Diode-Pumped Solid State Lasers

T.Y. Fan

■ The use of diode lasers instead of flashlamps as optical pump sources for solid state lasers offers significant advantages such as higher efficiency and longer lifetime. We have demonstrated three novel lasers based on this technology. The first is a zig-zag slab laser pumped by hybrid planar microchannel-cooled diode arrays that allow high-repetition-rate operation in a pulsed mode. The second is an end-pumped laser that uses multiple diode lasers for power scalability while maintaining high efficiency and good beam quality. The third is a Yb:YAG laser, pumped by strained-layer InGaAs diode lasers, that offers advantages over AlGaAs-pumped Nd:YAG lasers. These advances should lead to lower-cost higher-power solid state lasers.

INTEREST HAS INCREASED in the past few years in using semiconductor diode lasers to excite solid state lasers based on rare-earth ion-doped transparent solids such as neodymium-doped yttrium aluminum garnet (Nd:YAG). Traditionally, these solid state lasers are excited by flashlamps that emit broadband radiation. Lamp-pumped systems are inefficient, however, with typically 1% electrical-to-optical efficiency, and the lamps need replacement after approximately 200 hours when operated continuously. Diode laser pump sources allow operation at higher efficiency (10%) and longer life (20,000 hr).

The potential advantages of semiconductor light sources over lamps for optical pumping of solid state lasers were recognized in the early 1960s [1], but diode-pumped lasers did not become practical until the early 1980s, when efficient, high-power, reliable semiconductor lasers became widely available. Lincoln Laboratory has participated in the development of these lasers since the beginning; the first diode-pumped laser was a U^{3+}:CaF_2 laser demonstrated at Lincoln Laboratory by R.J. Keyes and T.M. Quist in 1964 [2]. Figure 1 shows a diagram of this device. Because diode laser operation required low temperatures at that time, the entire assembly was placed in a liquid-helium cryostat for cooling. Research continued at Lincoln Laboratory in the 1970s with most of the effort devoted to the investigation of solid state laser materials doped with relatively high levels of Nd [3, 4]. Two reviews of research in this area were published in 1988 [5, 6]. This paper reviews the advantages of diode-pumped laser technology compared with competing laser technologies, and discusses some of the research the Quantum Electronics Group at Lincoln Laboratory currently performs in the areas of high-average-power and high-pulse-energy lasers, novel laser configurations, and new materials for diode-pumped lasers.

Comparison of Diode-Pumped Lasers with Competing Technologies

The main advantages of diode lasers over flashlamps as pump sources are overall laser efficiency and extended pump-source lifetime. The increase in efficiency is due to improved use of the optical pump radiation. Figure 2, which shows the absorption spectrum of the most common solid state laser material (Nd:YAG), and the output spectrum of both a pulsed flashlamp and a diode laser, illustrates the increased efficiency. Nd:YAG has optical absorption only in relatively narrow wavelength bands; thus most of the broadband flashlamp energy passes through the material without being absorbed. On the other hand, diode laser output is narrowband; thus most of it is absorbed and utilized. Pulsed flashlamps convert electrical energy to optical energy more efficiently than diode lasers (80% efficiency compared to 30% to 50% efficiency), but, because of the inefficient

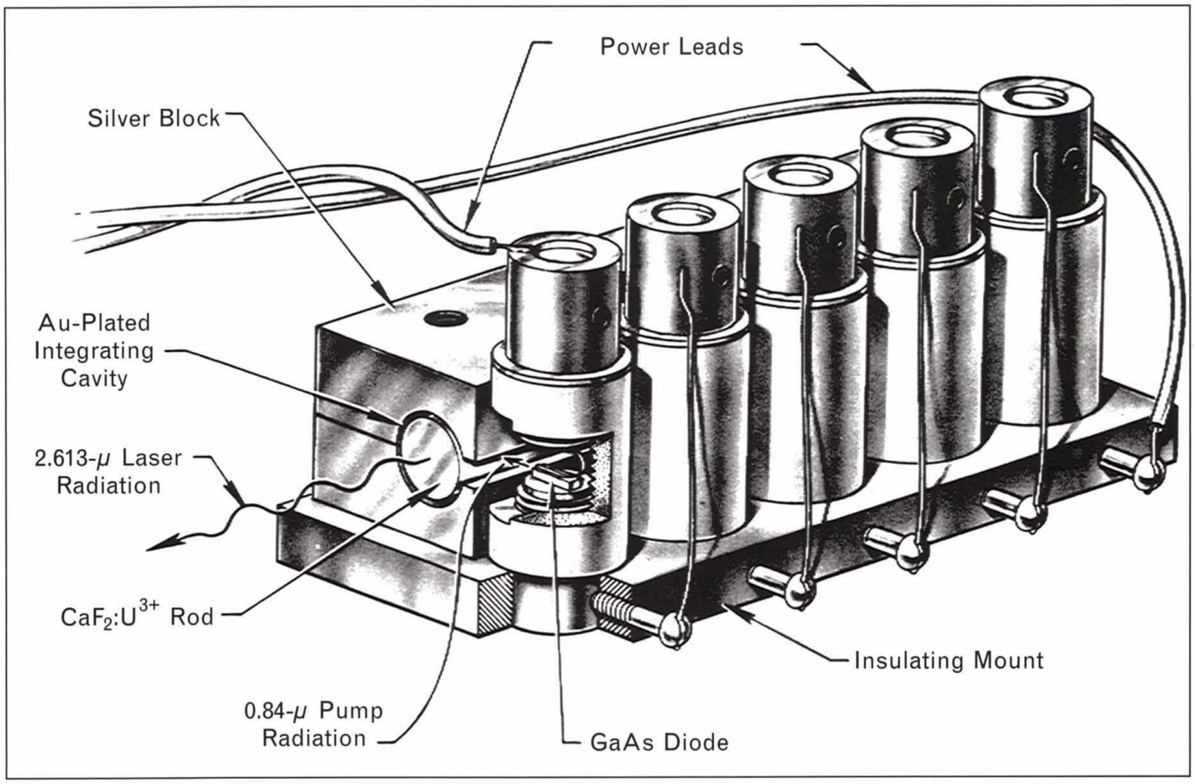

FIGURE 1. Schematic of the first diode-pumped solid state laser. This laser used five pulsed GaAs diode lasers to pump the U^{3+}-doped CaF_2 laser rod that was 3 mm in diameter and 4 cm long. The laser mirrors were coated directly on the ends of the rod.

absorption of the pump radiation, lamp-pumped Nd lasers are typically only 1% efficient while diode-pumped lasers are 10% efficient. This increase in efficiency has other favorable consequences. The amount of waste heat generated in Nd:YAG decreases by a factor of 3 compared to pulsed flashlamps [7], which reduces cooling requirements and allows the use of conduction cooling instead of flowing liquid in many cases. When Nd:YAG is pumped with continuous Kr arc lamps instead of pulsed flashlamps, the decrease in thermal load is less. Waste heat also causes thermal distortion of the gain medium, which decreases laser performance; these problems are reduced with diode pumping.

