9 optical cycles at 1470 nm. Fig. 2 (c) reports the intensity envelope and temporal phase of the synthesized pulse (retrieved from a phase and intensity from cross correlation and spectrum only). Thanks to the CEP-preserving properties between the output and the narrowband cw seed, we are able to generate a few-optical-cycle synthesized pulse. With intrinsic phase preserving to the cw laser, such an OPA system is believed to be of great interest for frequency comb generation, attosecond science and extremely nonlinear optics.

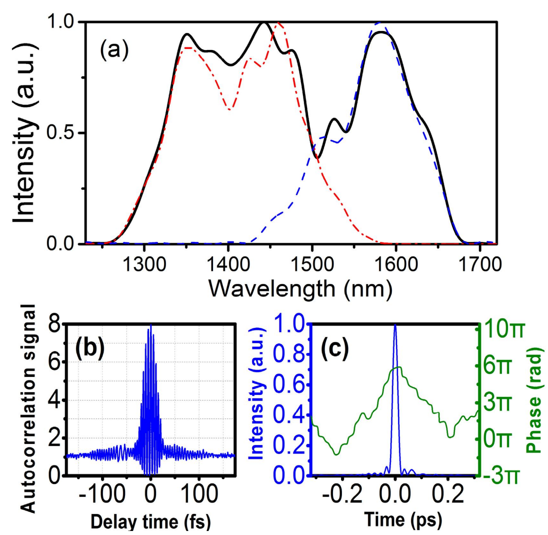

Fig. 2. Spectra, interferometric autocorrelation as well as temporal intensity envelope and phase of the synthesized pulses

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Few-cycle picosecond-pumped OPCPA system for relativistic laser-matter interaction experiments

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Abstract: Few-cycle pulses with relativistic intensity and excellent temporal contrast are of high demand for laser-matter interaction experiments. Here we report on the Petawatt Field Synthesizer that is an OPCPA system designed to generate such pulses.

I. Introduction

The Petawatt Field Synthesizer (PFS) under construction at the Max-Planck Institute of Quantum Optics is an optical parametric chirped pulse amplification (OPCPA) system designed to generate few-cycle pulses with petawatt-scale peak power and excellent temporal contrast[1, 2]. Such pulses are of high interest for laser-matter interaction experiments including the generation of isolated attosecond pulses with unprecedented efficiency[3] by surface high-harmonic generation (SHHG). Here we report on the current performance and upgrade plans of PFS.

II. PFS concept

The general scheme of the PFS laser system is shown in Fig. 1. Pump and seed chains are seeded by the same Ti:Sapphire master oscillator to ensure good temporal synchronization of pump and signal pulses in the OPCPA stages. A home-built diode-pumped Yb:YAG chirped-pulse pump laser, consisting of several amplifier stages, delivers J-scale sub 1 ps pulses with 10 Hz repetition rate after compression and frequency doubling.

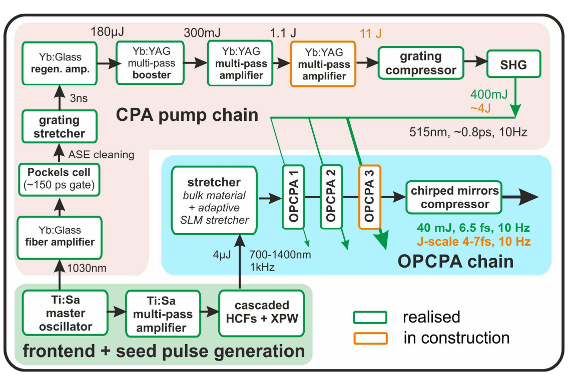

Fig. 1. Schematic layout of the PFS system.

The seed pulses with the spectral range of 700-1400 nm are generated by spectral broadening of the output of a Ti:Sapphire amplifier in two cascaded hollow-core fibers filled with neon, followed by a cross-polarized wave generation stage for temporal pulse cleaning. The seed is then amplified in OPCPA stages using LBO crystals. Two stages being currently in operation deliver more than 40 mJ and the third OPCPA stage being under construction is planned to scale the energy to 0.5-1 J. The measured after a chirped mirror compressor pulse duration of the amplified pulses is 6.4 fs corresponding to about 2 optical cycles. Using an f/1.3 off-axis parabolic mirror, a relativistic peak intensity of more than 4×10^{19} W/cm^2 was demonstrated.

The temporal contrast of amplified pulses measured with a third order autocorrelator is better than 5×10^{-12} (limited by the detector noise) on the few-picosecond time scale. This excellent result is achieved due to the sub-picosecond duration of our pump pulses without the implementation of a plasma mirror. The parameters of PFS system, namely excellent temporal contrast, relativistic intensity and few-cycle pulse duration, make it very suitable and promising for high field physics experiments. We report also on the first PFS experimental results on SHHG aiming on the generation and temporal characterization of intense isolated attosecond pulses.

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Progress in the development of high average power, high energy short pulse lasers

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Abstract: High energy, chirped pulse amplification lasers will be presented including the demonstration of a picosecond laser that produced 1.5J pulses at 500Hz repetition rate. Prospects for scaling in repetition rate and energy will be discussed.

The development of short pulse lasers with simultaneously high pulse energy and high average power is critical for progress in many active research areas and industrial applications. These include the production of both coherent and incoherent, short wavelength radiation through techniques including plasma-based soft x-ray lasers, high harmonic generation, incoherent plasma sources of extreme ultraviolet (EUV), soft and hard x-rays, and Compton-scattering-based sources of γ-ray. Additionally, these lasers are anticipated to play a key role in the development of practical, compact particle accelerators. Furthermore, the continued development of extremely short duration sources based on optical parametric chirped pulse amplification (OPCPA) and related techniques relies heavily on the development of picosecond-duration pump lasers, of which these lasers are particularly well suited.

We have developed an all-diode-pumped, chirped pulse amplification (CPA) laser that produces picosecond duration, 1 Joule pulses at 500 Hz repetition rate[1]. This laser is shown conceptually in Fig. 1(a). Stretched, millijoule-level $\lambda = 1.03\mu m$ pulses produced by the water-cooled laser frontend are amplified by a chain of two cryogenically-cooled Yb:YAG thick disk active mirror amplifiers, first to 100 mJ, and subsequently to the joule-level. Fig. 1(b) shows the measured pulse energy exiting the final amplifier as a function of pump energy. An amplified pulse energy of 1.5 J is obtained at 500 Hz repetition rate, 0.75 kW average power. These pulses have excellent beam quality ($M^2 \approx 1.3$) and excellent long term stability (0.75% RMS over 30 min continuous operation). and are then compressed to about 5 ps duration by a dielectric grating pair compressor. As a first application, this laser was employed to drive a $\lambda = 18.9$ nm plasma-based soft x-ray laser at 400 Hz repetition rate[1]. The cryogenically-cooled Yb:YAG active mirror-based power amplifier modules implemented in this laser are compact and reconfigurable allowing for a variety of pulse energy / repetition rate combinations as well as scalability to kilowatt average powers.

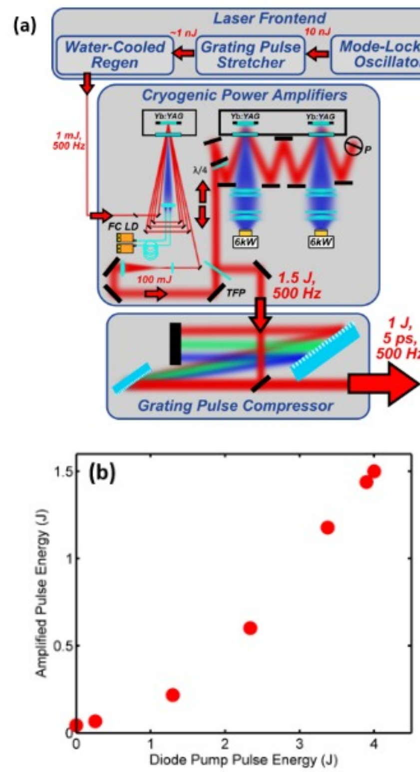

Fig. 1. (a) Layout of the 1 J, 500 Hz, 5 ps laser system. (b) Measured pulse energy exiting the final amplifier at 500 Hz repetition rate as a function of laser diode pump energy.

ACKNOWLEDGMENTS

The laser development was supported by the U.S. Department of Energy SBIR program under award DE-SC0011375 and by the DOE Accelerator Stewardship program under award DE-SC0016136. Soft x-ray laser work was supported by the National Science Foundation under grant ECCS-1509925 and by the DOE, Office of Science, Basic Energy Sciences, under Award #DE-FG02-04ER15592.

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Modelocked thin-disk lasers: towards kilowatt-class ultrafast oscillators

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Abstract: We present latest progress and ongoing challenges toward kilowatt-class modelocked thin-disk oscillators and review recent developments using these laser systems as drivers for compact high-power sources ranging from the THz to the XUV.

Ultrafast lasers based on the disk technology have made impressive progress in the last decade. Their geometry is particularly well-suited for power and energy scaling of ultrashort pulses: the thin, disk-shaped gain medium combined with large mode areas, results both in nearly unrestricted power scalability, and low accumulated nonlinearities. In the last few years, the kilowatt level has largely been surpassed by disk laser amplifier systems [1].
Among these laser systems based on the disk technology, one particular technology attracts attention as a potential path to achieve the desired level from a simple, one-box, multi-MHz repetition rate oscillator: modelocked thin-disk oscillators can reach hundreds of watts of average power with femtosecond pulses, with multi-MHz repetition rates. Exponential progress in the achievable levels is only an illustration of their enormous potential. So far, these oscillators reach up to 275 W average power, and pulse energies up to 80 µJ, both based on Yb:YAG thin-disk lasers [2]. The continuous progress achieved with these lasers is a clear illustration of their large potential to reach much higher levels in the very near future. Current active research directions for these laser systems are reducing their pulse duration by using novel gain materials, and increasing average power and pulse energy to the kilowatt and millijoule levels. In this presentation, we will review the state-of-the-art of these lasers system and present ongoing efforts towards reaching the kilowatt milestone.

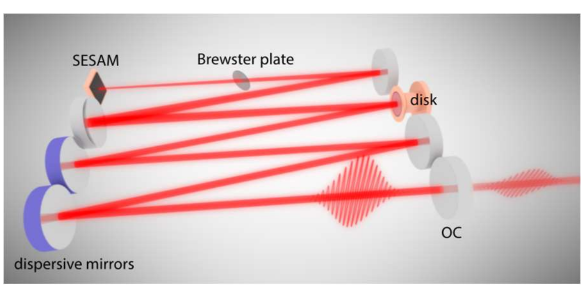

Fig. 1. A high-power modelocked thin-disk laser can deliver hundreds of watts in resonators with similar layout to that of a low power bulk ultrafast oscillator.

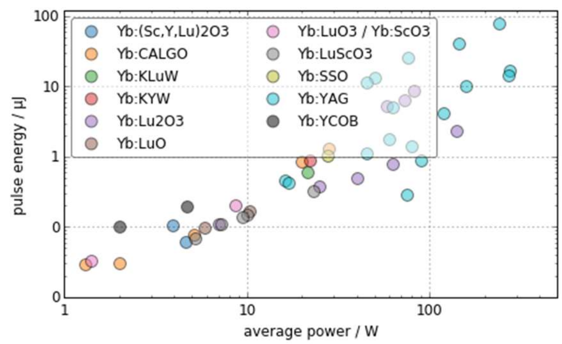

Fig. 2. Overview of modelocked thin-disk laser technology: pulse energy versus average power of laser systems demonstrated up to date.

Furthermore, important research efforts are currently being devoted to exploit the potential of these sources as compact driving lasers to reach a much wider wavelength range, spanning from the XUV via high harmonic generation [3], all the way into the THz range for a wide range of applications. We will present our first efforts towards using these sources for the generation of high-power THz pulses.

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Kerr lens mode-locked thin-disk lasers delivering 30-fs pulses from Yb:CALGO and 35-fs pulses from Yb:Lu_2O_3

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Abstract: For more than 15 years, ultrafast thin-disk lasers generated longer pulses than Yb-based bulk oscillators. We overcome this limit, achieving durations equal to the shortest Yb-bulk oscillators and 40 % shorter than previous thin-disk lasers.

Since their first demonstration, ultrafast thin-disk laser (TDL) oscillators delivered longer pulses than mode-locked Yb-based bulk oscillators (see Fig. 1). Yb-bulk oscillators generate pulses as short as 30 fs, but only at a low power level of 26 mW[1]. The power levels in the bulk geometry are limited by thermal effects and high nonlinearities in the gain crystal. Spectral bandwidths and consequently pulse durations are restricted by the need of pumping through an intra-cavity dichroic mirror with high pump transmission. On the other hand, TDLs do not require pump transmission mirrors and operate with a very thin gain medium. They were demonstrated to generate average output power up to 275 W in 583 fs pulses[2]. However, so far the minimum pulse duration of ultrafast TDLs was limited to 49-fs[3,4], being 60 % longer than Yb-bulk oscillators[1].

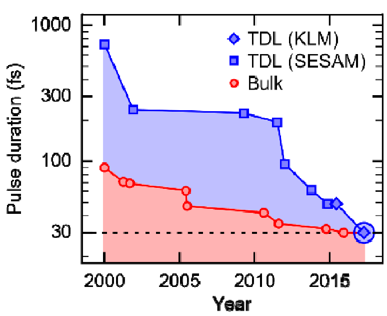

Fig. 1. Evolution of minimum pulse duration for Yb-based bulk (red) and TDL (blue) oscillators. The presented result is highlighted with a circle.

In this contribution, we present two Kerr lens mode-locked (KLM) thin-disk lasers that achieve the shortest pulse durations from their respective gain materials. Our KLM Yb:Lu_2O_3 TDL generates 4.5 W in 49-fs pulses and 1.6 W in 35-fs pulses (50 % shorter than Yb:Lu_2O_3 bulk lasers[5]). In addition, we demonstrate the first KLM Yb:CALGO TDL. It generates 30-fs pulses, which is the shortest duration ever obtained from ultrafast TDLs[3,4] and equal to the shortest pulses obtained from Yb-bulk oscillators[1].

The two lasers are based on a 160-µm-thick Yb:Lu_2O_3 and a 150-µm-thick Yb:CALGO disk. An undoped YAG plate is placed under Brewster's angle in the focal region between two concave mirrors with a radius of curvature of 400 mm for Yb:Lu_2O_3 and 250 mm for Yb:CALGO. The plate serves as Kerr medium while a water-cooled pinhole acts as hard aperture for mode locking. At an output coupling rate of 0.9 %, the Yb:Lu_2O_3 oscillator generates 1.6 W in 35-fs pulses at a repetition rate of 61 MHz. The Yb:CALGO laser emits 150 mW in 30-fs pulses at a repetition rate of 124 MHz, the output coupling rate is 0.3 %. With 34-nm FWHM, the optical spectrum of the 35-fs pulses is nearly 3 times broader than the emission bandwidth (FWHM) of Yb:Lu_2O_3, whereas the 30-fs pulse spectrum (46-nm FWHM) covers approximately 50 % of the fluorescence band of Yb:CALGO.

Our results indicate the advantages of KLM TDLs for reducing the pulse durations of Yb-based oscillators. We expect that Yb-based sub-20-fs TDLs with tens of watts output power will be demonstrated in the near future.

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Multi-mJ CEP-stable few-cycle pulses at 6 kHz from a thin-disk pumped OPCPA used for high-harmonic generation

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Abstract: We present an optical parametric chirped pulse amplifier (OPCPA) delivering CEP-stable ultrashort pulses with 7 fs and pulse energies > 1.8 mJ at 6 kHz repetition rate. High-harmonic generation in various noble gases is currently under progress.

I. OPCPA

High-energy few-cycle pulses at high repetition rates are favorable for high-harmonic generation (HHG) to increase the signal-to-noise ratio in modern attosecond time-resolved spectroscopy (Ref. 1). A multi-mJ OPCPA system at 6 kHz and its potential for HHG in various noble gases is presented.

I.A. Setup and experimental results

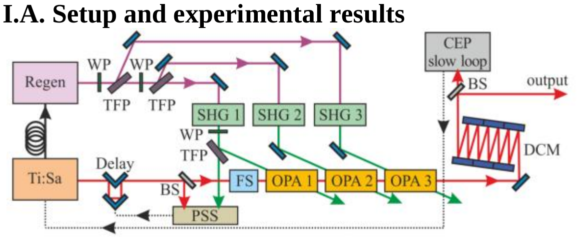

Fig 1. Layout of the system. Ti:Sa: Titanium-sapphire oscillator, Regen: regenerative thin-disk amplifier, BS: beam splitter, WP: waveplate, TFP: thin-film polarizer, SHG: second harmonic generation, PSS: pump-seed synchronization, FS: fused silica stretcher, DCM: double-chirped mirror compressor.

The schematic layout of the system is depicted in Fig. 1. A CEP-stable Ti:Sa-oscillator (venteon dual CEP) simultaneously seeds the regenerative amplifier and the OPCPA, providing optical synchronization between pump and seed source. The pump delivers 1.3 ps pulses with 28.3 mJ at 6 kHz from an Yb-doped thin-disk. Frequency doubling to 515 nm is performed in three separate SHG-stages, placed close to the OPAs to minimize nonlinear effects in air. The temporal overlap of the interacting pulses is locked in time with < 2 fs remaining timing jitter by active pump-seed synchronization (PSS) (Ref. 2). After stretching along 20 mm of fused silica, the seed is amplified from 0.5 nJ to >5 µJ in OPA 1, further to ~0.8 mJ in OPA 2 and finally to >2.0 mJ in OPA 3. The pulses are compressed to 7 fs by 14 bounces in a double-chirped mirror compressor (Fig. 2). Slow CEP-fluctuations, detected in an f-to-2f interferometer (Menlosystems GmbH APS800), are compensated via a feedback to the seed source to < 300 mrad, measured over 20 min. At the output, pulse energies > 1.8 mJ (10.8 W) with a peak power exceeding 160 GW are available. Pulse-to-pulse fluctuations < 1.8 %, measured over 100000 pulses, and excellent power long-term stability over hours render the system well suited for HHG, which is currently under progress. High order harmonics with a cutoff energy beyond 80 eV have recently been demonstrated in Neon.

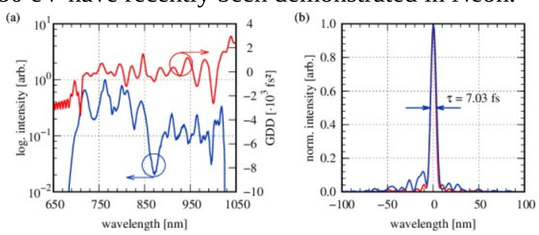

Fig. 2. OPCPA pulse characteristics, measured with SPIDER. (a) Fundamental spectrum and reconstructed GDD, (b) reconstructed temporal pulse shape (blue) and Fourier-transform-limited pulse of 6.6 fs (red).

II. CONCLUSIONS

Energetic CEP-stable few-cycle pulses at multi-kHz repetition rate are generated in an OPCPA. Their application to HHG is currently investigated.

ACKNOWLEDGMENTS

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All solid state multipass spectral broadening down to 10 fs Fourierlimit

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Abstract: 100 W, 220 fs pulses from a thin-disk Yb:YAG oscillator are spectrally broadened in a fiber-free manner down to 10 fs Fourier limit with an efficiency of 70%.

I. Introduction

Spectral broadening fibers operated at high average (>50 W) and high peak powers (>10 MW) are sensitive to alignment and prone to damage. A newly demonstrated concept for multipass bulk broadening in a waveguide-like structure [1] showed that previous limitations regarding efficiency and beam quality can be overcome [2, 3]. Here we show that this concept can be pushed further down to sub 10 fs in Fourier transform limit (FTL) by proper dispersion management. The high efficiency and good beam quality (see Fig. 1b) are preserved. This progress paves a way to all solid state, compact and robust diode pumped laser-oscillators for MIR and XUV generation with MHz repetition rate.

II. Setup

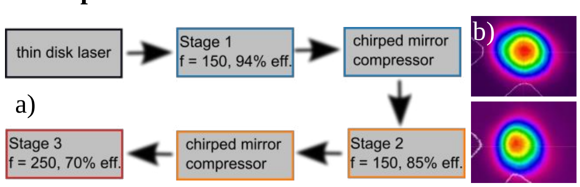

Fig. 1 a) Setup schematics b) Beam Profile at low power, no nonlinear effects (top) and high power throughput (bottom)

Schematics of the system are depicted in Fig. 1a. The driving laser, a high power Kerr-lens mode-locked thin-disk Yb:YAG oscillator similar to [4], emits over 100 W average power at 28 MHz with 3.5 µJ pulse energy and a pulse duration of 220 fs resulting in 14 MW peak power. The spectral broadening setup consists of three Herriott cells (HC). The first and the second HC comprise common highly reflective mirrors and anti-reflective coated substrates placed in the center of the HC. No dispersive optics are incorporated inside of these two cells. The HC are designed to provide a nonlinear phase shift per pass on the order of 0.5 rad. The first stage includes 1 inch mirrors with 300 mm radius of curvature (ROC) making 12 passes through two 6.35 mm thick fused silica (FS) windows. Subsequent chirped mirrors compress the oscillator output to 110 fs, thus, leading to a spectral broadening and compression factor of 2 (Fig. 2, blue line). The pulse energy measured after the compressor of the first stage is 3.2 µJ showing 94 % efficiency. The second broadening stage similar to the first one with a single FS window and chirped mirror compressor shortens the pulse further to 55 fs preserving above 3 µJ pulse energy with an overall efficiency of 85 % (Fig. 2, orange line). The final broadening is realized in a third stage consisting of 2 inch complementary dispersive mirrors with 500 mm ROC. 38 passes through a 6.35 mm broadband AR coated FS window are realized. The dispersive mirrors were designed to

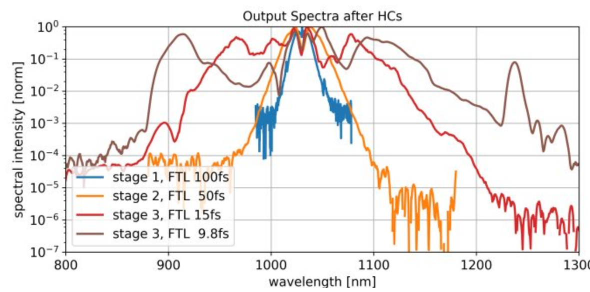

Fig. 2 Spectra after broadening stages

compensate for the material dispersion of the window. This compensation ensures approximately constant pulse duration and peak power over all passes such that during each pass a reasonable nonlinear phase-shift of 0.6 rad is accumulated. After the final stage the FTL of the pulse spectrum reaches sub 10 fs with 2.5µJ pulse energy (Fig. 2, brown line). Compressing the pulse close to the FTL would yield peak powers of 140 MW. With a different set of dispersive mirrors a FTL of only 15 fs can be achieved which highlights the importance of dispersion management (Fig. 2, red line).

III. Conclusion

We demonstrated an efficient fiber-free and power scalable pulse compression scheme down to 10 fs FTL. A spectral broadening factor of 22 is achieved by means of implementing three HCs with FS plates inside. The high power throughput of 70 %, the peak power increase by one order of magnitude, its robustness and simplicity make it an attractive alternative to fiber based systems.

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Compact megahertz repetition rate coherent XUV light source based on HHG inside a modelocked thin-disk laser

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Abstract: We demonstrate intracavity high-harmonic generation inside a SESAM-modelocked Yb:Lu_2O_3 thin-disk laser at ~2.3×10^{13} W/cm^{-2} peak intensity and 300 W average power, generating XUV light down to 60.8 nm (17th order) at 17.4-MHz repetition rate.

High-harmonic generation (HHG) inside passive enhancement cavities is one of the most successful techniques for high repetition rate extreme ultraviolet (XUV) light generation.[1,2,3] However, stable input coupling of pulses from a complex ultrafast amplifier system into a passive enhancement cavity is very challenging, even with state-of-the-art locking electronics. Placing the HHG interaction directly inside a modelocked laser is a simpler and more compact approach. In 2012, its feasibility was demonstrated using a Ti:sapphire laser.[4] However the intracavity average power was limited to 10 W since ultrafast lasers using bulk crystals are strongly limited in average power. This is not the case for thin-disk lasers (TDL), which achieve the highest average power and pulse energy of any modelocked laser.[5,6]

In this presentation, we demonstrate the first HHG inside an ultrafast TDL. We operate at ~300 W intracavity average power and generate harmonics up to the 17th order, corresponding to 20.4-eV photons. The TDL technology is power-scalable, therefore we expect that our approach can lead to a new class of compact, transportable, and powerful XUV sources for many applications.

Our SESAM modelocked TDL is built inside a vacuum chamber (Fig. 1a) and uses a 160-µm thick diamond-mounted Yb:Lu_2O_3 disk. The SESAM for self-starting passive modelocking is used as an end mirror in one cavity arm. The other cavity arm contains a tight focus with ~12-µm laser mode radius. A quartz nozzle with a ~100-µm opening is placed above the intracavity focus. The modelocked TDL operates with OC rate of 2×0.7 % at a central wavelength of 1033 nm with a repetition rate of 17.4 MHz. The 297-fs pulses have 17.7 µJ intracavity energy (Fig. 1b), corresponding to a peak intensity ~2.3×10^{13} W/cm^2 at the focus. We use a 250-µm thick sapphire wedged plate placed at Brewster's angle to out-couple the XUV light. HHG is observed when a xenon gas jet is emitted into the focus. We use ~3.4 bar of backing pressure. Our monochromator (1200-g/mm iridium-coated grating) was set to 3.4-nm resolution.

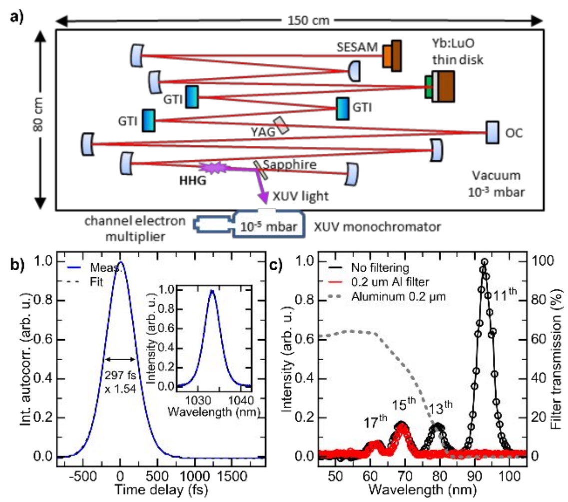

Fig. 1. Experimental setup (a), laser pulses intensity autocorrelation trace and optical spectrum (b), XUV light spectra (c).

The diffracted XUV photons are detected by a channel electron multiplier. We acquire the spectra of the generated XUV light (Fig. 1c) with and without a 0.2-µm thick Al filter to exclude any uncertainty on the observed harmonics' orders. High harmonics with orders up to the 17th (wavelength of 60.8 nm) are detected, in accordance with prediction from the cut-off formula.[7] As next steps, we plan measuring the conversion efficiency of the process and optimizing phase-matching conditions. We also target an increase of the intracavity average power and operation with shorter pulses by implementing Kerr-lens modelocking.

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Dual-comb spectroscopy with one unstabilized semiconductor laser

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Abstract: We can demonstrate a novel ultrafast dual-comb modelocked semiconductor source, optimized for high-performance, fast, and accurate dual-comb molecular spectroscopy, for key relevant applications in health, safety, energy, chemical, and environmental industries.

I. MIXSEL-comb

To date, stabilized gigahertz optical frequency combs (OFCs) have had to rely on rather bulky and complex ultrafast diode-pumped solid-state, fiber, or Ti:sapphire lasers. In comparison, optically pumped semiconductor disk lasers (SDLs) such as the MIXSELs (Modelocked Integrated eXternal-cavity Surface Emitting Lasers) [1] are often better suited for mass production and widespread applications, as they are based on a wafer-scale technology with reduced packaging requirements and potentially a higher level of integration. The MIXSEL-comb also provides very stable OFCs even without any further active stabilizations: for example without any further active stabilization a single 2-GHz MIXSEL comb has a comb line spacing variation of only $\approx 2.5 \ 10^{-4}$ integrated over a measurement time of 10 ms [2], which is a longer measurement time than required for most dual-comb spectroscopy applications (typically > 1 µs to ideally ≈1 ms). The high peak power supports significant spectral broadening in external fibers and waveguides. Furthermore, semiconductor bandgap engineering has the potential in the long run to adjust the OFC center wavelength.

II. Dual comb modelocking

The simplicity of the dual-comb MIXSEL allows for fundamental modelocking in a simple straight linear cavity. For a dual-comb modelocked operation [3] we insert a birefringent crystal inside this linear cavity, which splits the cavity beam on one side towards the MIXSEL chip into two spatially separated and cross-polarized beams with slightly different optical cavity roundtrip path-lengths, defining a small difference in the comb frequency spacing Δf_{rep} of 4 MHz. This frequency difference can be adjusted by the thickness of the intracavity birefringent crystal.

III. Dual-comb spectroscopy demonstration

We have demonstrated dual-comb spectroscopy on water vapor with a single modelocked laser cavity for the first time [4]. A fast scan rate and the single laser cavity approach supports such measurements even for a free-running laser without any additional external spectral broadening and stabilization. This is a potential paradigm shift in frequency metrology: to use a narrowband, stable OFC, which is then tuned to the desired spectral range based on the specific target to be tested and a dual-comb MIXSEL generates two OFCs from the same laser cavity.

IV. CONCLUSIONS

In this talk we will review the recent progress in MIXSELs [5], SESAM modelocked VECSELs [6], dual-comb modelocking and noise performance which makes these sources so attractive for dual comb spectroscopy and biomedical microscopy applications.

ACKNOWLEDGMENTS

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Supercontinuum generation with silicon-nitride photonic waveguides and 15-30 GHz ultrafast sources

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Abstract: We demonstrate coherent octave-spanning supercontinuum spectra and carrier-envelope-offset frequency detection in silicon-nitride waveguides using both electro-optic and microresonator ultrafast sources with repetition rates greater than 10 GHz.

Frequency comb sources with pulse repetition rates larger than 10 GHz, such as electro-optic (EO) combs[1] and microresonator combs[2], have been challenging to spectrally broaden[1]. Nevertheless, broadband, stabilized high-repetition-rate sources are valuable for applications in astronomy[3], microscopy[4], and precision spectroscopy[5], among others. In this work, we use ultrafast EO and microresonator sources at 15 and 30 GHz in combination with silicon nitride (SiN) waveguides to produce spectra having optical bandwidth beyond an octave. Furthermore, we demonstrate that spectral coherence is maintained in each case by detecting the comb offset frequency at the second-harmonic of the 1550 nm pump lasers.

The waveguide devices used in this work have an oxide-clad geometry and a length of 15 mm, thickness of 800 nm, and width of 1800 nm. A schematic of the experimental setup is shown in Fig. 1a. For both combs, a pulse shaper is first used to compensate fiber-path dispersion to achieve a compressed pulse at the output of a 4 W amplifier. After amplification, the pulse undergoes normal-dispersion broadening in 5 m of highly-nonlinear fiber before final compression with a grating pair. This compressed pulse is then free-space coupled into the waveguide with an insertion loss of approximately -1.5 dB.

Using this configuration, the 30 GHz EO comb seeds the waveguide with 80 pJ, 100 fs pulses. The SC spectrum, shown in Fig. 1c, exhibits a high-degree of smoothness between 800 nm and 1300 nm, an important quality for applications in astronomy. Dispersive-wave enhancement of the spectrum at 775 nm can be used to detect the comb offset frequency. However, due to the multiplication of thermal noise in the source RF synthesizer, the linewidth is >10 MHz and the signal-to-noise ratio is limited to about 20 dB (see blue curve in Fig. 1b).

Alternatively, the waveguides can be pumped with a 15 GHz silica-disc soliton microresonator source[6]. As with the EO comb, offset-frequency detection is enabled by efficient dispersive wave generation (red curve in Fig. 1b). Full stabilization of the comb has been accomplished by locking both the repetition rate, using pump laser feedback, and the comb offset, using an acousto-optic modulator.

With the significantly increased spectral coverage shown here, these developing comb technologies are now positioned to provide real benefits to the aforementioned fields.

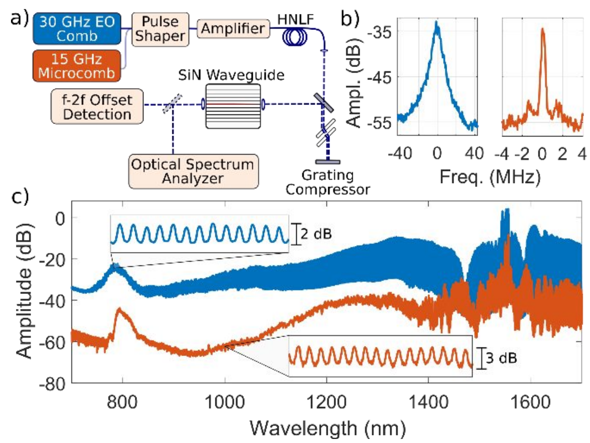

Fig. 1: a) Experimental schematic (HNLF: highly-nonlinear fiber). b) Detected offset frequency of 30 GHz EO comb (left) and 15 GHz microcomb (right) at 775 nm. c) Experimental supercontinuum with comb-mode-resolved regions as insets.

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A robust source of broadband infrared pulses from a few-cycle Er:fiber laser

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Abstract: We present a robust scheme for generating few-cycle pulses at 1.55 μm by employing normal dispersion broadening and bulk fused silica compression. This source is used to generate octave-spanning infrared spectra from 6-12 μm.

Broadband, long-wavelength infrared (LWIR) frequency combs generated from ultrafast lasers hold the promise of molecular fingerprinting for industrial, commercial, and scientific applications[1]. However, the availability of robust, broadband LWIR sources is still lacking. In this work, we demonstrate the development and utilization of a few-cycle source centered at 1.55 μm to generate octave spanning LWIR spectra via difference frequency generation (DFG) in an orientation patterned gallium phosphide (OP-GaP) crystal.

To generate the few-cycle seed at 1.55 μm, we start with an Er:fiber oscillator with a repetition rate of 100 MHz. We amplify the pulses to 175 mW using an erbium-doped fiber amplifier (EDFA), resulting in a pulse duration of 50 fs. The output of the amplifier is then spliced directly to a 5 cm normal dispersion highly non-linear fiber (ND-HNLF), resulting in non-linear broadening of the spectrum. In contrast to previous work[2], spectral broadening in the normal dispersion regime results in a positive frequency chirp that can easily be compensated to compress the pulse to the few-cycle limit by using anomalously dispersive, bulk fused silica. The compressed pulse contains 150 mW of power and exhibits a duration of 15 fs (see Fig. 1).

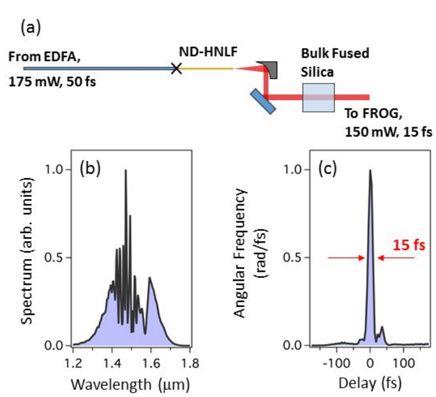

Fig. 1. (a) Scheme for generating a few-cycle 1.55 μm pulse. (b) Spectrum and (c) reconstructed pulse envelope of the few-cycle pulse.

