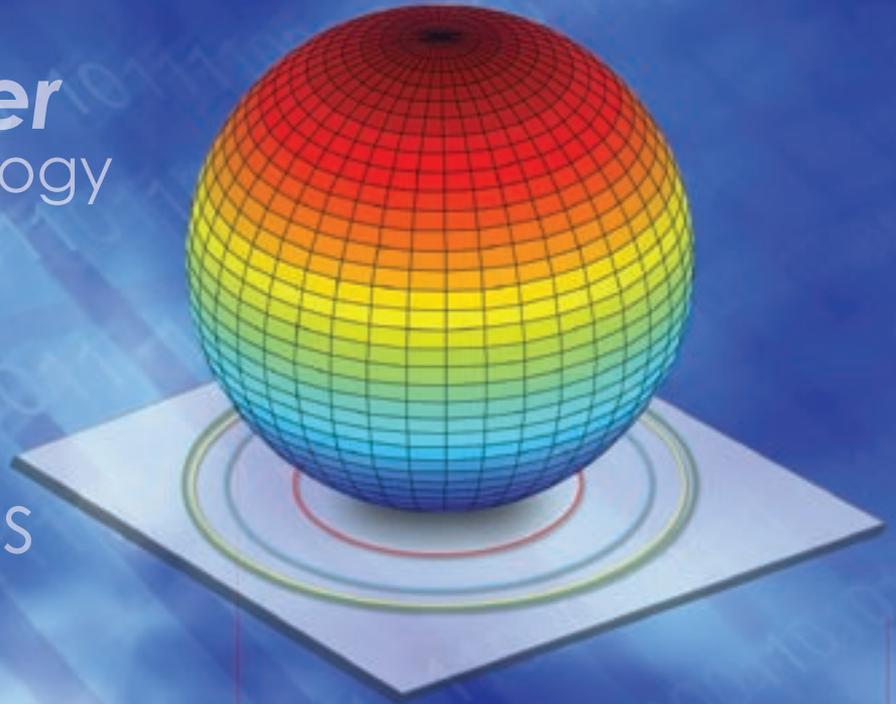


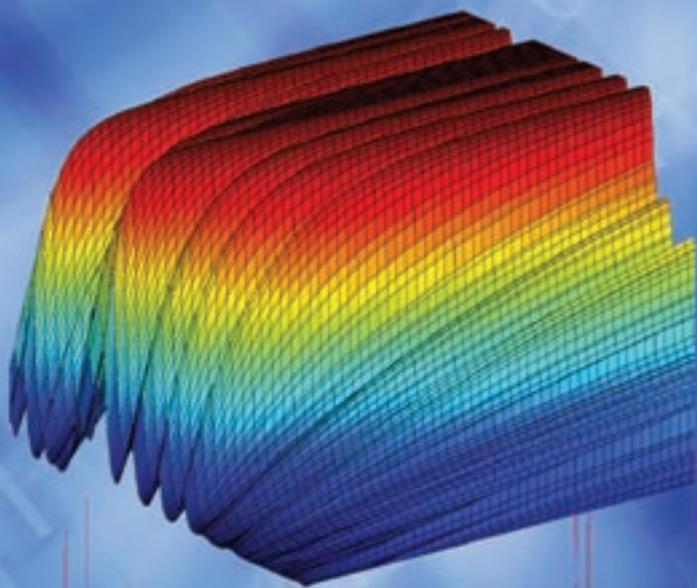
Crystallographic Properties

Ultrafast Laser
Technology

Material
Properties



Spectroscopy



HIGH Average
Power Lasers

Nonlinear
Conversion

Solid-State Lasers:

Steady Progress Through the Decades

David C. Brown and Jerry W. Kuper

More than three decades after solid-state lasers were developed, physicists and engineers have made an extraordinary amount of progress, and the pace of development is accelerating.

Much has changed since we began working on solid-state lasers in the mid-1970s at the University of Rochester. At that time, these lasers were in their infancy; optical pumping was done almost exclusively with flashlamps; and personal computers were non-existent. Vibrant industrial laser research groups at General Electric, Bell Labs, RCA, TRW, Hughes Research, and other companies enjoyed substantial government and corporate support. And laser fusion efforts were under way at Lawrence Livermore National Laboratory, Los Alamos, KMS Fusion, and the Laboratory for Laser Energetics at the University of Rochester. In 1972, physicist John Nuckolls predicted that about a kilojoule of laser light would be needed for a laser fusion break-even, an estimate that has continually increased over the years. (The National Ignition Facility is now reaching completion with more than 4 megajoules of energy output.)

