Transparent-media characterization dedicated to laser damage studies: a key task, multi faceted and always renewed.

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ABSTRACT

The session Materials and Measurements deals with laser-induced damage to the bulk of transparent optical media, in relation with the material fabrication and its structure. Damage measurements are reported together with the characterization of all the material properties connected to the damage process (optical losses, luminescence, linear and non linear optical properties, thermal properties, elastooptic coefficients… and defects). Moreover are included the new diagnostic tools developed for measuring these quantities, which presents a continuing challenge as materials are improved in quality and diversity. The whole results serve as a foundation in modeling works for the understanding of fundamental mechanisms. The studied materials and their characterization are required by numerous applications. This wide and multi-faceted field generated more than thirty per cent of the whole conference papers over the last ten years. Among the important topics of this period are DUV materials and measurements, characterization of non linear materials and effects, the non destructive detection of nanoprecursors, damage at short pulses and the novel materials and geometries: micro and nano materials and structures. An overview of the session is given, mainly focused on the last ten years, some important achievements and trends for the future are presented.

Keywords: Materials, Measurements, Deep Ultra Violet, Non linear, Precatastrophic indicator, Nanoprecursors, Short pulses, Nanomaterials, Microstructured fibers

1. INTRODUCTION

As an introduction to this review paper concerning Materials and measurements session in forty years of Boulder Damage symposium, it is interesting to have a look on quantitative data relative to the conference, especially the total number of presented papers and the part of the four different sessions[1,2]. The part of Materials and measurements session in Boulder Damage symposium decreases from 55 to 17 per cent the first five years from 1969 to 1973, likely related to the low total number of papers of the beginnings (from 11 in 1969 to 32 in 1973). In the following thirty five years this part oscillates around 30%. The average part over the 40 years is 30% of the whole conference papers and is 34% over the five last years which shows a still vital need of measurements. About 660 papers were presented over 40 years in the Materials and measurements session, among them 127 papers in the five last years. These figures demonstrate a permanent, regular and important need of measurements and characterization of materials, generally driven by new applications.

In this paper we present first an attempt of overview of the session. We shall see that it deals with a wide and multi-faceted field, addressing issues of materials as well as metrology for numerous applications and their specific needs. Furthermore this work of instrumentation and characterization is a key task for the development of new high quality materials, and the understanding of fundamental mechanisms. However, we will not attempt to survey the technical data and achievements over the years in any detail because of the extent of the task. Thus to illustrate the key points, we have chosen to highlight some selected topics over the last ten years because of their scientific or economical importance. This selection is a personal and so subjective choice based on the experience of the author. Because of this I apologize in advance for not referencing some works and I would hope that the reader will have some tolerance for these oversights.

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2. ATTEMPT OF OVERVIEW

The traditional session Materials and Measurements deals with laser-induced damage to the bulk of transparent optical media, in relation with the material fabrication and its structure (amorphous, polymeric, crystalline, or polycrystalline…). Damage measurements are reported generally associated with the characterization of all the material properties that influence the damage process or give information on material evolution under irradiation, such as structure, chemical composition, optical properties (optical losses, linear and non linear absorption and scattering, luminescence, linear and non linear refractive indices), thermal properties (conductivity and diffusivity), stress optic and elastooptic coefficients… A special interest is taken in the detection and identification of inhomogeneities and defects. Moreover are included the new sensitive instrumentation and procedures developed for measuring these quantities, which can be realized in situ in the damage set-up and which present a continuing challenge as materials are improved in quality and diversity.

The derived data are analyzed and scaling laws can be deduced. The whole results serve as a foundation in simulation and modeling studies for the understanding of fundamental mechanisms. We see that the collection of these data is a key task for understanding of damage phenomena and also for the development of new materials answering to the requirements of applications and/or for materials improvement. Furthermore quality, accuracy, coherence and compatibility of experimental data are major assets for success. Because of the diversity of applications, wavelengths, pulse durations, materials…. it as a wide and multi-faceted field always renewed. We will light various facets on the basis of three key words: applications, materials, and measurements.

2.1 Applications

The studies of materials and the associated measurements are mainly driven by numerous applications and their specific requirements.

Short wavelength applications are an example of very dynamic field. Today laser lithography uses pulses of deep UV (DUV) radiation from excimer lasers (193 nm from the ArF laser). To reproduce small structures (size lower than 65 nm) special illumination systems, phase shift masks and imaging systems including immersion liquids have been developed. To enable high throughput in wafer steppers new laser systems including two stage optical amplifier systems for high pulse energies (10 to 50 mJ) and/or higher repetition rates ($\geq$ 6 kHz) have been developed. These technological steps of microlithography have dramatically raised the requirements which have to be fulfilled by optical materials concerning minimum attenuation (lowest absorption and scattering losses) in optical systems at increasing laser fluence. High quality of virginal material is no longer sufficient. High durability ($>10^{11}$ to 10^{12} laser pulses) is requested. 157 nm systems and specific optical components have been developed; however they will probably never be used in a production line and the next generation lithography will use XUV (11 to 13nm). Generally DUV lithography needs the use of low absorbing materials, large aperture optics, reflective optics, high repetition rates, very long lifetime, and optics in controlled atmosphere …

In similar manner UV laser micro processing (machining, micro engineering, surgery…) has raised the requirements to be fulfilled. Calcium fluoride and fused silica are low absorbing key optical bulk materials for pulsed DUV laser applications.

