Path Toward a High Energy Solid-State Laser

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Lasers have come a long way since the first demonstration by Maiman of a ruby crystal laser in 1960. Lasers are used as scientific tools as well as for a wide variety of applications for both commercial industry and the military. Today lasers come in all types, shapes and sizes depending on their application. The solid-state laser has some distinct advantages in that it can be rugged, compact, and self contained, making it reliable over long periods of time. With the advent of diode laser pumping a ten times increase in overall laser efficiency has been realized. This significant event, and others, is changing the way solid-state lasers are applied and allows new possibilities. One of those new areas of exploration is the high energy laser. Solid-state lasers for welding are already developed and yield energies in the 0.5 to 6 kilojoule range. These lasers are at the forefront of what is possible in terms of high energy solid-state lasers. It is possible to achieve energies of greater than 100 kJ. These sorts of energies would allow applications, in addition to welding, such as directed energy weapons, extremely remote sensing, power transfer, propulsion, biological and chemical agent neutralization and unexploded and mine neutralization. This article will review these new advances in solid-state lasers and the different paths toward achieving a high energy laser. The advantages and challenges of each approach will be highlighted.

1. INTRODUCTION

The advance of laser technology since its inception is very much a modern day phenomenon. Lasers have gone from curiosities to household items in less than forty years. As a research item and tool lasers have been breaking intensity, power per beam spot size, records since birth. A laser as a light source offers unique capabilities such as: high intensity, spectral purity, high directionality and Poissonian photon statistics. Basically a laser is a device that takes some fraction of available energy and converts it to identical photons. Photons, being bosons, are able to exist in the same quantum state and hence are able to be in identical states. The fraction of energy not converted to laser photons is usually mostly heat and this heat affects the lasing properties. The interaction of lasers with matter causes a number of interesting effects. Any absorption usually leads to heat, and temperature change, which can result in an irreversible phase change, damage.

The subject of this review is the path towards developing the high energy solid-state laser (HESSL). What exactly does high energy laser mean? A 100 W incandescent light bulb with an efficiency of 5-8% results in a 4π distribution of 5-8W of light energy. A typical laser pointer, by contrast, has 1-5 mW output but it is at one wavelength and highly directional, say 1mrad total divergence. With the brightness, B, defined as the power, energy per sec and measured in Watts, of the beam divided by the solid angle of the beam the comparison in brightness is: bulb B ~ 0.5W/sr, laser pointer B ~ 800W/sr. On average the laser pointer is 1,600 times brighter than the 100 W light bulb. And the laser pointer is far from a high energy laser. Typically a near infrared solid-state laser with energy output of 1kJ per pulse (or 1kW for a continuously running laser) or above can be considered a high energy laser. This is enough energy to melt metal. This is 10^6 times higher brightness than the laser pointer.

There have been fantastic gains in recent years in laser peak power. This has come about by combining femtosecond seed lasers with the ability to Q-switch a temporally stretched beam and recombine it to a femtosecond or shorter beam. But these beams, although intense, do not have much energy per pulse or even when averaged over a second. The ability to generate high energy beams requires the conversion of a large amount of available energy to coherent photons. As with the light bulb the more efficient the conversion the less heat is generated and the more likely the laser will operate as intended. The highest energy lasers are chemical lasers which can generate MW's of average power. Other types of high energy lasers, which are not yet able to generate MW's but can generate 1-30 kW's, are free electron lasers, gas

lasers such as CO_2 lasers and solid-state lasers, the subject of this paper, such as Nd:YAG lasers. High energy lasers include applications for both the military and commercial sectors. Applications now include laser welding with higher energy lasers able to weld larger and deeper metal joints. Possible future applications include: directed energy weapons, countermeasures to sensors, remote sensing, laser illuminators, land mine and unexploded ordinance neutralization, and beaming such as for power transfer or propulsion.

The first ruby laser was a solid-state laser with a flashlamp excitation source. Since then lasers have come to be made in all manner of types, each with its own unique characteristics. Solid-state lasers have a number of characteristics that for many applications are very attractive. Solid-state lasers can be made rugged and reliable hence able to withstand rough handling. They can be made relatively compact. They are driven by available electrical power, either from a battery or from the wall plug. Finally there are several possible laser types and hence different available wavelengths. But for high energy lasers the lasers being pursued generate wavelengths mostly in the 1 micron range. This wavelength easily propagates through the atmosphere with little absorption and less Rayleigh scattering than visible light.

The path to high energy solid-state lasers is such that the lasers share some common features. Presently all attempts involve diode pumping to maximize conversion efficiency. All involve a rare earth ion doped into a transparent host, which is usually a single crystal. The use of a single crystal, as opposed to glass, complicates the gain media and limits the size but single crystal offer a tremendous advantage over glass in terms of heat conduction and extraction, at least for bulk solid-state gain media. For glass fiber lasers this is not an issue because heat can be efficiently extracted along the long fiber length. The most mature paths involve Nd or Yb as the rare earth ion and all emit near one micron laser radiation with the exact wavelength dependent on the particular host single crystal.

There have been innovations over the years that have allowed high energy solid-state lasers to mature to their current state with demonstrations of CW lasing and good beam quality at the 2-5 kW level and promises of 25 kW in the near future, within a year, and 100 kW in the near future. The foremost innovation has been the advent of diode laser pumping. By exciting the gain media with an optical source with most of its output energy at an efficient absorption wavelength the overall laser efficiency has increased from ~1% to > 10%. Diode lasers have an electrical to laser conversion efficiency of about 50% so these are excellent excitation sources. Nd:YAG has a narrow absorption band of 4 nm so this is a challenge for diode arrays but with recent advances in diode array manufacturing and quality control this is less of a problem than in the past. Another advance in making reliable diode pump sources has been the elimination of Al as a constituent element. The use of slabs as opposed to rods allows for larger surface areas and hence more heat to escape. Innovative end pumping schemes that TIR the pump beam yield a better beam quality as well. End capping of the single crystal gain media is a big innovation because it reduces the probability of surface damage and reduces the effects of crystal heating, which distort the beam. End capping involves bonding an undoped host crystal to the doped gain media crystal at the surfaces where the laser propagates. In order to reduce parasitic modes from robbing the energy of the laser beam tapers or absorbers can be placed around the gain media. However, absorbers, although they work well, will introduce heating which must be taken into account when designing the laser. Sapphire cladding about the single crystal gain media serves to help extract heat, allow unwanted fluorescent light to escape and can serve to guide the pump beam within the gain media. Expected innovations that are now being researched are 80% diode laser electrical to photon efficiency. This will have a huge benefit to the realization of a high energy solid-state laser. Research on engineered gain media is also ongoing with work on reliable and large area bonding to allow the building of the gain media from various crystals. Also ceramic gain media are being explored. Ceramics hold the promise of large size gain media with tailored doping schemes and new combinations of materials that could not be attempted due to the high melting points. Fiber lasers have advanced significantly in recent years and 1kW with good beam quality is now possible. A number of innovations have allowed for this development such as dual cladding, asymmetric large diameter cores, various means to suppress SBS and other nonlinear effects.