More than 30 years later, it is both satisfying and astonishing to look back at the progress that has been made in solid-state lasers. Sadly, however, most of the pioneering laser industrial research groups that contributed so much to early progress are no longer in existence. Fortunately, in their place have come academic institutions from around the world, such as Cambridge University, the Max Planck Institute, along with U.S. centers at the University of Rochester, MIT, Stanford University, the University of Arizona, the University of Central Florida and the University of Michigan. These institutions have expanded to fill the void and continue to produce outstanding solid-state laser research and innovations. Universities remain important incubators of small innovative startup laser and photonics companies.

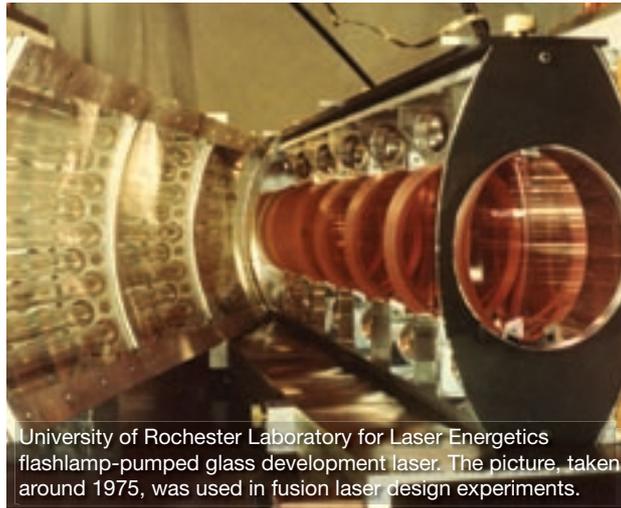
Three decades ago, solid-state laser research was conducted almost exclusively in the United States and the former Soviet Union, with much smaller efforts in Europe and Japan. However, over the past two decades, the field has become truly international, with substantial research and development and commercialization efforts throughout Europe, Asia, and North and South America. The Internet has made the world smaller as well, by making it possible to easily keep track of developments from all parts of the globe.

Expansion of the engineering database

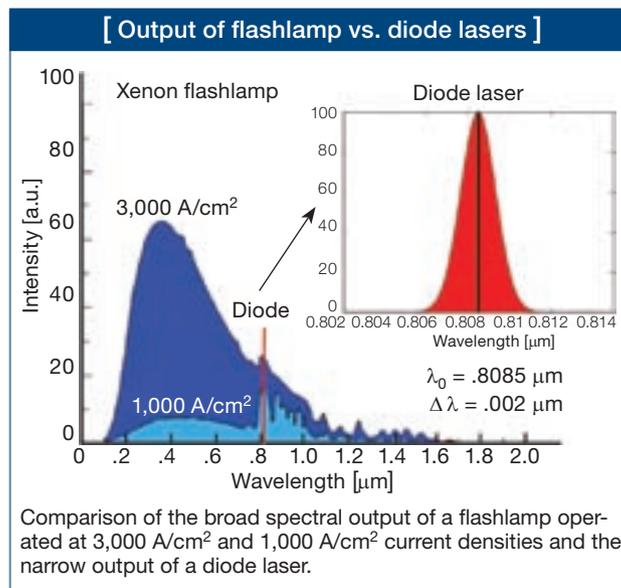
Before the mid-1970s, those in the field worked hard to collect critical laser design parameters, such as stimulated-emission cross-section information and absorption cross-section data, as well as the physical and thermal parameters needed to generate credible laser designs. Because lasers were flashlamp-pumped, with output typically from the ultraviolet to the near-infrared spectral region, lasing ions that efficiently absorbed the broad-band light from Xe and Kr lamps were preferentially investigated, and yttrium aluminum garnet ($\text{Y}_3\text{Al}_5\text{O}_{12}$) or YAG became the gold standard of crystalline laser materials. Nd:Glass was also important because of its broad-band absorption characteristics, although Nd:Glass lasers were either single-shot devices or devices operated at low repetition rates due to poor thermal conductivity and low thermal shock resistance.