Both lamps and diode lasers have limited operational lifetimes, but diode laser lifetimes are significantly longer. In continuous operation, lamps must be replaced every few hundred hours while diode lasers have lifetimes on the order of tens of thousands of hours. In pulsed operation, diode laser lifetime is on the order of 10^9 shots compared with pulsed-flashlamp lifetimes of 10^7 shots. The long lifetime of diode laser pump sources is a particular advantage in space-based laser systems because pump-source replacement would be expensive.

The main disadvantage of diode lasers as pump sources is economic; they are much more expensive than flashlamps or arc lamps. At current prices, a lamp needed to excite a 10-W-average-power laser is a few hundred dollars; the cost of an equivalent number of diode lasers is tens of thousands of dollars. Projections indicate, however, that the price of diode lasers will drop significantly as the volume of production increases, in a manner similar to other semiconductor technologies such as integrated circuits.

Solid state lasers have several advantages over diode lasers. For example, solid state lasers can operate in wavelength ranges in which diode lasers either are not available or have poor performance. In addition, the output of the solid state laser can have higher radiance and is more coherent than the diode laser pump source. The solid state laser in Figure 1 is a good example of increased radiance and coherence from a solid state laser. The diode lasers emit separate output beams and are not coherent with respect to each other, but the solid state laser that they pump emits a single coherent beam with higher radiance than the diode lasers. The solid state laser can produce higher peak power than the diode laser pump source. Diode lasers are peak-power-limited devices; pulsing the output creates only a small increase in peak power. By contrast, a solid state laser can store the pump power from a diode laser for a few hundred microseconds. This stored energy can be released in 10-nsec pulses by Q-switching, which leads to a peak output power 10^4 times greater than the diode laser. Also, a solid state laser can have a narrower linewidth than a diode laser. The fundamental limit for laser linewidth decreases as the quality factor Q of the laser resonator increases. Solid state laser materials have less optical loss than the semiconductor material in diode lasers and can therefore have a larger-Q optical resonator.

The disadvantages of using diode lasers to pump a solid state laser, instead of using the diode laser output directly, are greater complexity, lower efficiency, and higher cost. In practice, the requirements of a given application, such as the desired overall efficiency, peak power, wavelength, and radiance, determine the choice.

Diode-Pumped Zig-Zag Slab Lasers

One aspect of our program in diode-pumped lasers is to produce relatively high-average-power and high-energy-per-pulse lasers for laser radar systems. This laser is required to have short pulses (5 to 10 nsec) for accurate range measurements by time of flight, to operate at high repetition rates (100 pulses/sec or greater), to provide output wavelength in the visible, to have average power output in the 10-W range, and to have a design that is scalable in energy per pulse and repetition rate. Our approach is to use a zig-zag slab of Nd:YAG for the gain medium, pumped by microchannel heat-sink-cooled planar arrays of diode lasers. These arrays are described in an accompanying article by J.P. Donnelly in this issue [8].

To obtain high energy per pulse a large number of diode lasers are necessary because of their peak-power limitation. The output energy from a pulsed solid state laser depends on the pump power from the diode lasers times the upper-state lifetime of the solid state laser material. The typical technique to achieve large energy per pulse is to use what are known as rack-and-stack arrays, which are the most common form of large two-dimensional arrays of diode lasers. The rack-and-stack

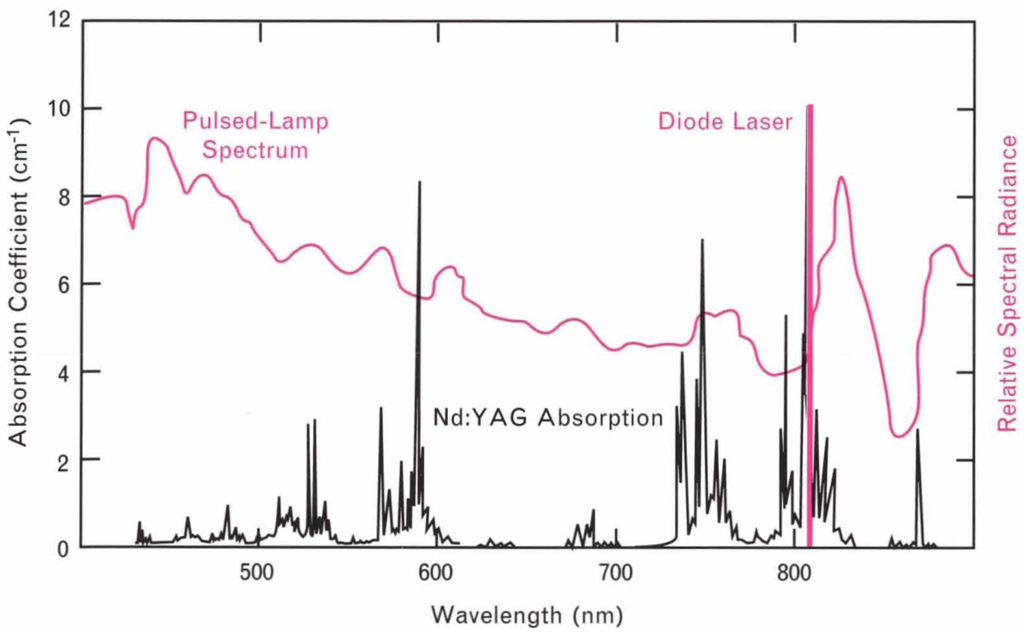

FIGURE 2. Absorption spectrum of Nd:YAG and the emission spectra of a diode laser and a pulsed flashlamp. The absorption spectrum is for 1%-doped Nd:YAG. The pulsed flashlamp emits radiation at all wavelengths while the diode laser emits radiation at essentially a single wavelength that can be tuned to a particular absorption line of the Nd:YAG.