Lasers for inertial confinement fusion (projects NIF and Megajoule) were another extremely powerful motivation for characterization of materials and have induced a great number of papers presented by the LLNL, the CEA and other laboratories involved in related collaborations. Lasers for fusion are concerned with ultra large area optics, YAG fundamental wavelength and harmonics, generation of second and third harmonics, contamination, lifetime, debris shields…. Fused silica and KDP crystals are key bulk materials for fusion lasers.

Ultra-short pulse systems are considered as innovative laser sources for a variety of applications in micro material structuring, medicine and diagnostics, fundamental physics. Current commercial systems are still lacking in output power limiting the throughput and the economic efficiency within a production line. In the optimization of ultra short pulse sources of the next generation, special effects in optical components during interaction with ultra-short pulses play a major role. Especially, low damage thresholds and non-linear absorptance have been observed. The development of high power lasers (few hundreds of Terawatts and more) (examples of projects PETAL, ELI…) addresses especially the questions of pulse compression by gratings, beam shaping thanks to diffractive optic elements (DOE) … Monocrystalline sapphire and titanium-doped sapphire are key bulk materials for high peak power laser technology.

Spatial applications (projects ALADIN , CHEMCHAM….) are probably more confidential in terms of number of papers but they require materials accepting large temperature range specifications, optics in vacuum or in controlled atmosphere, long term life… Many other fields such as mid and far IR applications, CW lasers and applications, fiber lasers and amplifiers, high power diode lasers, micro components require specific properties for used materials and an adequate characterization.

2.2 Materials

Many transparent bulk materials have been studied and the results discussed at Boulder over the forty years: wide bandgap dielectrics (fused silica, quartz, CaF_2….), silicate and multicomponent glasses, alkali halides crystals, rare earth doped glass laser materials (YAG, Ruby, Sapphire, Yb:S-FAB…) and composite ceramics (YAG and variable doping), semiconductors (Silicon, ZnSe…), many non linear crystals for different applications (Pockels cells, harmonic generation…) ($LiNbO_3$, KDP, DKDP, KTP, RTP, LBO, $CsLiB_6O_{10}$, LiInSe2, LiInS2 ….), PMMA and Streched PMMA as debris shields for example in HELEN installation, carbon-based materials and carbon nanotubes, optical fibers, photonic bandgap fibers, gratings, microlens, diffractive optic elements…..

2.3 Measurements

Many measurements have been performed with a special focus on metrology and oriented toward "absolute" measurements allowing comparisons or use of measured values as data for modeling and simulation. Laser Damage thresholds are measured according to the International Standards ISO. A robust metrology is required and it is extremely important to control all the parameters, laser beam and sample parameters, damage detection, procedures, to estimate error bars on each axis… Optical properties (linear and non linear absorption and scattering, laser induced fluorescence, linear and non linear indices), thermal and thermooptic properties are characterized.

Many sensitive new measurement methods and procedures have been specifically developed for these characterizations and also for detection of damage. Especially optical characterization has been widely used in laser damage studies by most laboratories for many purposes: inspection before irradiation, detection of damage, study of damage site morphologies, measurement of optical properties of damage sites, to image stress and cracks in damage sites, to investigate fundamental mechanisms. Damage initiation, growth as well as conditioning and mitigation phenomena have been addressed.

Optical characterization in laser damage studies is a good example of importance and diversity of works and publications. It is a wide field including: Optical microscopy, dark field and Nomarski used for inspection, detection of damage, study of damage site morphologies ; Optical profilometry used for inspection, study of damage site morphologies, roughness characterization ; Scattering measurements[3-6] for roughness, surface quality, defect imaging, detection of damage ; Optical coherence tomography[7] for imaging of cracks, for growth and mitigation study ; Photoluminescence measurements, spectroscopy, imaging, time resolved, plasma emission spectroscopy for studying fundamental mechanisms, damage initiation, damage growth, study of laser induced defects, surface contamination [7-17] ; Raman scattering spectroscopy and imaging for stress measurement, fundamental mechanisms [9,11,12]; Z-scan techniques for measurement of non linear refractive index[18] ; Thermo luminescence, IR imaging for fundamental mechanisms, damage growth, conditioning ; Infrared spectrophotometry[19] for chemical analysis, fundamental mechanisms ; Photothermal techniques[20-30] for absorption measurement and imaging, thermal properties characterization, for studying fundamental mechanisms.

Because of this diversity of applications, materials, and measurements, there is no possible exhaustiveness. The author made a choice of five subjects to illustrate some of the results obtained and questions which remain. Among the important topics of this period are characterization of DUV materials and measurements, Non linear materials and effects, Search of a precatastrophic damage indicator or the non destructive detection of nanoprecursors, Damage measurements at ultrashort pulses, Novel materials and geometries: micro and nanostructures.

3. SELECTED TOPICS

3.1 DUV materials and measurements

We have here an example of topic driven by the applications which led to the development of high quality materials such as for example calcium fluoride crystals [31-35] and to the development of many specific characterization tools [36-45]. A huge work has been done by laboratories and companies, especially in Germany (Laser Zentrum Hanover, Tech. U. Berlin, Fraunhofer Iena, Schott, Zeiss…) and Japan (Union Materials Inc., Osaka Women's University, Nikon…).