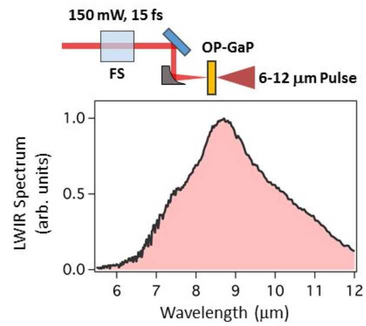

Fig. 2. Experimental layout and resulting LWIR spectrum generated from the 15 fs signal pulse.

The temporally overlapped, broadband spectral components in the few-cycle 1.55 μm laser opens the possibility of LWIR generation through intra-pulse DFG[3]. In this work, we demonstrate the generation of broadband, LWIR spectra in an OP-GaP crystal, a material exhibiting a very high nonlinearity and broad transparency range (0.5 – 12.5 μm)[4]. By simply focusing the few-cycle pulse into the OP-GaP crystal, we can generate ~ 100 μW in an octave spanning spectrum centered at 8.5 μm (Fig. 2).

Future work will investigate scaling the LWIR power by compressing the few-cycle driver, scaling the input power, and engineering the orientation patterning of the GaP crystal. With such a robust and simple source, dual comb spectroscopy should become a reality within the molecular fingerprint region spanning 6 – 14 μm.

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Watt-level femtosecond 10-GHz SESAM modelocked Yb:CALGO laser operating in the normal dispersion regime

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Abstract: We present a straight-cavity SESAM-modelocked 10-GHz Yb:CALGO laser delivering 166 fs at 1.2 W, which features a low-loss fanout-apodized-PPLN crystal providing negative self-phase-modulation via cascaded second-order nonlinearities and acting as a defocussing lens for Q-switching-damage-suppression.

Compact SESAM-modelocked diode-pumped solid-state lasers with repetition rates in the multi-gigahertz regime[1-3] are attractive sources for all applications where individually resolvable frequency comb lines are desired. The main challenges when designing multi-gigahertz solid-state lasers consist of the small cavity size, which limits the choice and arrangement of optical components, and the intrinsically low intracavity pulse energy increases Q-switching instabilities[4] when using a semiconductor saturable absorber mirror (SESAM).

Here, we present a novel 10-GHz straight cavity design containing a 1.5-mm long Yb:CALGO crystal as the gain medium, a fanout and apodized periodically poled lithium niobate device (PPLN)[5], and a SESAM for starting and stabilizing the modelocking (Fig.1). The gain crystal is pumped at 980 nm using a spatially multimode ($M^2\approx36$) diode.

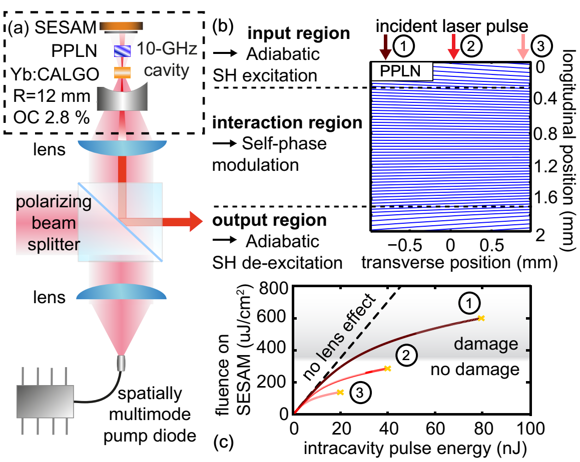

Fig. 1. (a) Straight cavity setup. (b) Fanout + apodized PPLN device. (c) Fluence on the SESAM as a function of pulse energy for different transverse positions of the PPLN with respect to the incident pulse.

The PPLN device serves three purposes:

1) It provides large, laterally tunable negative self-phase modulation by operating in the so-called cascading-$\chi^{(2)}$-regime, and hence enables soliton modelocking using positive material dispersion.

2) It acts as a negative, i.e. self-defocusing Kerr lens, which increases the laser mode on all cavity elements as a function of intracavity pulse energy, thus protecting the elements from damage that would otherwise occur due to Q-switching instabilities when ramping up the power.

3) It helps to lower the overall Q-switching threshold in order to reach stable continuous wave (cw) modelocking at low intracavity pulse energies.

Using this technique, we have achieved self-starting modelocking with an average output power up to 1.2 W and transform-limited pulses as short as 166 fs (optical bandwidth of 7 nm, Fig. 2.), which corresponds to the first demonstration of a Watt-level femtosecond directly diode-pumped SSL with a repetition rate > 10 GHz.

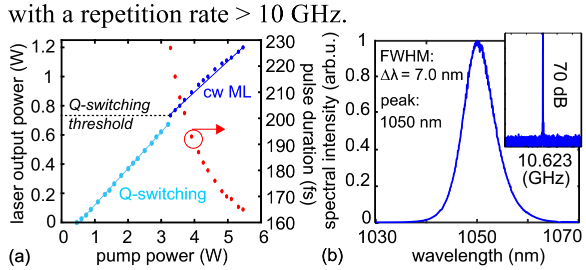

Fig. 2. (a) Laser output power and pulse duration as a function of pump power. (b) Optical spectrum and radio frequency trace (inset) with a span of 5 MHz and a resolution bandwidth of 3 kHz.

ACKNOWLEDGMENTS

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Towards high-energy, sub-cycle pulses at PHz frequency

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Abstract: We report on the design of an OPCPA-field synthesizer for generating mJ, sub-cycle pulses. A 1-ps, Yb:YAG thin-disk amplifier is used as the front end of the system. A superoctave, CEP-stable spectrum is generated directly from the amplifier and subsequently amplified in two OPCPA channels of the synthesizer.

I. INTRODUCTION

So far, generation of high flux, isolated attosecond pulses via high harmonic generation (HHG), has been limited to 530 eV [1]. Extension of the harmonics cutoff to X-ray regime calls for single-cycle to sub-cycle pulses, with multi-millijoule energy and at longer central wavelength. We report on the design and preliminary results of a field synthesizer based on Yb:YAG-pumped optical parametric chirped pulse amplification (OPCPA). The system keeps promise to extend the HHG cutoff to higher photon energies.

II. EXPERIMENTAL RESULTS

The experimental setup is illustrated in Fig. 1 [2,3]. An Yb:YAG thin-disk regenerative amplifier delivering 20mJ, 1ps pulses at 5kHz repetition rate [4] is used as the front end of the system. 1 mJ of the total energy of the amplifier is separated by using an attenuator and used to generate intrinsically carrier-envelope phase (CEP) stable supercontinuum in a setup containing several nonlinear processes [5]. The supercontinuum spans from 450 nm to beyond 2500 nm and contains 4 µJ energy (Fig. 2-a).

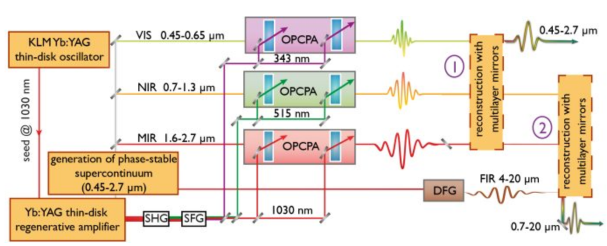

Fig. 1. Schematic architecture of a three-channel OPCPA field synthesizer.

The rest of the output of the regenerative amplifier is frequency doubled in a 1.5 mm-thick BBO crystal, yielding an average power of 70 W and 70% conversion efficiency. We aim to boost the energy of the seed pulses to tens of µJ in the first amplification stages. The supercontinuum is divided to two spectral regions of comparable bandwidth [6] and used to seed the respective few-cycle OPCPA channels. 1 mJ pulses at 515 nm and 1030 nm are used to pump a 4 mm-thick LBO crystal and a 2-mm-thick PPLN, respectively, to amplify the near-infrared (NIR) and mid-infrared (MIR) portion of the supercontinuum to 40 µJ. Afterwards, both channels are temporally compressed to 6 fs and 20 fs (Fig. 2).

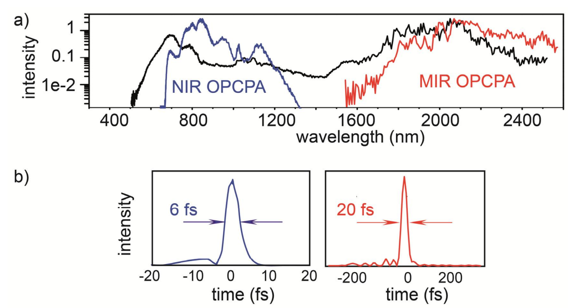

Fig. 1. a) CEP stable supercontinuum (black) amplified portion of the spectrum in the NIR channel (blue) and in the MIR channel (red). b) Compressed pulses of the NIR (blue) and the MIR channel (black).

III. OUTLOOK

In the next step, the broadband pulses of both OPCPA channels will be amplified to mJ energy and after temporal compression will be spatially combined and temporally synthesized to generate sub-cycle light transients [1,2]. The presented concept is scalable in terms of peak-power and average-power.

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Extraction of >90% Stored Energy from Large Core Fiber in fs FCPA System Utilizing Coherent Pulse Stacking Amplification

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Abstract: We demonstrate extraction of nearly all (>90%) of the stored energy (10mJ extracted) from an 85µm CCC fiber using the coherent pulse stacking amplification technique. The amplified pulses are also stacked and compressed.

I. Coherent Pulse Stacking Extension of CPA

Coherent pulse stacking amplification[1] is a technique that we are developing that can extend the effective pulse duration in optical amplifiers to the 100ns range, which is a two order of magnitude increase beyond conventional chirped pulse amplification[2]. This is accomplished by phase and amplitude shaping a burst of pulses from a modelocked laser before stretching. The stretched burst of pulses are then amplified to the point that nearly all of the energy is extracted from the amplifier. The burst of pulses is then stacked into a single pulse using a sequence of Gires-Tournois interferometers (GTIs) before finally compressing back down to the fs regime using a standard grating based compressor.

For fiber-based chirped pulse amplification (FCPA) systems, this technique can allow extraction of nearly all the stored energy from large core fibers (>10mJ from 85µm core fibers) with sufficiently low nonlinearity that the pulses can still be stacked and compressed after amplification. This can be done due to the extremely long effective pulse durations that can be achieved in the amplifier.

II. Extracting 10mJ Burst of Compressible Pulses

The experimental system used to generate a 10mJ burst of pulses is shown in Fig. 1. The system generates a burst of 81 pulses with a total burst energy of 10mJ at a repetition rate of 1kHz. The burst envelope is tailored from a 1GHz modelocked oscillator to equalize the nonlinear phase across the burst of pulses in order to optimize the interference during the pulse stacking as well as the compression. This burst envelope tailoring is achieved using high speed electro-optic modulators. The burst is amplified using an 85µm core CCC fiber as the power amplifier. The burst of pulses is then sent through the multiplexed sequence of 4+4 GTIs, which is designed to stack the burst of 81 pulses into a single pulse. The stacked burst is then sent through a standard grating based compressor to achieve fs pulse durations. We calculate the B integral to be about 4.5 radians at 10mJ.

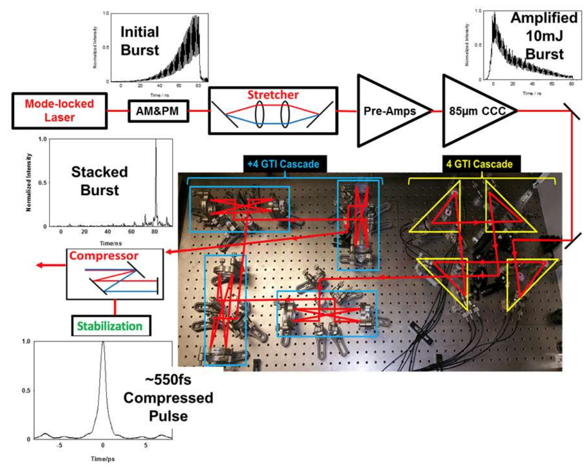

Fig. 1: Coherent pulse stacking amplification system schematic. The initially modulated burst before amplification as well as the amplified 10mJ burst are shown. The layout for the GTI pulse stackers is given with the beam path through the GTIs. Also included is the autocorrelation trace of a compressed amplified burst giving 550fs pulses. Additionally an image of a stacked burst of 81 pulses is shown at the output of the GTI stackers.

III. CONCLUSIONS

The 10mJ obtained from the 85µm core CCC fiber is the highest energy for ultrashort pulses extracted from a single fiber to the best of our knowledge. This exceeds the ~100µJ energy achievable with this fiber from conventional CPA by two orders of magnitude.

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Towards 10 TW few-cycle IR pulses using Frequency domain Optical Parametric Amplification (FOPA)

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Abstract: Using a non-collinear FOPA, a source delivering 1.8 µm, 30 mJ, 13 fs laser pulses is demonstrated. This is the first step towards 100 mJ for ~10 TW. This laser opens the way for high brightness soft X-ray attosecond pulses.

For the past two decades, tremendous efforts have been put towards the development of intense, ultrashort sources in the infrared (IR) spectral range. This region of the electromagnetic spectra is of great interest for applications such as High Harmonic Generation (HHG) [1] or the generation of THz fields through $\omega - 2\omega$ mixing [2]. These techniques require ultrashort, intense IR sources, as their efficiency and/or bandwidth show a clear dependency with respect to the wavelength and intensity. Sources in the IR spectral range, combined with high-intensity, are the key for the production of bright intense sources from soft X-rays to THz.

Recently, Frequency domain Optical Parametric Amplification (FOPA, [3,4]) appeared as a new ultrabroadband amplification scheme. Here we extend its capability to amplify a 1.2 mJ, 14 fs, 1.8 µm source up to 30 mJ while conserving its properties. Figure 1 shows the layout of the developed FOPA.

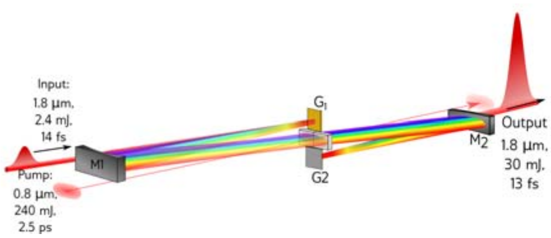

Fig. 1: Layout for high energy Frequency domain Optical Parametric Amplification.

In figure 1, the seed pulses enter the FOPA from the left side. Angular dispersion is applied through the grating G1, giving rise to a horizontal spatial separation of the different spectral components. Next, the spectrally separated components are collimated after reflection on a cylindrical mirror (M1, f=+60 cm), focusing only in the horizontal direction of the Fourier Plane (FP) to generate narrowband pulses of 2.5 ps duration. Here, broadband phase-matching from 1.4 to 2.2 µm can be achieved using two BBO crystals of 6 mm thickness. The FP is pumped by 240 mJ, 0.8 µm, 2.5 ps pulses at 10Hz. The pump has a spatial top-hat shape to ensure homogeneous amplification across the FP. A non-collinear geometry is used here, to simplify the separation between signal, idler, and pump beams. The amplified beam is then recombined by refocusing using an identical cylindrical mirror M2 and by applying an opposite angular dispersion using grating G2.

Figure 2 displays the unamplified and amplified SHG-FROG traces, with the autocorrelation signal showing that the temporal properties are conserved after amplification.

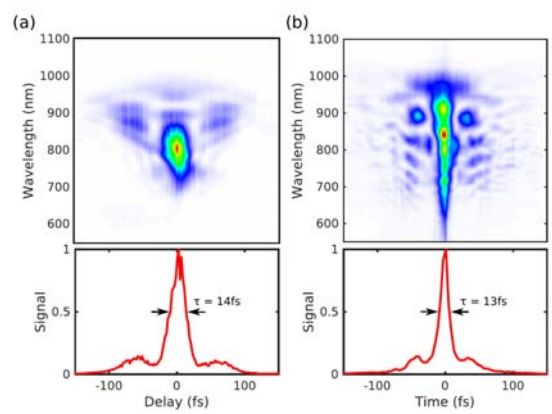

Fig. 2 : SHG-FROG Traces obtained (a) before and (b) after amplification, with their respective autocorrelation traces. Reconstruction demonstrates sub-12 fs pulses.

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CEO frequency stabilization of an ultrafast fiber laser by opto-optical modulation (OOM) of a semiconductor absorber

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Abstract: We present the first CEO-stabilization of a fiber laser by semiconductor-OOM, overcoming bandwidth limitations of standard pump modulation and enabling a CEO-locked Yb-fiber laser with 600-kHz feedback frequency and 350 mrad residual integrated phase noise.

I. INTRODUCTION

Currently, most commercial frequency comb systems are based on ultrafast fiber lasers. They combine simple turn-key operation with compact and efficient operation. The carrier-envelope-offset (CEO) stabilization is usually achieved by feedback to the pump diodes. However, both Yb- and Er-based systems exhibit long upper-state lifetimes, which limit the usable feedback bandwidth to a few tens of kHz. For low noise operation, additional modulators such as EOMs are required, which however increase complexity and price of the system. Recently we have demonstrated CEO frequency stabilization of an Er/Yb-doped glass solid state laser by opto-optical modulation (OOM) of the SESAM [1]. An additional cheap low-power cw-laser slightly changes its absorption, thus enabling a fast intracavity power modulation. Here we demonstrate the first semiconductor-OOM of a fiber laser. Instead of a SESAM, we used a vertical-external-cavity surface-emitting laser (VECSEL) chip with high modulation depth to stabilize the CEO of the Yb-doped fiber laser.

II. EXPERIMENT

The Yb-fiber laser follows a design similar to [2]. The laser is mode-locked using nonlinear polarization rotation (NPR). It operates in the stretched pulse regime at a repetition rate of 125 MHz with 26 nm FWHM optical bandwidth. The output is amplified in an Yb-doped fiber and sent to a grating compressor. The output has up to 500 mW average power in sub-100 fs pulses. The cavity contains a VECSEL gain chip used as folding mirror, which is pumped by an 808-nm fiber coupled laser diode for OOM. The VECSEL is pumped at low intensity with a few hundred mW, thus it does not reach transparency and is simply used as a controllable semiconductor absorber with high modulation depth. The laser and pump spot diameters on the chip are around 1 mm. The output pulses are coupled into a photonic crystal fiber to generate a coherent octave-spanning supercontinuum followed by an *f*-to-2*f* interferometer. The detected CEO beat signal at 20 MHz is compared to a reference signal at a phase detector. The phase error signal is fed into a PID controller with the output driving the 808-nm laser diode for modulation. We achieve a CEO-stabilization bandwidth of 600 kHz. The CEO frequency is tightly locked (Fig. 1 (a)) and stabilized with 342 mrad residual integrated phase noise (integrated from 1 Hz to 6 MHz) (Fig. 1 (b)).

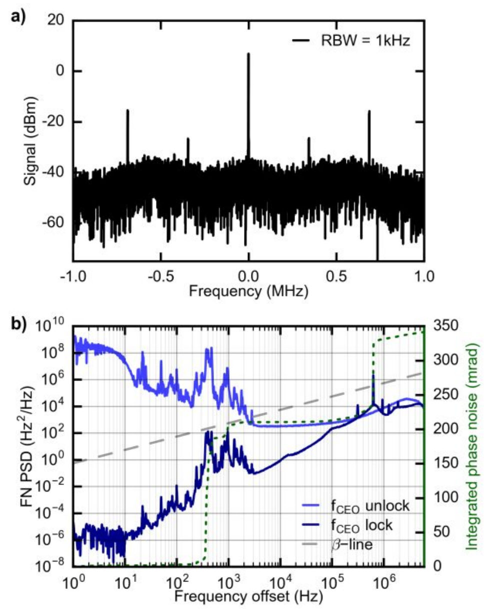

Fig. 1 a) RF spectrum of the CEO beat showing a coherent peak with an SNR of 40 dB at a RBW of 1 kHz. b) Frequency noise power spectral density (FN-PSD) of the CEO beat in free-running (light blue) and stabilized (dark blue) conditions, and corresponding integrated phase noise as a function of the upper cut-off frequency (right axis).

III. CONCLUSIONS

In conclusion, we stabilized the CEO frequency of an Yb-doped fiber laser using a VECSEL chip as a loss modulator, achieving 342 mrad (1 Hz to 6 MHz) of residual integrated phase noise of the CEO. The achieved high feedback bandwidth of 600 kHz proves that the simple and cost-efficient semiconductor-OOM is an excellent solution for ultrastable fiber combs.

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Linearizing Nonlinear Optics

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Abstract: We demonstrate how Fourier nonlinear optics elegantly merges the simplicity of linear optics with the power of nonlinear optics to achieve the decoupling of frequencies, amplitudes and phases in nonlinear processes.

I. Introduction

Unlike in linear optics, broadband fs laser pulses can interact nonlinearly in a medium which couples their amplitudes phases in a convolution process.

Here, we describe a new regime where nonlinear interactions can occur without mixing of different frequencies [1]. We demonstrate how frequency domain nonlinear optics (FNO) overcomes the shortcomings arising from the convolution in conventional time-domain nonlinear optics (TNO). We generate light fields with previously inaccessible properties by evoking the uncontrolled coupling of amplitudes and phases. We show that arbitrary phase functions are transferred linearly to the second harmonic frequencies while the output spectrum is exactly equal to the square of the input. Our current work provides a generalized description of FNO that also covers the recently introduced Frequency domain Optical Parametric Amplification (FOPA) [2]

II. Setup & Results

In TNO (Fig. 1b), all frequencies interact simultaneously in a single focus and the second harmonic spectrum (blue curve) shows a smooth function without the initial central hole. Aa result of the convolution.

In contrast, the key aspect of FNO, shown in Fig. 1c, is the intrinsic ability to achieve a very narrow bandwidth for the nonlinear light-matter interaction even though the input pulse contains a broad bandwidth. Experimentally, this is realized by aid of a 4f configuration [3]. The optical FT provides a reduced frequency content in each focal spot of the frequency plane where the nonlinear interaction takes place. All these independent picosecond interactions are coherently recombined at the second grating G2 denoting a second Fourier transformation back to the time domain.

We will explain how this approach enables the linear transfer of arbitrary phase functions as well as the decoupling of amplitudes and phases and why this is not possible in time domain interactions.

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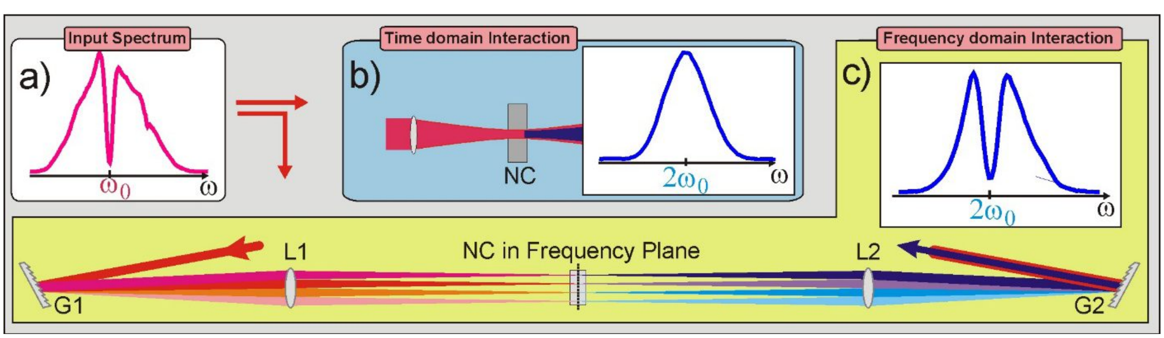

Fig. 1: A shaped input spectrum (a) is frequency doubled either in (b) conventional time domain nonlinear optics (TNO) or (c) via Frequency domain nonlinear optics (FNO). The convolution of different frequencies in TNO (b) leads to a smoothening of the input function while in FNO the shape is preserved since the mutual frequency crosstalk is turned off. This decoupling permits a transfer of arbitrary phase functions. NC: nonlinear crystal.

Intense Single-Cycle Pulses Made Easy

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Abstract: Strategic placement of thin solid plates at the waist of an intense femtosecond laser beam has resulted in the generation of terawatt-level single-cycle pulses that enable novel isolated attosecond pulse generation and ultrafast pump-probe studies.

Intense single-cycle femtosecond pulses are ideal for generating bright isolated attosecond pulses via high-order harmonic generation (HHG) and for investigating the dynamics of atoms and molecules, nano-materials and bio-molecular systems that require unprecedented temporal and spatial resolution.

The predominant approach to single-cycle and few-cycle pulse generation is by compression of an ultrabroadband light pulse obtained in a meters-long hollow-core fiber filled with a noble gas[1,2]. However, the hollow-core fiber scheme requires careful alignment and is sensitive to the beam-pointing stability of the input laser, straining the long-term stability of the source. For a long time the alternative of generation in a bulk medium is marred by multiple filamentation and a low optical damage threshold in the bulk medium, making the alternative unattractive for high power applications.

Some time ago we showed that the problems associated with a solid medium could be circumvented by proper management of the medium; thus achieving high power femtosecond continuum generation. By strategically placing thin plates of fused silica at or near the waist of an intense laser pulse, we have generated an intense ultrafast white light supercontinuum. The generated octave-spanning spectrum covers from 450 nm to 980 nm at the -20 dB intensity level with good conversion efficiency and high transverse mode quality[3]. FROG measurement and spectral interferometric measurement indicate that the pulse is phase coherent and can be compressed to a few femtoseconds. We call the supercontinuum generated from multiple plates the MPContinuum.

With rigorous effort in the last few years, we have shown that the MPContinuum power is scalable up to more than 1 mJ ina 25-30 fs pulse, that it is compressible to near-transform-limited pulse duration by active phase compensation or to sub-two-cycle duration at the terawatt peak power by using chirped-mirrors.

The MPContinuum approach works for a variety of lasers and different wavelengths. It has been used to generate isolated EUV light of different polarization state[4,5].

Inaddition the multiple-plates approach to single-cycle pulse synthesis is viable for a broad range of input lasers and pulse energies. Since it is a solid-state approach, it is compact, easy to align and simple to operate. Meanwhile the output pulse energy and transverse mode quality match and exceed those obtained in the hollow-core fiber medium and is useful for many applications.

ACKNOWLEDGMENTS

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Picometer and attosecond resolution measurements from mid-IR driven electron recollision

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Abstract: We report measurements which probe the electronic structure and the lattice of condensed matter systems with isolated attosecond soft X-ray pulses with photon energies ranging from 250 to 500 eV.

I. Isolated attosecond soft X-rays at 300 to 500 eV

The source for our measurements is based on high harmonic generation with 1850 nm, 1.8-cycle and CEP-stable pulse in a jet of Neon or Helium. Such implementation[1] resulted in the first successful generation of an isolated soft X-ray pulse in the water window and we have previously demonstrated streaking of the pulse at 300 eV. An investigation showed that the unfavorable scaling of the photoionization cross section in the soft X-ray regime makes streaking and successful extraction of a pulse duration problematic. We have hence implemented the lighthouse technique which allowed us to place an upper temporal limit of 322 as on the isolated pulse[2] with a spectrum covering 250 to 500 eV.

II. Attosecond X-ray absorption in condensed matter

X-ray absorption fine-structure spectroscopy (XAFS) is well established at synchrotron light sources providing electronic as well as structural information of samples in the gas, liquid and solid state. Attosecond science provides the enticing prospect of combining unprecedented temporal resolution with the element and site selectivity of X-rays. An important aspect is the fact that the tremendous bandwidth of an attosecond soft X-ray pulse presents no impediment to achieve acceptable energy resolution. Using our attosecond pulse, we have previously demonstrated near-edge-XAFS (NEXAFS) in an organic film at the K-shell edge of carbon at 284 eV with successful extraction of the electronic structure of the material[3].

Here, we demonstrate an important next step in which we leverage the attosecond resolution to interrogate changes in the electronic excitation of the dichalcogenite material TiS_2 in real-time. Figure 1 shows the response of the material after excitation with a weak 1.8-cycle and CEP-stable pulse at 1850 nm which promotes carriers into the conduction bands of the material. We will show that the experiment is able to probe the material inter and intra-band transitions with attosecond resolution.

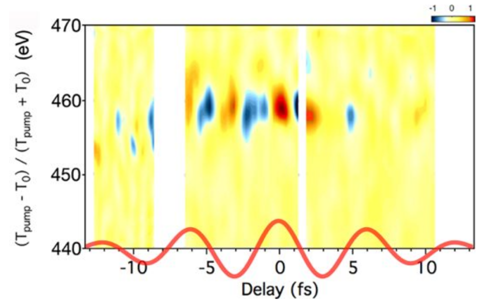

Fig. 1. XAFS spectrum of TiS2 after excitation with a 1.8-cycle duration field at 1850 nm.

III. CONCLUSIONS

We demonstrate first isolated attosecond soft X-ray pulses with an upper temporal limit of 322 as and spectral coverage of the entire water window. These pulses were leveraged for XAFS measurements in condensed matter to elucidate the inter and intra-band dynamics of a dichalcogenite semi-metallic material in response to a 1.8-cycle stimulus. These experiments demonstrate that it is possible to interrogate condensed matter carrier dynamics in real time in combination with element and site selectivity.

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High photon flux table-top fiber-laser driven high harmonic sources

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Abstract: We report on high photon flux XUV sources driven by ultrafast fiber lasers. This includes Milliwatt-level XUV sources realized by cascaded frequency conversion as well a soft X-ray sources enabled by Tm-based fiber lasers.

Table-top sources of coherent XUV radiation can be achieved via high harmonic generation (HHG) of ultra-short laser pulses. Due to the inherently low conversion efficiency of HHG and the low average power of the frequently used Ti:Sapphire lasers the generated number of photons is usually very limited. A significant increase in repetition rate and average power of HHG sources is necessary to serve the needs of (multi-dimensional) spectroscopy, coincidence-based detection schemes or nano-scale coherent diffractive imaging.

In this contribution recent advances in high average power XUV sources based on HHG of state-of-the-art fiber laser systems will be presented. Phase-matching aspects and macroscopic effects will be discussed. Finally suitable implementations to efficiently convert 100 W- class ultra-short laser pulses to photon energies ranging from 20-300eV will be presented. The achieved average power level can be in the milliwatt (at 21eV), 100µW (30eV) and few-µW range (up to 70eV). Fig. 1 displays the current state-of-the-art in high photon flux HHG. Fiber laser driven systems are represented by the blue ??? points.

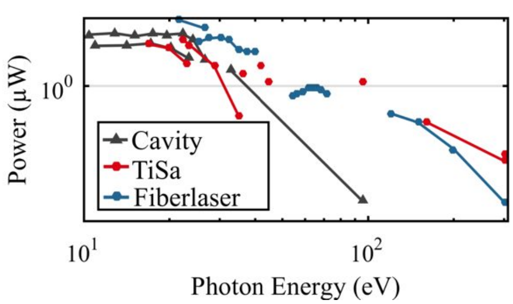

Fig. 1. Overview on high photon flux HHG sources.

Direct HHG with a 90 W / 30 fs fiber laser system reveals ~100 µW-level harmonics at ~ 30 eV. A typical spectrum is displayed in fig 2 a)

Cascaded frequency conversion (second harmonic generation followed by HHG) allows achieving a much higher conversion efficiency than direct HHG with infrared driving lasers. By implementing this technique a 80 fs / 100 µJ fiber laser system we were able to generate >0.8 mW of average power at 21.6 eV.

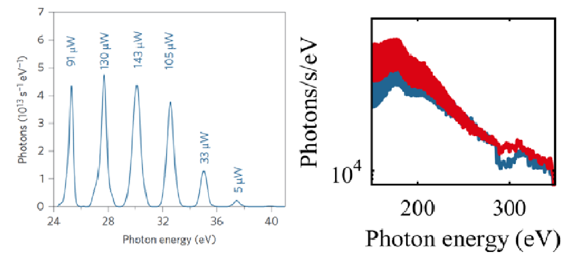

Fig. 2. a) 100 µW HHG spectrum. B) Water window HHG with 2µm lasers with (blue) and without (red) a Mylar filter.

In contrast, longer driving wavelength increase the phase-matched cutoff energy. Thus, Tm-based fiber lasers at ~2µm wavelength have the potential for high photon flux soft X-ray sources up to the water window. First experiments confirmed this cutoff extension up to the water window. Pulse compression to few-cycle durations and optimized interaction geometries will enhance the conversion efficiencies and enable high photon flux in the water window. Thus spectroscopy and nanoscale coherent diffractive imaging will be feasible on organic and biological samples with simple table-top setups soon.

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Generation of EUV singular beams: vector and vortex beams

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Abstract: High-harmonic generation offers a unique route to generate singular beams in the EUV/soft x-ray domain. We review our recent results for the generation of short-wavelength harmonic vortices and vector beams, from radial to azimuthal polarization.

Harnessing topological light properties paves the way towards new degrees of freedom for the observation and control of nature at extreme spatio-temporal scales. Topological properties of light –such as polarization and orbital angular momentum (OAM)– have drawn the attention of the scientific community as tools to unveil new scenarios of laser-matter interaction. Light vortices –possessing a twisted phase structure and thus carrying OAM– add a new degree of freedom to light-matter interactions revealing unique properties such as chirality or circular dichroism. Vector beams, –light beams with spatially variant polarization– have become an indispensable tool in many areas of science and technology. In particular, radial vector beams allow to sharply focus light below the diffraction limit, whereas azimuthal vector beams can induce longitudinal magnetic fields with potential applications in spectroscopy and microscopy.

Light vortices and vector beams are routinely obtained in the visible/infrared domains. Considering their applications, there is an obvious interest to bring these singular beams into the extreme-ultraviolet (EUV) and x-ray regimes. To this end, high harmonic generation (HHG) offers a unique opportunity to produce short wavelength singular beams from harmonic up-conversion of an IR beam. Different schemes have been applied already in HHG to control the polarization of EUV/soft x-ray harmonics[1,2]. In this contribution we review our recent results in the generation of singular beams through HHG.

On one hand HHG has been demonstrated as an efficient process to generate single-OAM harmonic vortex beams. However, in order to make EUV vortices widely useful, it would be desirable to span the choice of OAM modes at any particular harmonic frequency[3]. To this end, we have recently exploited the non-perturbative nature of HHG to find a regime where harmonic vortices are generated with a broad OAM content, obeying to new OAM conservation rules[4] (see Fig. 1b). We have also derived a technique to generate *non-integer* or *fractional* OAM beams using conical refraction[5].

On the other hand, in a theory-experiment work[6], we have generated EUV vector beams by transferring the complex structure of an infrared vector beam through HHG (see Fig. 1b). We have used an s-waveplate to generate IR driving vector beams (from radial to azimuthal) that are up-converted to shorter wavelength radiation. Our experimental and theoretical results demonstrate that HHG imprints the polarization state of the fundamental infrared beam, ranging from radial to azimuthal, into the higher frequency radiation. Our numerical simulations also demonstrate that the generated high-order harmonic beams can be synthesized into attosecond vector beams in the EUV/soft x-ray regime[6].