Nd:Glass lasers were the primary tool of the laser fusion community; that is one of the few things that has not changed in three decades. The first comprehensive book devoted strictly to engineering solid-state lasers was written by Walter Koechner and published by Springer-Verlag in 1976. It heralded the arrival of solid-state lasers as a distinct discipline, and contained a wealth of information about fundamental laser physics, laser materials, flashlamp-pumping, thermal effects, nonlinear optics and damage effects in solid-state lasers. At the time, the book was a most-welcome development that began filling in some of the missing information and database needed for intelligent solid-state laser design.

Today, the field is considerably more mature and complex. In the past two decades, dozens of books have been published about solid-state lasers, lasers and related materials. In addition, we now have a detailed knowledge of the energy-level structure, spectroscopy and crystalline properties of laser materials for a large number of laser crystals, including entirely new crystals that did not exist two decades ago, or whose development was delayed until the arrival of a new pump source: the laser diode. The majority of laser and nonlinear crystals in use today were improved or made possible due to diode-pumping; these include Nd:YVO₄, Nd:YALO, Ti:sapphire, alexandrite,



University of Rochester Laboratory for Laser Energetics flashlamp-pumped glass development laser. The picture, taken around 1975, was used in fusion laser design experiments.



Cr:LiSAF, Cr:BeAl₂O₄, Nd:GGG, Cr,Nd:GSGG, Co:MgF₂, Nd:GdVO₄, KTP, BBO, LBO, PPLN, PPKTP, and many others.

Within the past 20 years, researchers have made a number of significant discoveries and improvements in laser materials. We now have a richer understanding of heat generation in solid-state lasers, the important role that excited-state absorption and up-conversion play in some solid-state laser materials, and the best designs to maximize laser performance, beam-quality and efficiency. The management of thermal effects in solid-state lasers—once a major impediment to their advancement as high average power devices—has gradually yielded to improvements because diode-pumping delivers the pump energy in a narrow spectral band that is efficient in 1) exciting the desired optical transition, 2) developing the low quantum defect laser materials, 3) managing and reducing thermal gradients through the use of clever designs like zig-zag slab or thin-disk amplifiers, 4) cryogenic cooling, and 5) incorporating

adaptive-optic elements into laser resonators.

The development of ultrafast lasers has enhanced our understanding of the physics and engineering of solid-state lasers and related optical materials in which the management of dispersion and nonlinear effects is of paramount importance. Peter Moulton's discovery of titanium sapphire (Ti:Al₂O₃), with its unprecedented broad-gain bandwidth, set the stage for the development of few-cycle mode-locked femtosecond laser sources. These devices have allowed the investigation of entirely new physical phenomena and the elucidation of complex atomic and molecular dynamics down to the attosecond regime.

This work has given us a detailed understanding of the many nonlinear processes that can either enhance or seriously degrade the performance of a solid-state laser. In fiber lasers, for example, the threshold for stimulated Raman scattering must be addressed in the system design to control this higher-order nonlinear process. Self-focusing can be used to self-mode-lock ultrafast lasers and can also seriously damage laser crystals or glass in other high-peak-power systems.

The past decade has witnessed the development of new ceramic laser materials in Japan based on nanotechnology. These

materials offer unprecedented size scaling for lasing crystal elements with optical, lasing, spectroscopic and other physical properties that are nearly identical to bulk single crystals grown by more classical methods. This technology promises to spawn new laser materials or combinations of laser materials and the possibility of tailoring the dopant profile—a development that can be important in suppressing parasitic oscillations and generating more uniform gain and thermal profiles, for example.