Among the more important techniques for characterization are linear and non linear scattering at 193 and 157nm [36,39,40], linear and non linear absorption at 193 and 157nm by photothermal or calorimetric techniques [37,38,42,43], wide spectral range spectrophotometric measurements [44,45], laser induced fluorescence (LIF) [41,43]….

Synthetic calcium fluoride crystal is a key material in 193 nm lithography and 248 nm excimer laser applications because of the lack of rarefaction and compaction effects known from fused silica. The band gap energy of 12 eV in combination with the high purity of current CaF_2 crystals are the main reasons for the excellent laser damage behavior of CaF_2. We give in figure 1 an example of characterization of CaF_2 crystals of different durability at 193nm tested for 248nm high fluence application[34]. The results indicate a high life time of CaF_2 even at high fluences in the case of homogeneous beam profile.

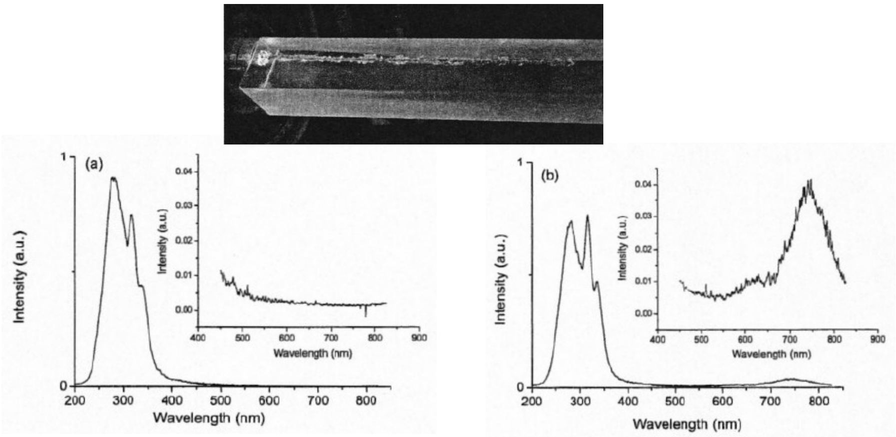

Fig. 1. Top: Example[34] of CaF_2 sample with destruction channel initiated by a surface damage at 248nm. Bottom a) LIF spectra with excitation at 193nm of a CaF2 sample with high laser durability and b) with low laser durability

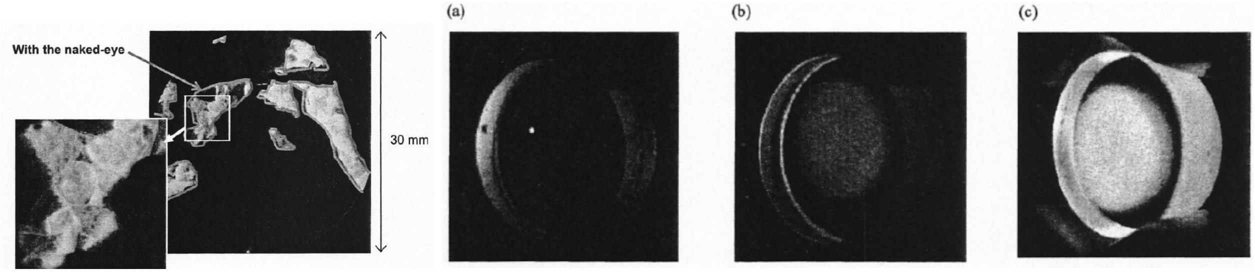

Fig. 2. Study of haze in artificially grown single crystal calcium fluoride[35]. Left: X-ray transmission topography of the crystal. In the naked-eye, sub-grains can be observed. Note the size of the crystal (30mm). Right : Photographs of illuminated calcium fluoride samples : (a) without haze, (b) with slight haze, and (c) with strong haze. A relation between haze strength and oxygen concentration can be established.

The figure 2 presents another example of characterization of CaF_2 single crystals. A correlation is observed between haze and oxygen concentration deduced from Secondary Ion Mass Spectroscopy.

3.2 Non linear materials and effects

This field has been very active and exhibits important results such as the characterization of behavior of KDP, an example of widely studied material, or a better understanding of some specific aspects of LIDT measurements in non linear biaxial crystals. Furthermore the important efforts carried out made it possible to obtain different coherent sets of data especially of non linear refractive index, and also of self-focusing and front surface damage in silica. These sets of coherent and comparable data are of a great utility for understanding of phenomena.

3.2.1 KDP behavior, an example of widely studied material

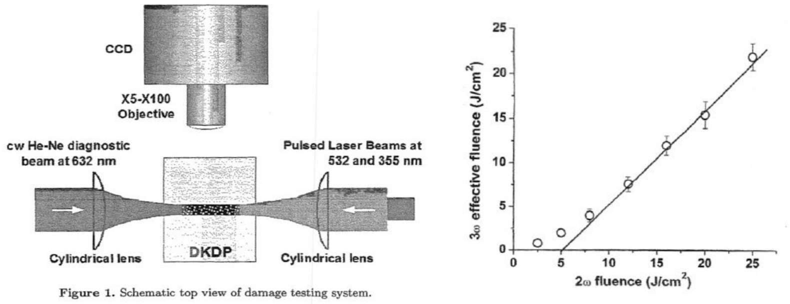

Figure 1. Schematic top view of damage testing system.