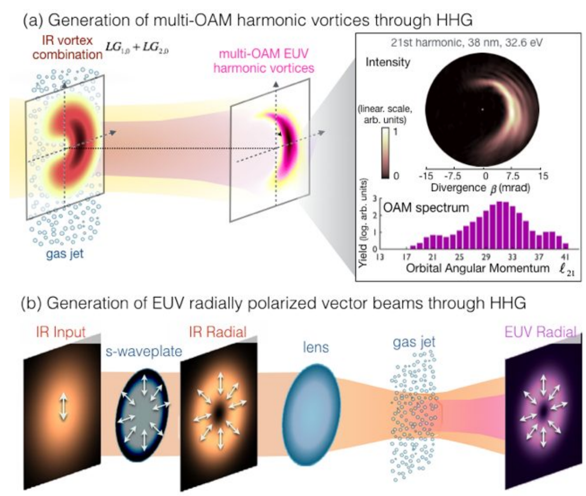

Fig. 1. (a) Generation of multi-OAM beams through HHG, using two IR drivers with different OAM[4]. (b) Generation of EUV radial vector beams through HHG. The harmonic emission is composed of a train of radially polarized attosecond pulses[6].

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Attosecond photoionization self-probing spectroscopy

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Abstract: We demonstrate a new spectroscopic approach by replacing tunneling ionization with XUV photoionization in high harmonic generation spectroscopy. Our method resolves the underlying mechanism and allows reconstructing the ionization dynamics in strongly IR-driven helium.

Attosecond self-probing[1] exploits a built-in pump-probe process in high harmonic generation (HHG). Here, strong-field tunneling ionization acts as a pump, removing an electron and creating a hole in the system, followed by strong-field acceleration and radiative recombination. This nonlinear parametric process serves as an internal clock, encoding the evolution of the system between ionization and recollision with attosecond precision. The technique's main limitations are imposed by the starting point – tunneling ionization. Tunneling is confined to the peak of the infrared field. Moreover, only a narrow range of valence shell orbitals can be addressed.

In our work we experimentally demonstrate a conceptually new spectroscopic approach in attosecond science that integrates one of the most fundamental light-matter interactions – single-photon photoionization – with strong-field recollision dynamics. Ionization by single photons accurately probes, in a linear manner, the quantum state of the matter under scrutiny. Here we combine the universality provided by photoionization with the unique resolution and versatility provided by the self-probing mechanism. Our approach is based on XUV-initiated HHG[2,3] which decouples the ionization step from the subsequent steps of the interaction by replacing tunneling ionization with photoionization driven by an attosecond XUV pulse (Figure 2a).

Our study demonstrates that XUV-initiated HHG constitutes a multiple path quantum interferometer (Figure 1b): Photoionization initiates an attosecond electron wavepacket, launching a set of quantum paths; each path is associated with a spectral component of the wavepacket. Strong-field trajectories define the propagation of the wavepacket, controlling the phase accumulated along each quantum path. Finally, recollision superimposes these paths, creating an interferogram in the form of a series of new higher harmonics. Such an interferometer projects the coherent properties of the electronic wavepacket via recollision trajectories into the high harmonic signal. In a proof-of-principle experiment in helium, we demonstrate how accurate control of the relative delay between the attosecond pulses and the IR field allows the extraction of the interaction dynamics from the interferometric measurement. In addition, by adding a weak sub-optical-cycle perturbation[4] (Figure 1c), we isolate the two fundamental components of the interferometer – ionization and recollision, and probe their temporal evolution. Our study enables us to decompose the quantum paths that underlie the process and reconstruct the photoionization dynamics of the system as it is driven by the strong laser field (Figure 1d).

Looking ahead, our spectroscopic method enables probing the full laser-matter interaction dynamics of an atomic, molecular or solid system on a sub-cycle time scale, with full control over the initial and excited states and the timing of ionization (pump) and recollision (probe). Far beyond the capability to extract ionization dynamics demonstrated here, we expect that photoionization self-probing spectroscopy will be able to resolve multi-electron dynamics such as hole decay in inner shells of complex atoms and molecules.

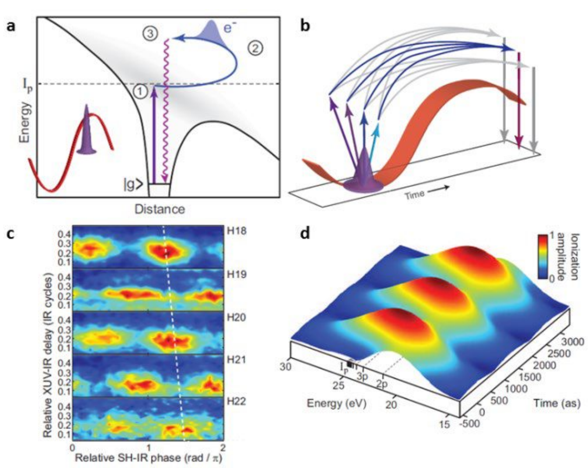

Fig.1. (**a**) Principle of photoionization self-probing spectroscopy. (**b**) Interferometer picture of XUV-initiated HHG. (**c**) Perturbative probing of the HHG dynamics. (**d**) Reconstruction of the photoionization dynamics in strongly IR-driven helium.

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Efficient 220 eV source based on Yb laser amplifier for solid-state physics applications

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Abstract: We present HHG driving using a novel 10 mJ 20 fs Yb source at 1.03µm. The HHG spectrum covers spectral range of sulfur, terbium and gadolinium edges and is therefore directly usable in applications where photon high flux is needed. To demonstrate the utility of the source we show the absorption spectrum of SF_6.

The 140-220 eV spectral range covers important magnetic and molecular materials, such as the N-edge of gadolinium and terbium (145 and 155 eV) and $L_{2,3}$ edge of sulphur [1]. Although high-order harmonic generation (HHG) allows performing ultrafast dynamics measurements with sub-fs temporal envelopes that are intrinsically synchronized to the near-IR driving laser pulses, many applications requiring high photon flux, such as probing of ultrafast magnetization dynamics in ferromagnetic materials or liquid phase attosecond spectroscopy were previously impossible due to lack of sufficient brightness sources.

We present HHG reaching 220 eV range using 10 mJ post-compressed 20 fs 1.03 µm pulses directly from a kHz 14 mJ $Yb:CaF_2$ chirped pulse amplifier that offers highly efficient and scalable source in this photon energy range. The ytterbium laser used here has two main advantages over the more common Ti:Sapphire laser technology: the 30% longer wavelength of 1030 nm as compared to 800 nm allows extending the cut-off by a factor of ≈1.6 due to λ^2 scaling of the cut-off [2]. We show absorption-limited HHG driving in helium with the cut-off reaching 220 eV. In addition, the solid-state Yb laser technology allows scaling the concept to high average power and high pulse energy.

In order to improve the HHG efficiency and to extend the cut-off, the input 200 fs 14 mJ driving laser pulses were post-compressed [3,4,5] in a stretched large core hollow waveguide with the inner bore diameter of 750 µm with high throughput (>70% transmission over 3m long waveguide) and high peak power handling.

As a demonstration of the utility of this source, we recorded L-edge absorption lines of SF_6. While the 20-fs driving pulses yield HHG spectrum with discrete harmonics, the SF_6 transmission was obtained from the envelope of the spectrum. The pulse compression approach can be extended to a two-stage compression thus providing few-cycle pulses for continuous spectrum HHG generation for the applications that require it.

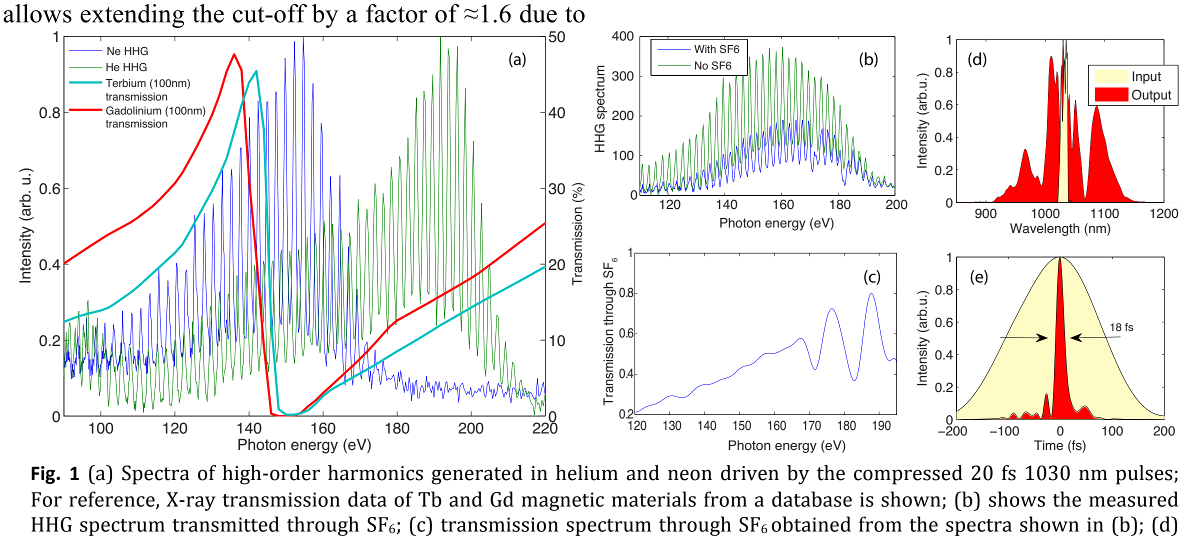

Fig. 1 (a) Spectra of high-order harmonics generated in helium and neon driven by the compressed 20 fs 1030 nm pulses; For reference, X-ray transmission data of Tb and Gd magnetic materials from a database is shown; (b) shows the measured HHG spectrum transmitted through SF_6; (c) transmission spectrum through SF_6 obtained from the spectra shown in (b); (d) and (e) spectra and temporal profiles from FROG characterization of the post-compressed 18 fs pulses.

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High performance nanoscale imaging with table-top high harmonic sources

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Abstract: Todays high harmonic sources provide high photon flux, short wavelengths and excellent coherence. We will present a number of experiments, including record-13 nm resolution imaging, which have been performed with fiber laser driven XUV sources.

Lensless Coherent diffractive imaging (CDI) is a technique where a sample is imaged by recording the far field intensity diffraction pattern and subsequently phase retrieval by iterative computer algorithms. It nowadays enables imaging with only a few-nanometers resolution by employing X-ray radiation usually provided either by free-electron lasers or synchrotrons [1]. Table-top coherent XUV sources using high-order harmonic generation (HHG) have seen enormous progress during the recent years. Nowadays, they can provide high photon flux combined with excellent coherence and femtosecond pulse durations, which makes them highly attractive for high-resolution imaging [2]. In this contribution, we present CDI experiments performed with a 68.6 eV XUV source, driven by a 1µm wavelength, 0.66 mJ, 33 fs, 30 kHz high-average power femtosecond fiber laser system [3]. A high photon flux of $\sim 1\times10^{10}$ photons/sec was generated at 68.6 eV and focused onto the CDI sample by a pair of multilayer mirrors. Excellent coherence and beam quality have been observed. The intensity and phase of the illuminating beam has been characterized by CDI of a uniform array of 100 nm diameter holes as shown in fig. 1. The transmitted intensity samples the beam profile and indicates a round Gaussian-like beam profile with ~ 4 µm width ($1/e^2$).

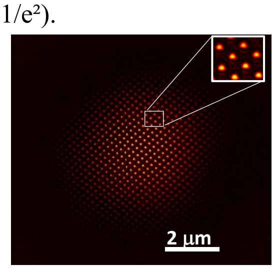

Fig. 1. XUV beam profile at the focus characterized by coherent diffractive imaging of a uniform array of holes.

Coherent imaging of a test sample at high numerical aperture (NA=0.7) has been driven up to a half-pitch resolution of only 13 nm – among the highest resolution from any table-top CDI microscope so far [3]. The corresponding results are displayed in fig. 2. Due to the high-photon flux of the source, such high-NA diffraction patterns are recorded within few-minutes of acquisition time.

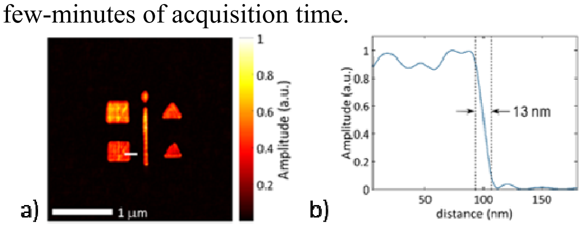

Fig 2. Left: Reconstructed nanoscale image of a test sample. Right: Cut along the small white bar.

To apply coherent imaging to extended samples (ptychography) and 3D reconstructions (tomography), hundreds of diffraction patterns have to be recorded. To this end, we optimized the setup to achieve resolutions of 23 nm with only 3 seconds of integration time. Thus, a typical ptychography scan on a 50 µm^2 area can now be recorded in < 10 minutes with this setup. We will present our latest results in ptychographic CDI of extended samples at the conference.

In addition, we will discuss the possibilities of pushing the resolution to the sub-10 nm range and increasing the photon energy for imaging into the soft X-ray domain and up to the water window spectral region.

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Demonstration of ultrafast laser driven gain-saturated soft x-ray lasers down to 6. 9 nm and gain down to 5.9 nm

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Abstract: We have extended the wavelength of compact, repetitive, gain-saturated x-ray lasers to 6.89 nm in Ni-like Gd, and observed amplification in several lower wavelength transitions down to 5.9 nm in Ni-like Dy ions.

Plasma-based soft x-ray lasers can generate bright high energy ultrafast pulses of soft x-ray radiation in compact setups. These lasers provide extremely monochromatic radiation that, when injection-seeded, can reach full spatial and temporal coherence. Gain saturation in soft x-ray plasmas was demonstrated for wavelengths as short as 5.8 nm at large laser facilities. However, these lasers were only able to operate at repetition rates of a few shots per hour at best.

Herein we report the extension of gain saturated repetitive soft x-ray lasers down to 6.9 nm in Ni-like Gd. These lanthanide ion-based collisionally pumped lasers provide the necessary pulse energy (microjoule/pulse) to obtain, for example, a nano-scale resolution image with a single laser shot, Furthermore, in the same experiments we observed gain down to 5.8 nm in Ni-like Dy, opening the possibility of table-top gain saturated laser at shorter wavelengths.

The results were obtained by irradiating solid slab targets with a sequence of two laser pulses from a λ=800 nm Ti:sapphire chirped pulse amplification (CPA) laser. The two pulse sequence consisted of a normal-incidence pre-pulse followed by a main sub-picosecond pulse impinging at a selected grazing incidence angle of 43 degrees with a traveling-wave excitation velocity of (1.0 ± 0.03)c. The versatile pump laser allowed us to adjust the length of the pre-pulse from 45 ps to 300 ps to find the optimal conditions for laser amplification. The plasmas were created by normal-incidence irradiation at $I = 3.2\times 10^{13}$ W/cm^2 with a 185 ps duration pre-pulse focused onto the target to form a line focus of approximately 15 μm × 9 mm FWHM using the combination of a spherical and a cylindrical lens. The plasma created by the pre-pulse is allowed to expand to reduce the density gradient and is subsequently rapidly heated by irradiation shaped into a line focus of approximately 35 μm × 8 mm FWHM and $I = 4.3\times10^{15}$ W/cm^2 with a 8.4 J pulse of 0.7 ps FWHM duration. To assist in achieving efficient pumping, we developed a focusing geometry designed to create a plasma column of constant width along the target.

The spectra of Fig. 1 shows the resulting laser lines of different lanthanide ions. Measurements of the laser line intensity as a function of plasma column length showed gain saturation was reached in the 7.4 nm line of Ni-like Sm and in the 6.9 nm line of Ni-like Gd. Gain coefficients of 27.3 cm^{-1} and 26.3 cm^{-1} with a gain-length product of 16.6 and 16.2 were obtained for Sm and Gd respectively. Laser pulse energies of 1-2 μJ were measured. This demonstration of gain-saturated tabletop lasers at wavelengths as short as λ= 6.9 nm using reduced pump energy also opens the prospect for bright high-repetition-rate plasma-based lasers at shorter wavelengths. In progress toward this goal we made use of isoelectronic scaling along the elements of the lanthanide series to obtain lasing in several shorter wavelength transitions. The spectra of Fig. 1 show that the use of similar irradiation conditions resulted in strong amplification in the λ= 6.6 nm and λ=6.1 nm transitions in Ni-like Tb. Finally, we have also observed weak amplification in the λ=5.8nm and λ=6.4 nm lines in Ni-like Dy. The results will make possible applications requiring bright laser pulses with large pulse energy at these short wavelengths to be realized on a table-top.

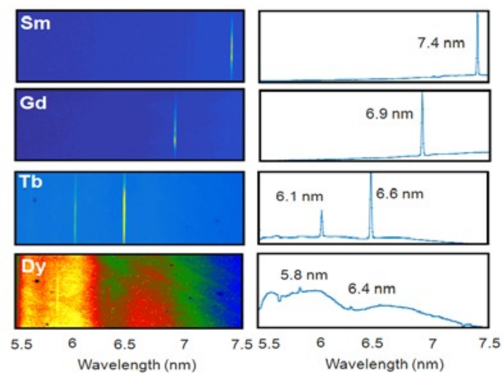

Fig. 1. End-on spectra showing lasing at progressively shorter wavelengths in the $4d^1S_0$-$4p^1P_1$ line of nickel-like lanthanide ions, down to λ= 5.8 nm in nickel-like Dysprosium.

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Using second harmonic generation as an ultrafast, surface sensitive probe of THz-driven structural dynamics

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Abstract: Intense, terahertz pulses are a powerful tool for understanding and controlling material properties through low-energy resonances, such as phonons. Combining this with optical second harmonic generation (SHG) ultrafast structural changes can be observed with surface sensitivity.

I. THZ-PUMP, SHG-PROBE SPECTOSCOPY

One of the primary goals of ultrafast laser spectroscopy is to optically control a material's properties [1]. Ultrashort pulses at THz frequencies give direct access to resonances associated with specific degrees of freedom, such as magnetism, ferroelectricity or lattice symmetry. Still, to achieve this goal, methods for directly visualizing the resulting, atomic-scale ultrafast dynamics are needed. Much like X-ray diffraction (XRD), SHG yields information about the lattice, electronic and magnetic symmetries of a crystal [2]. SHG also provides surface and interface selectivity [2]. Here, in the topological insulator Bi_2Se_3, we demonstrate a unique approach for understanding and controlling THz light-matter interactions, combining resonant excitation of a polar phonon mode with optical SHG.

II. EXPERIMENT AND DISCUSSION

Fig. 1(a) shows a schematic of our experiment [3]. The THz beam (peak E-field ≈ 150 kV/cm), resonant to a phonon mode at 1.9 THz, is focused tightly at the Bi_2Se_3 sample. After a time delay τ, a co-propagating and co-linearly polarized 800 nm probe pulse arrives, and the reflected 400 nm SHG signal is collected with a photomultiplier tube (PMT). We measure the photoinduced symmetry changes after THz excitation by varying the azimuthal angle ϕ [2].

The measurements in Fig. 1 represent a THz pulse induced symmetry change leading to a large (up to ~50%) modulation of the SHG signal. Analysis of this data shows that the signal consists of two components: one from the surface, oscillating at the phonon frequency (1.9 THz) and another at twice that (3.8 THz), originating from transient phonon-induced symmetry breaking in the bulk that "turns on" the bulk SHG. Tuning the time delay between a pair of driving THz pulses also allows us to coherently control the symmetry changes [3].

In conclusion, we used intense THz pulses to drive a phonon mode and probed the dynamic symmetry changes with SHG. This work both reveals a novel nonlinear optical effect and a new approach for studying ultrafast structural dynamics.

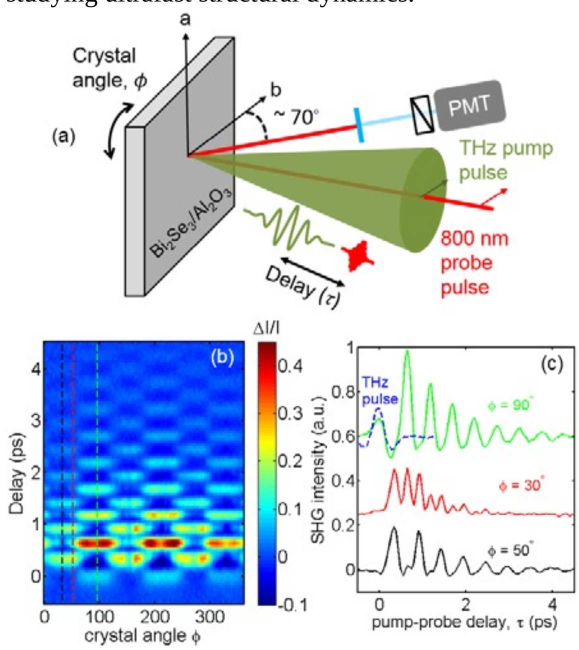

Fig. 1. (a) Experimental setup for THz-pump, SHG-probe measurements. (b) The THz-induced change in the SHG versus delay τ and crystal angle ϕ. (c) The THz-induced SHG change at a few different angles. Data taken from [3].

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Intense THz generation and nonlinear THz applications

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Abstract: The recent advent of laser-driven Terahertz sources at extreme brightness and tunability opens new opportunities in science. We use Terahertz as tool to manipulate nonlinear optical and electronic properties in semiconductors, superconductors, insulators and air.

I. Introduction

The production of bright and tunable Terahertz radiation in the THz frequency gap (0.1-10 THz) by a laser has been a formidable challenge. The recent advance in intense single and multi-cycle THz pulses enable the non-resonant and selective control of fundamental properties in condensed matter, respectively on a sub-cycle timescale. Here we report on a laser-based THz source which is able to provide both intense single-cycle pulses up to 80 MV/cm as well as narrowband radiation at MV/cm field strength tunable across a frequency range of 0.5-8 THz. This unique Terahertz source at extreme brightness and tunability is used to explore time-resolved nonlinear dynamics in GaP, VO_2, diamond and air.

II. THz source based on organic crystals

Optical rectification of an intense mid-infrared laser source in various organic crystals such as DSTMS[1], OH1[2,3], DAST[4], BNA[5] gives rise to a multi-octave spanning, single-cycle pulse at field strength >50 MV/cm (Fig 1, left). Alternatively, extremely narrowband terahertz emission from the same organic crystal is emitted when an intensity-modulated pump pulse is employed (Fig.1 right). The intensity modulation is formed by beating of two chirped replicas which are delayed in time. This scheme provides a direct control on the spectral central frequency and bandwidth by chirp and delay adjustment of the pump beams. The THz spectral width can be continuously tuned between broadband (100%) and narrowband emission. The corresponding relative bandwidth of $\Delta\lambda/\lambda$ ≈2% approaches the performance of modern THz free electron lasers.

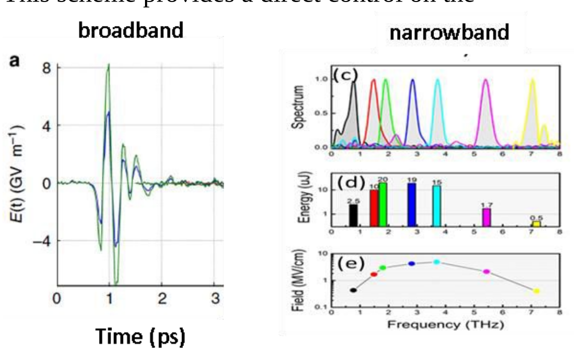

Fig. 1. Broadband, 80 MV/cm single-cycle pulses (left) and narrowband THz radiation (right). The latter is tunable across 0.5-8 THz and offers up to 20 uJ.

III. THz Strong-field interaction with matter

The interaction of strong-field, low-frequency THz pulses with matter gives rise to extreme modification of optical, electronic and magnetic properties. In this presentation we will discuss the nonlinear response in the electro-optical active gallium phosphite [5] (Fig 2), in diamond [6] and in air [7]. We will also present the recent discovery on a metastable phase in VO_2 and THz-induced dynamics in superconductors.

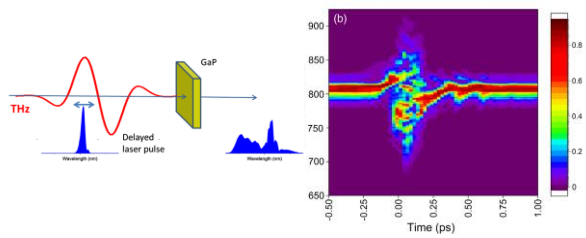

Fig. 2. THz induced XPM giving rise to extreme spectral broadening of the nIR probe pulse.

ACKNOWLEDGMENTS

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Ultrashort pulse generation in multimode fibers

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Abstract: Recent developments in the area of nonlinear propagation of ultrashort pulses in multimode fiber will be reviewed briefly, and first demonstrations of locking of transverse *and* longitudinal modes of a fiber laser will be presented.

I. INTRODUCTION

There is growing interest in the properties of multimode optical fiber, driven partially by interest in scaling of high-power lasers and space-division multiplexing in telecommunications. Fundamentally, wave propagation becomes spatiotemporal in multimode fibers. In the last few years, several new phenomena have been observed, including:

- Self-cleaning of optical beams[1]
- Spatial control of ultrafast nonlinear processes[2]
- Self-organized instability[3]

Some of these processes can be understood in terms of the dynamics of multimode solitons.[4]

II. SPATIOTEMPORAL MODE-LOCKING

The field of ultrafast science is built on the principle of locking the phases of the longitudinal or axial modes of a laser resonator. Virtually all modelocked lasers operate on a single transverse or spatial mode. Locking of multiple spatial modes, or spatial and longitudinal modes, were briefly considered in the early years of laser development. Apart from an isolated observation of locking of two spatial modes in Ti:sapphire laser,[5] no attention has been paid to multimode, or spatiotemporal, modelocking since then.

The disparate frequency spacings of longitudinal and transverse modes, distinct group-velocity and modal dispersions, and complex nonlinear interactions among modes all present challenges to modelocking. We extend the techniques of normal-dispersion modelocking to the spatial domain to lock modes in space and time. The use of parabolic-index fiber results in comparable group-velocity and modal dispersions, and strong spectral and spatial filtering dominate pulse shaping and enforce the periodic boundary conditions of the cavity. In reasonable agreement with numerical simulations, a wide variety of spatiotemporally-modelocked states are observed (Fig. 1).

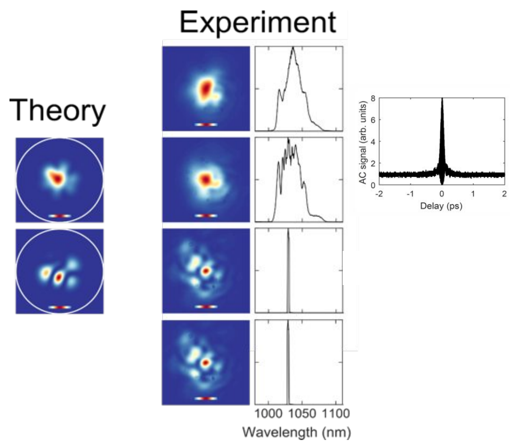

Fig. 1. Theoretical and experimental spatial and spectral profiles, and autocorrelation of modelocked state.

Multimode modelocking should open new directions in three-dimensional nonlinear wave propagation. Orders-of-magnitude increases in peak power over prior modelocked fiber lasers should be possible, and eventually controllable spatiotemporal fields may be generated by this approach.

ACKNOWLEDGMENTS

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20 W average power sub-3-cycle pulses from a nonlinear pulse compression stage at 2 µm wavelength

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Abstract: We demonstrate a laser system delivering 50 µJ few-cycle pulses around 2 µm wavelength at >20 W average power based on a Tm-doped fiber CPA system and nonlinear pulse compression in an antiresonant gas-filled hollow-core fiber.

Powerful, few-cycle laser systems with an emission wavelength around 2 µm are attractive tools for the study of high-field light matter interactions and in particular for efficient generation of ultra-broadband mid-infrared frequency combs [1] or high-order harmonics within the water-window [2]. However, a significant increase in photon flux is required to expand and enhance the impact of subsequent applications like molecular spectroscopy or high-resolution diffractive imaging. Hence, there is a strong application driven demand for power scaling of the driving laser sources, which deliver intense few-cycle pulses around 2 µm wavelength. Thulium-doped fiber laser systems (TFL) are, in analogy to their well-established ytterbium-based counterparts, an average power scalable solid-state laser concept, which is scalable to hundreds of watts in ultrafast operation [3]. One way of pushing the typically achieved hundreds of fs-pulses towards the few-cycle regime is nonlinear pulse compression.

In this contribution, we demonstrate the nonlinear compression of pulses from a thulium-doped fiber CPA system (Tm:FCPA) to the few-cycle regime at >20 W of average power with only one compression stage. This stage consists of an antiresonant argon gas-filled hollow-core fiber (53 µm inner core diameter) allowing for >90% transmission around 2 µm wavelength. Due to its dispersion properties and the appropriate choice of gas pressure leading to sufficient SPM-broadening, the launched 100 fs-pulses from the Tm:FCPA are self-compressed to sub-3-cycle pulse duration as they reach the fiber output. The compressed average power was 21.4 W, corresponding to a pulse energy of >50 µJ at the laser repetition rate of 392 kHz. A measured autocorrelation trace at this performance level can be seen in Fig. 1 together with the one of the input pulse. Assuming a Gaussian deconvolution factor the measured pulse-width is 14 fs, which corresponds to 2.3 cycles.

We are currently working on further optimization of the compression setup, which will allow for more average power and shorter pulses with sub-2 cycle duration. Nevertheless, this is the highest average power few-cycle laser source delivering GW-class pulses around 2 µm wavelength.

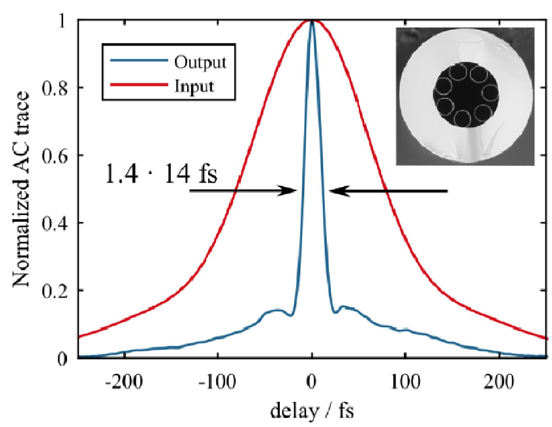

Fig. 1. Measured AC traces before (red) and after the nonlinear compression (blue) Inset: Cross-section of the antiresonant hollow-core fiber.

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High average power few-cycle laser for ELI-ALPS

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Abstract: We present a characterization and an analysis of the scaling potential for the ELI-ALPS HR1 laser system emitting 100 W of average power, 1 mJ of pulse energy and <7 fs CEP-stable pulses.

In the last years, titanium-sapphire and optical parametric amplifiers have become the standard technologies for generating carrier-envelope-phase (CEP) stable laser pulses. However, although both approaches have accomplished impressive improvements[1,2], their main drawback is the average-power restriction resulting from intrinsic thermo-optical limitations. The results presented herein are based on another approach: high-power fiber-laser-driven nonlinear pulse compression[3]. The concept utilizes state-of-the-art high average power ultrafast fiber laser technology. The starting point is a CEP-stable oscillator emitting comparatively long pulse in the range of a few hundred femtoseconds. These pulses are amplified in a high-power fiber chirped-pulse-amplification (FCPA) system. By using coherent combination technology, these systems have recently proven to allow for impressive laser parameters, e.g. the simultaneous generation of kilowatt-level average power and multi-mJ pulse energy[4]. Finally, the emitted high-power beam is temporally compressed to the few-cycle region by using two nonlinear-compression stage based on noble-gas-filled capillaries and chirped mirrors. CEP-stability is achieved by measuring its state at the system output and using a feedback loop.

The presented CEP-stable laser system represents record power values with an average power of 100 W and 1 mJ pulse energy at 7 fs pulse duration. It will be employed as the so-called HR1 laser at the ELI-ALPS research facility in Szeged, Hungary. The system consists of a 3 mJ, 300 W, 100 kHz, 300 fs FCPA system, which utilizes coherent combination of eight main-amplifier channels. We present measurements of average-power stability, pulse-to-pulse stability and pointing stability. This driving laser is followed by two noble-gas-filled capillaries and chirped mirrors after each stage. In the first stage, spectral broadening in the capillary and subsequent compression yields 30 fs pulses that are further down-compressed to <7 fs in the second nonlinear compression stage. Due to the excellent beam quality of the FCPA system, this two-stage approach reaches a throughput efficiency on the order of 40%. We will show detailed measurements and characterization of the FCPA system as well as the compression unit. General scaling properties of hollow-fiber compressors towards multi-mJ operation at kW-level average powers will be discussed.

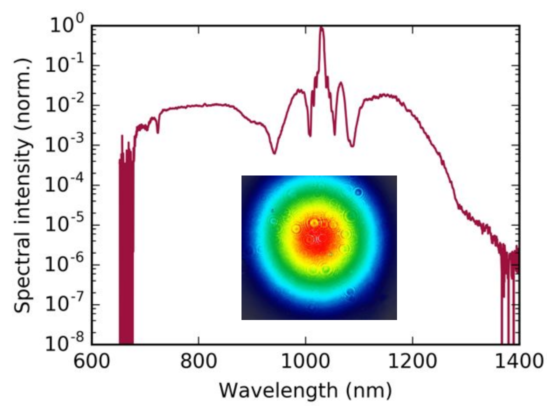

Fig. 1. Measured spectrum of the HR1 laser output. The inset shows the collimated beam profile after the second compression stage.

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Enhancement of temporal contrast by filtered SPM broadened spectra

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Abstract: We demonstrate a novel technique based on self-phase modulation and spectral filters to enhance the temporal contrast of laser pulses by several orders of magnitude with high efficiency and peak-power conservation.

In high-pulse-energy ultrafast lasers, temporal contrast is an increasingly important topic. Established contrast-enhancement techniques are, for example, cross-polarized wave generation [1] and nonlinear ellipse rotation [2]. We present a novel approach for contrast enhancement based on self-phase modulation (SPM) and subsequent spectral filtering, allowing for high efficiency, high contrast enhancement while being peak-power maintaining. The contrast enhancement achievable with this method is only limited by the contrast and spectral steepness of the filters, as the SPM-generated signal is outside the spectral hard-cut of the CPA.

In a first proof-of-principle experiment the output from an ultrafast fiber CPA system [3] is coupled into a gas-filled hollow-core fiber (HCF). The incident spectrum (Figure 1), which is centred at 1030 nm is spectrally broadened by self-phase modulation. Then, the signal is filtered with two longpass filters with an edge at 1050 nm. The broadening is adjusted by the gas pressure, such that the minimum spectrum coincides with the filter edge. The filtered signal has a very smooth spectrum centred at 1060 nm and an energy content of 20 – 30% of the HCF-output pulses. The signal is detected by a third-order autocorrelator (Amplitude Technologies, Sequoia) with a dynamic range of ten orders of magnitude.