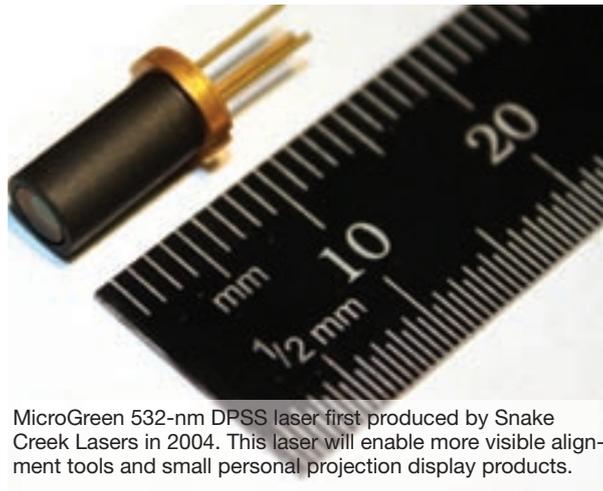
Also, researchers and engineers have made much progress in their ability to manipulate crystals through the use of various bonding methods to form very small devices or integrated devices that offer simplicity and ease of use. Diffusion-bonding, as pioneered by Onyx Optics, can be used to bond un-doped end caps, for example, on rods or slabs to minimize strain-induced distortion at lasing surfaces, or to create unique laser waveguides. Crystals that are difficult to diffusion-bond, such as Nd:YVO and KTP, are used in green lasers. They can be contact-bonded or, for low-power lasers, glued together to form miniature devices whose dimensions are measured in millimeters. A new bonding technique that uses chemical diffusion-bonding or indium promises to extend this trend and allow even more dissimilar materials to be combined into complex structures.

Solid-state lasers have evolved from their initial discrete wavelength coverage of the infrared, visible and ultraviolet spectral regions. Enormous progress has also been made in developing new nonlinear crystals, and solid-state lasers are now routinely made to be much more frequency-diverse. Laser systems are commercially produced that span the mid-infrared to the ultraviolet range using frequency doubling and tripling and optical parametric oscillators, respectively. In the past decade, we've seen the emergence of periodically poled nonlinear crystals that eliminate walk-off between the fundamental and harmonic wave in the crystal and offer high nonlinear coefficients, thus further enabling high-efficiency operation in processes such as sum-frequency mixing and optical parametric generation.

Another significant trend is the production of devices that are increasingly compact and efficient. Many technologies have made this trend possible. Devices are now routinely produced whose power density (watts per unit volume) is orders of magnitude greater than those of even a decade ago.

Laser diode technology

The single most important change that has taken place in solid-state lasers over the past 30 years is the development of laser diode sources, especially those that have been specifically developed for pumping solid-state lasers. Even during the first decade of solid-state laser development, it was well known that the factors that were most impeding the scaling of solid-state



MicroGreen 532-nm DPSS laser first produced by Snake Creek Lasers in 2004. This laser will enable more visible alignment tools and small personal projection display products.

laser average power was the generation of large amounts of heat from flashlamp-pumping and the subsequent removal of heat from the lasing element. The spectral output of Xe flashlamps typically extends from 300 to more than 1,000 nm. For Nd, in which pumping occurs even in the ultraviolet, the average quantum defect between the absorbed and lasing photons was very large, and this was the primary cause of the typically low

efficiencies of early solid-state lasers.

For crystals that utilize dopant ions like Yb—whose absorption occurs only near 940 and 975 nm—pumping using flashlamps resulted in very low efficiencies. The large amount of heating that occurred contributed to significant ground-state absorption, reducing the obtainable gain and increasing the laser threshold. The first commercial diode-laser-pumped laser products were introduced in the mid-1980s. The motivation for this development was spurred by the recognition that bright quasi-monochromatic sources with bandwidths measured in a few nanometers were far superior as a pumping source for solid-state lasers than a low-brightness broadband flashlamp. The higher efficiency achieved by laser pumping of a solid-state laser produced better quality lasers in much smaller packages. This technology allowed the development of diode-pumped lasers, where previously small microchip lasers were not feasible.

In the mid-1970s, there were no commercial laser diode suppliers, and the technology to produce reliable devices and tailor the output wavelength to specific solid-state laser absorption bands was in its infancy. By the mid-1980s, significant programs were in place—at General Electric and RCA David Sarnoff Labs, for example—to demonstrate high-power GaAs laser diodes suitable for pumping Nd:YAG. Around the same time, a start-up company, Spectra Diode Laboratories (SDL), was beginning to offer low-power single-emitter diode lasers whose output was measured in tens or hundreds of milliwatts. The laser group at Stanford University led by Robert Byer was just beginning to develop low-power diode-pumped solid-state lasers, and they pioneered many advancements in compact high-performance solid-state lasers.