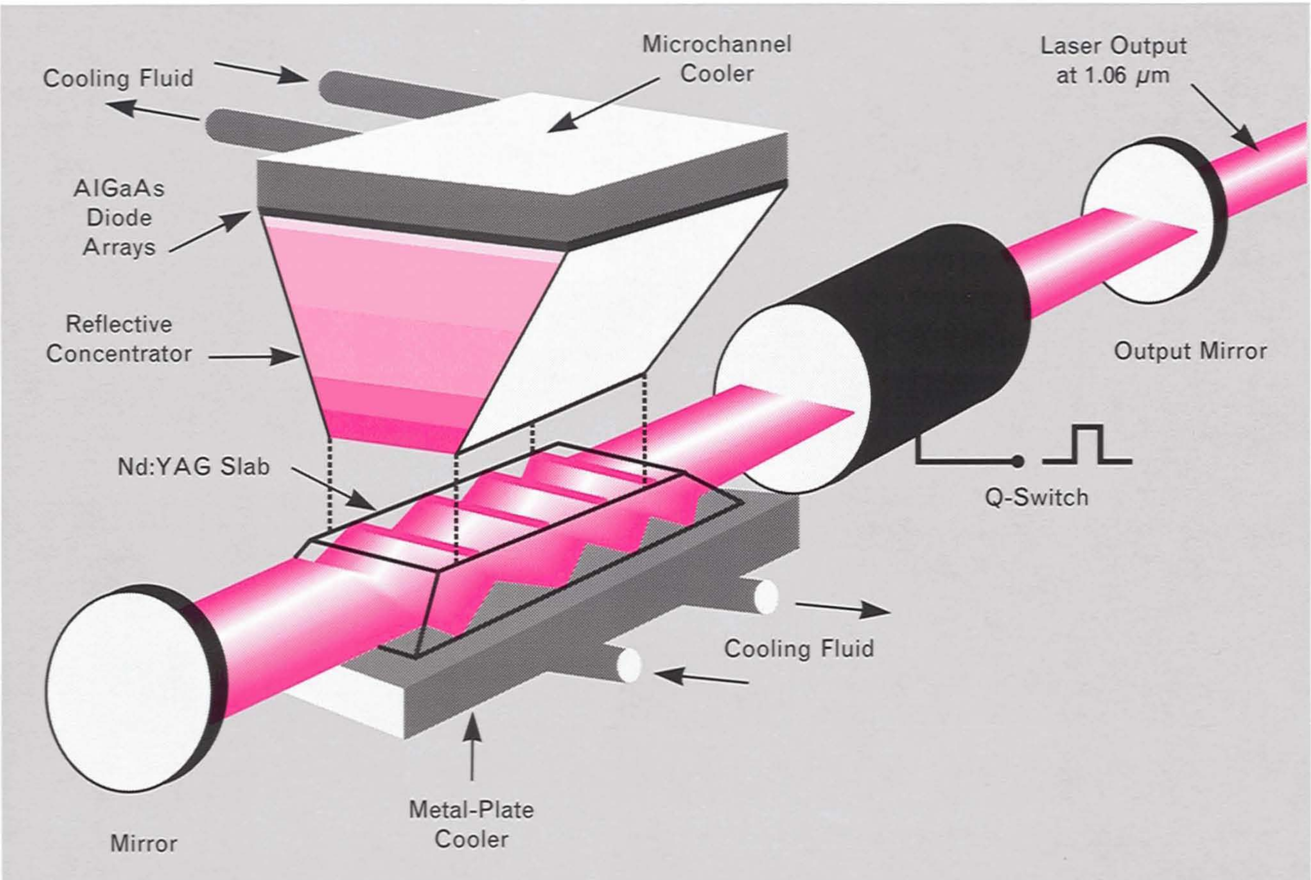

FIGURE 3. The concept of a diode-laser-pumped zig-zag slab laser.

array has produced up to 1 J of energy per pulse from Nd:YAG lasers [9–11]. The difficulty with rack-and-stack arrays is that they are limited by thermal effects to a 1% duty cycle, which is equivalent to a 50-Hz repetition rate with a 200-μsec pump pulse, and they cannot be run at high repetition rates. At Lincoln Laboratory we use planar geometries cooled with microchannel heat sinks to obtain high-repetition-rate performance.

For the solid state laser, a zig-zag slab is chosen to allow average power scalability by reducing thermal effects such as lensing and stress-induced depolarization [12, 13]. Thermal gradients induce these effects in the gain medium because the refractive index varies with temperature and differential thermal expansion causes stress. The gain medium is shaped to have the laser beam enter near Brewster's angle and then zig-zag through the slab by total internal reflection. The pump radiation is directed through the total internal reflection faces, and heat is extracted through these faces only; thus under uniform pumping conditions the heat flow is essentially one-dimensional. This flow eliminates stress-induced depolarization to first order, and the zig-zag path averages temperature-gradient-induced differences in index of refraction to zero across the beam cross section.

Figure 3 shows the overall concept for our diode laser system. The output from the diode arrays enters a reflective concentrator that increases the pump intensity delivered to the slab. A total of 10 cm^2 of diode arrays are used; each array contains eight 1-cm laser bars and the arrays emit pulses that are 150 μsec long. The concentrator transmits approximately 70% of the pump radiation to the slab surface; an improved concentrator with greater efficiency is currently being tested. The pump radiation is double passed in the Nd:YAG by a reflective coating on one side of the slab. The slab is $4 \times 6 \times 67$ mm^3 and is designed to have a total of nine internal reflection bounces. An electro-optic crystal (KD*P in this example) is also inserted in the cavity to allow Q-switched operation. Figure 4 is a photograph of