Fig. 3. KDP damage behavior in the presence of multiple colors[46]. Left : Schematic top view of damage testing system. Right : Plot of effective 3ω fluence which leads to equivalent damage effects under simultaneous 2ω and 3ω irradiation, as a function of 2ω fluence.

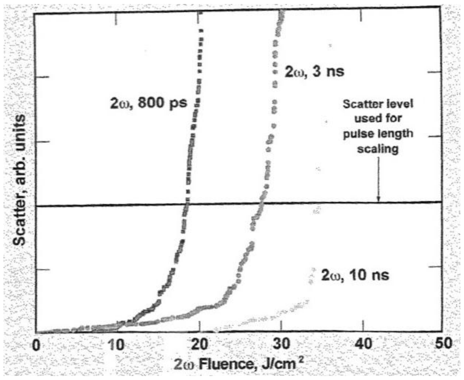

Fig. 4. Study of KDP Conditioning[47]. Example of plot of ordered pairs of scatter curves versus 2ω damaging fluence, for 3ω, 3ns conditioned KDP at the pulse lengths labeled for the 2ω damaging pulses.

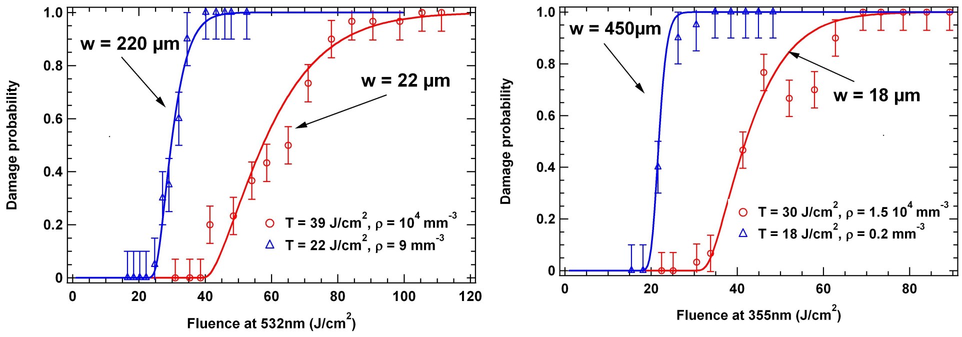

Fig. 5. Influence of wavelength and beam size in KDP[48]. A complete data set of damage probabilities curves for three wavelengths (ω,2 ω,3 ω), two or three beam sizes and for procedures 1/1 and S/1.

We present in figures 3 to 5, three important results obtained on KDP. In figure 3 the KDP damage behavior in the presence of multiple colors[46] is studied and results show a modified LIDT when there is coexistence of the two wavelengths 2ω and 3 ω. We can define an effective 3 ω fluence which leads to equivalent damage effects under simultaneous 2 ω and 3 ω irradiation and plot it as a function of 2 ω fluence (fig 3 left). The wavelength and pulselength dependence of conditioning of KDP has been studied[47]. In figure 4 is presented a result of KDP conditioning at 3ω with 3ns pulses. Ordered pairs of scatter are plotted versus 2 ω damaging fluence, for 3 ω, 3ns conditioned KDP at the pulse lengths labeled for the 2ω damaging pulses.

In figure 5, the influence of wavelength and beam size in KDP[48] is studied. A complete data set of damage probabilities curves for three wavelengths (ω,2 ω,3 ω), two or three beam sizes and for procedures 1/1 and S/1. These results show that damage is induced by precursors and that damage precursors exhibit different LIDT and densities for irradiations at 1ω,2ω,3ω. The test in R:1 mode demonstrates the ability of precursors to be conditioned differently at 355nm and 532nm and not at 1064nm.

3.2.2 Metrology in non linear biaxial crystals

Laser damage measurements in nonlinear optical crystals, in particular in biaxial crystals, may be influenced by several effects proper to these materials or greatly enhanced in these materials[49]. Effects that possibly modify the maximum intensity in a biaxial nonlinear crystal are: focusing aberration, walk-off and self-focusing. Depending on focusing conditions, propagation direction, polarization of the light and the position of the focus point in the crystal, strong aberrations may change the beam profile and drastically decrease the maximum intensity in the crystal. A correction factor for this effect can be proposed, but quantitative corrections are not possible without taking into account the experimental beam profile after the focusing lens. Finally, parasitic second harmonic generation may influence the laser damage behaviour of crystals. The important point for laser damage measurements is that the amount of externally observed SHG after the crystal does not correspond to the maximum amount of second harmonic light inside the crystal.

3.2.3 A coherent set of non linear refractive index measurements

A Z-scan technique is used to measure the nonlinear refractive index of dense materials in the nanosecond and sub-picosecond regimes[50]. An accurate and sensitive measurement requires a Z-scan set-up with well-correlated reference and signal arms, noise reduction, an accurate beam control and characterization tools, and a numerical model (thin or thick sample configuration, beam simulation). By using measured beam parameters it is possible to obtain a good agreement between experimental Z-scan curves and simulation.