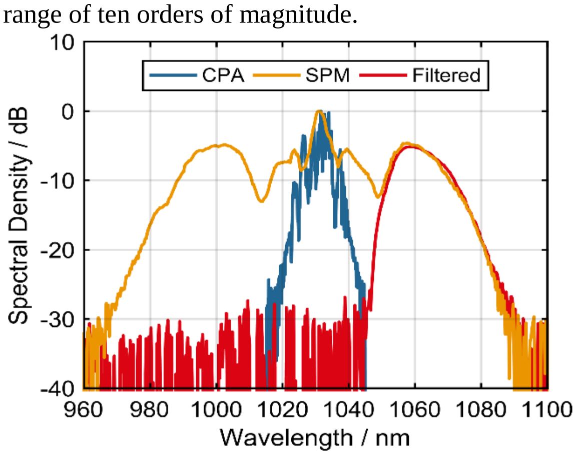

Fig. 1. Spectrum of CPA-signal, which is broadened by SPM and filtered.

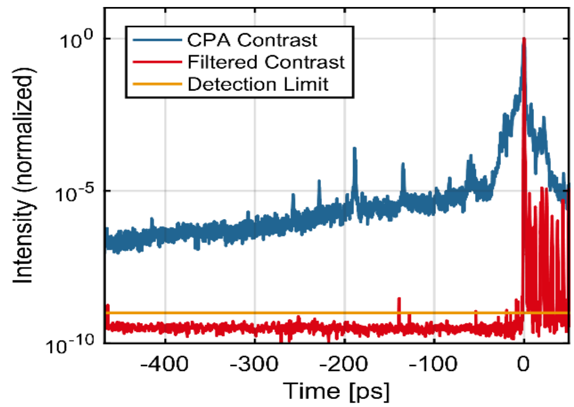

Fig. 2. Pulse contrast of the CPA system before and after SPM contrast enhancement.

As shown in Figure 2 the measured contrast of the filtered signal is better than 10^{-9}. Compared to the contrast of the incoming pulses of about 10^{-2} we have achieved a contrast enhancement of at least seven orders of magnitude. In this case two filters with a contrast of six orders of magnitude each were used. The post-pulses in the filtered signal are caused by internal reflections in the spectral filters and could be avoided by using wedged filters.

In conclusion, we have demonstrated a novel technique for contrast-enhancement based on SPM in a proof-of-principle experiment. The method is simple to implement and allows highly efficient temporal pulse cleaning.

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Microjoule, femtosecond fiber laser seeded by a gain-switched diode

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Abstract: We generate 2.4-μJ, 140-fs pulses from a fiber system based on a gain-switched diode. Deliberately managing nonlinear propagation effects results in coherent pulses with transform-limited quality.

I. INTRODUCTION

Lasers generating femtosecond-scale pulses are indispensable for ultrafast science and applications. While modelocked oscillators deliver unparalleled performance, difficulties in maintaining modelocking limit their impact outside of academia. Gain-switched diodes (GSDs) provide a robust, alternative means of short pulse generation. However, the long (>10 ps), low-energy, semi-coherent pulses they emit are useless for many applications. Here, we present a fiber system seeded by a GSD which solves these problems using a combination of a Mamyshev regenerator and parabolic pre-shaping. These techniques grow the pulses' coherence while also shaping and compressing them, allowing 2.4-μJ, 140-fs pulses to be obtained.

II. EXPERIMENTAL RESULTS

We seed our system with a commercial GSD which emits nanojoule-scale pulses near 1030 nm. Autocorrelations reveal a prominent, partially coherent, 14-ps peak on top of a broad, incoherent pedestal (Fig. 1b, black). We use a Mamyshev regenerator[1] to simultaneously compress these pulses, suppress the pedestal, and improve the pulse coherence. The pulses are launched into passive fiber, where the intense, coherent component alone experiences strong spectral broadening. A bandpass filter thus allows us to isolate clean, coherent, 3-ps pulses from the GSD seed (Fig. 1a-b, red).

Further pulse shaping is performed using amplification by parabolic pre-shaping.[2] The filtered pulses propagate in passive fiber, where they transiently become parabolic.[3] The pulses are then amplified in two Yb-doped fibers. There, they experience strong self-phase modulation, which the parabolic shape converts to a linear chirp. The pulses can then be dechirped with a standard grating pair, and we thus obtain 2.4-μJ, 140-fs pulses (Fig. 1c-d). The transform-limited duration and the 8:1 autocorrelation ratio indicate that the pulses are highly coherent, despite being seeded by a GSD. Pulse-to-pulse seed fluctuations result in 2% energy jitter in the output, which future work will address.

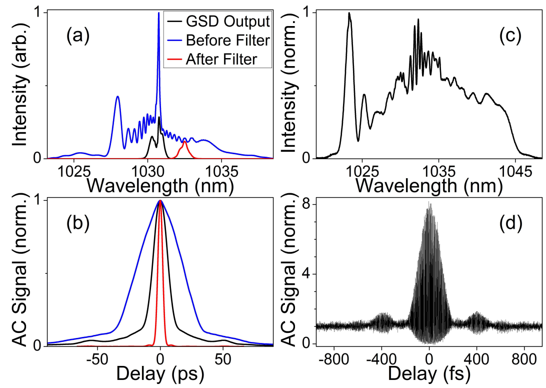

Fig. 1. Spectra and autocorrelations at various points in the Mamyshev regenerator (a-b), and at the compressed output of the system (c-d).

III. CONCLUSIONS

We demonstrate a fiber system seeded by a gain-switched diode. Using a combination of a Mamyshev regenerator and parabolic pre-shaping, we generate pulses comparable to those from an amplified modelocked oscillator, in a highly robust system that does not require modelocking.

ACKNOWLEDGMENTS

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Ultrabroadband fiber lasers and applications in subcycle quantum physics

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Abstract: Ultrafast fiber laser technology provides the ultrabroad bandwidth necessary for the synthesis of single-cycle pulses characterized by passive control of the carrier-envelope phase. These transients enable the investigation of fundamental quantum phenomena on subcycle timescales.

I. ULTRAFAST FIBER LASERS

The development of ultrafast Er/Yb:fiber laser technology combines the outstanding flexibility and robustness of fiber-based solutions with operation at high repetition rate and short pulse duration[1,2]. All these ingredients are crucial for advanced precision experiments exploiting extreme nonlinearities and/or sub-cycle optics with optimum noise performance and long-term stability. In particular, a high repetition rate ensures maximum detection statistics in the investigation of fundamental ultrafast phenomena.

The core of the technology is generation of well-behaved and coherent supercontinua in highly nonlinear fibers with tailored spectra for specific experiments. This step allows us to (i) produce few-femtosecond pulses with passive locking of the carrier-envelope phase (CEP), (ii) seed high-power Yb:amplifiers and optical parametric stages for energy scaling and (iii) generate broadband field transients in the mid and far infrared that are characterized by electro-optic sampling with high sensitivity.

II. SUBCYCLE QUANTUM PHYSICS

II.A. High harmonic generation

Intense 2.3-cycle pulses, produced via parametric amplification driven by the combined Er/Yb laser, are exploited for generation of even and odd harmonics in solids up to seventh order. Operating at a repetition rate of 10 MHz, our system represents an attractive table-top source of photons in the deep UV for ultrafast experiments. In addition, the emitted spectra show a clear dependence on the CEP of the driving pulses, revealing fundamental aspects underlying the generation process

II.B. Quantum measurements of the electric field

Vacuum fluctuations represent one the most fundamental phenomenon in quantum physics. Multi-terahertz electro-optic sampling and ultrabroadband Er:fiber laser technology together provide the extreme sensitivity needed for direct investigation of the quantum noise of the electric field. Squeezed vacuum transients exhibiting subcycle intervals with fluctuations below the pure quantum vacuum have been generated and characterized in the time domain[3]. Enhanced fluctuations in adjacent time segments are a signature of correlated quantum radiation which results as a consequence of the uncertainty principle.

II.C. Single-electron nanotunneling

A single-cycle optical field with passive phase stabilization is focused to a nano-scaled junction equipped with a plasmonic nanoantenna. This device constitutes an electronic circuit with nonlinear and antisymmetric current-voltage characteristics. An effective bias then arises when the exciting optical field is cosine-shaped because the global field maximum occurs only for one polarity. Consequently, the transport symmetry of the electronic structure is broken even when integrating over the entire transient and a net tunneling current of individual electrons results through the potential barrier represented by the free-space gap[4].

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Vectorial reconstruction of NIR-VIS optical field by XUV interferometry

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Abstract: Field and polarization sensitive optical processes require precise knowledge of the electric field vector **E**(t) of the interacting pulse at every time instant. A novel measurement technique with attosecond resolution is described and demonstrated experimentally.

An optical pulse is fully determined by the magnitude and polarization of the electric field vector **E**(t) in time. These two quantities drive many light-matter interactions at the fundamental level. Several techniques have been developed to completely determine these two dynamical quantities experimentally [1, 2] and methods to control them are routinely applied. In the present contribution we demonstrate a novel all-optical full characterization technique that is capable to handle weak pulses of 10-100 nJ pulse energy, corresponding to intensities of 10^9 W/cm², and that is free of systematic errors. The method relies on two cornerstones: the implementation of extreme ultraviolet (XUV) interferometry [3] of isolated attosecond pulses, and the demonstration that an attosecond electron wave packet created by an intense laser pulse allows to sample an unknown electric field along a direction selectable in the experiment. Once two orthogonal directions are measured, the full time dependence of **E**(t) is obtained.

The experiment exploits a phase step plate to generate two adjacent foci in which two independent but identical electron wave packets are released through tunnel ionization from noble gas atoms by an intense driving laser field. Subsequent acceleration and recombination with the parent ion generates two identical, coherent, closely-spaced isolated attoseond pulses (IAP), the driving field being shaped according to the polarization gating technique. The spatially resolved spectrum of these two IAP provides a measurement of their relative phase and amplitude through the position and contrast of the interference fringes on a 2D detector. The unknown field $\mathbf{E}_{\mathbf{unk}}$(t) is now superimposed on only one of the two identical foci with a variable time delay τ relative to the driving pulse while the other focus acts as a reference. $\mathbf{E}_{\mathbf{unk}}$(t) modifies the motion of the first electron wave packet during its sub-fs excursion in the continuum, thereby inducing an additional phase. By recording the modulation of the phase shift with delay, the electric field projection along the polarization of the electron wave packet is obtained. The procedure is then repeated with the driving pulse rotated by 90° to obtain the full vector $\mathbf{E}_{\mathbf{unk}}$(t). Fig. 1 shows the results of such a measurement on a pulse which polarization state was sculpted according to the polarization gating technique, as the unknown field. The reconstructed field clearly shows the predicted time-dependent polarization state for such a pulse starting circular, through linear and back to circular.

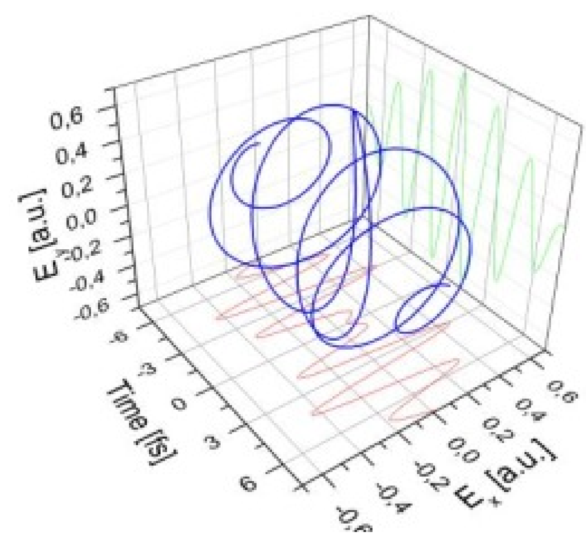

Fig. 1. The field of a polarization-gated few-cycle pulse (blue) reconstructed from two orthogonal projections (red, green) measured experimentally.

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Genetic algorithms for advanced phase retrieval in tomographic pulse characterization techniques

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Abstract: A new retrieval method for techniques like FROG and dispersion scan is demonstrated. Based on differential evolution, the algorithm proves to be fast and virtually immune to local stagnation, even for complex pulse shapes.

I. INTRODUCTION

Phase retrieval algorithms are essential to obtain the pulse shape from techniques such as FROG, MIIPS, sonogram, and dispersion scan (d-scan) [1], which measure the spectral dependence of the nonlinear signal on one parameter, e.g., the delay between two pulses or a group delay dispersion variation of the input beam. We present a new solution for the retrieval problem, for which we employ the differential evolution (DE) algorithm [2], which uses a population of possible solutions that undergo processes such as mutation and cross-over in search for a global optimum.

II. APPLICATION OF DE TO D-SCAN

D-scan is one of the most recent additions to the toolbox of ultrafast optics. Unlike other methods, the pulse is not split into two, as it only passes through a variable amount of dispersive material before being focused on the nonlinear crystal. But despite having the advantages of tight-focusing and simplicity, the weak spot of d-scan is the retrieval, for which the Nelder-Mead (NM) algorithm, as well as generalized projections (GP), has been exploited[1].

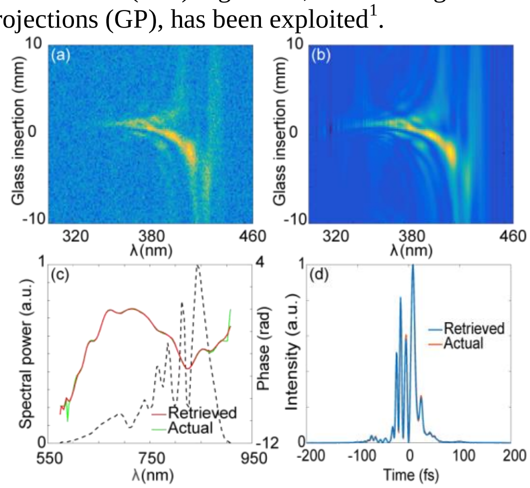

Fig. 1. (a) The d-scan trace with 10% noise, (b) the retrieved trace, (c) pulse in wavelength domain, and (d) in time domain, showing excellent agreement.

While GP had been found superior compared to NM in our tests, both algorithms often fail to converge within a reasonable time for complex pulse shapes as they frequently appear in supercontinuum pulse compression experiments, cf. Fig. 1. DE, in contrast, could consistently reconstruct the complicated spectral phase of the pulse in Fig. 1 within about 10 seconds. Despite the massive 10% added noise, the algorithm was still able to correctly reconstruct the intensity ratios of a sequence of 4 major and several minor temporal satellites. We are not aware of any other self-referenced pulse characterization method that would allow for equally accurate reconstruction of such a complex pulse sequence. We also attempted DE for FROG, which in our tests eliminated local lockups without suffering from increased retrieval times. As DE is much more adaptable than GP we can also use it for interferometric FROG traces and other variants of tomographic pulse retrieval methods.

III. CONCLUSION

We believe that we found a highly interesting new method for phase retrieval in tomographic pulse characterization methods. The method seems to be virtually free of local lockups, robust to measurement noise, and is at least as fast as the fastest competing algorithms. Further optimization of the convergence behavior can be expected from utilizing massively parallel computing environments. DE may therefore bring us an important step closer to the functionality of a real-time optical oscilloscope, which can reconstruct complex temporal transients with video-rate refresh.

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Time-Domain Ptychography

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Abstract: Through rigorous analytic calculations, dedicated simulations and via different experiments we demonstrate the robustness of time domain ptychography as a tool to reconstruct ultrafast events from frequency resolved cross-correlation (XFROG) measurements.

I. INTRODUCTION

One of the most robust techniques solving the so-called phase problem in X-ray diffraction imaging is ptychography. It produces the correct real-space image if the illumination beam is known[1], but works even if it is unknown[2]. Our aim is to extend ptychography to the time domain and further to the reconstruction of spatiotemporal objects. In comparison to existing algorithms, ptychography minimizes the data to be recorded and processed, and thereby significantly reduces the computational time of reconstruction.

II. RESULTS

We show that time-domain ptychography is related to Gabor frames allowing us to use the theory of frames to calculate the range of optimal reconstruction parameters, which so far are determined mostly via trial and error. Then, we experimentally verify time-domain ptychography with the probe pulse (1) being known, (2) unknown but derived from the temporal object, and (3) completely unknown[3,4,5]. Next, we demonstrate that the properties of time-domain ptychography are especially well suited for the reconstruction of complex light pulses with large time-bandwidth products[6], for example supercontinua from nonlinear fibers.

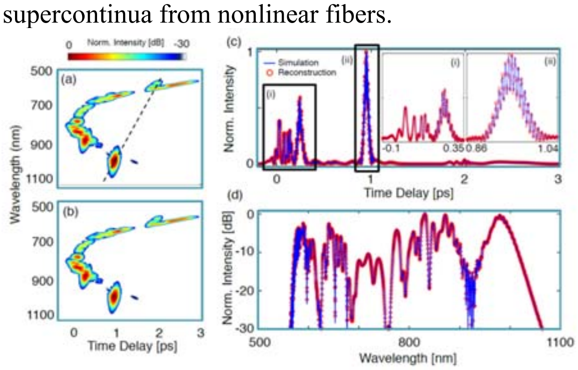

Fig. 2. (a) Simulated; (b) reconstructed spectrogram. (c) Temporal intensity and (d) logarithmic spectrum.

We simulate and measure the spectrogram of different supercontinua with one example shown in Fig.2. The spectrogram is sampled on a MxN grid and in ptychography no further interpolation is required. In contrast, previous reconstructions of complex supercontinua needed to be interpolated on a much larger MxM grid. The simulated and reconstructed spectrograms are displayed in Figs. 2(a) and 2(b) and the agreement between the two is excellent. Two especially challenging structures for the reconstruction are highlighted in Fig. 2(c): (i) the densely packed solitons around 0 fs; and (ii) the overlap of the strongest soliton with a dispersive wave at 950 fs, which causes an extremely fast temporal beating with a 6.5 fs period. Finally, the comparison of the spectra in Fig. 2(d) shows that the ptychographic reconstruction is accurate even down to the -30 dB level and hence achieves precise phase retrieval even in sections of the pulse where the spectral intensity is low. Finally, we show that time-domain ptychography can be extended to attosecond pulse characterization or photo-electron streaking experiments in general[7].

ACKNOWLEDGMENTS

We acknowledge support by NCCR MUST which is funded by the Swiss National Science Foundation.

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Rapid, Complete Spatiotemporal Intensity-and-Phase Measurement: Long, Complex Multi-Mode Pulses from a Multi-Mode Fiber

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Abstract: A complete spatiotemporal intensity-and-phase measurement technique is introduced to characterize relatively long, spatiotemporally complex pulses emerging from multi-mode fibers. Pulses ~3ps long containing more than ten modes were measured, and the various dispersions were intuitively visualized via spatiotemporal movies.

I. INTRODUCTION

We are developing a simple, convenient technique for completely measuring the intensity and phase of arbitrary pulses in space and time, and we use it here for measuring pulses emerging from multi-mode fibers (MMFs). Such pulses have many important applications,[1,2] and several MMF measurements have been reported.[3,4] Our complete spatiotemporal measurement method, STRIPED FISH, has previously measured spatiotemporally simple, several-mode pulses[5] and can measure pulses with space-time-bandwidth products (STBPs) as high as ~10^6.

However, it is important to be able to measure longer, more complex pulses, such as pulses comprising more modes. We solve this problem with *multiple delays* and *time concatenation*[6] of ~100 delayed temporal pieces of the pulse in a STRIPED FISH device, yielding ~100 STRIPED FISH traces. This delay-scanned spatio-temporal measurement technique can measure pulses with STBPs as high as ~10^8 and can directly measure the full information of complex output pulses from MMFs.

II. EXPERIMENT AND RESULTS

The experimental layout is shown in Fig.1. The Ti:Sapphire laser delivered femtosecond pulses with 25nm FWHM bandwidth centered at 792nm. After the spatial filter (two lenses and a 75µm pinhole), the pulses had a clean spatial profile and a relatively flat spatial phase. 80% of this energy passed through the beam splitter, BS1, into a piece of MMF to become a long unknown pulse, while the other 20% was reflected by BS1 and used as the reference pulse. Part of the reference pulse was picked out by a second beam splitter, BS2, for the temporal profile characterization of the pulse using GRENOUILLE (Swamp Optics, model 8-20).[7]

The ~3ps pulses emerging from the MMF with more than ten linearly polarized (LP) modes under different coupling situations were completely characterized by the technique, and the results were visualized in color movies (Table 1).

III. CONCLUSIONS

More than ten modes from a MMF were measured by delay-scanned STRIPED FISH. This device should be a powerful measurement tool for measuring even more spatiotemporally complex pulses.

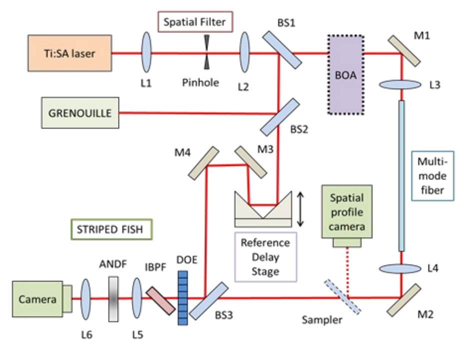

Fig. 1. Delay-scanned STRIPED FISH apparatus and experiment demonstrating its use for measuring MMF pulses.

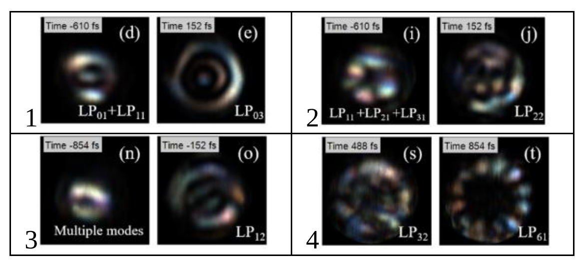

Table 1. Selected snapshots from the STRIPED FISH-measured color movies for four different coupling situations. Snapshots are shown for two times for each coupling situation. Pulses are propagating at the viewer. The color indicates the phase by showing the actual (false) color as would be seen by the eye if it had 10^{14} times faster resolution.

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Single-shot high dynamic range pulse contrast measurements at the Draco laser system in combination with plasma mirrors

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Abstract: We report on high pulse contrast operation modes of the Draco laser with focus on the on-shot characterization of the few-ps-contrast by novel techniques based on tilted beam self-referenced spectral interferometry with 10^8 dynamic range.

I. Introduction

High peak power ultra-short pulse lasers are state of the art drivers for new advanced plasma based particle accelerators. The dual beam Draco laser at HZDR represents the most powerful category operational on target for laser plasma experiments providing up to 30 J energy in 30 fs pulses[1]. Here, the focus will be on reliability and monitoring of the whole system, and in particular of the temporal pulse contrast.

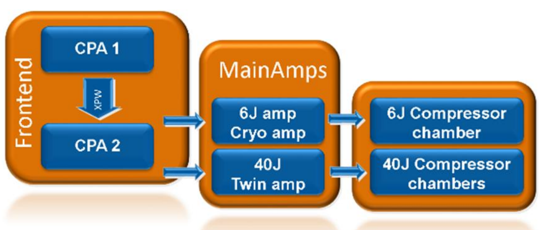

Fig. 1. Layout of the Draco laser system.

The Draco laser system was built and customized by Amplitude Technologies in cooperation with the HZDR. It consists of a double CPA frontend and two main amplifiers, the 150 TW arm with energies up to 6J and the PW arm with energies up to 40J. After amplification both beams are compressed and sent to the experimental sites for individual or combined operation. A variety of diagnostics for compression, contrast optimization and wavefront / pulsefront corrections are available at the laser output as well as on target.

II. Single-shot SRSI-ETE contrast measurement

As pulse contrast is determining the initial phase of every experiment, on-shot knowledge and control is of most importance. Not only the ns to ps ASE pedestal plays a crucial role, but also the rising slope of the pulse. Up to now concepts using scanning third-order autocorrelators are applied in multi-shot operation, or single-shot systems with lower dynamic and/or time resolution. We here present a new device developed in cooperation with Fastlite using the SRSI technique with extended time excursion, featuring a temporal window of 18ps, a temporal resolution of 20fs and a dynamic range of 10^{-8}. Also spatio-temporal coupling effects can be studied. We demonstrate the capabilities of the device using XPW filtered and un-filtered probe beams of the Draco system[2]. A first application is the measurement of the performance of a plasma mirror setup close to the experiment. All measurements are directly compared to a third-order AC (Sequoia).

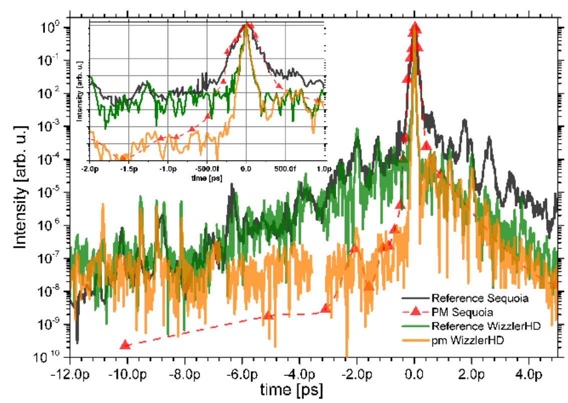

Fig. 2. Measurement of contrast with Sequoia and Wizzler HD with vs. without plasma mirror filtering.

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Measurement and correction of spectral phase in a few-cycle parametric amplifier

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Abstract: We study the spectral phase introduced by parametric amplification and how high extraction efficiency of energy leads to deterioration of the phase. Avoiding this regime, and using a pulse shaper, we achieve high-contrast ultrashort pulses.

I. INTRODUCTION

Due to its large gain bandwidth, optical parametric chirped pulse amplification (OPCPA) is one of the preferred techniques for the amplification of ultrashort pulses[1]. One of the problems that must be dealt with is the spectral phase distortion introduced in the seed during amplification. We measure this spectral phase as a function of amplification and discuss limitations and trade-offs with respect to gain and pulse compressibility.

II. GAIN-DEPENDENT SPECTRAL PHASE

We use the d-scan[3] technique to measure the spectral phase as a function of pump power for a single-stage OPCPA system, and compare it with the theoretical results for a non-depletion case[2].

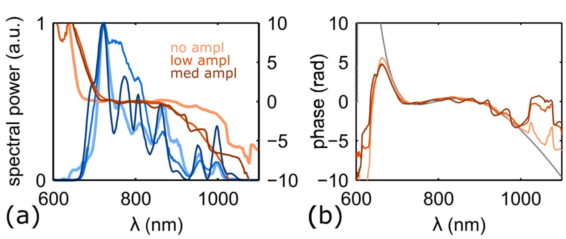

Fig. 1. Spectral phase measurement of (a) seed and amplified pulses, and (b) comparison of the parametric phase with theoretical value for phase-mismatch. Darker colors correspond to larger gain.

Fig. 1 shows an example of spectral phases for unamplified and amplified pulses. The parametric phase (Fig.1b) is obtained by subtracting the spectral phase of the seed. For amplifications far from depletion, the parametric phase is well behaved and easy to correct and/or pre-compensate. It fits well to the mismatch phase $\Delta kz/2$ (Fig.1b, gray line) for a wide range of gain.

As the extraction efficiency becomes high (typically over 20% in our case), the spectral amplitude starts to show strong amplitude modulations, and the phase starts to show strong oscillations, which translates to long, low contrast pulses, which are also difficult to compress. Choosing different geometric parameters it is possible to minimize high order spectral phase components, making it easier to correct with standard compressors[4].

Using a pulse shaper we pre-compensate the slowly varying spectral phase, and reach pulses with duration close to the Fourier limit. The very fast phase variations are more difficult to correct, and we found in our case, necessary to find a trade-off between pulse energy and temporal quality of the amplified pulses.

III. CONCLUSIONS

We present results on the spectral phase measurement of an OPCPA source as a function of gain, and discuss trade-offs in terms of energy and compressibility. The insight gained from such measurements allowed us to build a few-cycle, high contrast optical parametric amplifier.

ACKNOWLEDGMENTS

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Tracing the Phase of Focused Broadband Laser Pulses

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I. INTRODUCTION

Precise knowledge of the behavior of the phase of light in the focus of a laser beam is fundamental to understand and control laser-driven processes. More than a hundred years ago the axial phase evolution for focused monochromatic light beams was described and is now commonly known as the Gouy phase[1]. Recent theoretical work has brought into question the validity of applying this monochromatic phase formulation to the broadband laser pulses becoming ubiquitous today e.g. in high-harmonic and attosecond pulse generation, femtochemistry, optical coherence tomography and light-wave electronics.

II. METHOD AND RESULTS

Based on electron back-scattering at sharp metal tips, a method is available to measure strong light fields with sub-wavelength resolution and sub-optical cycle time resolution. We combine this effect with a high-precision carrier-envelope phase (CEP) meter based on atomic above-threshold ionization. We report a quantitative, direct, 3D measurement of the focal CEP evolution of a few-cycle (4-fs), near-infrared laser beam, spanning a range of seven times the Rayleigh range along the propagation axis and one and a half times the local beam radius perpendicular to the optical axis[3]. The nanotip is scanned through the focus and photoelectron spectra are recorded at a set of points in space using a time-of-flight spectrometer. The CEP modulation of the phase-tagged spectra reveals the local phase.

The results are summarized in Fig. 1. We find that not only the axial CEP behavior is more complex than the Gouy phase, even including extrema, but also a strong transverse curvature can be observed. A theory model[2] agrees well with our data. The observed deviations are due to the spectral geometry of the input beam, enabling an independent path to estimate the CEP-profile-determining parameter based on beam profile measurements.

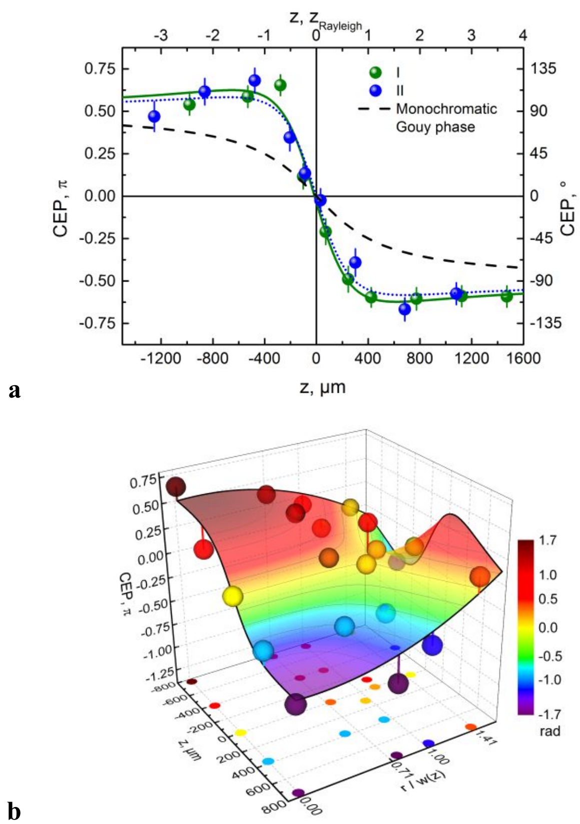

Fig.1. Carrier-envelope phase (CEP) evolution of focused, 4-fs, laser pulses on the optical axis (**a**) and off the optical axis (**b**) fit by a theoretical model[2].

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MIR driven attosecond sources and other new developments in attosecond research

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Abstract: Significant progress has recently been made in shortening the duration and extending the photon energy of attosecond pulses. Single isolated 53 as X-ray pulses has crossed the Carbon K-edge and entered the water window.

I. Introduction

Since the first demonstration of attosecond pulses 16 years ago, Ti:Sapphire lasers centered at 800 nm have been the workhorse for the first generation attosecond light sources[1]. The spectral range of the light sources with sufficient photon flux for pump-probe experiments has been limited to extreme ultraviolet (10 to 150 eV). It was demonstrated in 2001 that the cutoff photon energy of the high harmonic spectrum can be extended by increasing the center wavelength of the driving lasers[2]. In recent years, mJ level, few-cycle, carrier-envelope phase stabilized lasers at 1.6 to 2.1 micron have been developed by implementing Optical Parametric Chirped Pulse Amplification (OPCPA) techniques[3], which have used to generate high-order harmonics in the water window (280-530 eV). However, measure the spectral phase of the broadband soft X-ray pulses is a great challenge. In addition, increasing the peak power of extreme ultraviolet and X-ray pulses for attosecond pump-attosecond probe has been another major goal in attosecond science.

II. Isolated X-ray attosecond pulses generation using MIR lasers

When a mid-infrared driving laser was combined with Polarization Gating or Double Optical Gating, isolated soft X-rays in the water window (280-530 eV) were generated in our laboratory. The number of X-ray photons in the 120–400 eV range is comparable to that generated with Ti:Sapphire lasers in the 50 to 150 eV range[4]. The ultrabroadband isolated X-ray pulses with 53 as duration were characterized by attosecond streaking measurements.

It is expected that the photon energy of the attosecond X-ray pulses can be further increased to keV by driving high harmonic generation with two-cycle, CEP stable lasers centered at 3 to 8 micron[5,6]. Such ultrabroadband light sources can be used in time-resolved X-ray absorption near edge spectroscopy measurements for studying charge migration and other electron/nuclear dynamics in molecules, as well as charge dynamics and phase transition in condensed matter.

III. Intense XUV pulse generation with CEP stable 10 Hz lasers

We are developing a laser system to provide both high-energy (1.5 J) and short-duration (<15 fs) pulses for driving isolated attosecond pulse generation. We demonstrated a "fast CEP probe" technique for actively controlling the carrier-envelope phase of a low-repetition-rate, Chirped Pulse Amplification laser. To validate the carrier-envelope phase stabilization of the 10 Hz laser, the dependence of the high-order harmonic spectrum was measured. Progress on increasing the XUV pulse energy beyond 100 nJ is currently being made by improving the driving laser wavefront with a deformable mirror and by implementing sub-cycle gating schemes.

ACKNOWLEDGMENTS

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High harmonics with spatially varying ellipticity

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Abstract: We combine two orthogonally linearly polarized high-harmonic sources to produce a far-field distribution with spatially varying ellipticity. We characterize this spatially varying ellipticity with x-ray magnetic circular dichrosim and demonstrate a high degree of circularity.

High-harmonic generation (HHG) provides a unique and useful source of spatially and temporally coherent extreme ultraviolet (EUV) beams, which can access attosecond time scales and nanometer length scales[1,2] and enables a wide variety of magnetic spectroscopies.[3,4] Traditionally, HHG is driven by linearly polarized lasers to produce linearly polarized harmonics. Recently, the ability to produce bright circularly polarized HHG beams was developed, making it possible to sculpt the polarization state of the EUV light.

In this work, we produce HHG with spatially varying ellipticity by superposing two spatially separated high-harmonic sources in analogy to a classic double slit experiment[5,6] (Fig. 1a). However, when the two harmonic sources have *orthogonal* linear polarizations then there is no intensity interference. Instead there is phase interference, where the polarization state of the HHG varies across the far-field intensity distribution – ranging from linear to elliptical to fully circular polarization.[7]

We characterize the spatially resolved polarization state of the high harmonics using EUV magnetic circular dichroism (EUV MCD), in which the EUV absorption of a uniformly magnetized sample depends on the helicity of the light. The magnitude of this dichroic absorption varies with the ellipticity of the light and therefore provides a characterization of the polarization state. We measure the EUV MCD asymmetry of a thin film of cobalt and observe a sinusoidal spatial variation in the asymmetry that indicates a sinusoidal variation in the ellipticity of the high harmonics (Fig. b,c). Comparison of the measured EUV MCD asymmetry with literature values[8] shows that the polarization does indeed spatially vary from linear to nearly purely circular polarization (Fig. 1d). Furthermore, we show that this scheme allows for the measurement of the spectrally resolved EUV MCD asymmetry without the use of a grating, enabling hyperspectral magnetic imaging with HHG.