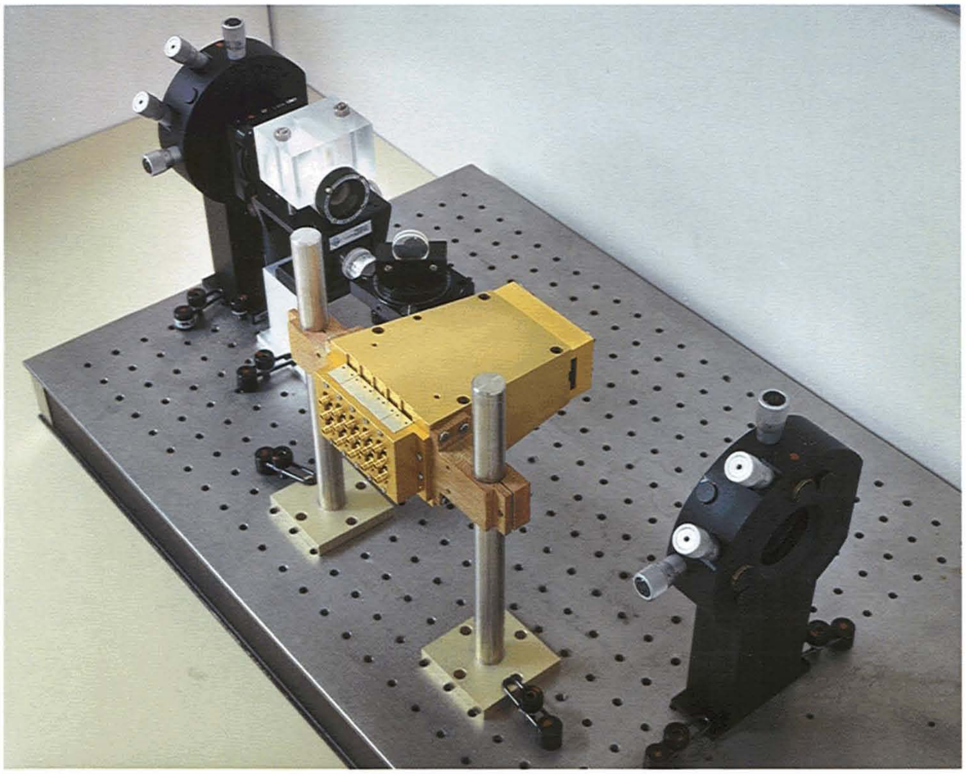

FIGURE 4. A 10-W diode-laser-pumped zig-zag slab laser.

the diode laser-pumped slab laser.

Figure 5 shows how we have generated up to 11 W average power by increasing the pulse repetition rate to 400 Hz in a long-pulse mode, at a pump energy per pulse of 138 mJ at the end of the concentrator. This repetition rate is not attainable by rack-and-stack arrays. As the repetition rate increases, the average output power deviates from a straight line because of limitations in the current drivers for the diode arrays and not because of thermal problems in the diode arrays or the slab. By using a set of diode arrays with an output energy per pulse of 196 mJ at the end of the concentrator, we have generated up to 70 mJ per pulse in a long-pulse mode, with a 36% optical-to-optical efficiency. With arrays that delivered 170 mJ at the output of the concentrator, we obtained 38-mJ Q-switched energy per pulse. The Q-switched 1.06-μm output was frequency doubled to the green with over 50% conversion efficiency in $KTiOPO_4$. Diode-pumped slab-laser technology should approach average output powers of 1 kW, given enough pump power, before thermal effects on the slab distort the beam quality; modeling and experiments support this expectation [14, 15].

Novel Laser Configurations

Side-pumped configurations such as the laser described in the previous section are the traditional method of

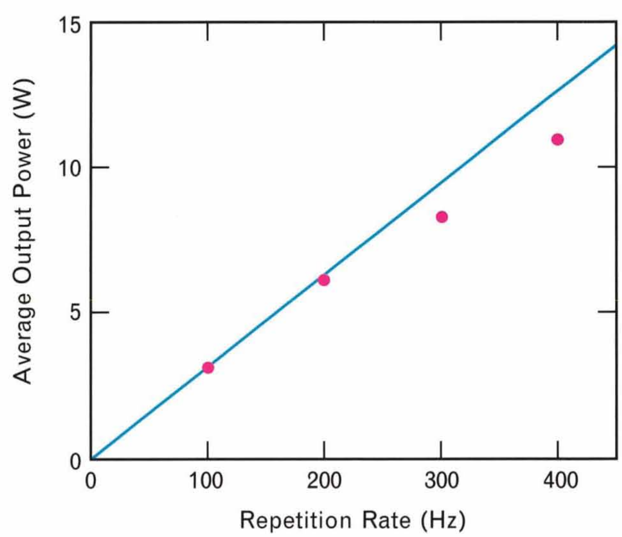

FIGURE 5. Average power output from the zig-zag slab laser as a function of the pulse repetition rate. The straight line is a fit to the low repetition-rate data points. The data points at a high repetition rate fall below this line because of power supply limitations.

scaling diode-pumped lasers to higher average power and energy per pulse because they provide a simple method of using large numbers of diode lasers to pump a solid state laser. The most efficient diode-pumped lasers that operate in the lowest-order transverse mode, however, have been end-pumped lasers in which the pump radiation is directed into the gain medium colinear with the laser output. Good beam quality and high efficiency are simultaneously achieved by overlapping the pumped volume in the gain medium with the laser mode. These lasers were not considered to be power scalable because the output from only a limited number of sources could be overlapped with the lowest-order transverse mode inside the laser cavity. In this section we discuss a proof-of-concept experiment that showed how multiple diode lasers in an end-pumped configuration can be used to attain good beam quality and efficiency simultaneously [16]. Then we discuss modeling of these types of pump sources, designs for high-energy-per-pulse lasers, and the use of fiber coupling of pump sources in diode-pumped lasers.

Figure 6 shows a schematic diagram of an experiment in which we used three high-power (500 mW) diode lasers to pump a Nd:YAG laser. Figure 7 is a photograph of the three-diode-laser pump source. A spherical lens collimates each diode laser, and then cylindrical lenses focus the laser outputs into the gain medium. The cylindrical lenses are used because the pump beam cross sections are not circularly symmetric. Figure 8 shows that the output of the laser is independent of the pump laser being used, and the output with all three diodes pumping simultaneously is approximately four times larger than the output from any single diode. Additional measurements showed that the laser operated in the lowest-order transverse mode.

These multiple diode laser pump sources can be further power scaled. We are currently building a source with four 1-W diode lasers. In a preliminary experiment we generated 1.2-W output at 1.06 μm for 2.5-W total input pump power from four lasers. To obtain higher energy per pulse a large number of diode lasers must be used. Based on a model of these multiple diode laser pump sources [17], we performed a preliminary design for a pulsed end-pumped laser with 400-mJ pump energy delivered in 150 μsec, as shown in Figure 9. The diode laser arrays are fabricated in monolithic two-