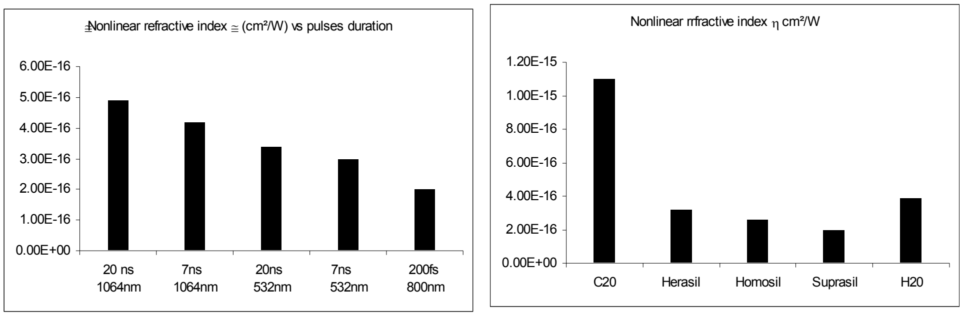

Fig. 6. Comparable measurements of non linear refractive index by Z-scan technique[50] at different wavelengths and pulselengths. Left : Pulse duration dependence of the nonlinear refractive index of fused silica ; right : Non linear index of silica, C20 and pure water obtained at 800nm, 200fs pulses.

The difference in nonlinear refractive index in the nanosecond and the sub-picosecond regimes is probably due to the contribution of electrostriction mechanism, not negligible in the nanosecond regime.

3.2.4 An example of coherent measurement data set of self-focusing and front surface damage in silica and its interpretation

In this paper the authors studied filamentation, front surface damage and rear surface damage at 1064 nm and 351 nm with nanosecond pulses on a fused silica optical window[51], with temporally single-mode and multi-mode pulses. The authors got a complete and coherent set of damage measurements given in figure 7.

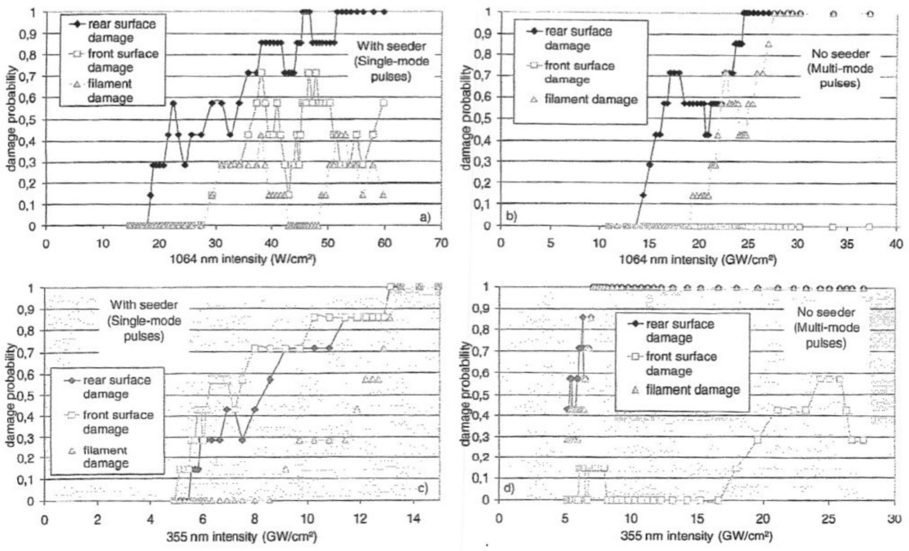

Fig. 7. Damage probability plots for 1ω single mode pulses (a), 1ω multi-mode pulses (b), 3ω single mode pulses (c) 3ω multi-mode pulses (d).

With temporally single-mode pulses, self-focusing occurs together with front surface damage, which is attributed to a Stimulated Brillouin Back Scattering (SBS) wave. The use of temporally multi-mode pulses suppresses the occurrence of front surface damage, and increases self-focusing. One of the parameters that need to be known to predict the lifetime of optical components on fusion lasers is the critical intensity by length IZ_f product where Z_f is the distance to self-focus. This product can be derived theoretically from Marburger model as in eq. (1).

$$(I \times Z_f)_{\min} = IZ_f(P^*) \approx 2.5\frac{n_0 P_2}{\lambda_0} \approx 2.3\frac{\lambda_0}{2\pi n_2} \approx \frac{2.3}{k_0 n_2} \qquad (1)$$

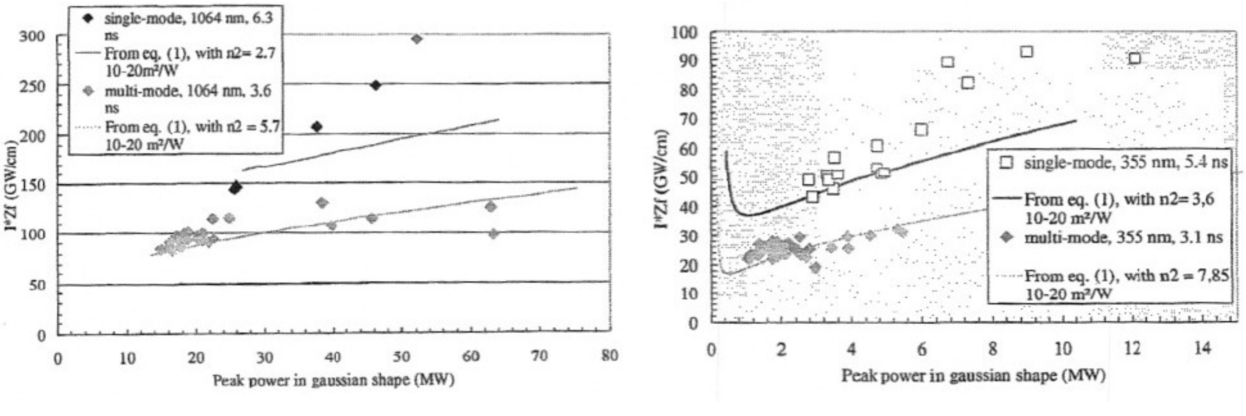

Fig. 8. intensity by length products I Z_f at 1ω (left), and 3 ω (right). Theoretical curves are derived from equation (1) with different values of n_2.