Because heat extraction from the diode array pump sources and from the gain medium itself is a major concern for the design of any high energy solid-state laser there are many possible solutions considered. Lasers fall into several classes, single aperture versus multi-aperture with beam combining, continuously cooled versus heat capacity laser types, and fiber versus bulk gain medium. Some of the differences among these will be addressed in the following discussions of major technological aspects of HESSL's, and others in the section on major approaches and architectures.

2. DIODE PUMPING SOURCES

Modern high power laser diodes (LD) are not only reliable and power-saving replacements for flashlamps and arc lamps as pump sources for solid-state lasers, thereby significantly reducing system size, weight and power consumption. They have also made possible some new solid-state laser concepts (such as disk and fiber lasers), which in turn opened new horizons in laser power scalability along with significant beam quality improvement.

Although laser diodes are much more efficient pump sources than flashlamps, they present their own technological challenges. These include the very large and astygmatic divergence associated with the typical diode geometry, scalability to higher powers, the increasing challenge of heat removal as powers increase, operation at new wavelengths, and the need for still greater efficiency. Thermal management will be dealt with in another section, whereas the others will be addressed here.

In addition to the familiar microlens, crucial for collimating the severe "fast axis" divergence from an LD, an important advance in LD light delivery is the lens duct (Figure 1). Now commercialized, this device is a waveguiding structure that

Figure 1. Technical layout of the Yb :YAG laser system pumped by a diode bar stack through the fused silica lens duct.[1]

both homogenizes and concentrates diode output without reliance on free space optics.[1] The tip can be shaped to facilitate pumping of a rod, slab or disk. The duct can be solid (made from optically transparent material, like fused silica), or hollow (mirror-polished, high reflection coated metal). The latter facilitates cooling for very high power systems, where even minimal absorption causes noticeable duct heating and deformation.
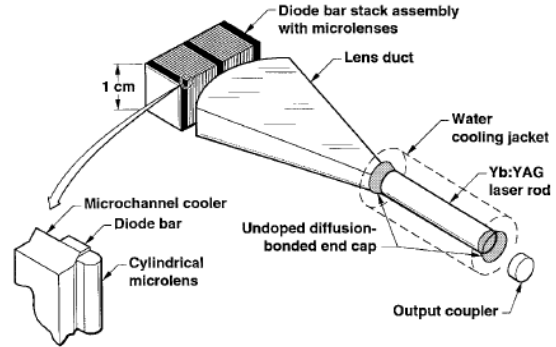
2.1 GaAs/AlGaAs laser diode development

Early practical laser diodes were based on the AlGaAs/GaAs structure, but Al-based diodes are known to experience detrimental effects due to Al oxidation. Thus, a major advance toward more reliable laser diode operation was the Al-free laser diode, first reported at 808 nm.[2] Further development in high power laser diodes has lead to invention of the broad waveguide quantum well diode laser, first reported for a AlGaAs/GaAs structure.[3] Because there is no laser mode wing in the clad in the broad waveguide design, optical losses are very low compared to conventional LD designs, and thus broad waveguide LD's can provide 50-80% higher slope efficiency.[4] This
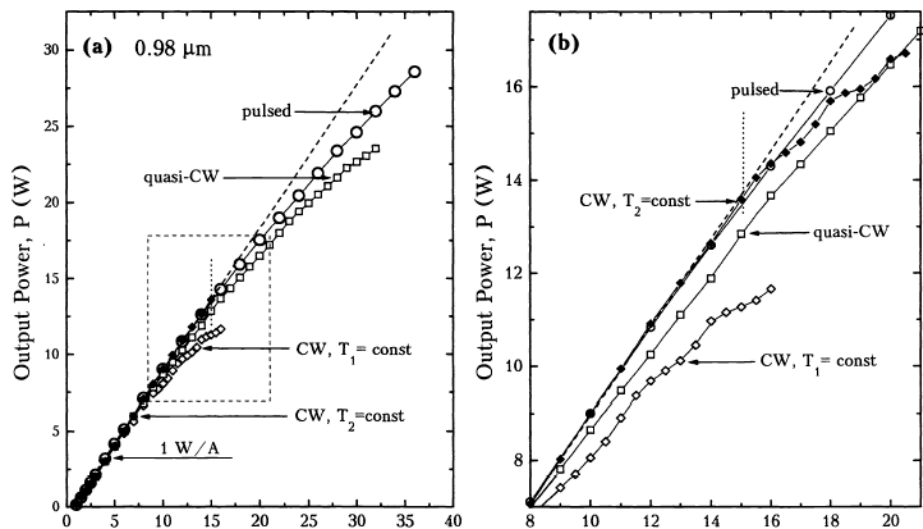
Figure 2. P-I characteristics of 0.98 μm InGaAs(P)/InGaP/GaAs Broadened Waveguide Separate Confinement Heterostructure Quantum Well Diode Laser. (a) 300 ns pulses, 0.1% duty cycle (open circles); 100 μs pulses, 1% duty cycle (open squares); CW regime at T_1=Const and T_2=Const (open and solid diamonds respectively). (b) - magnified area shown in (a) by a dashed line. The condition T_2=Const is broken at I >15 A (shown by dotted line).[5]

low-loss situation allows for very long cavity devices, so that much higher power per single LD is achievable.

Combining the Al-free approach with the broad waveguide design has led to particularly promising results, such as the record CW power (16.8 W) achieved for a single-emitter Al-free, broad waveguide 980-nm diode laser with a 2-mm-long cavity and a 200-μm-wide output aperture (Figure 2).[5]

Today, conventional (AlGaAs, GaAs based) laser diodes are capable of achieving very high powers from very reasonably sized devices. Companies such as Nuvonyx and JenOptik have recently commercialized GaAs-based arrays with CW power of 600 W from a 1.6 cm^2 emitting area.

2.2 Long-wavelength laser diode development

Today's most promising technologies for high power solid-state lasers result in wavelengths near 1 μm. For some applications, other wavelengths are needed. For example, the risk of ocular damage is reduced by operation in the 1.5-1.8-μm "eye-safe" band, and some applications require efficient laser sources at wavelengths within the 3-5 and 8-12 μm atmospheric transparency windows. 1-μm laser wavelength shifting via stimulated Raman scattering is possible, but at the sacrifice of the overall laser system efficiency and additional heat removal complications. Direct LD pumping of appropriate solid-state laser materials emitting in the eye-safe (~1.6 μm, Er:YAG) or mid-IR (~2 μm, Ho:YAG with further OPO frequency down-conversion) by GaAs-based pump arrays is possible and has been demonstrated. However, since these LD's are limited to wavelengths shorter than about 1000 nm, this approach is inefficient, and leads to excessive heat deposition and deleterious up-conversion processes in the active media. Thus, developing longer-wavelength high power LD's based on some other compounds is a more promising path toward efficient eye-safe or mid-IR lasers.