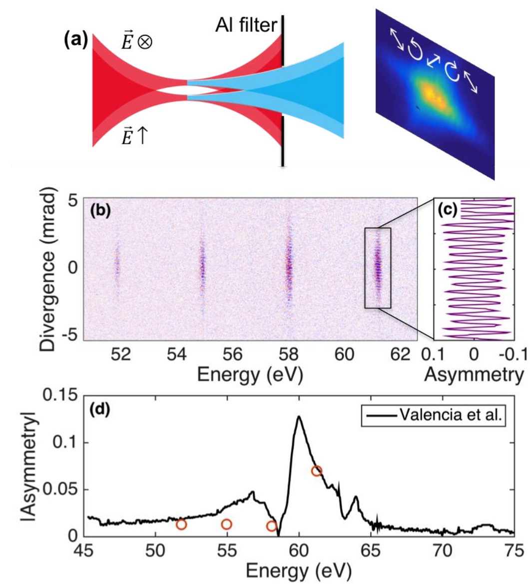

Fig. 1. (a) Two orthogonally linearly polarized beams are focused into a gas jet, producing orthogonally linearly polarized HHG beams that diverge and overlap in the far field. This produces a spatially varying ellipticity. (b) EUV MCD measurements of a thin film of Co reveal the spatially varying ellipticity of the HHG beam. Red regions are right-circularly polarized and blue regions are left-circularly polarized. (c) The spatial dependence of the EUV MCD of each harmonic order shows sinusoidal variations. (d) Comparison of the magnitude of the EUV MCD asymmetry with literature values shows that the spatial regions with the highest ellipticity are nearly purely circular.

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Polarization Control of Isolated Attosecond Pulses

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Abstract: By adjusting the ellipticity of counter-rotating polarized few-cycle pulses for non-collinear high order harmonic generation, we obtain full control of polarization states of isolated attosecond pulses for the first time.

Ultrafast Extreme ultraviolet (EUV) beams carrying spin angular momentum are currently thoroughly studied for their applications for investigating the structural, electronic, and the magnetic properties of materials, discriminating between enantiomers as well as working out how chiral molecules interact. Such light sources are already been produced by few free-electron laser facilities [1]. Although it's powerful, the pulse duration of FEL is typically tens of femtoseconds and the large-scale facilities with high costs results in a limited number of beamlines.

High harmonic generation (HHG) driven by femtosecond lasers makes it possible to capture the fastest dynamics of molecules and materials in attosecond (10^{-18} s) scale. In 2016, we experimentally demonstrated the generation of isolated circularly polarized attosecond pulses by non-collinear HHG driven by two few-cycle circularly polarized counter-rotating pulses (~3.6 fs, 1.4 optical cycles, generated by the MPContinua [2]). This produces a pair of HHG supercontinua beams, one with left-circular and one with right-circular polarization, and spanning photon energies from 25 to 40 eV with a Fourier limit pulse duration of 190 as [3].

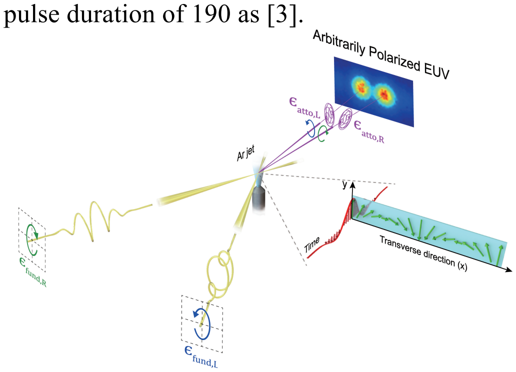


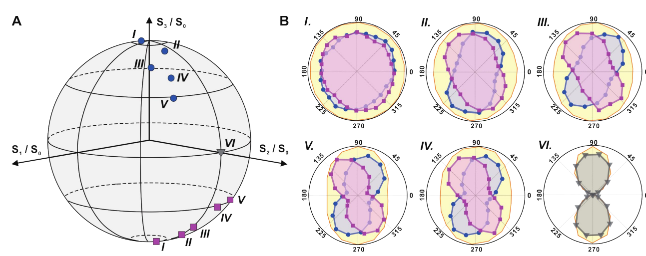
Fig. 1 (a) Schematic of the experimental setup. The inset shows the electric field distribution on the focal plane – local E-field vectors rotating crossing the transverse direction $\hat{x}$.

In this work, we further propose and experimentally demonstrate full polarization control of isolated attosecond pulses ϵ_{atto}, by adjusting the ellipticity of two counter-rotating driving pulses, ϵ_{fund}. Importantly, the polarization state of the attosecond pulses was fully analyzed with an EUV polarimeter, which unambiguously determines the ellipticity and helicity of attosecond pulses. Fig. 2A shows the polarization states of the isolated circularly, ellipticaly and linearly polarized attosecond pulses that have been produced.

To control the ellipticity of attosecond pulses, two elliptically polarized few-cycle fundamental beams with the same ellipticity ϵ_{fund} but opposite helicity are prepared and focused into a gas jet in a non-collinear geometry (Fig. 2). At the focal plane, z=0, the combination of electric field E_{focus} becomes

$$2[\epsilon_{fund}\cos(kx\sin\theta)\,\hat{x} - \sin(kx\sin\theta)\,\hat{y}]e^{-(t/\tau)^2 - i\omega t}$$

E-field vectors, rotating crossing the transverse direction $\hat{x}$ with a period of $2\pi/(k\sin\theta)$, were created. The local E-field of each position oscillates linearly as a HHG local emitter and superposes two elliptically polarized EUV beams in the far field. As a result, the ellipticity ϵ_{atto} of the attosecond pulses can be controlled with the fundamental ellipticity ϵ_{fund} as presented in Fig. 2. Moreover, this non-collinear scheme also supports generation of isolated attosecond pulses, when driven by few-cycle pulses. This has been theoretically and experimentally demonstrated [3,4].



I. $\epsilon_{fund,R/L} = 0.98$	II. $\epsilon_{fund,R/L} = 0.93$	III. $\epsilon_{fund,R/L} = 0.90$	IV. $\epsilon_{fund,R/L} = 0.85$	V. $\epsilon_{fund,R/L} = 0.80$	VI. $\epsilon_{fund,Linear} = 0$
$\epsilon_{atto,R} = 0.90$	$\epsilon_{atto,R} = 0.70$	$\epsilon_{atto,R} = 0.61$	$\epsilon_{atto,R} = 0.44$	$\epsilon_{atto,R} = 0.31$	$\epsilon_{atto,Linear} = 0.03$
$\epsilon_{atto,L} = 0.93$	$\epsilon_{atto,L} = 0.71$	$\epsilon_{atto,L} = 0.54$	$\epsilon_{atto,L} = 0.43$	$\epsilon_{atto,L} = 0.34$	

Fig. 2 (a) The polarization states, Stokes parameters, of isolated attosecond pulses have been generated, characterized, and marked on the Poincaré surface (blue circle and purple square represent positive and negative helicity, respectively), while one HHG pulse driven by single linearly polarized fundamental was also measured (gray triangle and inset VI). (b) Blue and purple (yellow) lines representing attosecond (fundamental) pulse intensity varied with the axis of a polarization analyzer, together with one table giving ellipticity relations between them.

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Polarization Control of Attosecond High-Harmonic Waveforms via Helicity-Selective, Circularly Polarized High Harmonic Generation

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Abstract: We experimentally demonstrate active polarization control of attosecond pulse trains (APTs) produced via circularly polarized high harmonic generation. The intensity ratio of the two-color driving field can be tuned to yield APTs with high ellipticity.

Circularly polarized high harmonic generation (CPHHG) driven by two-color counter-rotating circularly polarized (e.g. bicircular) laser fields is a versatile source of bright, coherent beams of extreme ultraviolet (EUV) and x-ray light, which are capable of probing ultrafast chiral dynamics in material systems [1]. Although high harmonics with highly circular polarization have been produced, the underlying attosecond pulse trains (APTs) consist of *linearly polarized* bursts of EUV and x-ray light, thus precluding interrogation of spin dynamics on the attosecond time scale [2, 3].

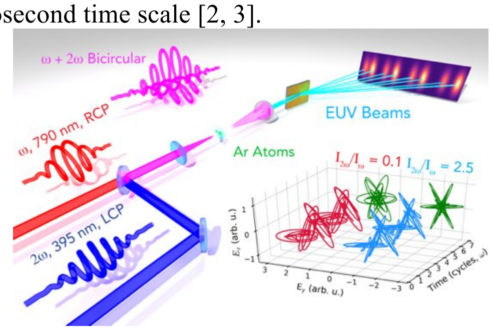

Fig. 1. Experimental scheme for controlling the ellipticity of APTs produced via bicircular-driven CPHHG. Theoretical APTs obtained from CPHHG spectra driven at different intensity ratios of the bicircular field (inset).

We demonstrate a method for controlling the ellipticity of high harmonic waveforms produced via CPHHG both experimentally and theoretically [Fig. 1]. We find that the intensity ratio, $I_{2\omega}/I_\omega$, of the bicircular field can be used to control the ellipticity of the underlying APTs. This control is due to the fact that as $I_{2\omega}/I_\omega$ is varied, the harmonic orders that co-rotate with the more intense component of the bicircular field are preferentially enhanced, resulting in highly chiral CPHHG spectra [Fig. 2]. Temporally, this spectral chirality manifests as direct control over the ellipticity of the APTs [Fig. 2, inset]. This wavefront control of the APTs is uncoupled from the polarization of the individual harmonic orders, thus preserving their circularity across the CPHHG spectrum. Moreover, we show that spectral filtering can significantly enhance the ellipticity of the APTs, allowing for highly elliptically polarized attosecond pulses at high photon energies.

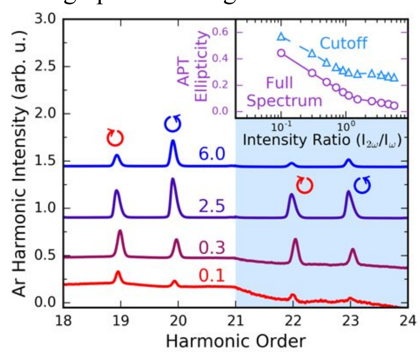

Figure 2. Experimental CPHHG spectra and theoretical ellipticity of the APTs (inset) in Ar for different intensity ratios, $I_{2\omega}/I_\omega$, of the driving field (experimental ratios given next to spectra).

In summary, we have demonstrated a method for active control over the polarization of attosecond pulse trains produced via circularly polarized high harmonic generation.

ACKNOWLEDGMENTS

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>12-W, 100-kHz, few-cycle mid-infrared source

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Abstract: We demonstrate a 100-kHz optical parametric chirped-pulse amplifier delivering pulses of ~42 fs at ~3.1 µm with an output average power exceeding 12 W. With active stabilization, single-shot carrier-envelope phase noise below 100 mrad is expected to be reachable.

The extension of High order Harmonic Generation (HHG) up to soft-x-rays requires driving sources with specific properties: mid-infrared wavelength, few-cycle pulses, high peak intensity, carrier-envelope phase stability and control, high energy and/or high-repetition rates. While long wavelength optical carriers extend the cutoff energy through the λ^2 dependency of the ponderomotive energy, shortening the pulses to few cycles increases the peak intensity and enhances the HHG conversion yield. Few-cycle pulses also reduce the number of attosecond bursts up to a single isolated attosecond pulse. In the latter case, CEP stability and control is paramount to ensure a shot-to-shot reproducibility of the driving electric field as well as of the HHG yield and spectrum.

Here, we demonstrate a supercontinuum-seeded optical chirped-pulse parametric amplifier (OPCPA) generating few cycle pulses at ~3.1 µm and optimized for CEP-stability. The system is pumped by a Yb:YAG regenerative amplifier delivering ~1.1 ps pulses with a pulse energy of 1.75 mJ at 100 kHz. Part of the pump energy (~0.65 mJ) is sent to a previously demonstrated frontend (three parametric stages), where single-shot CEP noise as low as 81 mrad was observed [1]. The remaining energy pumps a low-gain, non collinear parametric amplifier made of a bulk $LiNbO_3$ crystal heated to 120°C. The output pulse energy reaches ~130 µJ before compression for a pump energy of 1.1 mJ. Compression, at full power, in an AR-coated Silicon window yields a pulse duration of 42-fs pulses and an output pulse energy >120 µJ, which corresponds to a pulse duration slightly above four optical cycles, and a peak power of ~3 GW. At the time of the abstract submission the CEP noise of the full OPCPA system was not yet characterized, but it will be presented during the talk.

Compared to former publications, and in particular to references [2,3], our source provides important novel features:

(i) First 100-kHz class OPCPA pumped with a diode-pumped solid-state laser delivering 1-ps pulses and self-seeded with an infrared supercontinuum generated in a bulk crystal,

(ii) Combines chirp-reversal with acousto-optic pulse shaping (Dazzler) at 100 kHz and delivers, to date, the shortest pulses at this wavelength (3.1 µm) and average power (12 W),

(iii) Potentially achieves a non-averaged CEP stability with a phase noise below 100 mrad in the 0.1-5 kHz range.

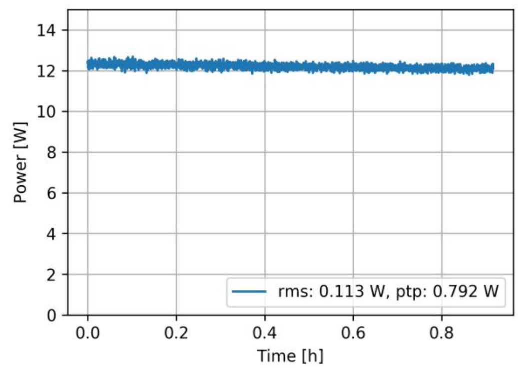

Fig. 1. OPCPA output power as a function of time.

Further optimization of the energy balance between the four OPA stages should allow to reach an output pulse energy of 150 µJ at 3.1 µm.

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Compact Multi-Millijoule, Multi-kHz, OPCPA Mid-IR Laser Optimized for keV High Harmonic Generation

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Abstract: We present a multi-mJ, 2-kHz, mid-IR OPCPA that produces >4W in the signal and >2W in the idler, in a compact setup. Excellent beam quality is achieved to support bright high harmonics up to ~1keV.

I. Introduction

The near-perfect temporal and spatial coherence of high harmonic generation (HHG) has recently enabled revolutionary advances in capturing the fastest charge and spin dynamics in materials[1,2] and in achieving the first sub-wavelength imaging[3] in the extreme ultraviolet (EUV) region. To extend these advances to shorter x-ray wavelengths, HHG needs to be driven with longer wavelength lasers[4-7]. In addition to phase matched HHG target geometries, stringent requirements are placed on the laser source i.e. stable, >1µm radiation with significant pulse energies (>1mJ) at repetition rates >kHz to enable applications. Currently, the most effective route to satisfying these requirements is the use of laser architectures such as optical parametric chirped pulse amplification (OPCPA) and optical parametric amplification (OPA). To date, most OPCPA systems either have very high rep-rates and low energies[8], or very high energies and low repetition rates[9]. Neither of these options is well-suited for stable, high-flux, high harmonic generation. Here we present a 2kHz, 3.1µm OPCPA system generating record 1.3mJ pulses with excellent mode quality and bandwidth to support 93fs pulses.

II. System description

The laser system is shown schematically in Fig. 1. It is seeded by a turn-key, integrated, fiber laser and OPA (KMLabs Inc. Y-Fi^{TM} OPA) that supplies 2 µJ pulse energy, 5 MHz, ~130fs, 1µm pulses and 1.5um pulses. The 1.5µm output is temporally stretched using a grism stretcher and sent to the OPCPA. The 1µm output is used to seed a cryogenic Yb:YAG pump laser, which is then perfectly synchronized to the mid-IR signal and idler beams. The cryogenic Yb:YAG amplifier chain consists of four stages of amplification: a regenerative high gain stage and three multi-pass booster stages. Finally, a three stage OPCPA based on MgO:PPLN delivers 1.3mJ pulses at 3.1µm, and 2.0mJ pulses at 1.55µm, and at 2 kHz repetition rate. Using KTA crystals, pulse energies as high as 2.5mJ and 3.7mJ were achieved at 3µm and 1.5µm respectively. Finally, a grating compressor is used to manage dispersion compensation.

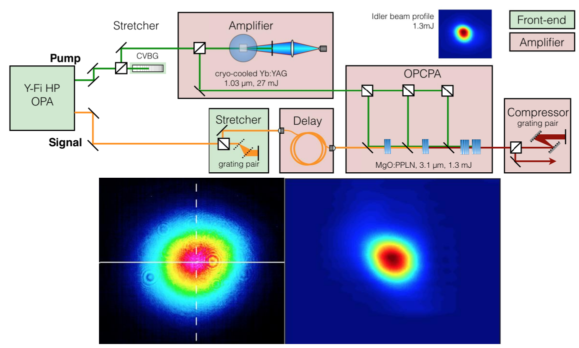

Fig. 1. Top) Schematic representation of the OPCPA system. Bottom left) 1.03µm pump profile, bottom right) 3.1µm idler profile.

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Parametric Generation of Ultrafast Pulses from Mid-Infrared to Long-Wave Infrared Range

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Abstract: Production of ultrafast coherent radiation up to long-wave infrared range is of significant interest to both fundamental science and applications. Our recent progress in developing parametric sources based on $ZnGeP_2$ and OP-GaAs material is discussed.

I. INTRODUCTION

Mid-infrared (MIR) and long-wave infrared (LWIR) ultrafast pulses are needed to support fundamental research and a wide range of applications, including molecular spectroscopy, attosecond pulse generation, remote sensing, and laser-particle acceleration. Ultrafast semiconductor and solid-state laser sources are limited to operation at shorter wavelengths; alternatives such as quantum cascade lasers are in turn limited to low power operation. Parametric frequency downconversion is therefore the prime candidate for scaling the production of high-power ultrashort pulses to the MIR and LWIR regime. Further developments in this area will require a solid understanding of the properties of nonlinear optical materials, features and limitations of pump laser technologies, and invention and validation of efficient downconversion schemes that can support broad bandwidths and scalability to high powers.

II. MID-INFRARED SOURCES BASED ON ZGP

In our recent work we used $ZnGeP_2$ (ZGP) for MIR ultrafast OPA near 5 µm due to its high nonlinearity, broad transparency range, good thermal conductivity, high damage threshold, and ability to grow crystals in cm^2-scale apertures. Similar to many crystals suitable for MIR pulse generation, ZGP requires pumping at longer wavelengths (≥2 µm). We adopted a simple design that does not use chirped-pulse amplification and developed another OPA to produce ultrashort pump pulses centered at 2.05 µm, which can pump a two-stage ZGP OPA that also uses ZGP as a 5-µm parametric fluorescence seed source. Up to ~50 µJ pulses were produced at 5 µm from ZGP OPA when pumped by 1.6-mJ, 2.05-µm pulses with high stability, uniform beam profile, and bandwidth that extends over >1000 nm (Fig. 1) [1]. For scaling ZGP to energies of ~mJ and beyond it will be necessary to use optical parametric chirped-pulse amplification (OPCPA) to keep the aperture of the crystals acceptably small, with the associated penalty in system complexity, footprint, and cost.

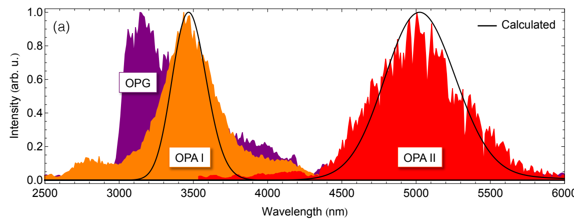

Fig 1. Normalized measured and calculated pulse spectra emerging from successive stages of a compact 2-µm pumped ZGP OPA [1]

III. LONG-WAVE-INFRARED SOURCE DEVELOPMENT USING OP-GAAS

Scaling parametric sources further to the LWIR range requires the use of materials transparent and phase matcheable at even longer wavelengths, such as the quasi-phase matched OP-GaAs and OP-GaP. Of those two crystals, OP-GaAs offers transparency up to longer wavelengths (~15 µm). Similar to ZGP, OP-GaAs needs to be pumped at >2 µm, but offers the prospect of ultrabroad bandwidth in the 10 µm range when pumped near 2.5-3 µm. We are developing OPCPA architectures that could result in few-cycle, high-pulse energy sources in the LWIR range using new pump sources such as coherenly pulse stacked Er:ZBLAN fibers at a center wavelength of ~2.75 µm. Intense sources based upon this concept may support exciting applications, including long-range energy delivery by LWIR filamentation in air.

ACKNOWLEDGMENTS

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High-energy 3.3-μm femtosecond laser pulse by dual-chirped optical parametric amplification

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Abstract: We demonstrate mid-infrared pulses at 3.3 μm with energy of 10 mJ and transform-limited duration of 60 fs using a dual-chirped optical parametric amplification (DC-OPA) scheme. Further energy-scaling to TW-class is feasible.

I. Dual-chirped optical parametric amplification (DC-OPA) [1]

In our previous works [2,3], DC-OPA was proved to have an excellent energy scaling ability and obtained 100 mJ class IR fs pulses in the 1-2 μm range for the first time. In addition, DC-OPA has the capability for energy-scaling in the mid-infrared (MIR) [4] and the far-infrared (FIR) wavelength range [3]. In this work, we experimentally demonstrate the possibility to obtain TW-class MIR pulses using the DC-OPA method.

II. Experiment and results

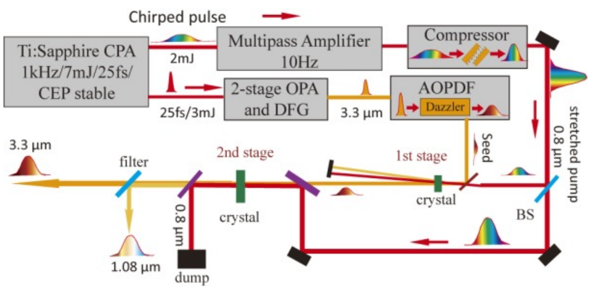

Fig. 1. Experimental setup of MIR DC-OPA.

The schematic of the experiment setup is shown in Fig. 1. The pump laser for DC-OPA is a Ti:sapphire laser with its output pulse energy of ~ 700 mJ, repetition rate of 10 Hz and central wavelength of ~ 810 nm. The pump pulse duration is stretched by changing separation between two gratings inside a compressor. The seed (3.3 μm) for DC-OPA is provided by the difference frequency generation (DFG) between a signal and idler pulses after a two-stage OPA (TOPAS, Prime). Its pulse duration and spectrum phase is manipulated by an Acousto-Optic Programmable Dispersive Filter (AOPDF). 3-mm-thick MgO:$LiNbO_3$ crystals under type-I phase-match are utilized in the 2-stage DC-OPA. Aperture sizes of 10 mm × 10 mm and 20 mm × 20 mm are used in the first and second stages. In the first stage, a very small noncollinear angle is employed in order to separate different pulses in space. The second stage is constructed in a collinear configuration.

We employ a pump energy of ~ 440 mJ with its pulse duration negatively stretched to ~ 5.5 ps. The pump intensities on the crystals are evaluated to be ~ 20 GW/cm^2. The seed pulse is positively stretched to ~ 1.8 ps, which is limited by the maximum dispersion value provided by the AOPDF. To fully overlap two pulses in the time domain, we plan to further stretch the seed pulse duration to similar as the pump duration by combining a Si bulk. Under the above experimental condition, we obtain a pulse energy of 10 mJ at 3.3 μm. The spectrum is shown by the red-solid curve in Fig. 2, which supports a transform-limited duration of 60 fs (FWHM). It can also be found that the spectra ranges after the first and second stages of DC-OPA are similar as the seed.

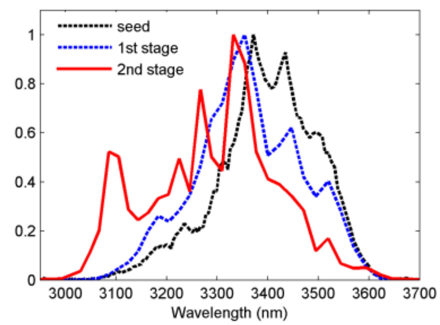

Fig. 2. Spectra of seed (black-dashed) and after the first (blue-dashed) and second (red-solid) stages of the DC-OPA system.

III. CONCLUSIONS

We demonstrate a 10 mJ pulse at 3.3 μm with its spectrum supporting a 60 fs duration. We will further increasing the pump pulse energy for DC-OPA to obtain a TW-class MIR laser pulse.

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High-energy infrared femtosecond pulse for attosecond sciences

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Abstract: We present our two novel laser systems: one is high-energy 3-channel waveform synthesizer for generating an intense isolated attosecond pulse and the other is 2.5-TW, 110-mJ, 1.5 μm laser system via dual-chirped optical parametric amplification (DC-OPA).

I. 50-mJ, 3-channel waveform synthesizer for generating GW-scale soft-x-ray attosecond pulses

Our waveform synthesizer system consists of CEP-stabilized Ti:sapphire laser pulse (pump: 44 mJ, 800 nm, 28 fs) [1] and two output pulses from a two-stage infrared OPA (signal: 6 mJ, 1350 nm, 33 fs; idler: 3 mJ, 1950 nm, 40 fs). By introducing PID-controlled feedback systems which monitored by the Mach-Zehnder interferometers and the balanced optical cross-correlator [2], we directly stabilize the delay jitter between all the three channels in the synthesizer.

To generate the HHG, the pulses are focused using two separate focusing lenses (4.5m for 800 nm, 3.5m for OPA pulses). Figure 1 shows the single shot harmonic spectrum from an Ar gas cell (10 cm, 2.36 Torr) while one-color and three-color pulses are focused into the gas cell. We can clearly see the discrete harmonic generated by one-color case changed to a smooth continuum harmonic spectrum near the cut-off region (> 50 eV). This is because the electric field at central of the main channel pulse is enhanced while the out of center electric field is markedly suppressed by the other two channels. Thus, the peak intensity of the synthesized electric field is close to a single-cycle pulse. The measured the continuum soft-x-ray (45 ~ 65 eV) flux is evaluated to over 200 nJ with conversion efficiency of 10^{-5} at the generation point. The spectrum supports a 200 as transform limited pulse. The estimated peak power of our tabletop light source approximately reaches 1 GW. To our knowledge, the obtained photon flux of the super-continuum in the soft-X-ray region is the highest energy ever reported.

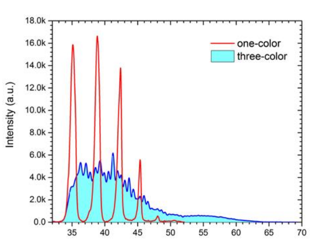

Fig. 1. Harmonic spectrums from Ar gas cell

II. 2.5-TW, 110-mJ, 1.5 μm laser system for generating high-energy sub-keV harmonic beams

Figure 2 shows the schematic of the DC-OPA setup. Our IR laser system consists of a frontend 1-kHz Ti:sapphire laser system, a 10 Hz back-end 1-J power amplifier, and a two-stage DC-OPA with Type-II BBO. Output of OPA (TOPAS) is used as a seed IR pulse with pulse duration stretched by an AOPDF. Pulse duration of pump (0.8um) to DC-OPA is optimized by changing the separation between two gratings in a compressor. In DC-OPA [3,4] scheme, it is easily to increase the pump energy for OPA while temporally stretched the pulse. In the final DC-OPA stage, we utilize 0.7-J pump pulse with 3.5 ps. AOPDF gives the optimized chirp value for the seed pulse, whose pulse duration is estimated to be 3.7 ps.

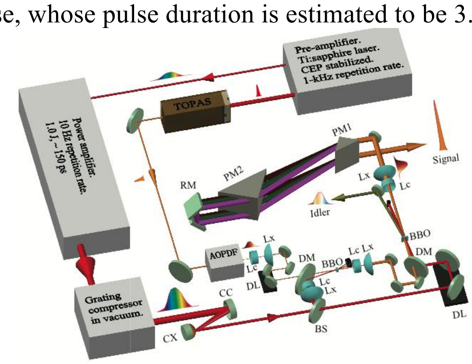

Fig. 2: Schematic of the DC-OPA setup

After the 2nd stage of DC-OPA, pulse energies of signals maintain 100-mJ-level in all tuning range. The signal pulse (1.5 μm) is compressed by a prism compressor. The temporal duration of signal pulse was evaluated to be 44 fs (FWHM) which was very close to its TL duration of 41 fs. This high-energy IR source very suits as a driver laser for extending high-order harmonic photon energy into the kiloelectronvolts region.

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Coherent Terahertz transition radiation from relativistic laser-foil interactions

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Abstract:
We have generated coherent transition radiation at terahertz regime when relativistic laser-driven energetic electrons crossing the rear surface of a thin solid target. Preliminary applications of such a source are demonstrated.

Over the last decades relativistic electron beams from conventional accelerators have been applied to generate strong THz radiation through transition radiation [1], *etc*. Relativistic electron beams can also be generated in the interactions of intense laser pulses with low-density gas or high-density solid targets. With the energetic electron beam accelerated by wakefields in gas target, Leemans *et al*. have observed a ~0.3 μJ THz pulse through transition radiation [2].Compared with the gas targets, electron beams from solid targets have much higher charge, up to nC-μC. For a foil target, fast electrons transport forward through the target and will induce transition radiation when crossing the rear surface-vacuum boundary. Usually the bunch length of the fast electrons driven by a laser pulse in tens of femtosecond duration is of the order of ~10 μm, which is smaller than the wavelength of THz radiation. This will lead to the coherent transition radiation (CTR) [3]. One can expect that the THz radiation energy will be high due to the high charge and short bunch duration of the fast electron beam as well as the steep foil-vacuum boundary.

To verify this idea, we have carried out a laser-foil experiment using a multi-TW femtosecond laser system. A *p*-polarized laser pulse in 30 fs and 2 J was incident onto solid targets at an incidence angle of 54° with a peak intensity of ~1.5×10^{19} W/cm^2. The laser prepulse contrast in the ns range is ~10^{-5}. Different types of targets were used in the experiment, including mass-limited metal targets with different sizes, polyethylene (PE)-metal double-layered targets and single PE targets.

In our experiment we demonstrated intense THz transition radiation of the laser-accelerated relativistic electron beams crossing the solid rear surface. The total THz energy from the rear of metal foils is estimated to be ~400 μJ/pulse, comparable to the energy level of the conventional accelerator based THz sources [4]. The corresponding energy conversion efficiency from the laser pulse energy on targets to THz radiation is ~2×10^{-4}. It can be well explained by the model of CTR considering the effects of diffraction radiation and formation zones [5].

We have used the THz source to carry out a single shot imaging and excitation of phase transition of Vo_2.

The laser-plasma-based THz transition radiation presented could be a promising compact strong-field THz source. Moreover, it may provide us a new tool to diagnose forward fast electrons in laser-plasma interactions.

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Acousto-Optic Pulse Shaping for THz Generation

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Abstract: We report on acousto-optic femtosecond chirped pulse shaping resulting in multi-GHz to THz envelope modulation. In experiments, we compared performance of several pulse shaping methods for producing pulse replicas and tunable THz generation.

I. INTRODUCTION

Optical rectification of ultrashort laser pulses is one of the methods for generation of THz radiation. Modulation of laser pulse envelope is required for obtaining narrowband THz pulses. Tunable modulation can be provided either using an interferometer-type delay line [1] or a pulse shaper [2]. In this research, a house built acousto-optic dispersive delay line (AODDL) has been used for pulse shaping and THz generation in a highly efficient organic OH1 crystal pumped by a Cr:forsterite TW laser [3].

II. METHOD AND RESULTS

Interference of two chirped pulse replicas results in envelope modulation with the frequency proportional to the delay [1]. To reduce energy loss at the output of the laser system, we studied the configuration of the setup with an acousto-optic pulse shaper placed before the amplifiers. Thus, the losses in the pulse shaper can be compensated by the gain but modulation depth may be reduced because of saturation of the amplifiers. Optimal pulse shaping method for this problem was analyzed. Generating a programmable sequence of ultrashort laser pulse replicas is one of general pulse shaping problems [4]. It can be implemented by a variety of algorithms including phase-only ones [2]. In experiments, we compared the performance of three different methods.

The first is amplitude-only modulation of a chirped laser pulse. In this case, envelope modulation directly corresponds to spectral modulation of a chirped laser pulse. The pulse sequence duration is determined by detuning of a stretcher/compressor pair and it can sufficiently exceed maximum group delay of the AODDL. However, typical modulation frequencies are in sub-THz region [5].

The second approach is to use both phase and amplitude modulation analytically corresponding to Fourier transform of several replicas. Amplifier gain saturation resulted in contrast degradation with increase in delay, but remaining phase modulation provided efficient narrowband THz generation in experiments [6].

The third method is phase-only pulse shaping based on representation of the continuous spectrum as several independent combs [7]. The disadvantage of such shaping is in undesired satellite pulses. However, the contrast after the CPA system was the highest, especially at a small delay between the replicas.

The experiments were conducted using a custom-built AODDL with 40% higher spectral resolution compared to previously reported results [8].

III. CONCLUSIONS

Acousto-optic pulse shaping at the front and of a CPA laser system has been efficiently used for obtaining pulse envelope modulation in multi-GHz and THz ranges. In all experimental schemes, maximum modulation frequency is limited by the laser emission bandwidth and the AODDL spectral resolution.

ACKNOWLEDGMENTS

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20-fold pulse compression down to 3-cycles in a 3 m long hollow-core fiber

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Abstract: We demonstrate 20-fold pulse compression by employing a 3-m-long argon-filled hollow-core fiber and chirped mirrors. The incident 1 mJ, 185 fs pulses at 1030 nm are compressed to 0.65 mJ, 9 fs (3-cycles) pulses.

I. INTRODUCTION

Few-cycle pulses are essential for modern ultrafast science. Such short pulses require ultra-broadband spectra, exceeding the limits of common laser gain media. The spectrum of femtosecond pulses can be further extended by means of nonlinear optical effects. In this context, self-phase modulation (SPM) in noble-gas-filled hollow-core fibers (HCF) has shown to provide a route for spectral broadening and pulse compression of energetic pulses. [1]

Ytterbium (Yb) lasers are becoming a popular solution for both scientific and industrial applications because of their compactness, affordable cost, highly-tunable performance and stability. [2] However, the typical pulse width of Yb lasers is larger than 100 fs, which limits their applicability for ultrafast science. In this work, we demonstrate a 20-fold compression of 185 fs pulses from a Yb:KGW laser down to three cycles by employing a stretched, 3m long HCF [3] whose output is compressed with chirped mirrors.