The experimental I Z_f products are plotted in figure 8, as a function of beam power. Theoretical curves are derived from equation (1) with different values of n_2. It was found that the temporal shape of pulses had a strong effect on self-focusing. With single-mode pulses, the observation of filaments seems coherent with standard Kerr self-focusing effect, and can be understood according to treatment by Marburger et al, using non linear index values measured in other experiments. However, when multi-mode pulses were used, filaments occurred for much smaller peak intensities, by about a factor of 2. For filamentation of multi-mode nanosecond pulses into fused silica, values of critical Intensity by Length products have been confirmed: at 1ω: 80GW/cm ; at 3ω: 20GW/cm. Electrostriction might have a strong effect for 3 ns phase-modulated pulses. A new modeling effort is necessary to account numerically for measurements.

3.3 The search of a precatastrophic damage indicator or the non destructive detection of nanoprecursors

Among the four papers of the Materials and Measurements session of 1969 we find a paper titled "Diagnostics and evidence of pre-catastrophic damage in transparent solids", by D.F. Edwards, Y.D. Harker, J.D. Masso, C.Y. She, where "Light-scattering techniques (quantitative Raman scattering) have been used to observe precatastrophic laser-produced damage in α-quartz". Thus the search of a precatastrophic damage indicator has been during these 40 years a continuous challenge often referred as the Holy Grail. With the evidence of the nanometric size of damage precursors in high quality bulk materials we can understand why it is still a challenge for optical characterization techniques. Different works have been performed and an overview is given in ref 52. The figure 9 presents an example of result obtained on artificial defects such as 250nm-gold inclusions embedded in silica, detected thanks to a High Resolution Photothermal Microscope (HRPD).

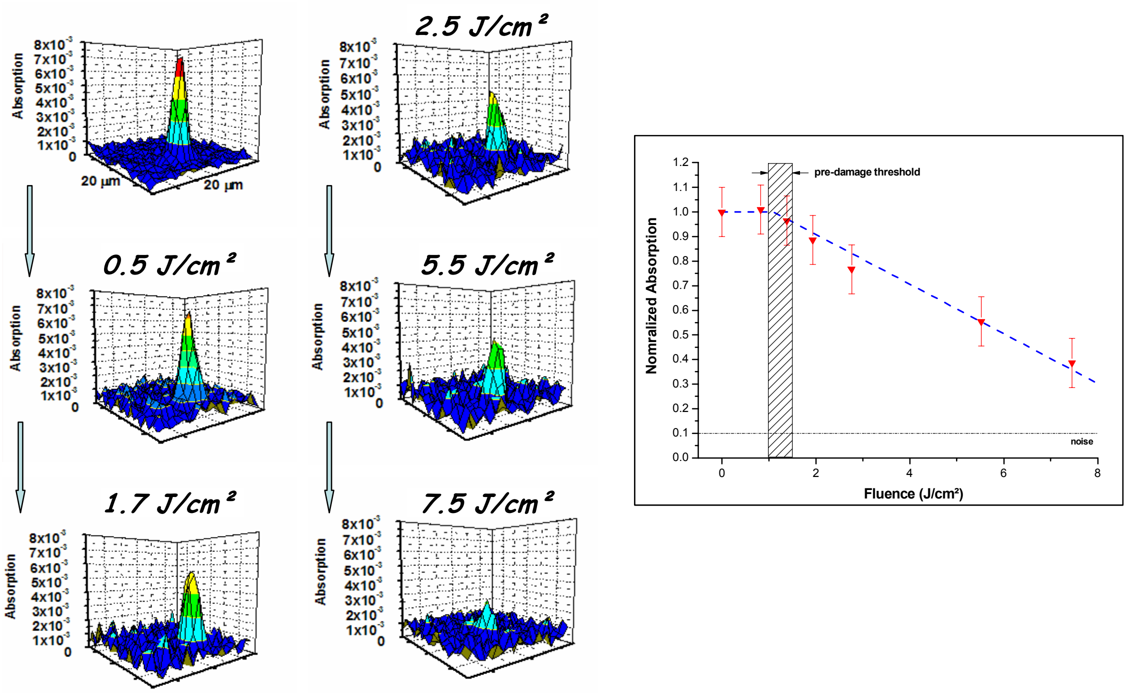

Fig. 9. Pre-damage stage for 250nm-gold inclusions. At left, evolution of HRPD (High Resolution Photothermal Deflection Microscope) images of 250nm-gold inclusions after one shot at the given fluence (from 0.5 to 7.5 J/cm^2). At right, evolution of the gold inclusion absorption under single shot irradiation, deduced from HRPD images.