Durability is also a critical issue in LD technology. Despite all the above-mentioned improvements, the lifetime of GaAs arrays is limited to 10^4 hours. Dislocation diffusion into the active region and mirror facet degradation are the main failure mechanisms for GaAs-based arrays. These mechanisms are much weaker in InP-based diode lasers, which currently appear to be the most technologically advanced long-wavelength pump sources. In contrast to the GaAs-based emitters, the catastrophic optical damage level for InP-based lasers is stable with time of operation even for the simplest mirror facet coating. This provides low cost and a potential for reliability at the level of 10^6 hours, at least for 1480-1550 nm pump arrays.[6]

In 1996, the broad waveguide design approach was applied to 1500 nm diode lasers and the resulting 5 W CW power remains the record for single element emitters at this wavelength.[4] Differential quantum efficiencies at 1450 nm and 1860 nm are 55% and 47%, respectively. The devices operate at a voltage 40% lower and with current twice as high as traditional 800-900 nm GaAs-based laser diodes. The output photon flux (per facet) at maximum current for both types of 1450 nm sources is 30-40% higher than that for commercial GaAs-based 2 W single elements or 50 W arrays.[6] InP devices at 1470 nm are now commercially available for Er:YAG (YLF) pumping.
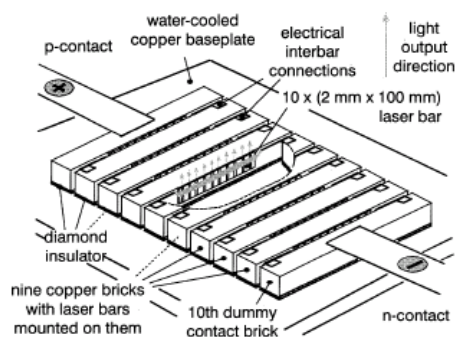

Figure 3. 218-W quasi-CW 1.83-μm two-dimensional (9x10) laser diode array.[7]

Significant progress has been made lately on 1.85-μm InP LD and LD arrays, which are of great interest for pumping tunable (around 2.5 μm) Cr^{2+}-activated ZnSe and CdSe lasers as well as 2-μm Ho^{3+} lasers. One of the best developments so far is the two-dimensional LD array fabricated using low-loss InGaAsP/InP separate confinement quantum well laser structures with a broad-waveguide region (the BW-SCH-QW laser).[7] The laser bars used for array fabrication have a cavity length of ~2 mm and their mirror facets were coated with high-reflectivity (HR - 95%) and anti-reflective (AR - 3%) coatings. To provide the array isolation needed for their series connection, diamond slabs with thickness of 0.3 mm were installed between the copper blocks and the heatsink plate. The overall view of the 9 x 10 element array is shown in Figure 3. The cutout section in the middle of the array illustrates a 10-element laser bar positioned on the brick and an electrical inter-brick connection.

2.3 SHEDS program

Ultimate progress in HESSL efficiency strongly depends on the efficiency of pump laser diodes. This is why DARPA has established a special program to develop super high efficiency diode sources (SHEDS.) The goal is ambitious – the improvement of diode laser power conversion efficiency from 45-50% to 80-85% within three years.

Any high power laser diode bar is built from an array of single emitters. Thus, as a first step to improving the efficiency of bars, one first focuses on optimizing the performance of single emitters. For example, single emitter efficiencies at 940 nm up to 66% have been reported.[8-10] Going from this to the program goal will no doubt require optimizing every facet of the diode design – materials and structures. This new program will bear watching, as results reach the publishable stage.

3. GAIN MEDIA

The emission wavelengths of high energy solid-state lasers are largely determined by the properties of the gain media, which properties also strongly influence the performance achievable and the technical approaches used. In considering the most important solid-state gain media for high average power use, we will continue our focus on diode-pumped insulating lasers, rather than direct use of diode laser output.

Two trivalent rare earth ions dominate the field of HESSL's, namely Nd^{3+} and Yb^{3+}. These both emit at wavelengths just longer than one micron, at which atmospheric propagation is relatively good. However, the primary reasons for their importance have less to do with their emission wavelengths than with several key physical properties of the ions and their solid-state hosts.

3.1 Nd^{3+} in solids

As is well known, Nd^{3+} is among the earliest and most successful active ions for solid-state lasers. Its attractive features include the fact that its strongest emission line in most hosts ends well above the ground state, permitting four-level operation and thus low laser threshold. With an upper state lifetime on the order of 200 µs, it has a favorable balance between sufficient storage time and stimulated emission cross section. Early interest focused on its rich set of energy levels above the upper laser level, providing reasonably efficient lamp pumping, but the strength of absorption into its $^4F_{5/2}$ and $^2H_{9/2}$ manifolds near 808 nm makes it very attractive for diode pumping as well.

The most widely used host for Nd^{3+} is yttrium aluminum garnet, (YAG,) attractive for its relatively good thermal and mechanical properties and its advanced state of crystal growth. In this host, the Nd^{3+} upper state lifetime is 230 µs, the effective stimulated emission cross section at room temperature is 2.8×10^{-19} cm^2, and for reasonably low Nd concentrations the fluorescence quantum efficiency is near unity.[11,12] The strongest absorption for diode pumping is at about 808 nm and laser emission is at 1064 nm, giving a quantum defect of 0.24, that is, a minimum of about 24% of the energy of each absorbed photon is converted to heat rather than to light output.

Other hosts for Nd^{3+} hold promise for scaling to higher average power. For example, GGG (gadolinium gallium garnet) grows without a core, in contrast to YAG, so that pieces of GGG nearly as wide as the boule can be fabricated for laser use. Of even greater potential for scalability in size are the laser quality ceramics, including Nd:YAG, recently developed in Japan.[13] These materials can be formed in sheets of very large size, and the technological limitations on their further scalability are probably far less severe than are those for single crystal growth. They exhibit surprisingly good optical, thermal and mechanical properties, comparable to or even exceeding those of single crystal YAG.[14] Of course, for some uses the random orientation of the crystallites in a ceramic may be a disadvantage, as for example the minimization of thermally induced depolarization in YAG for the (110) direction.[15] Fiber lasers and amplifiers are now also showing promise for significant power scaling, so that silicate glass host materials for Nd^{3+} should also be mentioned. Glass has, of course, poorer thermal conductivity than crystalline material, but the short diffusion path for heat removal from a fiber compensates for this limitation.

Although Nd^{3+}-doped solids have been very successful as solid-state laser gain media, this ion has certain limitations of importance for scaling to high average power. These include its substantial quantum defect, which assures that about a quarter of the energy deposited in the medium by the pump contributes to heating the crystal – a substantial thermal load in a high power system. Its large stimulated emission cross section, so useful for many purposes, makes it relatively

difficult to suppress amplified spontaneous emission, which can be a substantial energy loss mechanism. The intermediate states between the upper and lower laser levels permit quenching by cross-relaxation in many hosts, and the ionic size mismatch between Nd^{3+} and Y^{3+} causes lattice distortions and precipitation for Nd concentrations above about one percent in YAG and related hosts. Together these phenomena limit the useful Nd concentration in many hosts.