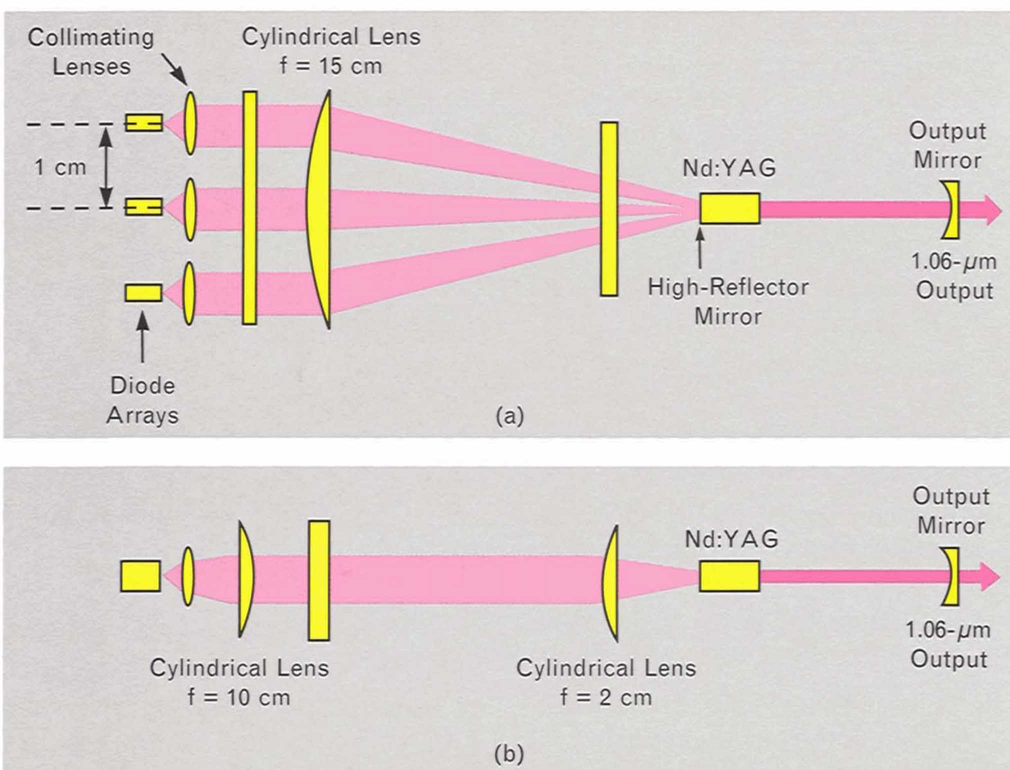

FIGURE 6. Schematic diagram of the scalable multiple diode laser end-pumped laser: (a) Plane perpendicular to the pn junction of the diode laser. (b) Plane parallel to the pn junction.

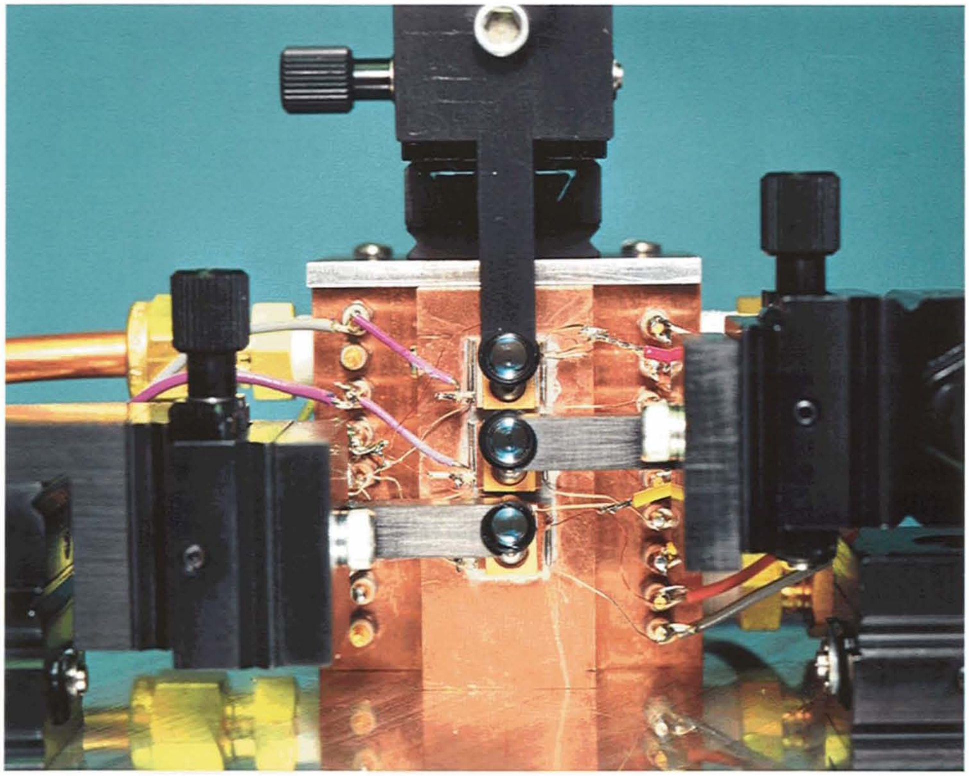

FIGURE 7. Photograph of the three 500-mW diode laser pump source. The pump beams are directed out of the plane of the paper. The three black round objects are the collimating lenses that are each mounted on translators. The diode laser mount is the gold piece behind each collimating lens.

dimensional arrays in which the positions of all elements are lithographically defined [8]. Monolithic two-dimensional lenslet arrays have been fabricated at Lincoln Laboratory with binary optics techniques [18] and mass-transport techniques [19]. The combination of monolithic diode arrays and monolithic lenslets reduces the number of components in the pump source and simplifies the alignment between lenses and large numbers of diode lasers. Thermal effects in the gain medium limit average power scalability, either by excessive thermally induced optical distortion or thermal stress-induced fracture. Recent work on the modeling of end-pumped systems showed that thermal effects can be reduced by making the gain element a spinning disk that is pumped off-axis [20]. A single spinning disk of Nd:YAG should allow over 1-kW output with high efficiency and good beam quality.

Figure 10 illustrates how these multiple diode laser sources can be efficiently coupled into a single multimode optical fiber, which allows power from a large number of sources to be delivered in a convenient manner [21]. Other demonstrations that couple multiple high-power diodes to a single fiber have combined beams by polarization, which limits the number of diode lasers to two. Our calculations show that, in principle, tens of watts and nearly one hundred diode lasers can be coupled into a fiber that is currently used by commercial vendors to deliver the power from a single high-power diode laser. We performed a proof-of-principle experiment that coupled a five-diode laser source with 68% coupling efficiency to a fiber with a 400-μm diameter and 0.12 numerical aperture. In principle, nearly 100 of these 1-W diode lasers can be efficiently coupled into this fiber.