II. EXPERIMENTAL RESULTS

We employ pump pulses with an energy of 1 mJ and a repetition rate of 1 kHz. These incident pulses are focused by means of a f = 1000 mm convex lens into a 3-m-long HCF with an inner diameter of 500 μm (*few-cycle* Inc.). Once the HCF is vacuum-pumped, Ar gas is slowly injected. The output pulses are compressed after 5 bounces on broadband chirped mirrors (-150 fs^2/each). Then the pulse duration is optimized through dispersion compensation using multiple silica windows. For an Ar pressure of 1.73 bar, significant spectral broadening is observed. For all input energies and gas pressures up to 2 bar, the transmission was constantly 70%. Following the addition of six silica windows in the beam path (total thickness of 12 mm, corresponding to a total GDD ~ 234 fs^2), the incident pulses are compressed from 185 fs to 9 fs, which is less than 3-cycles at 1030 nm.

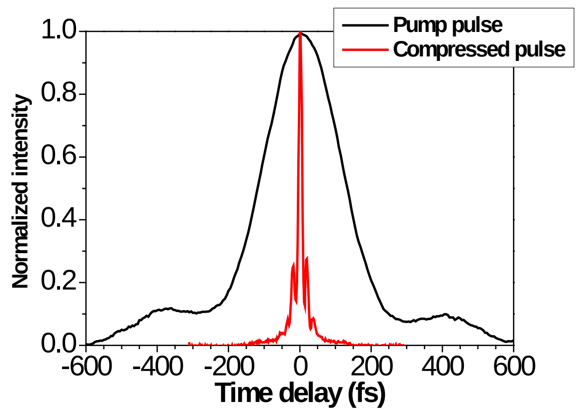

Fig. 1. Normalized autocorrelation of the input pump pulse (185 fs) and the compressed pulse (9 fs) after the Ar-filled HCF (1.73 bar Ar) and chirped mirrors.

III. CONCLUSIONS

We have demonstrated a straightforward and efficient 20-fold pulse compression by means of a long Ar-filled HCF and chirped mirrors. Our results promise to readily extend the applicability of commercially-available Yb-based lasers with relatively low cost to ultrafast investigations in the sub-10 fs regime.

ACKNOWLEDGMENTS

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Spectral phase noise upon amplification in Ti:Sapphire: effects of cooling and polarization encoding

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Abstract: Spectral phase noise of ultrashort pulses due to amplification in Ti:Sa has been measured using spectral interferometry. Effects of repetition rate and pump energy have been investigated in water-, cryogenically cooled, and in polarization-encoded arrangements.

I. INTRODUCTION

The most widely used laser material for generation of sub-50 fs ultrahigh peak power pulses has been Ti:Sapphire (Ti:Sa). While for low repetition rate, low average power systems room-temperature cooling of the gain medium is sufficient enough, stable operation at high average power requires cryogenic cooling.[1] Recently, the technique of polarization-encoded CPA (PE-CPA) was proposed, which could provide a gain bandwidth that supports few-cycle pulses after amplification and compression.[2] The design and realization of carrier envelope phase (CEP) stable Ti:Sa amplifiers require the complete understanding of phase distortions due to these subsystems.

II. EXPERIMENTAL RESULTS

Measurement of the spectral phase distortions and CEP noise was performed by using spectrally resolved interferometry (SRI), which provided high sensitivity and low background noise. The sample amplifier in every case was incorporated in the sample arm of a two-beam interferometer. Two water-cooled Ti:Sa amplifiers were tested. By increasing the pump energy, the measured CEP shot-to-shot noise increased linearly, while towards the lower repetition rates an exponential like increasing tendency was observed. The temperature fluctuations due to unstable cooling were found to be responsible for the CEP drift and also noise in both amplifiers. Seed energy and saturation did not contribute to the noise within the sensitivity of our measurement.[3]

Amplification in a cryogenically cooled, double-pass amplifier was also tested, where the Ti:Sa was cooled down below 30 K. Spectral phase fluctuations were measured for different operation stages, and the noise spectrum was compared to vibration measurements. CEP noise was also retrieved due to thermal and mechanical origin.[4] Measured CEP noise values are visualized in comparison with water cooling in Fig. 1.

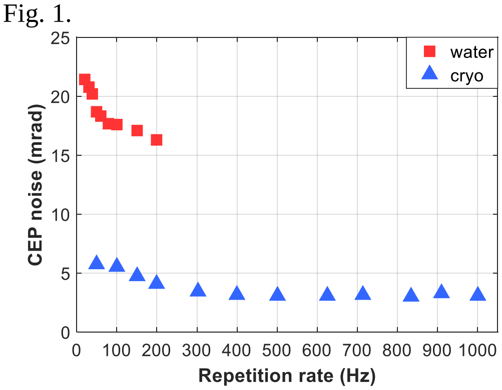

Fig. 1. Thermal originated CEP noise at different repetition rates in a single pass for the water-cooled (red) and cryogenically cooled amplifier (blue).

PE amplification was investigated by using a novel quasi common path interferometer, which ensured extremely low background noise. Spectral phase noise of the PE amplifier was compared to a conventional stage, and identical level of phase noise was observed. Investigation of the gain induced phase changes and CEP drift in the PE amplifier are on the way.

III. CONCLUSIONS

Water- and cryogenically cooled Ti:Sa amplifiers were tested for spectral and CE phase stability. Main sources of fluctuations were identified. PE amplification was shown to be as stable as conventional amplifier stages.

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Self-starting 12.7 fs pulse generation from a Ti:sapphire synchronously pumped by a mode-locked Yb:KGW laser

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Abstract: we have demonstrated a self-starting femtosecond Ti:sapphire pulse synchronously pumped by a frequency-doubled mode-locked Yb:KGW. The maximum power is 256 mW and the 12.7 fs pulse is obtained at a repetition rate of 151 MHz.

I. INTRODUCTION

Dispersion managed Kerr-lens mode-locked (KLM) Titanium-Sapphire (Ti:sapphire) are most commonly used for ultrashort solid-state laser. Recent years, the synchronously pump is a feasible method to generate self-starting mode-locked Ti:sapphire femtosecond lasers [1]. With this approach, the Ti:sapphire laser system with cavity optimization free, and also without any additional starting components. Most important, it overcomes poor starting performance in the region of high repetition rate KLM lasers. In this letter, we have demonstrated self-staring femtosecond pulses generated from a Ti:sapphire laser synchronously pumped by a 75.5 MHz mode-locked, lithium tribo-rate (LBO) frequency-doubled femtosecond Yb:KGW laser. The pulse duration is compressed to 12.7 fs with a maximum power of 256 mW under the pump power of 3.6 W. The oscillator cavity length is about 993 mm corresponds to a repetition rate of 151 MHz, which is equal to double of that of the Yb:KGW laser.

II. EXPERIMENT RESULTS

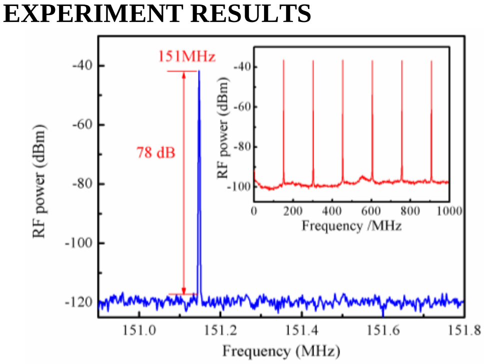

Fig. 1. RF spectrum of fundamental beat note with the RBW of 1 kHz; inset: wide RF spectrum of 1GHz with the RBW of 100 kHz.

The synchronous self-starting mode-locked pulse is easily obtained when the cavity length is matched to the half that of the pump laser. The typical radio frequency spectrum (RF) of the mode-locked Ti:sapphire laser pulses is recorded with a spectrum analyzer. The corresponding high SNR extinction down to 78 dB at 151 MHz with the resolution bandwidth (RBW) of 1 kHz is shown in Fig. 1.

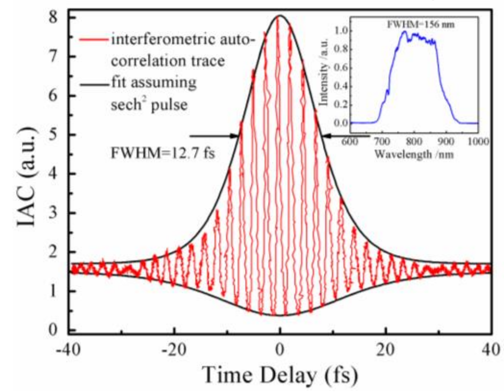

Fig. 2. Interferometric autocorrelation traces. Inset: corresponding the spectrum.

Under a pump power of 3.6 W, the maximum output power of the Ti:sapphire is 256 mW. As shown in Fig. 2, the pulse duration is measured as 12.7 fs, assuming a sech^2-shape pulse. As depicted in the inset of Fig. 2, the full width at half maximum (FWHM) of the laser spectrum is 156 nm with a 3% OC at a central wavelength of 811 nm and the transform-limited pulse is 7.6 fs calculated by Fourier transforming the spectrum without dispersion.

Ⅲ. CONCLUSIONS

We have demonstrated a self-starting femtosecond Ti:sapphire laser synchronously pumped by a 75.5 MHz frequency-doubled mode-locked Yb:KGW oscillator. The maximum average output power is 256 mW under the pump power of 3.6 W. The pulses as short as 12.7 fs are obtained at a repetition rate of 151 MHz, corresponding to the second harmonic of the pump laser frequency.

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Octave-spanning, CEP stabilized, repetition rate-scalable OPCPA frontend based on Yb:KGW laser

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Abstract: We present a simple setup producing multi-μJ, octave-spanning, passively CEP stable pulses for seeding NIR optical parametric chirped pulse amplifiers. The setup is readily adaptable for 1 to 100kHz repetition rates.

I. INTRODUCTION

Optical parametric chirped pulse amplification (OPCPA) is the state-of-the-art technique for producing powerful ultrashort light pulses for advanced scientific applications[1]. We present a cascaded OPA setup that takes advantage of reliability, compactness and stability of mature femtosecond Yb:KGW laser systems, and exploits these properties to produce broadband multi-μJ pulses ideal for seeding OPCPA operating in the NIR range.

II. EXPERIMENTAL SETUP

The experimental setup is presented in Fig. 1.

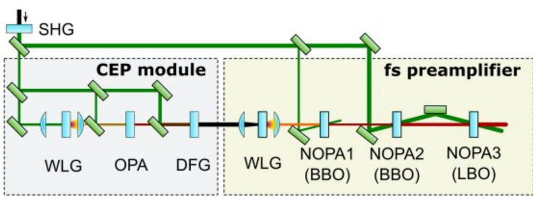

Fig. 1. Schematic of the OPCPA frontend. SHG: second harmonic generator; WLG: white light generator; (N)OPA: (noncollinear) optical parametric amplifier; DFG: difference frequency generator

Difference frequency generation between 515nm SH pulses and the Stokes extension of WLG pumped at 515nm results in passively CEP stabilized pulses tunable from 1.3μm to 2μm. Filamentation of these pulses in YAG or sapphire produces CEP stabilized white light, smoothly covering the 500nm-1.7μm range, well suited to seed subsequent NOPA stages. Since parametric fluorescence is confined to the ~250fs duration of the Yb:KGW pulses, excellent temporal contrast is maintained on longer timescales.

III. OPCPA FRONTEND PERFORMANCE

We tested 3 different frontends based on the general scheme shown in Fig. 1. The parameters of the three systems are summarized in Table I.

Table I. Parameters of tested OPCPA frontends

System #	1	2	3
Rep. rate	1kHz	1kHz	100kHz
Crystals	BBO+LBO	BBO	BBO
Pump energy (1030nm)	1mJ	1.3mJ	150μJ
Output energy	60μJ	100μJ	3μJ
CEP stability	<120mrad (BBO only[3])	<220mrad (after OPCPA[4])	<350mrad

Fig. 2(a) shows the energy of the pulses delivered by the CEP module of system #2 measured over 12 days of continuous operation. The module's capability to operate without user intervention while maintaining excellent <0.25% short-term energy stability is crucial when the setup is used as the initial stage of a large OPCPA system[4]. Fig. 2(b) compares the output spectra amplified with BBO-only or combined BBO-LBO amplifiers, measured with system #1. The amplified spectrum supports 1.2-cycle pulses.

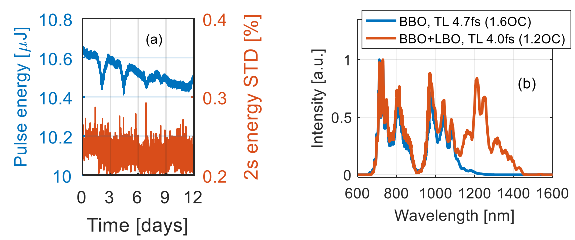

Fig. 2. (a) DFG pulse energy and energy stability (b) Spectra of pulses produced by BBO and BBO+LBO-based OPCPA frontends.

IV. CONCLUSIONS

The presented OPCPA frontends produce octave-spanning, multi-μJ pulses with high CEP and energy stability and long-term reliability. Our systems will facilitate continued progress in the development of pump sources for attosecond science.

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Ultra-low noise frequency comb based on a Kerr-Lens Mode-locking Yb:CYA laser with feed-forward scheme

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Abstract: A novel solid state frequency comb using feed-forward method was demonstrated based on a home-made Kerr-Lens Mode-locking Yb:CYA oscillator. Integrated phase noise of carrier envelop offset (CEO) frequency of 200 mrad was measured from 3Hz-10MHz.

I. INTRODUCTION

Solid-state frequency combs with high averaging power and low noise have important applications in numerous fields, such as attosecond pulse generation, molecular precision spectroscopy and optical clocks *etc* [1]. However, a Carrier Envelope Phase (CEP) controlled femtosecond Yb doped laser is limited as frequency comb by feedback bandwidth, which is less than 10kHz normally. Since the feed-forward frequency comb was proposed in 2010 [2], it shows excellent performances, such as wider bandwidth, simpler configuration and higher robustness. In this presentation, we report a feed-forward frequency comb with a home-made Kerr-Lens Mode-locking (KLM) Yb:CYA oscillator as the laser source[3], 30 dB signal to noise ratio (SNR) of f_{CEO} was obtained and integrated phase noise (IPN) amounted to 200mrad from 3Hz to 10 MHz. We measured the modulation bandwidth increased to several hundreds of kHz, and IPN amounted to only 90 mrad integrating from 3Hz to 100kHz.

II.EXPRIMENTS

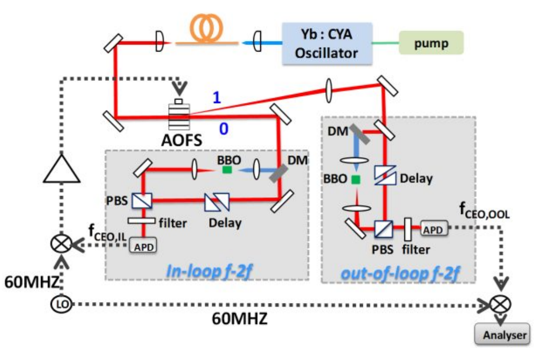

Fig. 1. The experiment setup of Yb:CYA frequency comb with feed-forward scheme. DM: dichroic mirror .

The experiment setup is shown as Fig. 1. We use a KLM Yb:CYA oscillator as laser source[3], octave spanning spectrum covered from 700nm to 1400nm was obtained by injected the laser pulse into a section of photonic crystal fiber (PCF). Laser beam through AOFS was diffracted into two orders, which were fed into in-loop and out-of-loop interferometer with 50% diffraction efficiency. Out-of-loop CEO frequency was stabilized at 60MHZ with 30dB SNR and the linewidth was less than 1Hz. The integrated phase noise was 200 mrad from 3 Hz to 10 MHz. It was 116 mrad lower than IPN of CEO locked by phase locked loop feedback frequency comb reported in Ref 3.

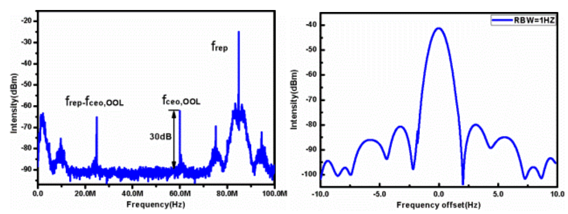

Fig. 2. Spectrum of In-loop and out-of loop f-2f interferometer CEO beat signals.

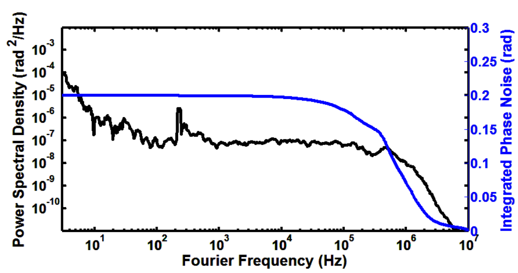

Fig. 3. Integrated phase noise of out-of-loop CEO frequency from 3Hz to 10 MHz.

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Picosecond thin-disk pump laser system for high energy OPCPA

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Abstract: We present the design of a pump laser system based on Yb:YAG thin disk technology for a 100 mJ, 1 kHz picosecond OPCPA. This pumping scheme is evaluated and validated using a 225 mJ regenerative amplifier.

I. INTRODUCTION

A high repetition rate OPCPA-based beamline is under construction at ELI-Beamlines in the Czech Republic with the following target parameters: 100 mJ pulse energy, 1 kHz repetition rate, <20 fs pulse duration, and a central wavelength of 830 nm. The pump lasers for this beamline are based on Yb:YAG thin disk technology[1,2] and are designed to provide picosecond pulses at 515 nm with more than 300 mJ in case of the final stage. Here we present the design of the pump lasers for the final three OPCPA stages in the beamline and we report on the performance of the pump laser system using a 225 mJ, 1 kHz regenerative amplifier.

II. PUMP SYSTEM DESIGN

The system presented here is intended to amplify broadband 830 nm-centered pulses from 10 mJ[3] up to 100 mJ in three stages of picosecond OPCPA. This requires the compression and second harmonic frequency conversion of three high energy Yb:YAG thin disk regenerative amplifiers, with one of them being further amplified by a multipass amplifier. The three compressors (each with 4 m gratings separation) as well as the SHG crystals are housed in a single vacuum chamber on a dual-level optical table. The three pump beams are then routed to the OPCPA vacuum chamber housing the 3 OPCPA crystals.

While this design is discussed, the main topic of this work is the characterization of the pump laser system and its actual performance, as described below.

III. PUMP SYSTEM CHARACTERIZATION AND PERFORMANCE

The pump laser system design is evaluated using a 225 mJ, 1 kHz laser. The output of this amplifier is compressed at full power to 1.6 ps with 90% efficiency through one of the 3 compressors housed in the vacuum chamber. Relevant parameters for stable OPCPA amplification such as control of temporal synchronization, beam pointing, spatial beam quality, power stability, and also warm-up time are measured and discussed. Furthermore, potentially deleterious effects such as self-focusing and thermal lensing of the high energy picosecond pulses through optics are calculated and measured.

IV. CONCLUSIONS

Here we present the scheme for pumping multiple high energy stages of OPCPA with picosecond pulses. In addition to providing context and motivation by describing the full system design and concept, we present measured results on the performance of the pump system with high energy, high average power pulse trains. We believe these measurements make a convincing case that such a pump scheme is a viable path towards high energy picosecond OPCPA pumping.

ACKNOWLEDGMENTS

We would like to thank the HiLASE project for their generous loan of lab space for these tests.

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High repetition rate and high photon flux HHG source enabled by ultrafast fiber laser

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Abstract: A commercial 100W turn-key fiber-laser system is used for HHG at 0.5MHz. The source offers record-high photon flux of >$4.5\cdot10^{10}$ photons/s (68.6eV) or a narrowband harmonic with $8.6\cdot10^{11}$ photons/s (26.6eV).

High harmonic generation (HHG) of ultrashort laser pulses is an elegant way for the generation of coherent extreme ultraviolet to soft X-ray radiation. It is attractive due to the potential of being used in a plethora of applications[1]. One particularly interesting application is photoelectron spectroscopy and microscopy that, however, demands for high repetition rate and high photon flux sources[2,3]. As such, fiber-laser driven HHG has emerged as a powerful source to provide the highest photon fluxes in combination with unprecedented repetition rates[4].

Here, we present an extremely compact (footprint:~1m x 2m) HHG source employing a 0.5 MHz repetition rate nonlinearly compressed high average power fiber laser and its second harmonic.

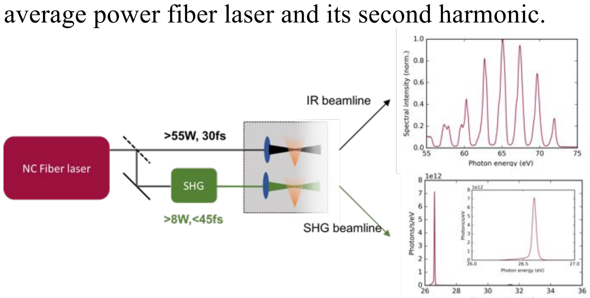

Fig. 1. Simplified experimental together with respective spectra of the generated harmonics (NC – nonlinearly compressed).

Figure 1 shows a generic experimental setup. The AFS fiber-chirped-pulse-amplifier system delivers 100W of average power and up to 300µJ of pulse energy with <300fs pulses. For the HHG experiments the laser is operated at 100W, 200µJ and a repetition rate of 0.5MHz. For efficient HHG the pulses are temporally compressed in a gas-filled capillary followed by chirped mirrors. The resulting >55W (110µJ), 30fs pulses are either directly used for HHG or frequency doubled to >8W,<45fs at 515nm central wavelength. Both beams can be send into a vacuum chamber where they are focused onto an argon gas-jet mounted on a xyz-translation stage. Optimization of the HHG signal for the IR beamline is done at 68.6eV resulting in >$4.5\cdot10^{10}$ photons/s in a single harmonic. It has to be noted that the detector was saturated in that case and that the resulting flux is underestimated, but still the highest achieved so far in that wavelength range[5]. For the 515nm the optimization is performed for smallest possible bandwidth in a single harmonic by utilizing a resonance in the absorption spectrum of argon[6]. The achieved photon flux of $8.6\cdot10^{11}$ in the narrowband ($\Delta E/E<1.7\cdot10^{-3}$) harmonic is similar to the latest record value, but at significantly higher repetition rate[6].

In summary, we present a HHG source with record-high photon flux operating at 0.5MHz repetition rate. The source uses an industrial-grade turn-key frontend on a compact footprint to provide a stable source of high-photon-flux coherent EUV radiation.

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SPM-enabled femtosecond source tunable from 1.3 to 1.7 µm for multi-photon excitation microscopy

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Abstract: We demonstrate a 31-MHz femtosecond fiber source tunable from 1.3 to 1.7 µm. The resulting ~10-nJ, <100-fs pulses are applied for multi-photon excitation microscopy.

Ultrafast sources emitting femtosecond pulses with the center wavelength continuously tunable are required in many microscopy and spectroscopy applications. For example, high energy femtosecond sources in the wavelength range of 1.3 or 1.7 µm are desired by deep tissue multi-photon optical microscopy. In this submission we demonstrate an Er-fiber laser enabled, energy scalable femtosecond source producing ~10-nJ pulse energy in the 1.3-1.7 µm wavelength range and the pulse duration can be as short as ~50 fs. The essence of our method is to minimize the dispersion effect during the fiber-optic spectral broadening (Ref. 1). Consequently self-phase modulation (SPM) dominates the spectral broadening and dramatically expands the input spectrum, forming a series of well separated spectral lobes. Use of proper optical bandpass filters to select the leftmost/rightmost spectral lobe produces nearly transform-limited femtosecond pulses.

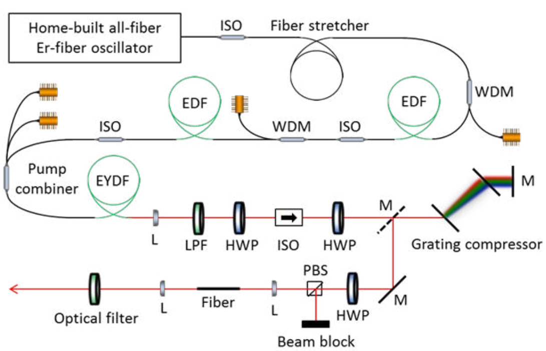

Fig. 1. Schematic setup. WDM: wavelength-division multiplexing, EDF: erbium-doped fiber, EYDF: erbium ytterbium co-doped fiber, L: lens, M: mirror, ISO: isolator, HWP: half-wave plate, PBS: polarization beam splitter, LPF: long pass filter.

Figure 1 shows the schematic setup of the tunable femtosecond source based on a home-built all polarization-maintaining Er-fiber laser system operating at 31-MHz repetition rate. The system provides >160-nJ and 290-fs pulses centered at 1550 nm. We adjust the pulse energy coupled into a short piece of optical fiber for SPM-dominated spectral broadening followed by optical filtering of the leftmost/rightmost spectral lobes. Figure 2 shows the rapid broadening of the output spectrum as we increase the coupled energy into highly nonlinear fibers (HNLFs) of different fiber length: 4 cm and 2 cm. Using shorter fiber can nearly double the filtered pulse energy, producing >4.5-nJ pulse energy in 1.3-1.7 µm.

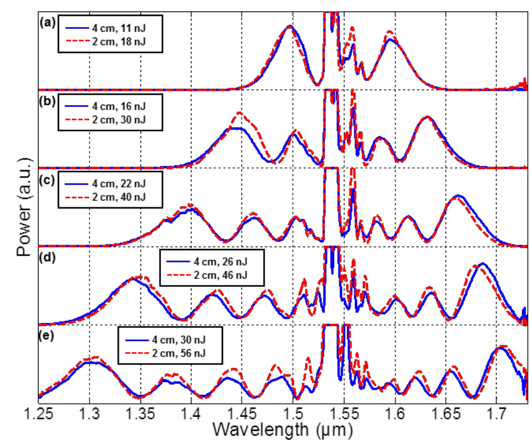

Fig. 2. Output spectra from highly nonlinear fiber at different fiber length (4 cm versus 2 cm) and coupled pulse energy.

To further increase the pulse energy, we replace the HNLF by 4-cm dispersion-compensating fiber (DCF) with larger mode area. The four representative filtered spectral lobes are shown in the left column of Fig. 3. The red curves right column shows the measured autocorrelation trace. These pulses are slightly positively chirped and are then dechirped to nearly transform-limited duration (purple curves) by fused silica plates. We are now applying such a powerful femtosecond source to multi-photon excitation microscope imaging of biological samples.

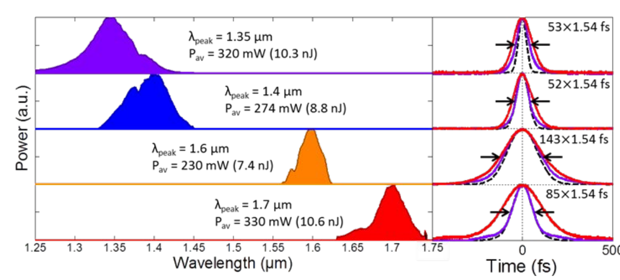

Fig. 3 (Left column) Filtered spectra from 4-cm DCF. Their peak wavelength, pulse energy, and average power are labeled in the figure. (Right column) Autocorrelation traces of the pulses before (red curves) and after (purple curves) being dechirped by fused silica plates. Black dashed curves plot the calculated autocorrelation traces of the transform-limited pulses allowed by the filtered spectra.

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Trial Results of the SYLOS Few-cycle Laser System of ELI-ALPS

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Abstract: The 5TW, 1kHz, passively CEP-stabilized ELI-ALPS SYLOS few-cycle laser system demonstrated state-of-the-art output parameters, excellent overall stability and reliability during the recently finished half-year trial period. Long-term performances were cross-checked by several different experimental methods.

ELI-ALPS, one of the three pillars of the Extreme Light Infrastructure, will further deepen our knowledge in fundamental physics by providing high repetition rate intense light pulses on the attosecond timescale [1]. One of the five main laser systems for driving plasma and gas-based HHG stages, is a state-of-the-art 1 kHz few-cycle laser called SYLOS. Output parameters to be reached within the next two years are 20 TW peak power, a pulse energy of 100 mJ and a duration shorter than two optical cycles (<5 fs), with outstanding energy, carrier-envelope phase (CEP) and pointing stabilities as well as high spatiotemporal quality.

The current state of SYLOS laser system already sets a new standard in ultrafast laser technology [2]. During the recently finished first implementation phase and subsequent trial period, the laser system demonstrated outstanding performance and reliability while it was running with full specifications for 6 months at least 8 hour a day. The front-end utilizes passive DFG method to provide excellent CEP-stabilization [3]. The overall stability is primarily ensured by an advanced diode-pumped solid state pump system [4], which drives a sequence of NOPCPA stages [5]. This technology allows the central wavelength of the pulses to be easily tunable and the spectrum could be tailored by simply changing the pump pulse delays and phase-matching angles. The negatively chirped pulses are compressed by large aperture bulk glass blocks and then positively chirped mirrors under vacuum conditions. The current measured output parameters are 54 mJ pulse energy and sub-9 fs duration, which translates into 5.5 TW peak power, long-term CEP stability around 220 mrad RMS, energy stability better than 0.9% while the spectrum spans over 300 nm around 880 nm central wavelength at the highest peak power.

During the half-year long trial period, various experiments were performed to verify the pulse characteristics. Chirp-scan, autocorrelation, Wizzler and stereo-ATI measurements have independently confirmed the sub-9 fs pulse duration. The in-loop and out-of-loop CEP stability was cross-checked between f-to-2f and stereo-ATI devices. Moreover, the inherent CEP stability of the system without feedback loop was also found to be surprisingly good thanks to the passive CEP stabilization of the front-end. The polarization contrast was better than 1000:1. The temporal contrast was also measured independently with Sequoia and Tundra cross-correlators, and on the ns scale with a fast photodiode and GHz oscilloscope as well. According to these measurements, the pedestal consists of parametric superfluorescence almost exclusively and stays below the 10^{-7} level on about 100 ps long duration, which correlates to the pump pulse length. By proper adjustment of the pump pulse delay, a pre-pulse contrast of 10^{-11} was reached at 30 ps before the pulse peak. In order to reveal the influence of temperature changes, pointing- and wave front stability was recorded for eight hours on several occasions. Except the short warm-up times caused by intentional pump energy level changes, the wavefront and the beam pointing stability remained constant during the whole time.

To sum up briefly, the ELI-ALPS SYLOS laser system has demonstrated excellent long-term stability and reliability. The start-up and shutdown procedures takes only few minutes and the well-designed command control system enables to modify the pulse parameters instantly. While its development is still ongoing, it exhibits state-of-the-art output parameters already. Detailed findings on all the examined pulse characteristics of the SYLOS laser will be reported in this presentation.

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Generation of megawatt pulses from a Mamyshev oscillator

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Abstract: We report parabolic pulse propagation in a Mamyshev oscillator, which generates ~50-nJ and ~ 40-fs pulses. The ~1-MW compressed peak-power is 10 times higher than prior single-mode fiber oscillators.

Ultrafast fiber lasers provide significant advantages over solid state lasers, such as efficiency, high-quality spatial mode, compact size, and potential for low manufacturing cost. However, the widespread use of these lasers is still limited by either output performance or lack of environmental-stability.

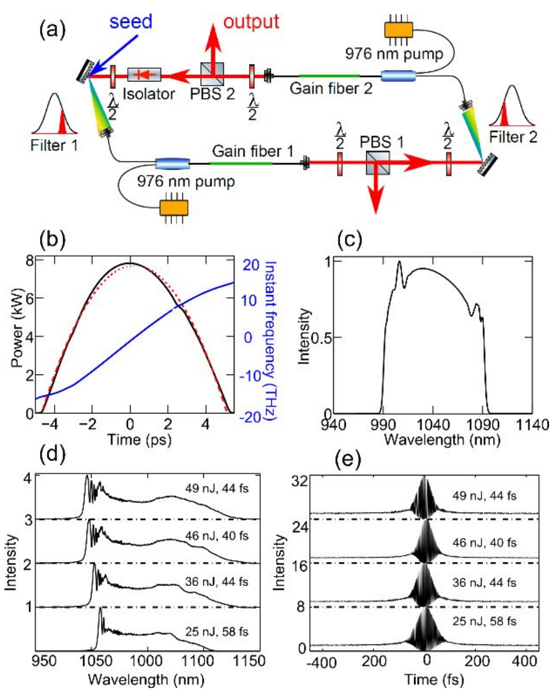

Fig. 1. (a) Schematic of the ring Mamyshev oscillator. The black curve indicates the gain bandwidth and the red curve shwos the passband of the filter. PBS: polarizing beam splitter, (b) simulated output temporal profile (black) with fitted parabolic shape (red) and instantaneous frequency (blue) and (c) simulated output spectrum, (d) measured output spectra and (e) autocorrelation traces of the compressed pulses for the indicated energies.

In this letter, we report the design and performance of an environmentally-stable mode locked laser based on cascaded Mamyshev regeneration that can reach peak power at least an order of magnitude higher than that of previous lasers with similar fiber mode area (Ref 1-3). The cavity includes two bandpass filters without overlap bandwidth, which prevent the occurrence of the continuous-wave field. All the fibers are polarization maintaining. Numerical simulations predict the cavity can support chirped pulses with 190-nJ energy and a compressed duration of <20 fs, which correspond to ~8 MW peak power. One simulation example (50-nJ pulses are produced) is shown in Fig. 1 (b, c). The output in the time domain is a near linearly-chirped parabola (Fig. 1 (b)) with ~110 nm bandwidth (Fig. 1 (c)), which corresponds to ~ 30-fs Fourier-transform limited pulses. This performance follows from the Mamyshev oscillator's excellent capacity to manage nonlinear phase by the formation of parabolic pulses in the laser cavity.

Experiments were performed with the cavity of Fig. 1(a). The oscillator does not start from noise, so) and a seed pulse is directed into the cavity to initiate pulsation. The seed pulse can be blocked after the starting process, and the output pulse are independent of the seeding pulses. As the energy increases, the spectrum broadens (Fig. 2 (d)), and the dechirped duration decreases. Using only a grating compressor, the dechirped pulses appear relatively clean, without pedestals or structure (Fig. 2 (e)). Performance is currently limited by the available pump power and damage to the PM fiber.

We have demonstrated an environmentally-stable fiber oscillator, relying on parabolic pulse propagation and the Mamyshev pulse shaping mechanism, which can generate ~ 50-nJ and ~ 40-fs compressed pulses. Current efforts are aimed at scaling to the microjoule-level by using fiber with larger mode area and demonstration of self-starting operation. The present study shows a path to a high-peak power, all-fiber, and environmentally-stable laser.

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Multiple plate continuum driven by high power OPCPA at 1.55 μm

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Abstract: We demonstrate 3.3 mJ, 81 fs, 1.55 μm pulses produced by optical parametric chirp pulse amplifier (OPCPA) at 1-kHz repetition rate. The spectrum broadened in 11 thin-plate, supporting 18 fs (3.5-cycle) transform-limited pulse width.