3.2 Yb^{3+} in solids

During the last 10-15 years, diode-pumped Yb^{3+} has become a serious competitor to Nd^{3+} for solid-state gain media, including scaling to high average powers.[16] As illustrated in Figure 5, the strongest stimulated emission line for this ion has a wavelength quite similar to that of Nd^{3+}, about 1030 nm in Yb:YAG. It has only the two manifolds of 4f electrons shown in that figure, and its absence of visible absorption, which limited its flashlamp-pumped performance, has the advantage of virtually eliminating loss mechanisms such as excited state absorption and cooperative upconversion. Modern InGaAs quantum well diode lasers can pump the $^2F_{5/2}$ manifold directly in the 930-980 nm range, giving a far smaller quantum defect, and hence less heating of the gain media, for Yb^{3+} than for Nd^{3+}. This is possible because the lower laser level is only a few hundred wavenumbers above the ground state, but this also means there is significant absorption at the laser wavelength at room temperature. At least 5.5% of the Yb^{3+} ions in YAG must be excited for the gain to excede this absorption loss, making the laser threshold higher than for Nd^{3+}. Fig. 4A shows that the peak stimulated emission cross section of Yb:YAG is an order of magnitude smaller than that of Nd:YAG. This increases the saturation fluence, and hence the risk for optical damage, but it also suppresses amplified spontaneous emission. The small cross section results in a much longer upper state lifetime than that of Nd^{3+}, about 950 µs in Yb:YAG, facilitating energy storage for Q-switched laser applications.[12]

Another favorable feature of Yb^{3+} as a dopant for YAG is that any concentration of Yb can be substituted for Y with the retention of satisfactory optical quality and quantum efficiency. This is possible due to the better size match between Yb^{3+} and Y^{3+}, and because the absence of states between the upper and lower laser level manifolds greatly reduces concentration quenching. The wider concentration range available gives greater flexibility for controlling the pump absorption coefficient and the laser gain coefficient.
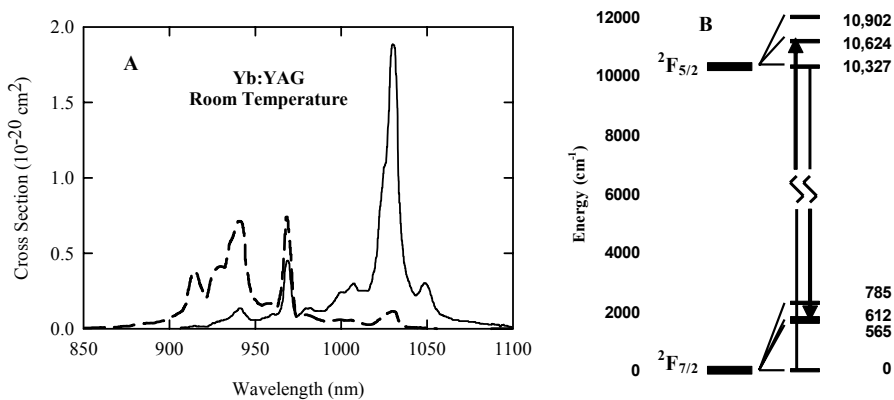

Figure 4. A: Absorption (dashed curve) and stimulated emission (solid curve) cross sections vs wavelength for Yb^{3+}:YAG.[17] B: 4f energy level diagram of Yb^{3+}:YAG, including pump and laser transitions.[16]

As is true for Nd^{3+}, other transparent hosts offer attractive features for Yb^{3+} laser operation. Yb-doped silicate fiber lasers are proving quite promising, with the smaller quantum defect of Yb^{3+} making the poor thermal conductivity of glass less critical and the popular double-clad fiber pumping scheme plus the long gain lengths achievable in fiber ameliorating the small absorption and stimulated emission cross sections of Yb^{3+}.[18] Ceramic technology is yielding very good results not only for Yb:YAG, but also for Yb-doped sesquioxides, which have favorable spectroscopic properties for Yb^{3+}, better thermal properties than YAG, and due to their high melting temperatures, are much more easily formed as ceramics than grown as single crystals.[19]

The laser performance of Yb^{3+}-doped gain media can be improved considerably by reducing the temperature. This depopulates the lower laser level, reducing laser threshold, increases the peak absorption and stimulated emission cross

sections, and improves the thermal conductivity of the host crystal.[20,21] Results so far suggest that impressive performance improvements are possible at cryogenic temperatures, say 100 K or below, at least in those applications where the requisite cryostat and coolant are feasible. More will be said about this strategy in the section on laser approaches and architectures.

3.3 Er^{3+} in solids

As noted in the discussions of laser diodes, there are cases in which wavelengths around one micron are undesirable. For example, when a high average power laser beam must be directed through the atmosphere, scattered light may present an ocular hazard to persons around the laser site and near the beam path. This ocular hazard can be reduced very considerably if the output wavelength is changed to the 1.5-1.8 micron range.[22] This may be accomplished by frequency shifting the output of a Nd^{3+} or Yb^{3+} laser, for example by stimulated Raman scattering or by optical parametric oscillation, but such approaches reduce the overall efficiency of the system by roughly one third due to the large quantum defect between those wavelengths.
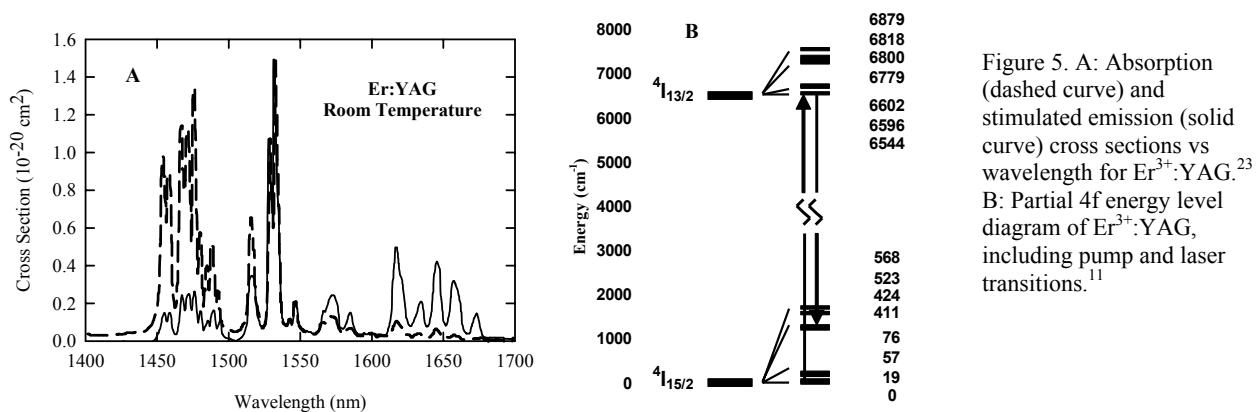

Figure 5. A: Absorption (dashed curve) and stimulated emission (solid curve) cross sections vs wavelength for Er^{3+}:YAG.[23] B: Partial 4f energy level diagram of Er^{3+}:YAG, including pump and laser transitions.[11]

Given the progress in longer wavelength laser diodes noted earlier, it is becoming possible to avoid this loss of efficiency by diode pumping the Er^{3+} directly into its $^4I_{13/2}$ manifold. As shown in Figure 5, this enables laser operation at wavelengths around 1.65 μm with very small quantum defect, analogous to the operation of Yb^{3+} lasers. The peak stimulated emission cross section is even smaller for Er^{3+} than for Yb^{3+}, so that extraction of gain without dangerously high fluences is more of a challenge. However, this should keep the amplified spontaneous emission problem very small, and the upper state lifetime of Er^{3+} is typically long enough for easy energy storage (about 7 ms in Er:YAG.)[23] As a cautionary note, Er^{3+} has a number of higher 4f manifolds such that excited state absorption and other efficiency-reducing upconversion processes are possible in this ion, in contrast to Yb^{3+}.