The field is now dominated by diode-pumped devices. In rapid succession, high-power single-emitters, high-power laser bars, and quasi-CW and CW stacks of diode bars became available, largely driven by military laser projects. Accompanying these advances has been the development of high-power fiber-coupled diode laser sources. Recently, every year has brought news about higher levels of output power and brightness. Diode-pumping has had a profound effect on solid-state laser development. In fact, we can now say with confidence that the technology has lived up to its early promise. Not only has diode-pumping led to more efficient lasers, and enabled pumping

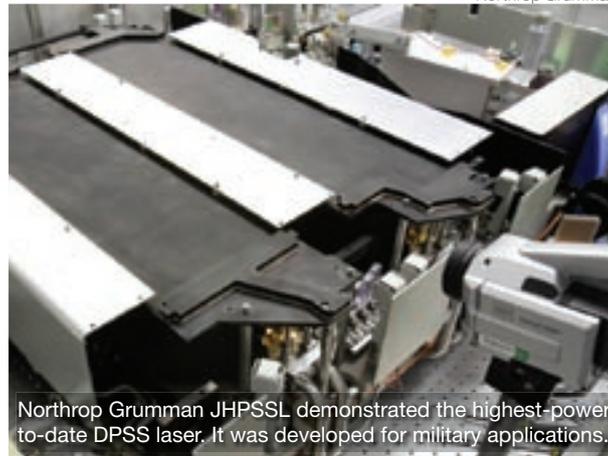
techniques such as spatially pumping directly into the resonator fundamental transverse mode, but it has also simplified the design of solid-state lasers.

Diode laser designs can be accurately modeled to verify the performance of new solid-state laser configurations. Today's computer models can unravel a parasitic effect such as up-conversion and heat generation due to the relative simplicity of a small-bandwidth quasi-monochromatic diode laser. This theoretical understanding was far more difficult to model with flashlamp-pumped devices. Diode-pumped solid-state-laser designs are not without their challenges, such as the pump diode output wavelength dependence on drive current and temperature. Recently, researchers have made much progress by inserting a Bragg grating into the diode structure, or by locking to an external volume Bragg grating, and thereby significantly reducing the sensitivity of diode lasers and bars to changes in ambient operating conditions.

The first CW kilowatt average power solid-state laser was demonstrated at the General Electric Corporate Research and Development Center by Joseph Chernoch, the inventor of the slab laser, and Mark Kukula. The device used an Nd:YAG zig-zag slab and was flashlamp-pumped. Since then, development of bright high-power diode laser pump sources has enabled the creation of high-average-power bulk solid-state lasers like JHPSSL with output powers measured in tens of kilowatts. Powers in excess of 100 kW are expected from a multiplexed system later this year. Diode sources are widely credited with enabling the rapid development of high-average-power fiber lasers. A decade ago, the output of fiber lasers was typically at the watt level. Today, a commercial 10 kW version is available.

Fiber laser technology

Major advances in fiber lasers began in earnest more than a decade ago. A paper describing a 110-W CW fiber laser was presented by Dominic et al. at the 1999 CLEO Conference in Baltimore, and this work announced that a major scaling in the power output of fiber lasers was under way. This advance resulted from the development of better fibers, particularly double-clad designs into which one could couple increased amounts of pump light from diode sources that were also growing in output power and brightness. Since that time, the scaling of CW fiber



Northrop Grumman JHPSSL demonstrated the highest-power to-date DPSS laser. It was developed for military applications.



The IMRA ultrafast fiber laser system is used in biomedical and micromachining applications.

lasers has steadily increased to the kilowatt level and beyond.

Fiber lasers have attracted a great deal of attention because of their potential to provide highly efficient solid-state laser sources with excellent beam-quality and reduced thermal-management problems. In addition, they are attractive platforms to amplify picosecond to nanosecond pulses generated by an external oscillator. However, it is difficult to Q-switch fiber lasers to produce those types of pulses as an oscillator. Fiber lasers have been used to great profit to produce mode-locked pulses and today produce watt-level average powers with pulse durations in the hundreds of femtoseconds regime down to less than 37 fs. Producing successful fiber ultrafast lasers involves a complex balancing of dispersion and nonlinear effects such as self-phase modulation, Brillouin scattering and Raman scattering. These lasers have

found niche applications in micromachining and two- and three-photon microscopy.