High-order harmonic generation (HHG) has been extensively studied for coherent, attosecond, extreme ultraviolet light source generation. Using a longer wavelength laser of 1 μm to 4 μm, bright coherent X-ray light source has been demonstrated due to a favor of a larger pondermotive energy (*1*). To develop efficient HHG in water window, 1.6 μm lasers will be very ideal because it has high pondermotive energy and also keeps a high recombination probability of HHG. One of the approaches is BIBO-based optical parametric chirp pulse amplifier (OPCPA) pumped by Ti:Sapphire laser (*2*). Sub-two-cycle 1.6 μm lasers have been demonstrated. An alternative way is KTA- or KTP-based OPCPA, Mitrofanov et. al. have demonstrated >100 mJ OPCPA at 1.5 μm pumped by matured 1.064 μm lasers with intense energy up to 1 J (*3*). However, due to phase-matching bandwidth limit of KTP, the pulse duration is limited to 80 *fs*.

In this work, we have built a similar 1.55 μm carrier envelop phase (CEP)-stabilized KTP OPCPA (3.3 mJ, 81 fs) but running at a repetition rate of 1-kHz as shown in Fig. 1(a-b) (*4*). To shorten the pulse width further, we employed multi-plate continuum (MPC) (*5*) and demonstrate spectral broadening in 11 pieces, 50 μm-thick quartz plates. For the lack of space, in the first try we only focused 0.83 mJ pulses by a lens of 1-m focal length. The intensity on the first plate is 8 TW/cm^2. Fig. 1(c) shows the broadened spectra after every plate. In the beginning, self-phase modulation effect dominates the spectral broadening process that bandwidth in blue and red part are equally increasing. After the 4th or 5th plates, self-steepening effects dominates and more blue part has been generated. The final transform-limited pulse duration is 18 fs. Fig. 1(c) inset shows the output beam profile after 11 quartz plates. The beam profile in the central lobe contains over 60.2 % overall conversion efficiency after 11 plates. We will use the 3 mJ in MPC, expecting to produce ~2 mJ, < 20 fs CEP-stabilized pulses in the near future for bright water window HHG.

In summary, we have demonstrated MPC system driven by milli-joule OPCPA at 1.55 μm running at a repetition rate of 1 kHz that expands the bandwidth of KTP-based OPCPA laser by > 4 times, while keeping a good output beam quality. After phase compensation, the peak power of these pulses could reach several gigawatts. Such intense, stable diode-pumped few-cycle 1.55 μm OPCPA will enable bright water window HHG for bio-imaging applications.

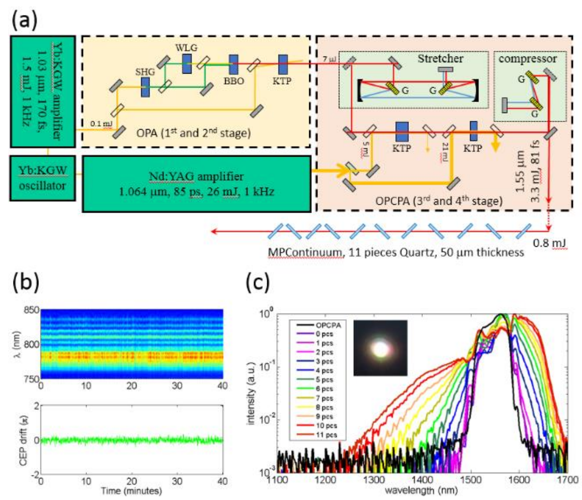

Fig. 1 (a) OPCPA setup. (b) CEP measurement of the front-end 1.55 μm pulses in a f-to-2f interferometry. CEP shifts with a fluctuation of 257 mrad acquired for 40 minutes. (c) Spectra of the pulses from OPCPA directly, passing through air only, and through different numbers of quartz plates. All the spectra are set to normalize its maximum value. Inset figure: Photographic image of MPC taken by a visible camera right after the 11th quartz plate.

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Compression, amplification and characterization of few-cycle short-wavelength infrared pulses

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Abstract: We present a Ti:Sapphire pumped optical parametric amplifier for the simultaneous amplification and compression of sub-10fs ultrashort pulses centered at 1.7um; third-harmonic generation dispersion scan in bulk glass is used for temporal pulse characterization.

I. INTRODUCTION

The generation of coherent light in the water window (280-530eV) can be realized by high harmonic generation (HHG) with an intense few-cycle short-wave infrared (SWIR) carrier-envelope-phase (CEP) stabilized pulse.[1] Spectral broadening in a gas-filled capillary followed by anomalous dispersion in bulk glass[2] is limited in pulse energy to ≲1mJ by the capillary, and a pulse duration of ≳8.5fs due to high order spectral phase. Increased energy would enable the simultaneous and synchronous generation of a few-cycle pump to initiate dynamics in a sample and a soft X-ray continuum (via HHG) to probe the dynamics.

II. THIRD HARMONIC GENERATION DISPERSION SCAN

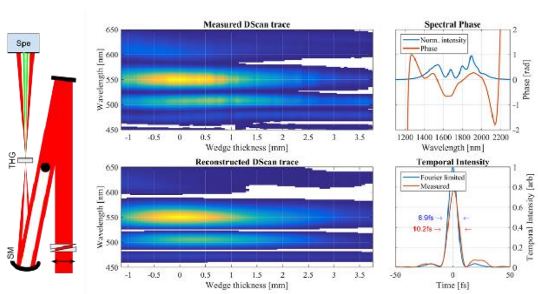

Fig. 1. THG-DS setup and results.

Temporal characterization of the few-cycle pulses is integral to experiments to enable optimization of the source or to provide maximum information from the experiment. The dispersion scan (DS) method is well suited due to its inherent experimental simplicity: utilizing wedges for dispersion control, a nonlinear medium and a spectrometer. For SWIR pulses, third harmonic generation (THG) is a preferred choice of nonlinearity since it results in the generation of visible light where readily available silicon detectors are most. Here we demonstrate THG-DS measurements of 10fs SWIR pulses (fig. 1), and show that the effects of phase matching and self-phase modulation need to be taken into account for accurate phase retrieval.

III. AMPLIFICATION AND COMPRESSION

We also present broadband amplification of few-cycle SWIR pulses in a Ti:Sapph pumped BBO optical parametric amplifier (OPA) – see fig. 2. Numerical modelling suggests the amplification bandwidth and dynamic gain can support the generation of single-cycle pulses, shorter than the optimally compressed unamplified output of the capillary. We have demonstrated the amplification of a seed bandwidth spanning 1200-2500nm with a gain of x3.5.

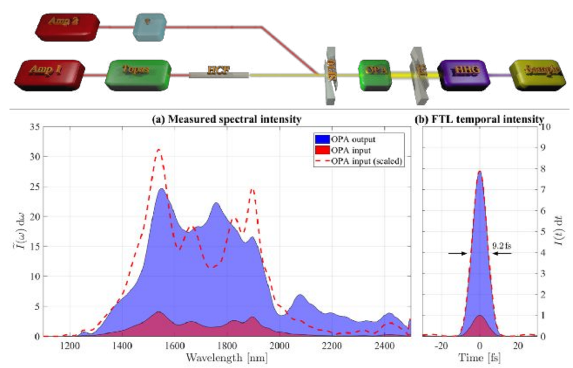

Fig. 2. Few-cycle SWIR OPA scheme (top) and measured amplified spectrum (bottom).

IV. CONCLUSIONS

We have demonstrated THG-DS for temporal characterization of few-cycle SWIR pulses, and amplification across the full spectrum in a simple OPA. We plan to perform temporal measurements on the amplified pulses and expect our method to be suitable for high flux HHG in the water window.

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High Power Lasers for Gamma source

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Abstract: We present the latest development of the ELI-NP interaction lasers. The targeted specifications are 300 mJ at 1030 nm, with pulse duration of 3.5 ps and 100 Hz repetition rate.

I. INTRODUCTION

The nuclear physics pillar of the extreme light institute European project (ELI) will be implanted in Magurele, Romania. A high intensity Gamma source is required for Nuclear Spectroscopy, this high intensity gamma source will be delivered by the interaction between accelerated electron and an intense laser beam [1]. Consequently, two high intense infrared laser beam are under development in Amplitude Custom Projects, a new entity in the Amplitude Laser Group [2]. A photocathode laser, delivering 32 pulses separated by 16 ns, will be used to generate the electrons, which will then be accelerated in the linear accelerator.

We will discuss here the current development of the interaction lasers. Those two lasers are based on a multi-stage amplification scheme that ended with a second harmonics generation stage to deliver 200 mJ, 3.5 ps pulses at 515 nm and 100 Hz.

II. INTERACTION LASER ARCHITECTURE

The oscillator is based on a standard product, the t-pulse oscillator, with the possibility of synchronization to the common optical reference of the machine. This is allowed by the means of a slow and fast feedback loop using step motor and piezo device implemented inside the oscillator cavity. The temporal jitter achieved is in the range of 120 fs rms, integrated from 10Hz to 10MHz.

The first amplification stage is a regenerative amplifier based on Yb:YAG technology, pumped by fiber coupled QCW laser diodes. This regenerative amplifier delivers pulses up to 30 mJ at 1030 nm and a 100 Hz repetition rate. The bandwidth is 1,0 nm wide and the beam was successfully compressed down to 1.5 ps.

A good spatial quality with a M^2 of 1.1 is delivered. This amplifier is integrated in a compact sealed housing with dimensions of 750x500x150 cm, which allows to achieve a pulse-pulse stability of 0.1% rms. A long term stability of 1,9% over 100 hours was achieved in an environment with +/-1°C temperature fluctuations. The main amplification stage uses a cryo-cooled Yb:YAG crystal used in active mirror configuration. The crystal is cooled at 130 K via a compact and low-vibration cryo-cooler, in order to avoid any additional phase noise contribution. Thanks to the low crystal temperature a high gain can be obtain in the cryo-cooled amplifier. The energy could be brought up to 340 mJ in a 6 pass scheme. The trade off to the gain of a cryogenic amplifier is the reduction of the bandwidth. At 130 K and 340 mJ the bandwidth goes down to 0.45 nm. The beam quality was characterized with a Strehl ratio of 0.9. Even with such a bandwidth, the pulses should be compressed down to 3.5 ps. For risk mitigation, a booster amplification stage is planned to amplify the regenerative amplifier before the main amplifier, in order to reduce the gain narrowing of the final amplification stage and therefore allow a higher bandwidth at the same level of energy.

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Generating long wave IR few-cycle pulses for strong field science

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We demonstrate a simple method for tunable few-cycle laser fields in the long wave infrared, capable of reaching peak intensities of 100 TW/cm^2. This provides a new wavelength regime for studying strong field science.

I. Introduction

The interaction of strong laser fields with atoms and molecules has been an area of considerable interest and research. Within many strong-field studies, the role of the carrier wavelength has received a great deal of attention. Recently, extension of strong field sources into the mid-wave IR has allowed for the generation of 300 eV attosecond pulses[1] as well as laser induced electron diffraction[2]. Recent work has shown the extension of strong field sources to wavelengths as far as 7 µm[3]. However, strong-field light sources in the long wavelength infrared (LWIR, 8-15 µm) regime are lacking.

We demonstrate a technique of difference frequency generation (DFG) which is capable of generating fields with carrier wavelengths ranging from 5 µm to 8.5 µm and a peak power at the Gigawatt level. These results promise to deliver strong-field science experiments in a new wavelength range[4].

II. Setup and Results

The system uses a 1 kHz rep rate, 20 mJ, 28 fs Ti:Sapph laser. 18 mJ of this laser pumps an optical parametric amplifier (OPA) delivering up to 6 mJ of signal and idler. Both beams are sent through an interferometer to optimize their spatial-temporal overlap on the nonlinear medium. We use a 1x1x0.1 cm $AgGaS_2$ (I) with an AR coating minimizing reflection of the OPA on the front and maximizing transmission of the LWIR.

The signal (idler) can be tuned from 1.38 µm (1.85 µm) to 1.45 µm (1.75 µm) to deliver a pulse with a center wavelength between 5-8.5 µm. The corresponding pulse energy is anywhere from 90 µJ (5 µm)-70 µJ (8.5 µm), depending on the wavelength the system is tuned to.

To characterize the electric field of the LWIR, we utilize a cross-correlation frequency resolved optical gating (XFROG) measurement. In this layout, a residual ~2 mJ of the Ti:Sapph laser is used to provide a gating field on the LWIR. By carefully measuring the gating field using standard FROG, the full LWIR electric field can be characterized

We found the pulse duration to be 80 fs for all measured fields. Thus, our LWIR system can deliver anywhere from a 4.8 (5 µm) to 3 (8.5 µm) cycle electric field, depending on the center wavelength. In addition, the phase indicates that the LWIR is near transform limited, giving us the cleanest electric field for performing strong field science experiments.

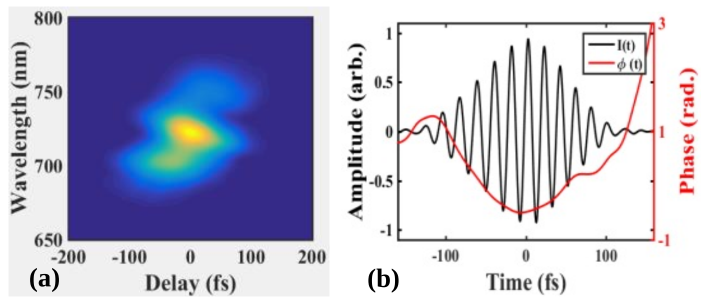

Figure 1 Example XFROG results for a few-cycle LWIR field **(a)** Retrieved XFROG spectrogram **(b)** Retrieved electric field.

The peak power of the system ranges from 0.9-1.1 Gigawatts. Our current efforts show the ability to generate peak intensities of 100 TW/cm^2 in a focusing geometry sufficient for charged particle detection.

III. Conclusion

We demonstrate a simple method of generating tunable few-cycle pulses in the LWIR with peak power at the GW level. We can achieve peak intensities at the level of 100 TW/cm^2 across the tuning range.

ACKNOWLEDGMENTS

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Development of a waveguide-based optical cross-correlator for attosecond timing synchronization

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Abstract: We present the design and characterization of a fully-integrated, waveguide-based, balanced optical cross-correlator (BOC). The BOC has a timing sensitivity of 79 mV/fs, making it well suited for use in next generation accelerator facilities.

I. INTRODUCTION

Optical cross-correlators have been shown to achieve sub-femtosecond timing needed for link stabilization systems in next-generation accelerator facilities[1]. Waveguide-based optical cross-correlators offer advantages over bulk-based devices because of the tight optical confinement within the material, which allows for the use of lower link power without sacrificing sensitivity. Additionally, fully-integrated waveguide-based optical cross-correlators provide robust, alignment-free operation in a compact footprint. In this summary, we outline the design and initial characterization of a fully-integrated, waveguide-based balanced optical cross-correlator (BOC) that achieved a timing sensitivity of 79 mV/fs, which is well-suited for use in link stabilization systems that will be required in future large-scale accelerator facilities.

I.A. BOC Design

The BOC device measures the arrival time difference of two orthogonally-polarized laser pulses while canceling errors due to intensity fluctuations and photodetector phase noise[2]. The fiber-pigtailed, fully-integrated waveguide-based BOC, illustrated in Fig 1, utilizes a dual-element design consisting of a periodically-poled waveguide to support Type II sum frequency generation (SFG) and a built-in directional coupler (DC) for wavelength division multiplexing (WDM) the pump and SFG light pulses. The use of waveguides instead of bulk operation improves the efficiency of the device, allowing for lower link power to achieve the same sensitivity, and permits full fiber integration which reduces optical complexity and increases overall robustness.

The waveguide BOC is fabricated using ion-exchanged waveguides in potassium titanyl phosphate (KTP), which was chosen because of its nonlinear optical properties, high-power handling, and wide acceptance bandwidth. The wide bandwidth of the Type II interaction is necessary for efficient SFG of the temporally narrow pulses, which have large spectral linewidths.

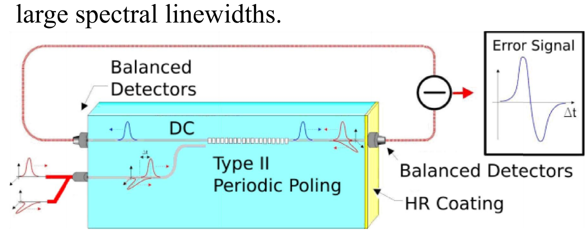

Fig. 1. A schematic of the waveguide-based BOC

A dual-element waveguide chip was packaged into a BOC device. The output facet was coated with an antireflection (AR) coating for 780 nm and a highly-reflection (HR) coating at 1550 nm to produce backward-propagating SFG. The WDMs were designed with a 127 μm separation to accommodate fiber-pigtailing at the input facet to a fiber array made up of two fibers with 127 μm core separation: a PM1550 fiber to deliver the short pulses and a multimode fiber to collect the generated SFG that propagates backward in the waveguide. Forward-propagating SFG is collected in a multimode fiber that is pigtailed to the output facet of the chip. Fiber-coupled silicon detectors spliced to the multimode fibers collect the forward and backward propagating light. Due to walk-off between the two input pulses, a mismatch in timing increases the SFG collected by one detector and decreases in the other, producing a high sensitivity error signal.

I.B. Initial Results

The sensitivity of the BOC device was measured at MIT using a 1560 nm mode-locked femtosecond laser with a pulse duration of 200 fs and 10 mW of power. The laser pulse was split into two paths with the polarization of one path rotated by 90 degrees. By varying the arrival time of the pulses, the balanced cross-correlation trace of the device is generated (Fig.

2). The measured sensitivity is 79 mV/fs, a factor of 8 improvement over a previous free-space coupled waveguide device[3].

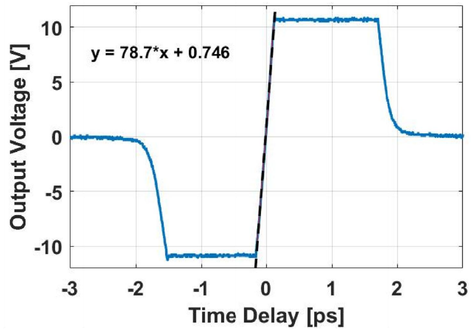

Fig. 2. Measured balanced cross-correlation of the integrated BOC device. The slope of the line is the sensitivity (79 mV/fs).

II. CONCLUSIONS

The results from the BOC show that a fully-integrated, waveguide-based device is significantly more efficient than a bulk device, with the additional benefits of alignment-free operation and increased robustness. This device will require lower link power than a bulk device, and with a measured sensitivity of 79 mV/fs, the waveguide-based BOC device is well-suited for use in future large-scale accelerator facilities that require attosecond timing synchronization.

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The impact of laser beam polarization on small-scale self-focusing in isotropic crystals

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Abstract: Direct measurements of spatial noise gain in an intense wave propagating in [001]-orientated BaF_2 were performed. Significant dependence of gain on the angle between the radiation polarization and the crystallographic axis predicted earlier was demonstrated.

I. INTRODUCTION

Laser intensity I is often limited by cubic nonlinearity, which results in small-scale self-focusing (SSSF). For a large B-integral ($B=n_2IL$, where n_2 is the nonlinear index of refraction and L is medium length), SSSF leads to strong beam intensity modulation and to destruction of optical elements. Even though SSSF in glasses was well-studied, the first theoretical investigation of SSSF in isotropic (cubic) crystals was undertaken only in 2016 [1]. A cubic crystal is a medium with isotropic linear properties but with anisotropic nonlinearity. As a result, there appear two important parameters: crystal orientation and tilt angle of radiation polarization. In the present work we made direct measurements of noise (inhomogeneities) gain in a BaF_2 crystal with [001] orientation *vs* radiation polarization.

II. EXPERIMENTAL RESULTS

We used laser pulses with a duration of 60 fs, energy of 4 mJ and beam diameter of 6 mm. A thin (200 µm) slightly matted glass plate placed at a distance of 17 mm in front of a 6 mm-thick BaF_2 crystal was used as a source of spatial noise. After passing the BaF_2crystal the radiation was focused on a mirror with a drilled aperture 1.5 mm in diameter to cut-off a noise-free beam (analogously to [2]). As a result, only noise radiation was reflected at the mirror from which the image was related to the CCD camera registering the angular noise spectrum.

The angular spectrum of non-amplified noise (B=0) is presented in fig. 1a. According to the SSSF theory, both in glass [3] and in an isotropic crystal [1] spatial perturbations gain depends on the angle α between the wave vector and the z-axis. For the chosen geometry of the experiment, the angular spectrum of gain is modulated, i.e., there appear rings in the intensity distribution of the amplified noise in the far field (see fig. 1b).

As was predicted in [1], unlike the case of glass, noise gain in an isotropic crystal depends on the angle φ between the electric field vector and the crystallographic axis, see fig. 1c. The appreciable spread is explained by the shot-to-shot fluctuations of the B-integral. Even weak fluctuations of B lead to strong fluctuations of gain, see the solid curves in fig. 1c. It is clear from the figure that nearly all experimental points lie within the 0.75<B<0.9 range. It is clear from fig.1c that in any case it is better to choose φ=45 deg to suppress SSSF.

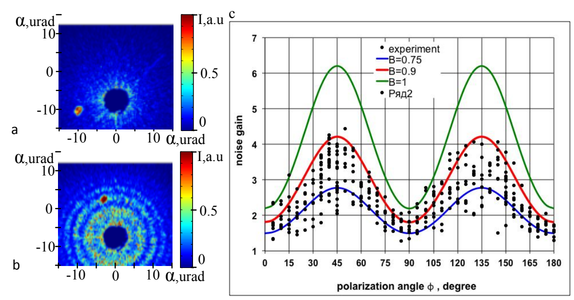

Fig. 1. Angular spectrum of non-amplified (a) and amplified (b) noise; and noise gain *vs* angle between polarization and crystallographic axis (c).

III. CONCLUSIONS

Direct measurements of small-scale perturbations gain in an isotropic crystal with cubic nonlinearity have been performed for the first time. The obtained results fully correspond to the theory developed earlier. Specifically, small-scale self-focusing depends significantly on the laser beam polarization. The most "safe" one is the polarization parallel to the crystallographic axis and the most "dangerous" one is with a tilt of 45 degrees.

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Timing jitter of dual-wavelength dual-comb mode-locked lasers

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Abstract: We characterized the relative timing jitter between the individual pulse trains emitted from one free running dual-wavelength mode-locked laser with sub-femtosecond precision by asynchronous optical sampling.

I. INTRODUCTION

Dual-comb scheme based on a pair of mode-locked lasers with offset repetition rate has been an enabling technology for ultra-precise molecular spectroscopy[1] as well as absolute ranging[2]. Both applications require real time acquisition of distortion-free beat notes between individual pulse trains. This highly relies on the intrinsic short term stability of mode-locked lasers, particularly the relative pulse train timing jitter[2,3]. In this work, we demonstrate that consecutive acquisition of non-interferometric beat notes permits direct timing jitter analysis for dual-comb mode-locked lasers in time domain. This technique has been utilized to investigate the quantum limited performance for the recent emerging dual-comb setup based on one dual wavelength mode-locked laser.

II. Experiment and results

Dual-wavelength mode-locked laser shows great potential for practical dual-comb spectroscopic applications. Picometer resolution has been achieved without using complex phase locking electronics[4]. The laser under test[4] simultaneously generates a pair of pulse trains working at 1531nm and 1555nm with ~50.6 MHz repetition rates and 2.13 kHz offset. This laser shows intrinsic long term stability with merely 2 Hz offset repetition rate drift during half an hour. Here, the output two wavelengths are separated by a CWDM for relative timing jitter characterization.

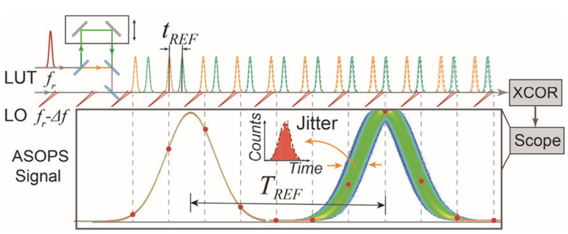

Fig. 1. Concept of timing jitter measurement based on ASOPS.

The measurement is based on asynchronous optical sampling (ASOPS) principle, as shown in Fig. 1. ASOPS is capable of linearly stretching ultrafast processes in time such that sub-femtosecond period jitter of optical pulse stream is visible to fast data acquisition electronics. As a result, a visual timing jitter standard deviation can be acquired from histogram analysis, resembling an eye diagram analysis routinely used in electronics. The period jitter of mode-locked lasers can thus be mapped back into the original femtosecond or even attosecond timescale as long as the stretching ratios are determined in advance.

The experimental setup and measurement procedure can be found from Ref. 5. The measured relative optical period jitter between the two combs is ~0.82 fs with 17 as uncertainty, as shown in Fig. 2. The inset shows the deduced timing jitter PSD. The measurement reflects a typical timing jitter performance for soliton lasers, indicating that, despite the splendid long term stability due to common mode noise suppression by the dual wavelength dual-comb scheme, the dual-comb relative timing jitter is not reduced. In the short timescale, the two pulse trains circulate in the same laser cavity independently and suffer from uncorrelated quantum noise.

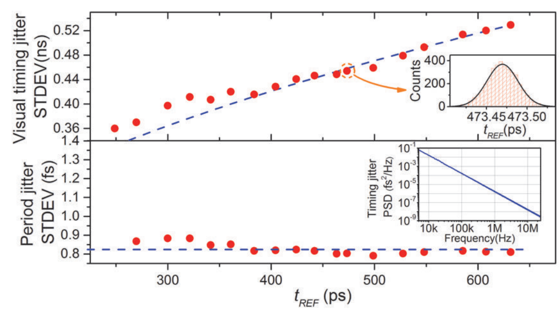

Fig. 2. Timing jitter measurement results for the dual-wavelength dual-comb system by ASPOS method.

In conclusion, we characterize the relative timing jitter of a free-running dual-wavelength mode-locked laser with sub-fs resolution. The timing jitter from the two pulse trains is uncorrelated in nature, defining the quantum limit for dual-comb applications.

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Unstable Multi-Pulsing Can Be Invisible to Some Ultrashort Pulse-Measurement Techniques

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Abstract: Simulations show that random or variable relative phase of a satellite pulse causes the satellite to wash out of a SPIDER measurement completely, with no indication of its presence. While FROG and autocorrelation measurements cannot determine its precise properties, they at least see such satellite pulses and can yield their strength.

I. Introduction

Most ultrashort pulse measurements average over many pulses when attempting to determine pulse properties. Recent publications have shown that this averaging is quite problematic in the presence of pulse-shape variations[1,2]. In this case, it is clearly impossible for a single measurement result to reflect all the pulses that were measured. Worse, there is no independent device that measures laser stability. So it is therefore imperative to understand which pulse properties can be faithfully measured by a given measurement technique in the presence of instability.

Popular pulse measurement techniques have varying degrees of success with measuring unstable, noise-like pulses in simulations[1,2]. Techniques like frequency-resolved optical gating (FROG)[3] always reveal the presence of instability when it is present and typically provide a good approximation of the temporal pulse length and complexity. Techniques like spectral interferometry for direct electric field reconstruction (SPIDER)[4] do not indicate whether instability is present and often significantly underestimate the pulse length and complexity, yielding only the coherent artifact.

But those findings are based on a particular model of pulse-shape instability, and there are many ways in which an ultrafast laser might be unstable. Here we perform simulations with a different type of pulse shape instability: unstable multiple pulsing, which is very common (especially in over-pumped lasers), and which cannot be determined by the spectrum.

II. Results

Previous analysis suggested that multiple pulsing would be apparent in a SPIDER measurement as long as the separations between pulses did not vary over a large range[2]. Upon further consideration, however, we find that those conclusions were overly optimistic, because they did not include the possibility of variations in the ubiquitous relative phase of the multiple pulses, which generally accompany such multi-pulsing. We show here that, in this case, SPIDER does not see satellite pulses at all when the relative phase of the two pulses varies by 2π or more. This is true regardless of whether the temporal separation of the two pulses varies. Since these compromised traces are indistinguishable from normal, correct single-pulse SPIDER traces, it will be virtually impossible to know when a random satellite pulse(s) may be present. This means that SPIDER is not capable of guaranteeing that the output of a given laser is stable using an averaged measurement.

We find that SHG FROG consistently under-estimates the intensity of satellite pulses, but the satellite pulses are clearly visible in SHG FROG measurements. Satellites retrieved from SHG FROG traces correctly represent the average pulse separation, and the RMS error for these traces is larger than what is expected for quality measurements. This is a clear indication of instability, as is also the case for other types of pulse instability. We demonstrate that the relative energy of the two pulses in a double pulse can be retrieved from the SHG FROG trace directly, even when the temporal separation of the two pulses is not stable[5]. This is because the measured and retrieved traces contain redundant information about the pulse characteristics.

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Dispersion Measurement of Large Aperture Mirrors at Arbitrary Incidence Angle and Polarization State

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Abstract: We report on a device to measure spectral phase of broadband mirrors up to 30 cm with ±0.5 fs^2 and ±2 fs^3 accuracy, at an incidence angle of 0°-55°, and at an arbitrary linear polarization.

The mirrors of femtosecond high peak power lasers have to comply with strict requirements in bandwidth, spectral phase shift, and laser damage threshold. Nowadays, PW class lasers with sub-30 fs pulse duration are operating [1], while the pulse duration would be further shortened below 15 fs [2]. To achieve the highest possible intensity on the target, a precise control of spectral intensity and spectral phase is required. One needs to ensure that the spectral phase is homogeneous over the mirror surface well exceeding 10 cm. Moreover, due to the technical limitations or requirements of experiments, some of the mirrors are intended to use at an angle of incidence far from normal or 45°, and for a pulse with linear polarization between S and P. In this paper we introduce a combined device which offers unique opportunity to scan the dispersion of large mirrors at an arbitrary degree of incidence and polarization state.

The measurement is based on Spectrally Resolved Interferometer [3], consisting of a Michelson interferometer illuminated by a combined visible and infrared white light source. The tungsten halogen lamp with 10 mW average power makes possible to measure the dispersion properties over 500-1300 nm spectral range. The sample arm of the Michelson interferometer contains the mirror to be measured. Using an adjunct mirror, we made possible to change continuously the angle of incidence at the chirped mirror within 3 and 55°. On the input part of the interferometer we placed a wire-grid polarizer, and sensitivity of the chirp mirrors to the polarization state have been measured at different incidence angles. Group Delay Dispersion (GDD) and Third Order Dispersion (TOD) are obtained up to ±0.5 fs^2 and 2 fs^3 accuracy from the Fourier Transform method of the interference fringes.

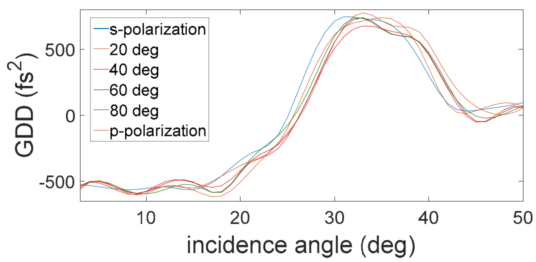

Fig. 1 Measured Group Delay Dispersion at 800 nm

To present the flexibility of the device we scanned two different chirped mirrors with +135 fs^2 and -500 fs^2 at the 800 nm central wavelength. The dispersion curves are shown on Fig. 1 at different incidence angle and polarization states. Fig. 2 shows the GDD scan over a large aperture mirror of the ELI-ALPS SYLOS beam transport system.

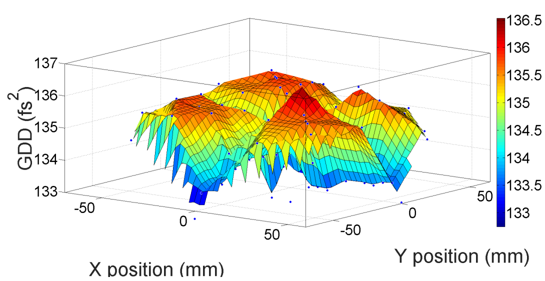

Fig. 2 Measured Group Delay Dispersion over 16 cm aperture mirror

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Broad-band mid-infrared measurements for time resolving shock-induced chemical reactions

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Abstract: Mid-infrared ultrashort pulses, sensitive to functional groups in molecules, are a direct probe of chemical reactions. Using four-wave mixing in air we generate and measure single-shot spectra of octave-spanning mid-infrared pulses to time-resolve shock-induced chemistry.

I. Probing ultrafast chemical dynamics

Absorption of light in the mid-infrared (mid-IR) spectral range often comes from vibrational modes of molecules which can be associated with specific functional groups. Absorption of ultrashort mid-IR pulses allows for monitoring ultrafast changes in molecular structure as bonds break and reform during chemical reactions. However, to get a full picture of the chemistry to deduce intermediate states and reaction pathways, very spectrally broad mid-IR pulses, spanning ideally from 500 to 3500 cm^{-1} (3 – 20 μm) are needed to see a range of functional groups appear and disappear as reactions proceed.

One important application of broad-band time-resolved mid-IR spectroscopy, which we address here, is to identify key chemical reactions in energetic materials. Very little is known about how these materials rapidly release energy, or fundamentally what makes a material an explosive, questions that are of scientific interest and important for safety.

II. Experimental setup and results

To answer these questions we are incorporating single-shot, ultrafast, ultra broad-band mid-IR absorption spectroscopy into a laser-driven shock-chemistry experimental setup, based on a 10 Hz, ~30 mJ, 150 fs Ti:Sa laser/amplifier system. The chemistry is started in our sample using a laser-driven shock [1], where a ~350 picosecond, ~3 mJ portion of the laser's output is focused onto a metal foil, vaporizing it. The quickly expanding metal vapor sends a shockwave into a sample mounted next to it, pressurizing and heating it, and starting a chain of highly exothermic chemical reactions.

To probe this chemistry we need broad-band mid-IR pulses and the ability to make single-shot measurements of their spectra. To generate the pulses, we use four-wave mixing up-conversion in air of collinear, temporally overlapping 784 nm and 392 nm pulses, following the method described here [2].

Due to a lack of large array detectors covering the full 500 to 3500 cm^{-1} spectral range, we also use four-wave mixing to up-convert the mid-IR pulses back to the visible spectral range to measure them. Following the method described here [3], we spectrally filter a second beam at 784 nm with ~1 mJ of pulse energy using a 1.5 nm bandpass filter. Spatially and temporally overlapping the near-IR and mid-IR pulses in air, a ~410 nm pulse is generated, in which the mid-IR spectrum is encoded (the frequency-domain nonlinear signal is a convolution the interacting fields). FIG. 1 shows single-shot up-conversion measurements of mid-IR transmission spectra through different polymers or nitromethane showing good agreement with commercial FTIR measurements and a spectral resolution of ~25 cm^{-1}. Our next step will be to improve the spectral resolution, replacing the band pass filter with a diffraction grating and slit, and then to incorporate this measurement as a probe in our ultrafast shock-chemistry experiments.

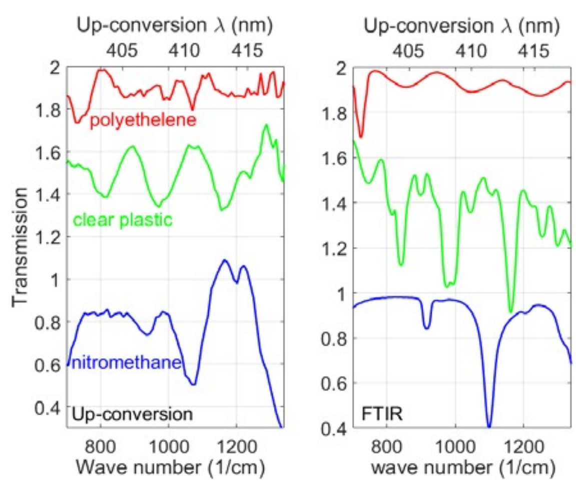

Fig. 1. Static mid-IR transmission measured with 4WM up-conversion (left) and an FTIR (right).