4. BEAM QUALITY AND THERMAL MANAGEMENT

Most applications for HESSL's call for high power density, so that the beam must be focused to a rather small spot or must propagate over a considerable distance with minimal divergence. Thus, beam quality is critical. For example, the Joint High Power Solid State Laser (JHPSSL) program goals call for a beam quality of at worst 1.5 times diffraction limited, with an ultimate goal considerably better than that.

To interpret a specification such as "1.5 times diffraction limited", one should know which definition of beam quality is being used. A "power in the bucket" specification compares the fraction of the beam power (or energy) within a specified cross sectional area in the actual beam to that expected for a truly diffraction limited beam (either a Gaussian or the central Airy disk due to the laser aperture's diffraction effect on a plane wave.) Another common measure of beam quality, Strehl ratio, compares the on-axis intensity (or pulse fluence) of the actual beam to that of a diffraction limited beam. Specification of "M^2" calls for fitting a focused beam to a Gaussian and comparing its $1/e^2$ radius to that for a diffraction limited beam. Not only do these three differ in how they treat non-Gaussian beam profiles, but the difference

between an area-based and a radius-based parameter gives inherently different beam quality numbers for the same imperfect beam. The JHPSSL goal stated above is based on a power in the bucket measurement.

Many factors affect the beam quality of a solid-state laser, including stresses grown into the gain medium, cavity optics, and their stability against vibrations. In a high average power system, beam distortions due to thermal effects are particularly important, including thermal lensing, thermally induced birefringence and depolarization. Thus, thermal management becomes one of the most critical issues for the power scaling of solid-state lasers, and is the subject of this section.

4.1 Magnitude of thermal management challenge

Figure 6 gives generic estimates of the efficiencies of the major segments of a high power diode pumped solid-state laser system. The details will vary significantly with design, but over all "wallplug efficiencies" of current systems are generally not much better than 10%. Thus, if a laser welding system requires several kW of optical output, several tens of kW of heat must be handled. For applications requiring, say, 100's of kW of optical output, removal of the resulting MW's of heat is a major burden on system size and weight.
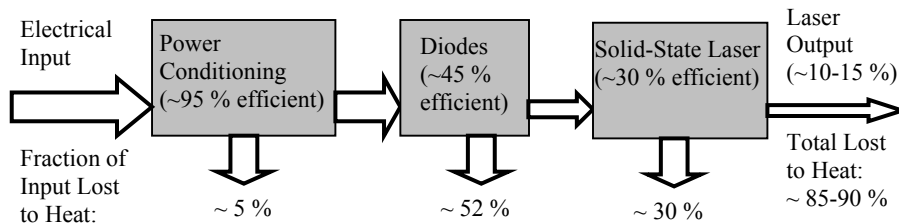

Figure 6. Typical power budget for a high power diode pumped solid-state laser.

Recent efforts offer promise of reducing this heat removal burden. If production diode arrays can achieve even half of the efficiency improvement envisioned from the DARPA super high efficiency diode laser program, the overall system efficiency would improve to 15-20%. Also, recent fiber laser results indicate that substantial power can be achieved with optical efficiencies on the order of twice the 30% noted above.[24,25] If that performance can be scaled to sufficient powers and combined with the above estimate for diode array improvement, overall efficiencies could potentially rise to the vicinity of 35%, cutting the heat removal burden for a given optical output by a factor of three to five.

4.2 Role of thermal conduction

Heat generated in a solid-state gain medium must first diffuse out of the material before any coolant can be effective. For high average power lasers, this places a premium on keeping the diffusion distance as small as possible, favoring thin disks, thin slabs, thin rods, and fibers. Architectures such as these will be treated in a later section.

One recent development takes advantage of high thermal conductivity in an optical material other than the gain medium, with diamond being the best.[21,26] In this approach, the gain medium is used in thin layers sandwiched between diamond disks, whose thermal conductivity is so great (about five times that of copper at room temperature) that even diffusion over distances exceding the width of the gain medium introduces very little thermal impedance. This greatly facilitates removal of heat to the surrounding coolant, and if the beam propagates normal to the thin dimension of the gain material there is very little lateral temperature gradient, minimizing thermal lensing and other distortions. Since application of such heat spreaders affects the entire laser architecture, it will be discussed further in the architecture section.

4.3 Liquid cooling approaches

Perhaps the most common way to extract heat from the surface of a solid-state laser gain element or a diode laser is by flowing liquid, usually water. This approach can remain useful as average powers are scaled up, but with the increasing thermal load ever more attention must be paid to maximizing fluid flow and thermal contact.

For the cooling of diode arrays, one recently developed very effective flowing liquid approach is silicon monolithic microchannel (SiMM) technology.[27] Here the water channels are fabricated in silicon, despite its inferior thermal conductivity compared to copper, because semiconductor lithography and etching techniques permit production of many very narrow coolant channels. Their large surface area and small coolant boundary layers enhance heat extraction at least enough to offset the difference in thermal conductivity, and the lithographic method facilitates cost-effective manufacture.

There is considerable recent interest in spray cooling as an alternative to flowing liquid. In this method, the coolant is applied as fine droplets and some fraction of each droplet evaporates upon striking the surface to be cooled, so that the fluid's latent heat of vaporization can be utilized, rather than relying exclusively on its specific heat. This permits heat extraction efficiencies, as measured by thermal impedance or the inversely related heat transfer coefficient, comparable to those for well-designed liquid flow devices (such as SiMM) using an order of magnitude lower coolant flow rates.[27-29] The cited papers treat the cooling of diode arrays, but solid-state gain media such as slabs can also be spray cooled.

Although somewhat beyond the scope of this paper, it is of interest to mention approaches that use a liquid gain medium, which circulates to be its own cooling fluid. This idea from the early years of lasers is now being reconsidered.[30,31]

4.4 Nonconcurrent cooling

One approach to high power solid-state laser operation, the heat capacity laser, passes the laser mode through the large faces of gain media slabs, so that efficient heat extraction must use these optical faces. However, it extracts heat from the gain medium only when there is no laser action, permitting cooling options that would be impractical during lasing.[32] The slab may be cooled by liquid or by spray, provided that means for rapid, clean drying are available, or it may be cooled by mechanical contact with solid cold plates, provided that surface scratches are avoided. A very promising method that avoids both wetting and scratches is to place the slab in close proximity to cold plates and provide thermal contact with the plates by flowing gas. The slab can be displaced to the side of the laser cavity for this cooling and then replaced in the cavity, so that the cooling hardware does not interfere with the laser.