Ultrafast bulk laser technology

Like fiber laser technology, ultrafast bulk laser technology has become a major sub-field of solid-state lasers. It is at the cutting-edge of laser physics, and its applications have become very important. The development of mode-locked solid-state laser oscillators capable of producing femtosecond pulses, down to less than 5 fs, happened over a period of decades, with each advance building on previous ones. Of critical importance was the development of the laser material Ti:sapphire, with its extraordinarily wide bandwidth, and recognition of the importance of high-order dispersion compensation to achieve near-transform-limited pulsewidths.

Another development of enormous importance was the invention of chirped-pulse-amplification (CPA) by the Mourou group in the late 1980s at the Laboratory for Laser Energetics at the University of Rochester. Using this technique, researchers could "stretch" femtosecond pulses using a diffraction grating to the picosecond or nanosecond regime amplified in a series of cascaded Ti:sapphire amplifiers while avoiding nonlinear effects and laser-induced-damage, and then compress them close to the original pulsewidth using a second diffraction grating.

The CPA technique is now the standard used in ultrafast laboratories worldwide. Ti:sapphire laser systems can now

produce 1 PW. The first petawatt laser, built at Lawrence Livermore National Laboratory, used a hybrid Ti:sapphire and Nd:Glass approach, and the laser was significantly impaired in throughput by the low repetition rate of the Nd:Glass amplifiers. The average power of a Ti:sapphire ultrafast system is currently limited to less than 50 W, primarily because the high-energy/pulse green lasers used to pump the Ti:sapphire amplifiers have limited average power as well.

Many applications do not require femtosecond pulses. Thus, in the past decade, researchers and engineers have been aggressively developing ultrafast sources based on materials other than Ti:sapphire. In particular, important work has been reported on room-temperature Yb-based sources, particularly Yb:KYW and Yb:KGW. The average power of non-Ti:sapphire ultrafast lasers is now approaching 100 W.

For materials processing and micromachining applications that require a pulsewidth of around or less than 10-15 ps where thermal effects are minimized, the development of these alternative ultrafast sources is driven by the simpler resulting laser architecture (particularly where CPA is not necessary) and cost, as well as simpler scaling of the laser average power. This is an important consideration for many applications, since process throughput is proportional to average power. While the ultrafast solid-state laser field has reached maturity, in the coming years we expect advances in the average power as well as a continual scaling-up of peak power in excess of the exawatt level.

Future trends

What may we expect from solid-state lasers in the coming decades? While some trends seem apparent now, we cannot often foresee surprise developments. An example would be the discovery of laser materials whose lasing ions could be directly excited by electron impact, enabling optical pumping to be eliminated entirely. More likely, however, the field will progress as it has for decades, with each incremental advance building upon previous work. We predict the following trends:

- ▶ Higher average and peak powers will be achieved, with solid-state laser average power exceeding the megawatt level, and peak power the exawatt level.
- ▶ Fiber and bulk laser technologies, which have evolved separately, will become entwined to form even more powerful and diverse devices. Recent work on direct-pumping into the upper laser level of bulk mid-infrared solid-state lasers with fiber laser sources shows that such combinations can be profitably employed.



All-solid-state ultrafast Ti:sapphire laser system Millennia/Tsunami, with the current state of the art, hands-free ultrafast Ti:sapphire laser Mai Tai in the inset.

- ▶ The best properties of bulk and fiber solid-state lasers will be fused together by the development of crystalline rather than glass fiber lasers. This exciting development is under way, and much progress has been reported recently.
- ▶ Integrated lasers in which the diode pump source and laser crystals are substantially integrated together to form very small devices will be developed.
- ▶ Solid-state lasers will become smaller, higher density, and more efficient devices. Engineering limitations posed by the aggressive removal of heat from small spaces will be addressed by micro- and nano-electronic cooling techniques.
- ▶ Cryogenically cooled lasers will become substantially more important because of the very significant cooling and scalability advantages, lasing advantages, elimination of thermally induced aberrations, and operation in a parameter space that may offer substantial benefits not yet realized.
- ▶ Additional lasing and nonlinear crystals will be discovered and lead to further wavelength diversity and perhaps higher efficiency.

After decades of steady progress, it would be easy to come to the conclusion that most of the important discoveries in solid-state lasers have already been made. We disagree. While the trends we predict for the future may or may not come to pass, surely the combination of a vast technological database and the hard work of creative individuals around the world will lead to a vibrant future for solid-state laser technology. ▲

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