Applications of high-power fiber delivery from diode lasers include pumping either bulk or fiber lasers, machining and marking, soldering, and power transmitting. High-power fiber-coupled diode laser sources could lead to the creation of compact high-power diode-pumped lasers. Similar systems that have been demonstrated either have relatively low power because they were limited to only one or two sources focused into a

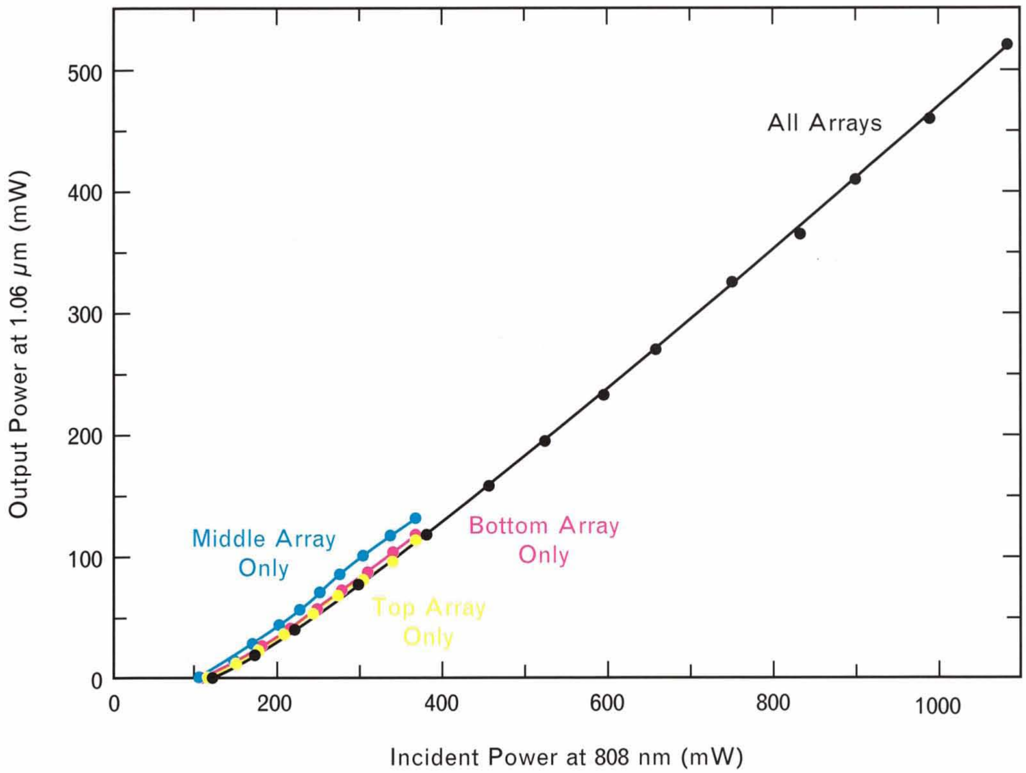

FIGURE 8. Experimental results from a scalable multiple diode-laser-pumped Nd:YAG end-pumped laser. The figure shows the output power for each diode laser pumping alone and for all lasers pumping at the same time.

fiber, or because they consist of a fiber bundle in which one or two sources were focused into a fiber and then many fibers were brought together to form the pump source [22]. A single fiber to carry all the power, as opposed to a fiber bundle, is desirable because it is less bulky and it maintains a greater degree of pump-beam brightness, which allows improved performance from diode-pumped lasers [17].

New Combinations of Pump Source and Gain Media

Most work in diode-pumped lasers has used AlGaAs diode lasers near 0.8 μm as the pump source and Nd^{3+} as the active ion in the solid state gain medium with output near 1.06 or 1.32 μm. The AlGaAs laser output can be tuned in the range of 0.70 to 0.86 μm by changing the relative amounts of Ga and Al, which pumps other rare-earth ion dopants and achieves laser operation at other wavelengths [6]. Some examples are Tm^{3+}, which is pumped at 0.78 μm and has laser output at 1.45 μm, 2.0 μm, or 2.3 μm, and Er^{3+}, which is pumped near 0.8 μm and has laser output near 2.8 μm [23].

A new type of diode laser, which is called strained-layer InGaAs and is being developed both here at Lincoln Laboratory and elsewhere, offers potential advantages over the AlGaAs diode laser. These strained-layer lasers consist of quantum wells of $In_xGa_{1-x}As$ grown on AlGaAs substrates. The lattice constants of the InGaAs do not match AlGaAs (thus the quantum well layers are strained), but for sufficiently thin quantum wells this mismatch does not cause accelerated degradation. In fact, the strained layer appears to impede propagation of crystal defects and thus results in a longer operational lifetime. Changing the In-to-Ga ratio and the thickness of the quantum well means that these devices can be tuned from approximately 0.87 to 1.1 μm. Even at a relatively early stage of development, these strained-layer InGaAs lasers have lower threshold current density, comparable efficiency [24], and similar if not better lifetime than AlGaAs quantum-well lasers [25, 26]. In addition, these devices degrade gradually, as opposed to the catastrophic failure seen in many AlGaAs diode lasers.