4.5 Optical cooling

One of the more innovative recent approaches to thermal management for the solid-state gain medium is the high power application of optical refrigeration, in which anti-Stokes fluorescence is used to carry away energy from the medium.[33] This is a technique applicable to quasi-three-level laser systems such as Yb^{3+}, exemplified by Fig. 4, since in such case there is usable ground state absorption at room temperature at wavelengths longer than the mean wavelength of fluorescence. If a system can be found in which adequately strong pump and laser transitions exist at the proper wavelengths relative to the mean wavelength of fluorescence, the anti-Stokes fluorescence can extract energy as rapidly as the Stokes laser emission deposits it. The fluorescence leaving the gain medium must generally be absorbed somewhere within the laser head, so that the system does not actually remove all need for active cooling, but rather switches the burden to cooling absorbing surfaces outside the laser cavity itself, where the deposited energy density can be reduced and heat removal is a less exacting challenge. Particularly promising hosts for Yb^{3+} for this "radiation balance" approach are $KGd(WO_4)_2$ and $KY(WO_4)_2$.[34]

4.6 Removal of thermal energy to the environment – continuous vs intermittent

The above subsections have all dealt with removal of thermal energy from the solid-state gain medium and laser diodes into a cooling fluid. Ultimately, of course, that energy must be rejected from the fluid to the environment. In a few cases, such as some aircraft, the energy may be transferred conveniently to the vehicle fuel or discharged with the coolant itself after one pass through the system. However, in most cases heat rejection to the environment requires a substantial cost in size, weight and energy. For a 10% efficient laser, this may well amount to tens of kg of cooling system mass per kW of laser output. For laser systems used in fixed facilities such as factories, this cost may well be acceptable.

For lasers on vehicles, the issue of volume and weight becomes quite critical. For at least some applications it may be possible to alleviate this problem by considering intermittent operation of the laser and thermal storage. For example, a

laser operating a significant fraction of the time, even if far from 100% duty cycle, may be an improvvement on a traditional weapon that can fire for only a limited time before depleting its ammunition magazine. The advantage for thermal management arises if the laser is operated for only a modest fraction of the time, 10% for example, while heat removal is carried out even during the off period. This permits scaling down the thermal extraction system by a fraction comparable to the fraction of time the laser operates. However, this requires thermal storage during laser operation, storage efficient enough not to cancel the weight savings. This suggests the use of phase change materials, rather than reliance on specific heat alone. Advanced devices in which the phase change material is in intimate contact with high conductivity material such as carbon fibers for efficient heat transfer hold great promise for this application.[33]

5. APPROACHES AND ARCHITECTURES

5.1 Cryogenically-cooled lasers

As mentioned in the section on Yb^{3+} laser media, cryogenic cooling is a powerful means of improving spectroscopic properties of the active medium (turning a quasi-three level system into a true four-level, increasing the stimulated emission cross-section, narrowing lines, etc.), greatly increasing solid-state laser efficiency. Early experimental demonstration of laser cryogenic cooling benefits for Yb:YAG laser was done by MIT Lincoln Lab researchers in 1998.[20] It was also recognized at that time that cryogenic cooling significantly affects physical properties (optical, thermal, mechanical) of the host materials – changes that are in most cases extremely favorable for high power laser applications, by minimizing heat generation and thermal distortion. Cryogenic cooling increases average power capability for any laser geometry – rod, slab, active-mirror or disk amplifier-type laser elements.[20,35-38] Favorable consequences of cooling YAG from room temperature to 77 K include: a factor of seven increase in thermal conductivity, a factor of four decrease in thermal expansion coefficient, and a factor of 12 decrease in dn/dT. As a result, thermal stresses and thermally induced birefringence practically vanish and the probability of fracture is dramatically reduced.[39] Figure 7 exhibits the impressively high laser efficiency and almost negligible birefringence effects reported in an early diode-pumped cryogenic Yb:YAG laser experiment.[20] Laser experiments have also demonstrated the benefit of the greatly reduced thermal lensing at liquid nitrogen temperature.[40]
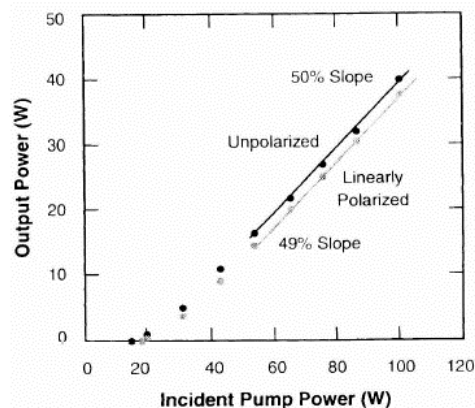
Figure 7. Diode-pumped cryogenically cooled Yb:YAG laser: CW output power at 1.03 μm as a function of incident 940-nm pump power both with and without an intracavity polarizer.[20]

One of the latest demonstrations of how critical the cryogenic cooling actually is for Yb:YAG laser efficiency was jointly reported by three Japanese groups.[41] Researchers comprehensively tested the material in the 10-180 K temperature range. Their best result, which is also, to our knowledge, the best laser efficiency result ever reported for Yb:YAG, is ~72.5% optical-to-optical conversion efficiency (~90% slope), which was also obtained at a very moderate pump fluence of 2.3 kW/cm^2 (Figure 8).

Designing lasers with cryogenically cooled solid-state active material is somewhat of a challenge, but it may be the only way of building very efficient high power lasers and amplifiers without significant thermal distortions and birefringence effects while not resorting to complicated adaptive optics or phase-conjugation approaches.
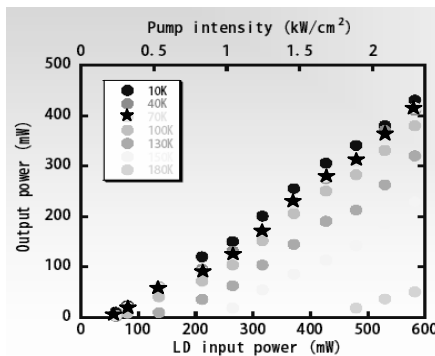
Figure 8. Diode-pumped Yb:YAG laser output as a function of pump power and intensity for a range of active sample operating temperatures. Output coupler reflectivity - 85%.[41]

5.2 Diamond cooling

Thermal lensing is one of the most detrimental effects in high average power solid-state lasers. Since thermal lensing is generally not well approximated by a spherical lens, it is difficult to compensate by simple optical elements. Thus, it must be minimized as much as possible. Thermal lensing becomes

even more complex in slab-like active elements, where cylindrical and "acylindrical" components contribute. A well-known method of thermal lens mitigation is face cooling, in which heat removal from relatively thin disks of laser material takes place along the laser cavity axis. In this case, to a first approximation, there are no radial thermal gradients and thus no thermal lensing. To be sure, this is only true if the entire active disk surface is pumped absolutely uniformly, but the approach does mitigate thermal lensing significantly. The best-known version of that approach is the thin disk laser architecture with either face or edge pumping. Such architecture completely turns away from the familiar rod geometry, with its design conveniences.