A pre-damage stage can be observed thanks to HRDP in the case of irradiations with fluence lower than threshold. Fig. 9 describes this pre-damage stage. The evolution of the absorption of several 250 nm gold particles after different single shot laser irradiations is presented. In each case, the fluence of the incident beam is less than the laser damage threshold associated to the gold inclusion. At left, we have the evolution of HRPD images of the different 250nm-gold inclusions after one shot at the given fluence (from 0.5 to 7.5 J/cm^2). At right, we present the decrease of the normalized gold inclusion absorption under single shot irradiation, deduced from HRPD images (maximum value of absorption). Until now these techniques did not allow to detect nanosized precursors in high quality bulk silica.

3.4 Damage measurements at ultrashort pulses

Ultra-short pulse systems are considered as innovative laser sources for a variety of applications in micro material structuring, medicine and diagnostics, fundamental physics. Current commercial systems are still lacking in output power limiting the throughput and the economic efficiency within a production line. In the optimization of ultra short pulse sources of the next generation, effects in optical components of interaction with ultra-short pulses play a major role.

The ablation of dielectrics with ultrashort pulses was investigated intensively by many research groups over the last decade and numerous publications dealt also with the theoretical modeling of the origin of laser-induced breakdown in this pulse duration regime [53-58, 61]. Most of the publications agreed upon the importance of multiple photon absorption and avalanche ionization for the generation of free electrons in the dielectric material and the following transfer of energy to the lattice leading to catastrophic damage. It is also mostly agreed that the incidence of damage is connected to a critical density value of electrons excited to the conduction band, for which the dielectric material becomes highly absorbing. Many experimental works have been realized [59-63] especially in optical coatings. I considered that I had not enough time for this important topic for which we expect further developments.

3.5 Novel materials and geometries: micro and nanostructures

New opportunities and new challenges will be offered in the future by the novel materials and by the micro and nano-structured materials. In the last decade only some papers have been presented on these topics.

For example greater flexibility in the design of the machining systems is made possible if laser pulses are delivered through a lightweight optical fiber system. For such reasons fiber delivery bas become standard for high average power processes such as laser welding and laser cutting, where the beam quality and peak power requirements are less stringent. There is clear demand therefore for a single-mode fiber capable of delivering high peak power pulses in the ns regime. Conventional single-mode fiber typically damages at pulse energies of 5 µJ with 532 nm, 8 ns pulses, whereas pulse energies of about 1 mJ are required for laser machining.

A new type of optical fiber which has recently been developed, the hollow-core photonic crystal fiber (HC-PCF) which has the potential to overcome these limitations as the majority of the power is contained within a hollow-core and is delivered in a single mode [64]. The HC-POF is a type of microstructured silica fiber fabricated by ordered stacking of silica capillaries to form a large-scale preform (Fig. 10 right). By omitting some of the capillaries a hollow core can be made in the centre of the microstructured region. This large scale preform is subsequently drawn down to fiber diameters whilst maintaining the periodicity, hence producing a microstructured fiber (Fig. 10 right).

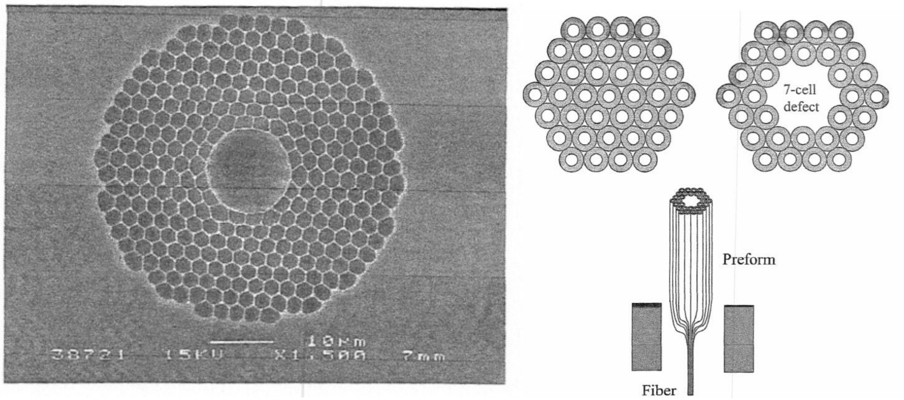

Fig. 10. Hollow-core photonic crystal fiber (HC-PCF)[64]. Right: Stacking of silica capillaries (top) to form a large scale preform for a microstructured fibre. 7 capillaries are omitted to form the hollow core. The large scale preform is drawn down in a fiber furnace to produce the micro-structured hollow core photonic crystal fiber (bottom). Left: electron micrograph image of a 19 cell hollow-core photonic bandgap fiber designed for use at 1064 nm wavelength.

Hollow core photonic crystal fibers show significant improvement over standard solid-core single-mode fibers : 60 ns pulse width and energies greater than 0.5 mJ at 1064nm were delivered in a single spatial mode through the hollow-core fiber, providing the pulse energy and the high beam quality required for example for micromachining of metals.

The damage threshold limitations of the HC-PCF were investigated, both by coupling the laser into the fibre core, and by focusing the laser spot directly onto the photonic cladding structure surrounding the hollow core.

An example of damage study is given in figure 11 for a fiber operating at 532nm.