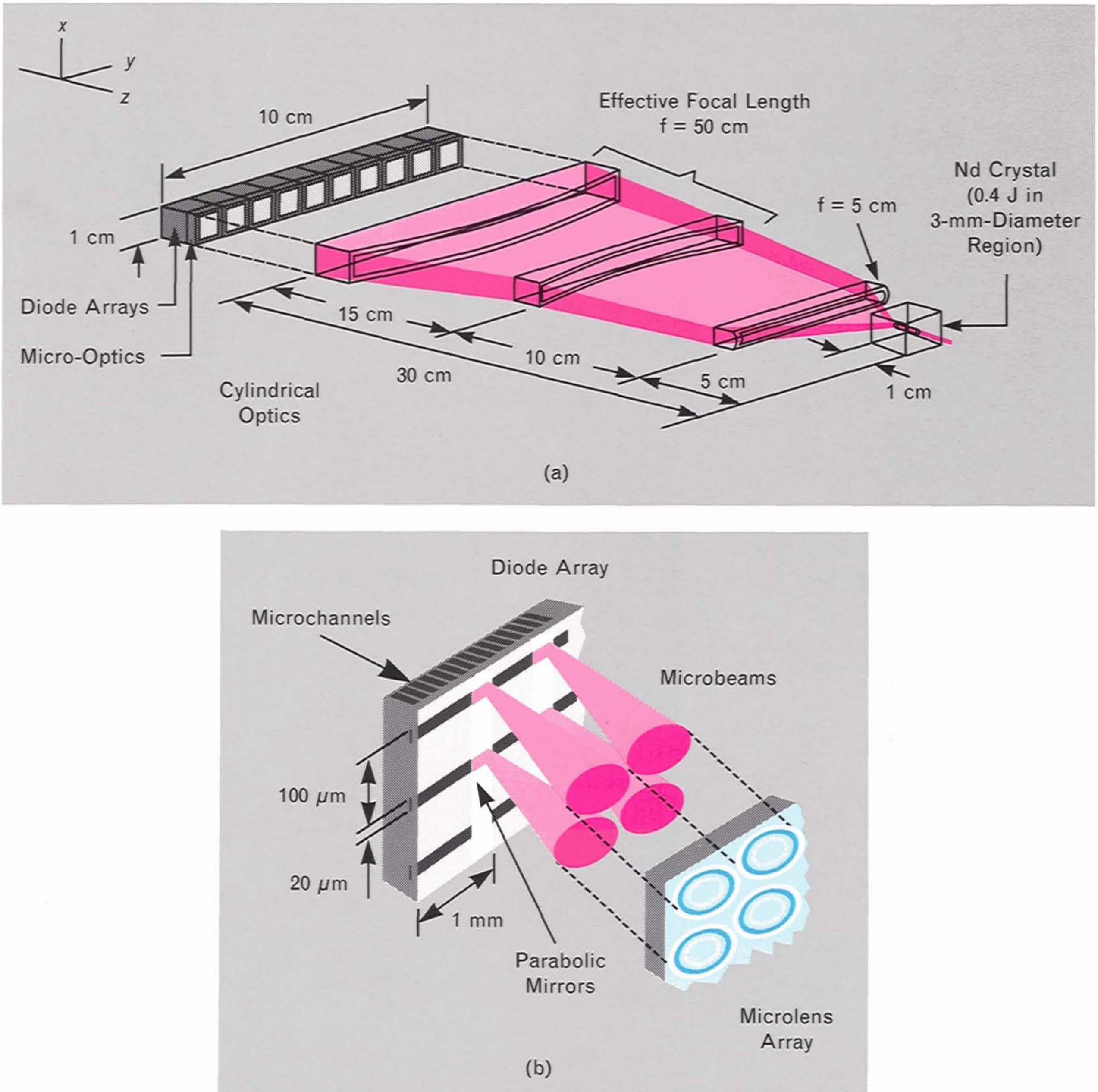

FIGURE 9. (a) Concept for a high-energy-per-pulse end-pumped laser based on monolithic diode arrays and monolithic lenslet arrays. A 1-cm crystal of Nd:YAG could be pumped with 400 mJ of energy delivered in 150 μsec into a diameter of 3 mm. (b) A blowup of the pump and lenslet arrays shows individual lenses and diode lasers. Each square centimeter contains a few hundred diode lasers and lenses.

Figure 11 shows how the strained-layer diode lasers can be used to pump several solid state lasers. The most interesting gain medium to date is Er^{3+}-doped optical fiber. The fiber is pumped at 0.98 μm; it can be made into either an amplifier or a laser oscillator at 1.55 μm, which is an important wavelength for fiber optic communications. Other gain media are Nd^{3+} pumped near 0.87 μm and operating near 1.06 or 1.32 μm, Er^{3+} pumped at 0.98 μm with output at 2.7 μm, and Yb^{3+} pumped at 0.94 to 0.97 μm and operating near 1.03 μm.

The most interesting laser for us is the Yb^{3+} laser pumped by InGaAs diodes. This laser offers several advantages over Nd^{3+} lasers; one of the most important advantages is three-times-lower heat generation because

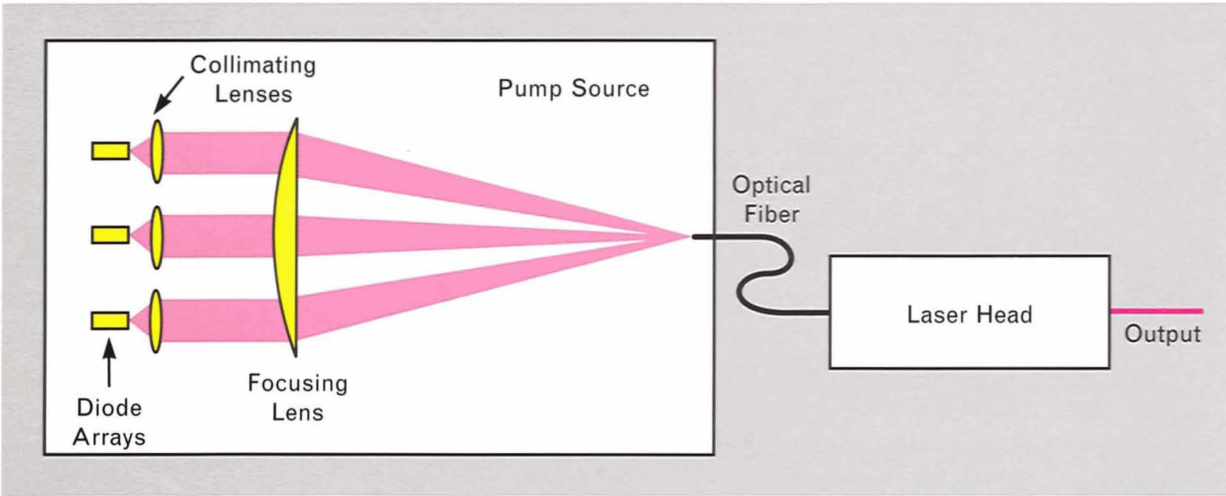

FIGURE 10. Multiple diode lasers coupled to an optical fiber that end-pumps another laser.

of the smaller difference between the pump and output wavelengths. Thermal loading decreases significantly when diode-pumped Nd lasers are compared with flashlamp-pumped Nd lasers, but the thermal load is still not insignificant. In fact, significant thermal lensing effects have been measured in high-power diode-laser-pumped Nd lasers [9].

Other advantages of the Yb lasers compared to Nd lasers are better energy storage and increased flexibility in allowed dopant concentration. Yb^{3+}-doped materials have longer metastable-level lifetimes; thus a Yb^{3+} laser operating in a pulsed mode should allow larger output energy for the same amount of pump power as a Nd^{3+} laser. The output energy per pulse is proportional to the product of the pump power and the metastable-level lifetimes. As an example, Yb:YAG has a lifetime of 1.2 msec compared to the Nd:YAG lifetime of 240 μsec. Also, Yb^{3+} can be doped to much higher concentrations (100 times higher) than Nd^{3+} because of an absence of dopant ion-interaction effects that occur in Nd^{3+}-doped materials. This higher concentration should allow a smaller-volume gain medium to produce the same output power or energy. Another advantage of the high doping is that the waste heat does not need to travel far to reach a heat sink. This reduced distance limits the total temperature rise in the gain medium and reduces the corresponding amount of stress induced by thermal gradients.