Recently a new cooling approach has been reported, combining benefits of face cooling with many conveniences of rod laser geometry. This approach is commonly referred to as "diamond cooling". Efficient cooling is achieved by interleaving multiple thin (1-2 mm) discs of the active medium, for example Nd(Yb):YAG or Ti:Sapphire, between diamond discs, which are typically ~1.0 mm thick or less. This approach takes advantage of diamond's exceedingly high thermal conductivity combined with its excellent transparency over the entire UV-LWIR wavelength range. The result is a composite element that integrates the thermal management capabilities of diamond with the optical amplification capabilities of the laser material. The approach is made possible by the current commercial availability of relatively large CVD and even single-crystalline diamond disks. Considerable power scaling should be possible by simple active medium cross-section area scaling if still larger diameter diamond of high optical quality diamond becomes available.

The theoretical foundation of the approach is built on simulations to examine a model laser gain element formed by integrating (via interleaving) diamond and Ti:Sapphire solid-state laser material.[21] Not only are the upper limits on average power due to thermal shock, thermal lensing, and thermal stress-induced birefringence in diamond much higher than those for typical laser materials at room temperature, but they improve still more as the temperature decreases from 300 K to 100 K. Thus, combining the cryogenic laser and diamond cooling approaches offers the prospect of power handling limits several orders of magnitude greater than is possible for more traditional laser materials at room temperature. The model results indicate that a properly tailored radial dependence of the heat transfer coefficient at the material interfaces is needed to achieve the highest average powers and highest quality optical fields. The authors outline paths to increase average output power of a lowest order mode laser oscillator based on these composite gain elements to megawatt levels.[21]
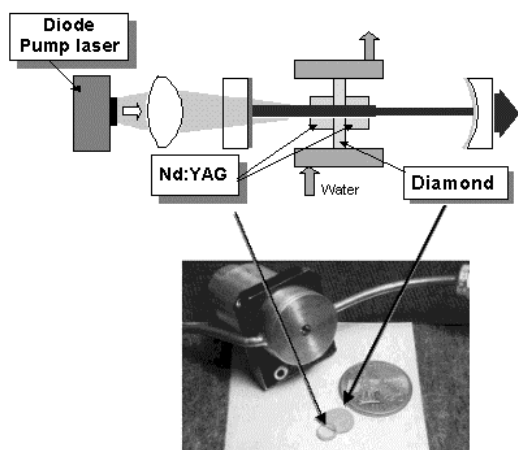

Figure 9. Diamond-cooled diode-pumped Nd:YAG test bed.[42]

The diamond cooling approach has recently been patented and first encouraging experimental results were reported with composite diamond-Nd:YAG active elements.[26,42] In the laser experiments conducted to date, the gain medium has been configured of one diamond disk between two Nd:YAG disks in the laser test bed diagrammed in Figure 9. Over 50% extraction efficiency has been experimentally demonstrated with average laser output power up to 50 Watts, which corresponds to a specific volumetric power extraction of 2000 W/cc and a 250 W/cm^2 heat removal rate for this very compact laser device. Beam quality of better than $1.1 \times DL$ has been measured in an oscillator configuration with the laser operating in TEM$_{00}$ mode.

This concept is amenable to scaling to very high average power levels and a conceptual design for a 100 kW class laser is summarized in Figure 10. A large aperture unstable resonator (power oscillator) design should provide a very compact and efficient HESSL. Transverse pumping of the individual "sandwich" gain modules may be arranged such that the diode pump radiation is incident at Brewster's angle to the outer diamond disk.
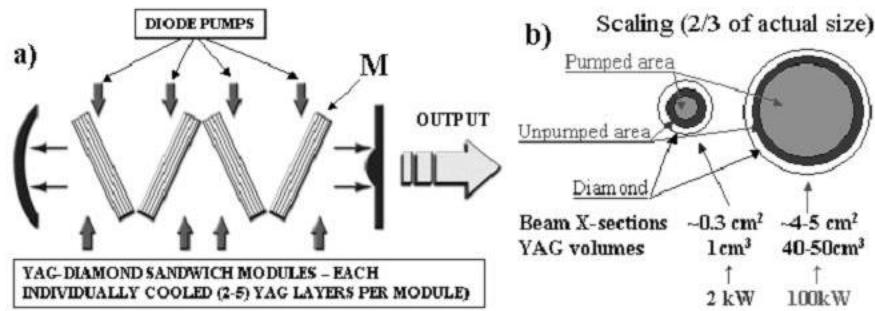
5.3 JHPSSL laser approaches

Figure 10. Conceptual design for a 100 kW class diamond-cooled laser.[42]

The Department of Defense, through its HEL Joint Technology Office, is sponsoring three programs to explore difference methods for scaling solid-state lasers to higher average powers, with 25 kW as a milestone. The first of these Joint High Power Solid-State Laser (JHPSSL) programs to begin is the Lawrence Livermore National Laboratory diode-pumped heat capacity laser. Like diamond-cooled lasers, it minimizes thermal distortions in a power-scalable laser by face cooling, but pursued in a radically different way. Here, the edges of the gain medium slabs are insulated to permit only face cooling, but cooling is not carried out during laser operation.[43] The result is very nearly uniform heating of the gain medium. The price to be paid for this advantage is that, after some seconds of operation, the gain medium becomes too hot to sustain laser operation, so that lasing must be interrupted while the material is cooled, or at least while a fresh slab of gain material is inserted and the hot slab is translated away for cooling.

The other two JHPSSL programs are too new for published results to be available, but brief introductions are possible.[44] The program at Northrop-Grumman Space Technologies scales to high power by combining several beam lines, each operated at a power level for which beam quality challenges are manageable. The beams are combined coherently by a proprietary technique. Somewhat more about this general approach will be said in the next section. The other program, at Raytheon, uses a single beam oscillator and amplifier system with cooling during laser action. This permits uninterrupted operation for longer periods than the heat capacity approach, but at the cost of substantial thermal gradients that can distort the beam. These distortions are corrected by phase conjugation based on a nonlinear thermal cell.[45]

5.4 Distributed energy and recombination for HEL

Distributed energy and recombination is another of the wide variety of strategies aimed at high average power levels in the multi-kilowatt range. Underpinning this approach is the expectation that high power splitting and recombining of beams, combined with the relatively mild distortions and thermal management challenges of a number of modest power amplifiers, may be more easily addressed than are the beam quality problems associated with scaling up a single-aperture laser.