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High-precision angular dispersion measurement in a non-collinear optical parametric amplifier of a 4-PW Ti:Sapphire laser

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Abstract: Angular dispersion, introduced by a non-collinear optical parametric amplifier used as a frontend amplifier of a 4 PW Ti:Sapphire, was measured precisely in a single shot using a 2-D spatially and spectrally resolved interferometer.

I. INTRODUCTION

For the prevention of gain narrowing and the improvement of contrast ratio of the 4 PW laser at CoReLS [1], a non-collinear optical parametric amplifier (NOPA) [2] was adopted. The measurement of angular dispersion in an ultrafast laser is important because the angular dispersion deteriorates the temporal profile of the laser and decreases peak power. Here we present a high-precision single-shot angular dispersion measurement method to measure the amount of angular dispersion of NOPA.

II. MEASUREMENT

The angular dispersion was measured with a 2-D spectrally and spatially resolve interferometer (SSRI). The main difference of a common Mach-Zehnder interferometer (MZI) and a rotated MZI, shown in Fig. 1, is in the rotation of transverse wave vector. Figure 2 shows the transverse wave vectors and interference patterns. Only the interference pattern of rotated MZI contains the full information on transverse wave vector difference.

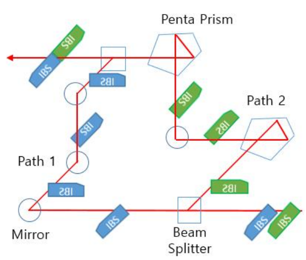

Fig. 1. Schematic layout of the Rotated MZI. The beams through path 1 and 2 are rotated 180 degrees from each other.

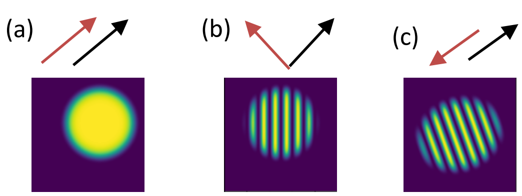

Fig. 2. Simulated interference patterns of (a) common MZI, (b) inverted MZI (Ref. 2), and (c) Rotated MZI.

The black arrows show transverse wave vector through reference path, while the red arrows show wave vector through sample path.

The schematic layout of the 2-D SSRI is shown in Fig. 3. The broadband input spectrum was modulated to a sharp peak spectrum using a Fabry-Perot interferometer (FPI). The grating separated the interference pattern formed on CCD according to the spectrum. Figure 4 shows the separated interference pattern by the FPI and the grating.

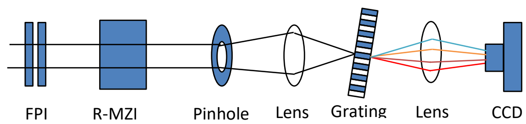

Fig. 3. Schematic layout of the 2-D SSRI.

Fig. 4. Experimental result of the 2-D SSRI.

IV. CONCLUSION

The angular dispersion measurement method was developed with the 2-D SSRI. The measurement accuracy of this single shot 2-D method was comparable to that of the 1-D method [2]. This measurement technique was utilized for the measurement and ellimination of the angular dispersion of the NOPA of the 4-PW laser.

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Probing ultrafast lattice dynamics in lead selenide quantum dots

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Abstract: We directly monitored the photo-induced lattice dynamics in PbSe quantum dots using ultrafast electron diffraction. The energy relaxation between the carriers and the lattice took place within 10 ps, showing no significant phonon bottleneck effect.

INTRODUCTION

Due to strong quantum confinement, the electronic density of states in PbSe and PbS quantum dots (QDs) with a few nm in diameter becomes discrete with an adjacent energy separation exceeding several optical phonon energies, leading to the phonon bottleneck effect. This opens a possible mean to exceed the Shockley-Queisser limit using QDs as solar cells [1]. To realize this and many other potential optoelectronic applications requires an in-depth understanding of how quantum confinement affects the dynamics of carrier and lattice coupling in QDs.

Experiment & Results

We directly monitored the laser induced lattice dynamics in PbSe QDs using ultrafast electron diffraction. The dynamics were initiated with 800 nm, 50 fs laser pulses and recorded by capturing the snapshots of diffraction patterns (DPs) at various pump-probe delay times. By tracking the changes of Bragg peak intensity and positions in these DPs, the lattice temperature and the spacing change, as shown in Fig. 1, were followed in real time.

We used a three temperature model (TTM) [2] to examine the kinetics of energy interchange among participating subsystems, including electron-phonon thermalization, lattice expansion, heat conduction between the QDs and the supporting Si_3N_4 substrate. We found that the energy relaxation between the photocarriers and lattice took place within 10 ps, showing no significant evidence of any phonon bottleneck [2]. Meanwhile, the dilation of the lattice showed some unusual features that couldn't be explained by the available mechanisms of photon-induced acoustic vibrations in semiconductors. In addition, our results indicate that the heat transport between the QD and substrate under nonequilibrium conditions deviates significantly from the Fourier's Law.

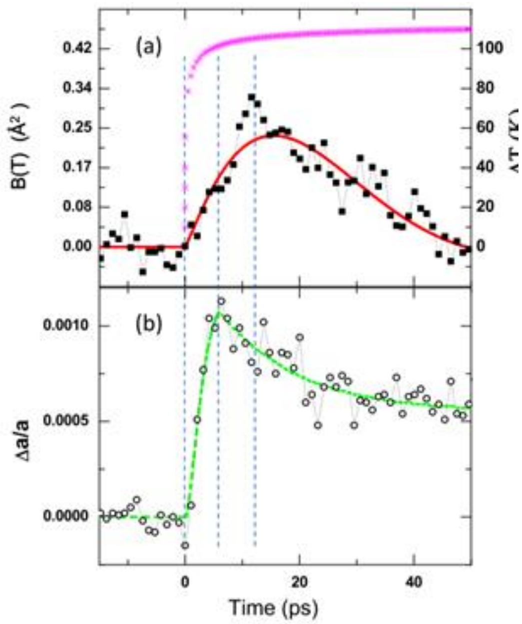

Fig.1 (a) Transient lattice temperature. The asterisk line is a simulation of Auger relaxation and the solid line is the TTM model fitting. (b) Relative lattice spacing change as a function of time.

ACKNOWLEDGMENTS

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Complete temporal characterization of highly chirped pulses

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Abstract: We describe a new interferometric self-referenced method for the complete characterization of highly (monotonically) chirped ultrabroadband pulses. The method is demonstrated on 55nm bandwidth pulses centered at 800nm and stretched to 32ps with 0.05% precision.

I. INTRODUCTION

Complete characterization of ultrashort pulses has been crucial for the advancement of novel ultrafast laser technologies, and in maximizing the knowledge extracted from ultrafast optical experiments. Chirped pulses are almost ubiquitous in ultrafast optics, e.g. in [optical parametric] chirped pulse amplification ([OP]CPA) laser systems and dispersive Fourier transform spectroscopy (DFTS)[1] style experiments.

Optimization of extremely large bandwidth [OP]CPA systems utilizing complex hybrid stretcher / compressor configurations[2] would benefit from the capability to measure the nonlinear dispersion over a larger range than that supported by current temporal characterization devices. In DFTS experiments that utilize the one-to-one mapping of time to frequency afforded by a large nearly linear chirp, the accuracy and temporal/spectral resolution can be improved if the nonlinear dispersion can be measured accurately.[3]

II. METHOD

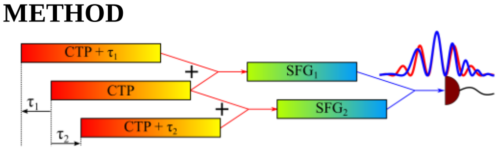

Fig. 1. CHIMP concept: three time-delayed replicas of the chirped test pulse (CTP) are upconverted in a $\chi^{(2)}$ nonlinear crystal and the sum frequency generation (SFG) signals are interfered on a spectrometer.

We present a method called "chirped heterodyne interferometry for measuring pulses" (CHIMP) that measures the spectrally dependent group delay dispersion (GDD) of monotonically chirped ultrabroadband pulses (i.e. the group delay is either continuously increasing or continuously decreasing with frequency). The concept (fig. 1) consists of frequency mixing of various time-delayed copies of the chirped test pulse (CTP) in a nonlinear medium and then spectrally resolving the interference of two or more sum-frequency fields. We derive an analytic expression for the phase of the interferogram as a function GDD of the CTP.

We verified the method by measuring the uncompressed output of a Ti:Sapph CPA system: 55nm bandwidth centered at 800nm with a pulse duration of 32ps (1% intensity), yielding a time-bandwidth product of 830. This formed the pump of a novel OPCPA system that requires careful dispersion matching of the pump and signal.[4] The GDD measured using CHIMP (fig. 2a) was compared with Fourier transform spectroscopy measurements of the stretcher, showing excellent agreement. The precision was also verified by measuring changes in the GDD as the stretcher grating separation was tuned by approximately 0.1-3mm (1-10%). The error in the measured GDD were calculated from Monte-Carlo simulations and indicate a precision better than 0.05%, corresponding to a temporal resolution of approximately 10fs.

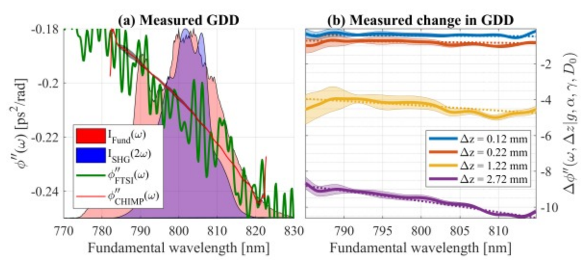

Fig. 2. (a) Measured fundamental and SHG spectra and retrieved GDD. (b) Measured change in GDD as stretcher grating separation is tuned (shaded regions indicate estimated standard error).

III. CONCLUSIONS

We have demonstrated the measurement of highly chirped pulses using a simple interferometric device that would simplify the optimization of complex/large CPA systems and easily provide accurate pulse durations in experiments that utilize chirped pulses.[5]

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Comparing ptychography to cross-correlation FROG, which is really also ptychography

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Abstract: Data diversity is required to solve 1-D phase retrieval problems. Data diversity, or ptychography, as an approach to pulse measurement has become popular. We compare traditional ptychography and Cross-Correlation Frequency Resolved Optical Gating (X-FROG).

I. Introduction

Frequency resolved optical gating (FROG)[1] is a technique to measure ultrafast laser pulses that uses data diversity to convert an unsolvable 1-D phase retrieval problem into a solvable 2-D phase retrieval problem;[2] gated spectra are recorded as a function of time delay between two pulses. Indeed, data diversity, or ptychography,[3] has been found to improve 2-D phase retrieval as well. Under the name ptychography, data diversity as an approach to phase retrieval has become quite popular, and 1-D ptychography using FROG-like data has been used to measure ultrafast laser pulses.[4]

In this work, we compare two separate branches of 1-D ptychography development, namely the extended Ptychographical Iterative Engine (ePIE) developed by Maiden and Rodenburg[3] and a method for measuring ultrafast laser pulses when one pulse is known, called Cross-correlation Frequency Resolved Optical Gating (X-FROG).[5,6] Using Principal Components Generalized Projections[7] derivation of the X-FROG algorithm, we find that the two algorithms are mathematically nearly identical and discuss expectations resulting from the similarities.

I.A. Ptychography

Ptychography is defined by the data. An underlying unknown function (i.e., field) is multiplied by a second function (field) that translates transversely, and the intensity of the product field propagated to another plane (or transformed to another domain) is measured.[2] Historically, ptychography has been applied to imaging applications where the transverse translation is spatial.[3] However, the distinct parallels between spatial propagation and temporal signals have been used to apply the ePIE to pulse measurement with success.[4]

I.B. X-FROG

X-FROG deconvolves an unknown pulse from time delayed spectrally resolved cross-correlations with a known pulse. The algorithm is extremely robust and virtually always converges.[6] The primary difference between the X-FROG algorithm and ptychography is the need for a complete "FROG" data set. The ramifications of this will be discussed in the presented comparison.

II. CONCLUSIONS

Using reduced data sets for ultrafast laser pulse measurement is an attractive option and recent reports indicate it is possible.[4] However, convergence of the ptychography engine will most likely be dependent on the sampling of the autocorrelation. The ptychography algorithm is a steepest decent algorithm and steepest decent algorithms typically converge more slowly than other optimization algorithms. FROG algorithms are all generalized projections algorithms that have good and predictable convergence characteristics.

ACKNOWLEDGMENTS

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Development of a compact single-shot mid-IR prism spectrometer

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Abstract: We report on the design and performance of a compact single-shot mid-infrared prism spectrometer used as a diagnostic tool for characterizing ultrashort mid-infrared laser pulses used in LCLS pump-probe experiments.

I. INTRODUCTION

Tunable mid-infrared (IR) laser pulses offer the unique ability to selectively excite phonons in solids to transiently induce phase transitions [1,2]. The mid-IR spectral region is therefore highly interesting for user experiments at free-electron laser (FEL) facilities, which provide unprecedented brightness and time resolution to explore the dynamics of matter on the atomic scale. Yet the mid-IR region presents some unique challenges not only in the production, but also in the measurement and characterization of high-energy ultrashort mid-IR laser pulses. Mid-IR diagnostic instrumentation is limited and typically requires bulky cooling apparatuses for operation. To address this need, we developed a compact, single-shot mid-IR prism spectrometer operated at room temperature that can be used to monitor the pulse spectrum of laser pulses generated. Using this device enables rapid optimization of desirable pulse characteristics, such as pulse energy, center wavelength, and spectral bandwidth.

The optical layout of the prism spectrometer is shown in Fig. 1. The spectrometer has demonstrated room-temperature detection of mid-IR laser pulses spanning λ = 4 – 17 µm generated in a commercial OPA laser source operating at a repetition rate of 120 Hz. The entire system fits on a compact 12-inch x 12-inch aluminum breadboard that can easily be transported and adapted to other optical tables.

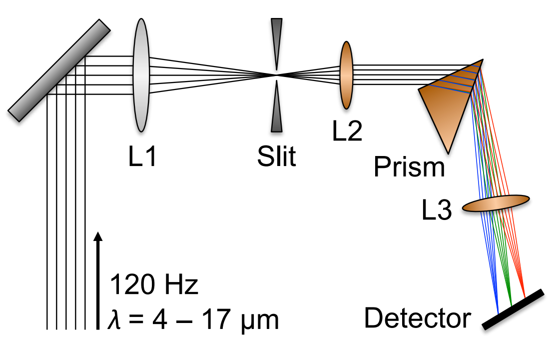

Fig 1. Optical design of the prism spectrometer. Mid-IR laser pulses are generated using a commercial OPA laser source (HE-TOPAS, Light Conversion).

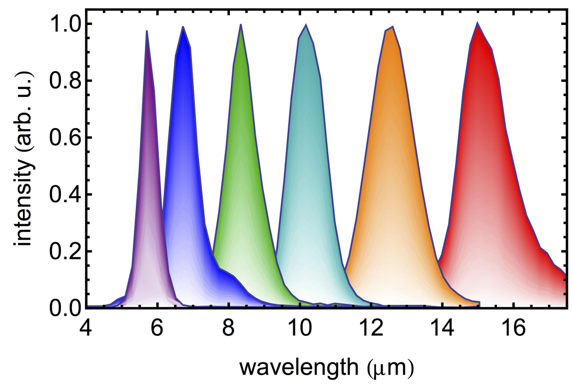

Fig. 2. Pulse spectra obtained from our mid-IR OPA source measured using the prism spectrometer

II. SYSTEM PERFORMANCE

A typical tuning curve of the mid-IR laser pulses we are able to generate is presented in Fig. 2, showing the pulse spectra obtained with the single-shot spectrometer described. Potential applications enabled by this device include ultrashort pulse characterization using dispersion scan retrieval [3] and high-sensitivity single-shot pump-probe spectroscopy. The spectral range of the spectrometer is currently limited by absorption of focusing and dispersing optics rather than the sensitivity of the detector. We hope to explore alternative materials for achieving THz detection with this device in the future.

ACKNOWLEDGMENTS

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Next Generation Ultrafast Time-Resolved Vibrational Spectroscopy at the Central Laser Facility

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Abstract: Time-resolved vibrational spectroscopy developments are presented as we increase sensitivity of high repetition rate techniques with CPA and OPCPA laser systems. Applications to solids, liquids and gases are described, with femtosecond to second dynamics.

I. Introduction

The ULTRA laboratory of the UK's Central Laser Facility provides time-resolved spectroscopy research facilities. The facility develops ultrafast laser-based spectrometers, with applications in time-resolved IR and Raman spectroscopy.

II.A. Laser Systems

For fast data acquisition and increased sensitivity, the present techniques use 1 – 100 kHz repetition rate lasers, based on cryocooled titanium sapphire (TiS) and ytterbium (Yb), chirped pulse and optical parametric chirped pulse amplifiers (CPA and OPCPA). The outputs are used directly or via wavelength conversion to the UV or IR. For spectral difference measurements, stable, broadband IR generation is a key aspect of the laser systems.

Typical ultrafast IR pulse generation is achieved by optical parametric amplification (OPA) of 800 nm TiS amplifier output, followed by difference frequency generation (DFG). Yb-technology has shifted the driver wavelengths towards the IR. Using high average power picosecond lasers to drive OPCPA stages provides high average power (> 10 W at 100 kHz), < 50 fs pulse output in the IR (1.5 – 4 μm). OPA/DFG stages on these outputs will provide ≥ 5 μm generation. This output will be higher average power and potentially broader bandwidth than currently used in IR pump – probe spectroscopy for molecular dynamics experiments.

II.B. Experiments

High repetition rate lasers coupled with shot-to-shot spectral acquisition are capable of sensitive spectroscopic measurements. For broadband pump on/off spectral measurements in the IR, pulse energies and data acquisition rates limit the presented techniques to ~ 100 kHz repetition rate[1]. A dual Yb:KGW amplifier system for time-resolved IR spectroscopy is described, measuring changes in optical density of 10^{-6} in a few seconds. Limitations of the Yb:KGW amplifier bandwidth / pulse durations are to be overcome by an OPCPA system being integrated in our laboratory, enabling fast (< 50 fs) and broader bandwidth (> 400 cm^{-1}) spectral measurement at 100 kHz.

Photo-excitation of molecules with UV/visible pulses can lead to dynamic changes covering orders of magnitude in time. For example, photo-excitation of light-sensitive proteins can initiate ultrafast (< 100 fs) changes in chromophore structure, followed by changes in the surrounding protein over milliseconds. Development in our laboratory of pump - probe - probe - probe techniques with low/high repetition rate pump/probe have enabled combined femtosecond to second measurements[1, 2].

As a facility, it is imperative to be able to study a variety of samples. We present novel measurements of molecular dynamics in the gas-, solution- and crystal-phases.

III. Conclusions

Laser and technique developments are presented to improve sensitivity, expand data collection parameters and widen application to diverse samples.

ACKNOWLEDGMENTS

The authors wish to acknowledge the STFC and BBSRC for funding.

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Ultrafast Valley-resolved Carrier Dynamics in Group IV Semiconductors

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Abstract: Attosecond transient absorption spectroscopy at the $M_{4,5}$-edge of Ge following ultrafast photoexcitation reveals valley-resolved hot electron and hole relaxation, carrier recombination and trapping in Ge and Si-Ge alloy in unprecedented clarity and simultaneously.

I. INTRODUCTION

Germanium and its alloys with Silicon have promise for creating multi-junction solar cells with higher efficiency and mid-infrared optoelectronics. However, measuring carrier dynamics is complicated by a multitude of energetically similar valleys and various relaxation and recombination pathways.

Here, attosecond transient absorption is employed to monitor carrier dynamics in Ge and SiGe of both electrons and holes simultaneously in the relevant valleys as well as induced band dynamics with few-femtosecond time resolution and high energy resolution.

II. EXPERIMENT AND RESULTS

In the experiment, a 5 fs VIS-NIR pump pulse excites carriers across the direct band gap of pure Ge and the largely indirect band gap in Si-Ge alloy. The dynamics are probed at the Ge $M_{4,5}$-edge (~30 eV) with a time-delayed broadband extreme ultraviolet pulse generated by high harmonic generation in xenon spanning ~20-45 eV.

A typical transient absorption signal at the Ge $M_{4,5}$-edge (Fig. 1a) contains the energetic distribution of both carriers, electrons and holes, due to state blocking as well as spectroscopic features induced by bandshifts (e.g. due to band gap renormalization) and excited state broadening (e.g. due to many body effects). These individual contributions are disentangled by an iterative procedure[1] yielding a representation of carriers over energy and time in unprecedented clarity (Fig. 1b) allowing the direct observation of hot carrier relaxation and recombination.

Specifically, hot carrier relaxation on a 100-fs time scale and carrier recombination on a 1-ps time scale are observed in pure Ge following excitation across the direct band gap. The fast recombination is attributed to the nanocrystalline nature of the sample. The high energy resolution further allows extracting valley-dependent carrier lifetimes (inset Fig. 1b) to obtain a full picture of the carrier dynamics.[1]

In contrast, in Si-Ge alloy phonon-assisted excitation across the indirect band gap is observed. Following hot carrier relaxation in the alloy, trapping of electrons in midgap states is experimentally observed and the asymmetry between electron and hole signal (Fig. 1c) indicates a significantly reduced recombination rate across the indirect gap.[2]

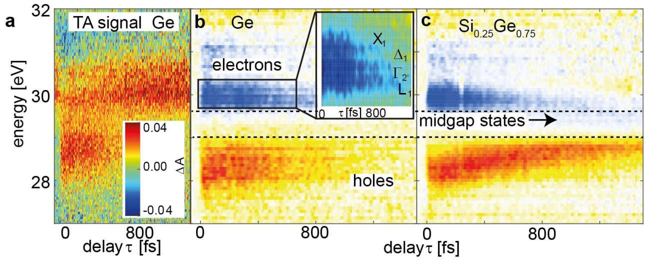

Fig. 1. (a) Typical transient absorption signal at the Ge $M_{4,5}$-edge. (b) Retrieved carrier dynamics from (a) featuring hot electron and hole relaxation and recombination (Inset: enlarged conduction band shows valley-specific carrier dynamics). (c) In Si-Ge alloy trapping of electrons in midgap states is observed.

III. CONCLUSIONS

In conclusion, attosecond transient absorption is successfully employed to track several electron volt wide spectroscopic features at the $M_{4,5}$-edge of Ge revealing valley-specific hot electron and hole dynamics. Applying the reporter atom concept as implemented for Si-Ge alloy holds great promise for studying carrier dynamics and localization in more complex systems such as ternary and quaternary semiconductors.

ACKNOWLEDGMENTS

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Terahertz-based attosecond metrology of relativistic electron beams

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Abstract: Here we report on experiment results of strong interaction between a quasi-single-cycle THz pulse and multi MeV high brightness relativistic electron beams which enables time-domain control and characterization at attosecond accuracy.

I. INTRODUCTION

High brightness electron beams play a central role in various modern tools for ultrafast sciences, including free-electron lasers and ultrafast electron scattering (diffraction, imaging, and spectroscopy) instruments. Strong terahertz radiation emerges as a new source for manipulating bright electron beams on ultrafast time scales. Particularly, with laser-generated THz radiation, the electron beams will be manipulated in a way tightly synchronized in time with respect to the driving laser pulse.

II. EXPERIMENT SETUP AND RESULTS

The schematic of the experiment is shown in Fig. 1. The interaction between a laser-generated quasi-single-cycle THz pulse and a co-propagating 3 MeV relativistic electron beam was enhanced by a metallic resonator structure. The THz field imprinted a time-dependent transverse angular kick to the electron beams, which was recorded as the transverse centroid motion on a downstream screen as we changed the time delay between the THz pulse and electron beam. The timing accuracy, defined as the pointing stability of the electron beams versus the streaking speed (angular kick over time), was at a-few-hundred-attosecond level.

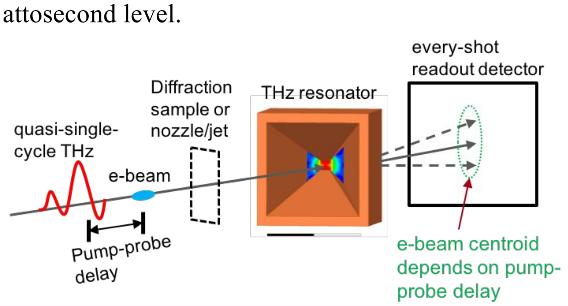

Fig. 1. Schematic of the THz streaking experiment, as well as the concept of a timing tool for pump-probe ultrafast electron diffraction measurement.

III. OUTLOOK

We've demonstrated for the first time THz-based clocking of relativistic bright electron beams with attosecond accuracy. This is a critical step for improving the temporal resolution of pump-probe UED toward femtosecond and better level. We are developing a THz-based timing tool to measure the timing jitter on shot-by-shot basis. We are also exploring the feasibility of THz compression for generation of electron beams with both femtosecond and shorter bunch length and timing jitter.

ACKNOWLEDGMENTS

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High contrast broadband seeder for multi-PW laser system

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Abstract: A hybrid Ti:Sa CPA/BBO OPCPA system with a XPW filter inbetween the two has been developed to produce a broadband high contrast seeder of 10 mJ for the two 10 PetaWatt beamlines of ELI NP infrastructure.

I. INTRODUCTION

The last decade has seen the tremendous development of CPA based on Titanium Sapphire crystals pumped by the second harmonic of a Nd:YAG or a Nd:Glass laser.
The next generation will be based on lasers delivering more peak power than currently including Extreme Light Infrastructure Nuclear Physics (ELI-NP) in Romania involving 2 laser beams of 10 PW each, awarded to Thales by the Romanian Nuclear Physics Institute IFIN-HH. The 10 PW beamline is based on an hybrid scheme involving a first TiSa based kHz CPA, a XPW filter [1] and an optically synchronized 532 nm-pumped OPCPA. The temporal contrast has been measured and has confirmed the enhancement by at least three orders thanks to the OPCPA.

II. LAYOUT OF THE SYSTEM

The frontend can be divided in five main parts: the oscillator, the Ti:Sa stage, the XPW stage, the OPCPA pump laser and finally the OPCPA stage**.**
We describe how the beam from the oscillator is divided in two parts. The 1064nm part is coupled into two Ytterbium dopped fibers to be amplified up to 80mW. The 800nm is propagated through a stretcher, then amplified (regenerative amplifier) and recompressed to be sent into an XPW system [1]. Starting from a contrast of $1{:}10^{7}$ at the output of the first sub-system the contrast is therefore increased to $1{:}10^{11}$. The final stage of this seeder is composed of a double stage OPCPA system which allows the injection of a very large bandwidth in the 10 PW amplifiers chain.

III PERFORMANCE OF THE SYSTEM

A complete modeling and simulation of the OPCPA stage has been performed in order to optimize the number of stages, size of the crystals, and pump energy distribution between the stages[2].
The two stages are pumped each with approximately the same pump energy (26mJ) but at different fluences. The experimental results obtained from this system presents a good stability (<1.5%rms) with an energy exceeding 10.5mJ. The spectral bandwidth is of about 100nm. Enhancement of the contrast on the tens of ps time scale is observed [2] (fig.1).

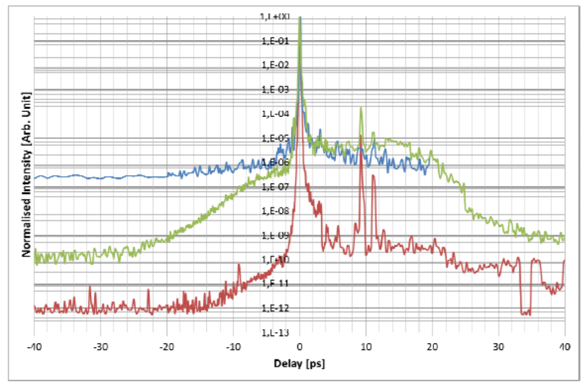

Figure 1: Contrast measurements: Blue line Ti:Sa stage alone; Green line Ti:Sa stage and OPCPA stagewithout XPW, Red curve Ti:Sa stage with XPW and OPCPA stages.

IV. CONCLUSIONS

In conclusion we have developed a broadband high contrast ($>1{:}10^{14}$) 10 mJ seeder for 2 x 10 PW laser system under development and integration for the ELI-NP project. The OPCPA design is compatible with pump lasers working at 1064nm and using the mature and reliable technology of flashlamp pumped Nd:YAG which will also allow future scaling to higher energies. A record optical efficiency of the OPCPA in the range of 20% has been reached without any spatial and temporal shaping device within the pump laser.

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Simulating Parametric Amplification in the Frequency Domain

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We develop a model to simulate the spectral gain of Frequency Domain Optical Parametric Amplification. The model agrees with experimental results and can be used to determine effective designs for future systems.

I. Introduction

The past decade has shown the success of amplifying stretched pulses via Optical Parametric Chirped-Pulse Amplification (OPCPA). This method increases the available pump energy for gain without exceeding the damage threshold of the nonlinear medium. Recently, it was demonstrated that amplifying with Frequency Domain Optical Parametric Amplification (FOPA) not only has the benefits of picosecond amplification, but can eliminate spectral gain narrowing due to its ability to implement an arbitrary number of crystals[1].

While FOPA is straightforward to understand, simulating the amplification is much less intuitive. This is because the amplification takes place in the Fourier plane (FP), which is spectrally dispersed and at a focus. Thus, not only does the wavelength and bandwidth change with transverse position, but the wavefront curvature must be included to most accurately describe the phase matching.

We present a model including these aspects of the FP and demonstrate its effectiveness by comparing it to experimental results[1]. This simulation can be used to design future FOPA's, allowing us to optimize parameters, such as crystal dimensions, while including effects of the Gaussian focus across the FP.

II. Model Description and Results

The model is constructed in Matlab while the parametric amplification is simulated mlSNLO from AS Photonics. First, the FP is constructed by considering the grating's dispersion and the focusing conditions of a curved mirror. This gives the center wavelength, bandwidth, and wavefront curvature at each transverse position in the FP.

To have an input suitable for the mlSNLO algorithm, we consider the fluence for both the seed and the pump as a function of FP position. The fluence at each point in the FP is used with a Gaussian profile to determine an input energy. Once mlSNLO has run the simulation for the given point of the FP, an output fluence for the seed is compared with the input to determine the spectral gain.

Our current work focuses on reproducing experimental results from a previous experiment on FOPA[1]. In particular, our goal is to replicate the spectral gain enhancement as well as the overall amplification of the seed.

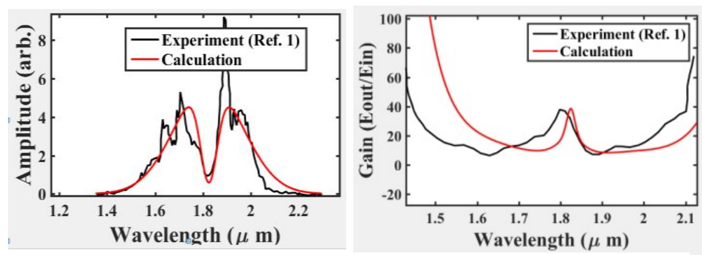

Figure 1: (a) The measured input seed to the FOPA1 versus the simulated seed. **(b)** Spectral gain after amplification in FOPA both experimentally1 and our simulation.

Figure 1a is a comparison of the experimental spectrum with our simulation while Figure 1b compares the spectral gain. As can be seen, the gain enhancement at ~1.8 μm is well produced in the simulation. In addition, the model predicts an overall amplification of the seed to 1.9 mJ, only 8% higher than the experimental value. The only obvious discrepancy occurs on the bluest edge of the spectral gain and its cause is being actively researched.

IV. Conclusion

In conclusion, we demonstrate a model which accurately predicts parametric amplification in the FP. In particular, we can replicate the overall gain of the parametric process as well as features of the spectral gain enhancement. We believe this model will serve as a tool for designing FOPA's requiring detailed knowledge of the geometry

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HHG Beamline, a unique turnkey system delivering a brilliant XUV beam

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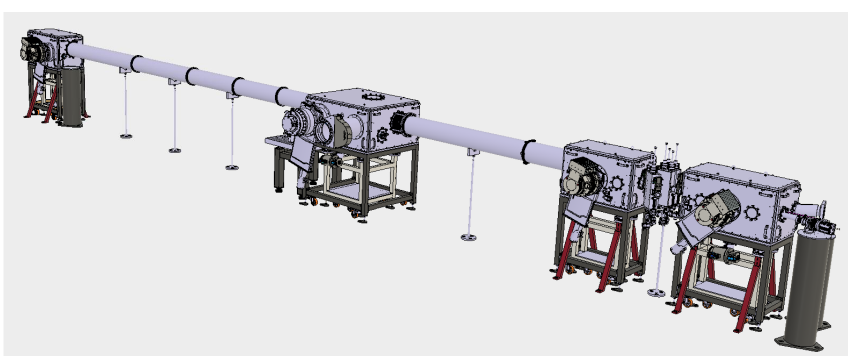
Over the past years, the ultra-intense laser field has continued to flourish as demonstrated by a growing number of scientific and technological projects. In particular, Europe's commitment towards ultra-high intensity physics is exemplified by the involvement of several European countries pooling research, network resources and experience to succeed in the completion of different state of the art laser facilities.

ELI consortium represents the core of the European effort to create unique laser facilities that can explore new regimes of laser-matter interaction as has never done before. It is divided into three facilities, ELI-Beamlines in Czech Republic, ELI-NP in Romania and ELI-ALPS in Hungary, each one equipped with unique laser systems and dedicated to a particular type of physics that will be studied. Most of the laser system will be used to generate secondary sources, like electron beams, Xray beams, gamma beams etc. In particular, ELI-Beamlines facility has been designed in order to let interact beams of different nature in unique pump-probe experiments. One of the beamlines – a High Harmonic Generation Beamline - has been designed, delivered and installed by a French company ARDOP as a turn-key system generating a broadband XUV beam.

The HHG beamline has been designed to accept two driving 1 kHz laser beams with pulse duration <20 fs and energy up to 100 mJ, to superpose and focus them on a gas cell, to filter-out the residual laser beams and to characterize the generated XUV beam. The system can generate a very broadband radiation in the XUV region (from 5nm to 120nm), thanks to its modular design that allows to work at different focusing geometries (focal lengths from 1 m to 20 m), the gas cell that has a variable length and the choice of different rare gases.

The beamline is composed of four meter-size vessels, a complete IR rejection system done of grazing incidence mirrors and thin metallic filters, and a diagnostic system including a focusing flat-field spectrometer, a wavefront sensor and a calibrated photodiode for photon flux measurements.



The HHG Beamline has been designed also to accommodate two parallel driving lasers, generating two parallel XUV beams. To our knowledge, this is the only HHG beamline that can generate such a broad spectrum at such high intensities.

The HHG Beamline has been delivered and commissioned in 2017 in Czech Republic.