Perhaps the largest advantage of Yb^{3+} lasers is that, in some gain media, the absorption band of Yb^{3+} is large compared with Nd^{3+}; this advantage relaxes the requirement on the output wavelength of the diode laser. The output wavelength of diode lasers varies from diode to diode because of small differences in fabrication, and the wavelength changes with temperature on the order of 0.3 nm/°C. The variation in output wavelength leads to increased cost because only diode lasers in a small wavelength range are usable. The change in wavelength resulting from temperature variation requires that the diodes must be temperature controlled. Perhaps the most difficult task in the engineering of diode-pumped lasers is the necessity of holding the diode lasers at the optimum pump wavelength. In continuous-wave lasers, the optimum wavelength is maintained by using thermoelectric coolers that consume significant power. In pulsed lasers that use large numbers of diodes, the diodes are typically wavelength selected, and a cooling fluid at the appropriate temperature circulates through the heat sink to maintain temperature. In pulsed lasers, heating causes the wavelength to chirp during the pump pulse, which further broadens the pump spectrum. Relaxed requirements on wavelength control lead to simpler thermal management and a significant decrease in cost. Figure 12 shows the absorption spectrum in Nd:YAG and Yb:YAG. The peak absorption feature has a full width at half maximum of 2 nm in Nd:YAG and 18 nm in Yb:YAG. Thus, in Yb:YAG, temperature control of the diode laser wavelength may be unnecessary and wavelength selection is less stringent.

Yb^{3+} has two disadvantages compared to Nd^{3+}. First, the gain cross section is 10 times less in Yb:YAG than in Nd:YAG. Second, the lower laser level is close enough to the ground state so that significant population is in

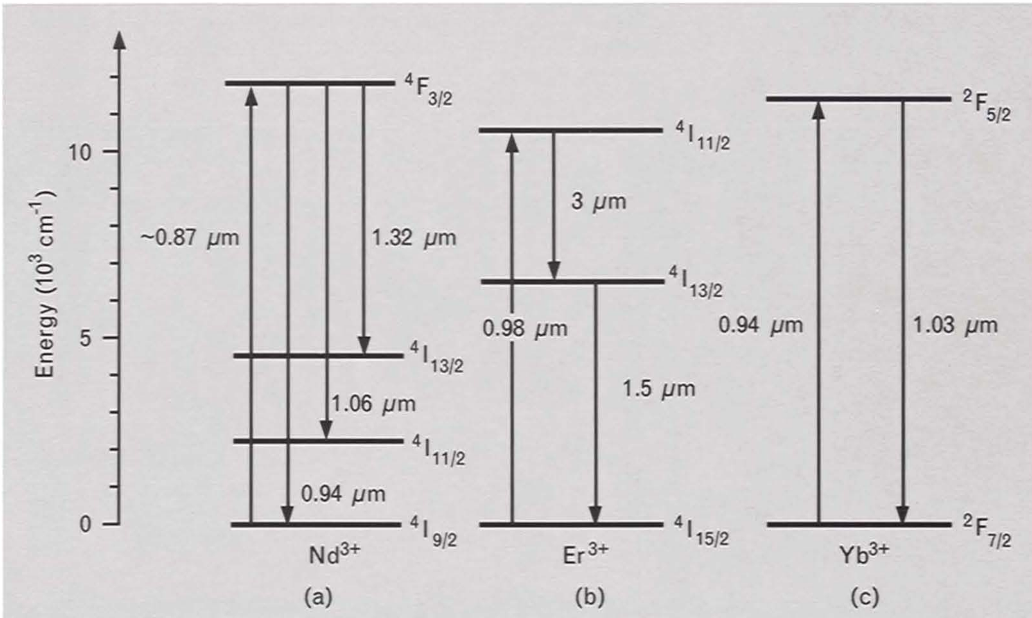

FIGURE 11. Energy-level schemes for solid state lasers pumped by InGaAs lasers. Nd has an absorption band near 0.87 μm with possible laser transitions near 0.94 μm, 1.06 μm, and 1.32 μm. (b) Er can be pumped near 0.98 μm with laser transitions near 3 μm and 1.5 μm. The 1.5-μm transition is particularly interesting for optical fiber amplifiers in communications. (c) Yb has absorption in the 0.94-to-0.98-μm range with a laser transition near 1.03 μm.

the lower laser level in thermal equilibrium at room temperature. Thus the Yb:YAG is a three-level laser with relatively high laser threshold.

An LED-pumped Yb:YAG laser was previously demonstrated, but the experiment was performed at 77 K so that the Yb:YAG was essentially a four-level laser [27]. With the higher brightness of the InGaAs diode laser, we demonstrated Yb:YAG laser operation at temperatures as high as 210 K in preliminary experiments; at this temperature the laser was a quasi-three-level laser. Our initial results were only at low power, and we are currently limited by InGaAs diode laser availability. We believe that further work in Yb^{3+} lasers in combination with the end-pumping schemes mentioned in the previous section will lead to room-temperature performance that compares with AlGaAs-pumped Nd^{3+} lasers. Because of their significant advantages, Yb^{3+} lasers may replace AlGaAs-pumped Nd^{3+} lasers as the diode-pumped solid state laser of choice for a number of applications.

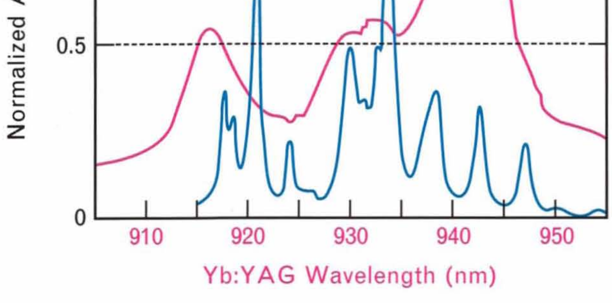

FIGURE 12. Absorption spectra in Nd:YAG and Yb:YAG. Each spectrum is normalized to the peak absorption. The line at 0.5 shows that the full width half maximum of the Yb:YAG absorption is much larger than for Nd:YAG.

Summary

We have demonstrated three novel diode-pumped solid state lasers. High-repetition-rate operation with high energy per pulse has been obtained in a zig-zag slab laser pumped by hybrid planar microchannel heat-sink-cooled diode laser arrays. A novel end-pumping scheme that utilizes multiple diode laser pump sources has been demonstrated, which should allow higher-power performance from end-pumped lasers with high efficiency and good beam quality. Finally, strained-layer InGaAs diode lasers have been used to pump a Yb:YAG laser. This combination offers significant advantages over Nd:YAG lasers pumped by AlGaAs, such as lower thermal loading and longer diode laser lifetime.

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TSO YEE FAN
is a staff member in the Quantum Electronics Group. He has been at Lincoln Laboratory since 1987, and his research is in solid state lasers and guided-wave optics. T.Y. received an S.B degree in electrical engineering and an S.B degree in materials science and engineering from MIT, and M.S. and Ph.D. degrees in electrical engineering from Stanford University.