Another significant hurdle, if merely scaling a single power oscillator is pursued, is lateral amplified spontaneous emission (ASE), which inherently limits area scaling. A sensible way of scaling up the power while eliminating the detrimental effects of thermal distortions as well as

Figure 11. Modular MOPA approach.[46,47]

ASE is: (i) to use a master oscillator-power oscillator (MOPA) architecture instead of a single power oscillator, and (ii) to scale the power through the use of distributed amplifiers with consequent beam combination. Figure 11 shows the conceptual modular design of such a high power laser, where MO is the master oscillator and A are amplifier modules used as building blocks of the system. Phase conjugation by stimulated Brillouin scattering (SBS) is a powerful way to achieve beam quality improvement while also providing coherent beam combination due to SBS-assisted four-wave mixing. Associated modules under development are beam splitting/combining elements (shown in Fig. 11 as dotted and
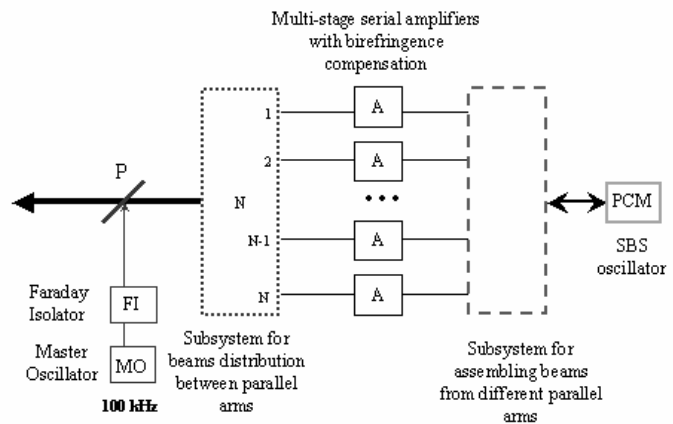
dashed vertical rectangles) based on diffractive and/or holographic principles. While these are being developed, the architecture and coherent beam coupling by SBS phase conjugate mirror (SBS PCM in Fig. 11) have been explored and demonstrated using polarization splitting/combining. Design and test results of a prototype repetitively pulsed (1 kHz), quasi-CW diode-end-pumped, diffraction-limited Nd:YAG MOPA system have been reported.[46,47] It has a single longitudinal/transverse mode passively Q-switched master oscillator and double-arm amplifier architecture.

5.5 High power fiber lasers

Thanks to the development of cladding-pumping techniques, fiber lasers are producing kW-level powers that compete with "bulk" and "thin-disk" solid-state lasers such as Nd:YAG and Yb:YAG. Due to the waveguide geometry of fiber lasers, they offer excellent beam quality and thermal management: the generated heat is distributed over a great length thus reducing the risk of thermal damage.[48]

Similar to traditional step index fiber, a double-clad fiber has a primary waveguide (core) for guiding the signal, surrounded by a lower-index glass inner cladding. The inner cladding also forms the core for a secondary waveguide that guides the pump light (Figure 12). The inner cladding is surrounded by an outer cladding of lower refractive index polymer or glass to facilitate waveguiding. Typically, the core is rare-earth doped, while the inner cladding is undoped. The core is generally located off-center within the inner cladding, so that pump light propagating in the pump waveguide reaches the core and excites the laser-active rare-earth ions. As in any rare-earth doped glass, the gain in the core is spectrally broad, allowing for broadband amplification and wavelength tuning.
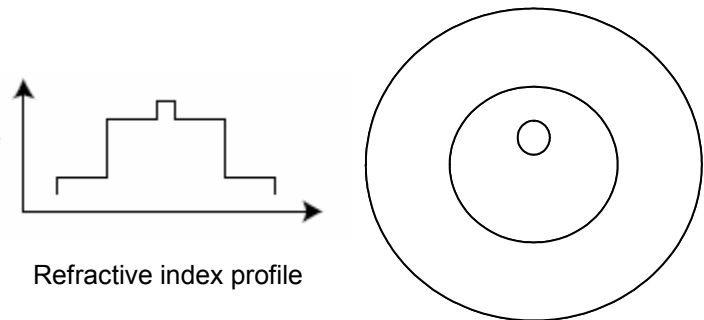
Refractive index profile

Figure 12. Typical structure of a double-clad fiber.

The high-power cladding-pumped fiber geometry is particularly attractive for Yb^{3+} lasers because of the high pump absorption and gain that are possible. Recent results from the University of Southampton have shown power levels of 1 kW from a Yb-doped fiber in the 1.1 μm regime with 80% slope efficiency and good beam quality when end-pumped through both fiber ends.[49] As part of a DARPA thrust, work is under way to extend the power and efficiency still more, including the use of MOPA architectures.

The attraction of erbium-ytterbium co-doped fibers is their unsurpassed performance in the important "eye-safe" 1.5 micron wavelength region. In an Er:Yb co-doped fiber, pump photons are initially absorbed by Yb-ions, taking advantage of this ion's stronger and broader absorption. Furthermore, Yb can be incorporated in much higher concentrations than Er, thanks to its relative immunity to self-quenching. As a result, a fully adequate pump absorption of several dB/m can be reached, even in fibers with a large inner cladding-to-core area ratio. Then, the energy is transferred nonradiatively from excited Yb^{3+} to Er^{3+}. Recent results show up to 120 W output from an Er/Yb-doped fiber at 1.56 μm.[48,50]

In recent years, an attractive alternative to step index fiber has been developed. "Holey fiber" uses an array of holes with periodicity comparable to the light wavelength to forbid light transmission over a band of wavelengths, the by now familiar phenomenon of "photonic band gaps".[51] For application to fiber geometry, the holes are parallel to the length of the fiber, so that the "photonic crystal" is two-dimensional, strongly confining light in the transverse directions.
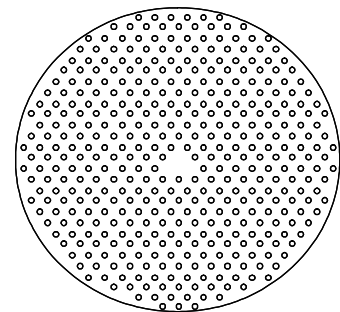
Figure 13. Conceptual example of a holey fiber cross section.

The main advantage of these fibers is that the strong confinement of light permits relatively large cores, allowing power scaling with relatively modest intensities. This suppresses nonlinearities which limit performance (pulse duration and

peak power). To date generation of megawatt optical solitons in hollow-core photonic band-gap fibers has been reported.[52]

6. LIMITATIONS OF HESSL'S

The maximum intensity from an active aperture in a single crystal is the saturation intensity given as: $I_{sat} = h\nu/\tau\sigma$ where τ is the excitation lifetime and σ is the cross section. For Nd:YAG: $I_{sat} \sim 2.5 kW/cm^2$ therefore to extract 100kW from a single aperture requires a beam diameter of 7.2 cm. This is not that difficult, so in principle 100kW solid-state laser is possible. The problem comes in extracting the heat generated and in our example here the crystal will melt due to the heat. Ways to overcome this limitation are through extremely efficient conversion via advanced diodes, conversion of pump to laser photons, advanced material development to remove heat generated and a robust beam combining scheme for multi-aperture lasers.

7. CONCLUSIONS

Advances in recent years have shown that high energy solid-state lasers are on the threshold of a new era, one that for the first time has enough technology development in the individual components to allow integration into a laser engine that can achieve 100 kW output in the near future. It remains to be seen if this assessment is accurate or if the component technologies are not yet mature enough. Presently there is momentum in a number of different technology areas so that the promise looks bright for this development, although the challenges are great. It is possible that the energy levels will be achieved but other factors, such as beam quality, will be lagging that no useful application will be forthcoming. That is a real possibility and requires each development to seriously consider the ultimate application and ensure that those important parameters are all being considered and advanced in order to achieve a useful high energy solid-state laser system.

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