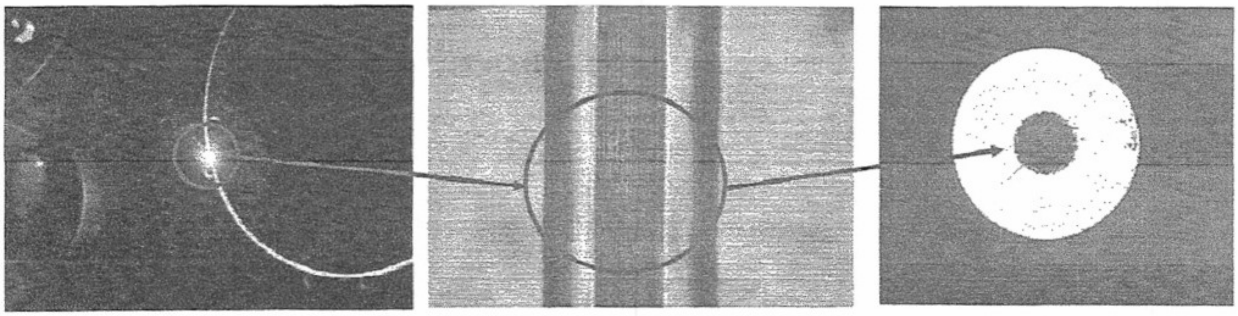

Fig. 11. Damage occurring along fiber length for HC-PCF operating at 532 mn. Strong scatter is visible from damage site (left) and damage to photonic structure observed (centre). Cleaving through fiber shows photonic cladding completely destroyed (right).

4. CONCLUSION AND PERSPECTIVES

« Materials and measurements » is a dynamic session at BDS. During 40 years there was a permanent, regular and important need of measurements and characterization of materials driven by the applications. Because of the diversity of these applications characterization of transparent materials is a wide and multi-faceted field. It is a key task for the development of new materials answering to the requirements of applications and also for understanding of damage phenomena. We have seen the importance of getting high quality and coherent sets of damage data which serves as a foundation for theoretical studies.

A huge work has been realized and important results have been acquired especially in the fields of metrology, DUV materials and measurements, Non linear materials and effects, and Optical characterization of precatastrophic behavior. The Holy Grail has not been found until today: what are the real damage precursors for the nanosecond regime in high quality bulk fused silica? How we could detect them non destructively in spite of their nanometric size?

The future like the past will be determined by the applications. Lasers for inertial confinement fusion (projects NIF and Megajoule) generated in the past an extremely powerful motivation for characterization of materials, however these projects are today in their final phase. Short wavelength applications are an example of very dynamic field. Many efforts were made for the development of lithography systems at 193 and 157 nm. The next generation of lithography will use XUV and require specific developments. The filed of UV laser micro processing (machining, micro engineering, surgery…) has still a glowing future with the development of new applications and the increase of energy.

Ultra-short pulse systems are considered as innovative laser sources for a variety of applications in micro material structuring, medicine and diagnostics, fundamental physics. Current commercial systems are still lacking in output power limiting the throughput and the economic efficiency within a production line. In the optimization of ultra short pulse sources of the next generation, effects in optical components during interaction with ultra-short pulses play a major role. The development of high power lasers (few hundreds of Terawatts and more) (examples of projects PETAL, ELI…) addresses especially the questions of pulse compression by gratings, beam shaping thanks to diffractive optic elements (DOE)…

Even if spatial applications are more confidential than the previous ones, their specific requirements (materials accepting large temperature range specifications, optics in vacuum or in controlled atmosphere, long term life…) will be addressed. Many other fields such as CW lasers and applications, fiber lasers and amplifiers, high power diode lasers, micro components will go on to require specific properties for used materials and an adequate characterization.

Finally new opportunities and new challenges will be offered by the novel materials, micro and nano-structured materials.

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Questions and Answers

Q. You have showed us that a lot of thinks have been done but what should we do to progress and to find the damage precursors.

A. There is no one answer. It depends upon the application and the needs of the application. For example, you can say to me, because you know very well the field of laser damage fusion so of course the damage for laser fusion, I still think there are needs for understanding problems not only in fused silica but in different materials perhaps low cost materials for debris shields because they are not the same materials that are used. After that, you have many problems of contamination. In the fields of special applications, the questions are quite different. For example, a very important question is, what is the difference for the vacuum threshold under vacuum or in the air. Why is there a difference? And, of course, we need very high quality laser damage thresholds in this field so you understand. I cannot only give one answer. It depends on the field and the application. Of course, a lot has to be done in microstructured materials especially for example non-transparent materials for optical limiting and nanostructured materials. I think we have a lot to do for understanding the interaction phenomena for light and these materials. Of course the Holy Grail is a good question. You ask often about the precursor for damage in bulk, high quality silica. I also would like the answer, but even today I don't have the answer. If we have time and money and PhD students, we can manage to correct this situation because PhD students are very, very important. They are the heart of research.

Q. What's your opinion of the optical materials that will become a hot topic of research in the near future?

A. I think for me the new materials will be the nanostructured materials, for example, the photonic bandgap materials, fibers because we don't exactly have applications today but the application is not so evident than in the deep UV material because in the deep UV material the application is photolithography and we have behind this application various use industries with a lot of money. For me, this is really the hot topic. Also, the same materials but used for short pulses, because around the world you have projects with high power lasers and with the short pulses, petawatt lasers and things like that.