Periodically, new technologies emerge that have a revolutionary, rather than evolutionary, impact on the photonics industry, such as charge-coupled devices (CCDs) and erbium-doped fiber amplifiers (EDFAs). In the area of industrial and scientific lasers, perhaps the most important technology advance in recent times has been the development of diode-pumped solid-state lasers. Initially, this technology was expected to offer significant improvements in electrical efficiency, reliability, and compactness. Diode-pumping has now gone far beyond these predictions by actually changing the fundamental rules of laser design. This has led to a new generation of lasers that offer “plug and play” performance benefits at infrared (IR), visible, and even ultraviolet (UV) wavelengths. This hands-free simplicity and high reliability have resulted in rapid growth in applications as diverse as semiconductor wafer inspection and production of fiber Bragg gratings (FBGs).

A number of different laser crystal materials can, in principle, be diode pumped. These include the neodymium-doped crystals and glasses and various chromium-doped colquirite crystals. Of the neodymium-doped crystals, vanadate (Nd:YVO₄) offers the highest gain but can only be produced in small crystals. Neodymium-doped yttrium aluminium garnet (Nd:YAG) is widely used in high-power lasers because large crystals are routinely available. Neodymium-doped yttrium lithium fluoride (Nd:YLF) is not widely used because of thermal fracture limitations. Amongst the chromium-doped crystals, chromium-doped lithium strontium aluminum fluoride (Cr:LiSAF) and lithium calcium aluminum fluoride (Cr:LiCAF) offer wide spectral bandwidths and can be used to produce diode-pumped tunable or mode-locked output. However, there are no commercial lasers based on these materials at this time.

In order to lase, these materials must be optically pumped. The high-voltage arc or discharge lamps traditionally used as pump sources introduce several limitations and drawbacks. First, these lamps are inefficient sources of light; most of the input electrical energy is converted into heat, which must be removed using cooling water. Although the spectral output of the lamps is broad, the neodymium-doped crystals only absorb light in a few sharp spectral bands, causing further inefficiency. The lamps also have lifetimes as short as 200 hours, and lamp degradation or replacement requires frequent realignment of the laser cavity. Lamps sometimes fail catastrophically, producing shattered glass that must be removed from the laser and/or cooling system. It’s just as important to note that these flashlamp-pumped lasers are notorious for poor beam quality and transient beam hot spots (see figure 1), which cause instabilities in frequency doubling (and tripling).
High-power diode lasers represent an attractive alternative pump source. These are edge-emitting semiconductor lasers with output at 808 nm, coincident with a strong neodymium absorption peak. Unlike lamps, these diode lasers convert much of their electrical input power directly into output light. Moreover, in a carefully designed laser, as much as 95% of the diode-laser output is absorbed by the laser crystal, in marked contrast to lamp-pumped designs. As a result, diode-pumped lasers can offer overall efficiencies an order of magnitude higher than those of lamp-pumped lasers.

There are several other important advantages inherent to diode pumping. Semiconductor pump lasers deliver very long lifetimes, which translates directly into greater system reliability and vastly reduced maintenance downtime. Also, it is possible to produce a much higher-quality beam (low M²) from a diode-pumped laser if the appropriate laser geometry is used. Finally, diode pumping can deliver up to an order-of-magnitude improvement in pulse-to-pulse stability.

**laser geometries**

The diodes used to pump commercial lasers come in two formats—bars and arrays. For low- to medium-power lasers (below 100 W), one or more laser bars provide sufficient pump power. A laser bar is a monolithic linear array of laser-edge emitters, i.e., a single chip with many emitting facets. A typical bar is about 10 mm × 1 mm × 0.1 mm in size and contains 20 to 70 individual emitters. The bars generally produce 30 to 50 W of continuous-wave (CW) output with a typical operating lifetime of more than 10,000 hours. Manufacturers of diode-pumped lasers often increase lifetimes to as much as 30,000 hours by de-rating the operating current.

High-power diode-pumped lasers (up to multiple kilowatts) are usually pumped by diode-laser stacks. A stack is a 2-D array in which individual bars are combined to produce higher total output power. Typical commercial pumps consist of stacks of six or 12 individual laser bars and offer continuous-wave pump powers as high as 600 W/stack.

A major design issue is how to efficiently couple the output of a bar (or stack) into the laser crystal. Both bars and stacks produce output from an extended area, and this output is rapidly divergent and astigmatic. The optimum solution depends on the laser crystal shape and cavity geometry and also on whether the laser is being designed for maximum power or for best mode quality. A number of different crystal shapes have been investigated, including rods, slabs, or thin disks (see figure 2). Today, most commercial lasers use rods or slabs. Slabs can generally be scaled to higher power and are thus favored for brute power applications. Rods can be optimized for good beam quality and are generally preferred for precision applications such as micro-machining and fine marking.

The laser crystal can be pumped through its end facets (end pumping) or through the side (side pumping; see figure 3 on page 46). End pumping generally leads to better mode qual-
ity, whereas side pumping usually produces poor beam quality but can be scaled to higher power. Each has its advantages and drawbacks.

End pumping delivers the highest optical efficiency. If the pump laser output is suitably shaped, it can be mode matched to the cavity, resulting in good transverse mode ($\text{TEM}_{00}$) quality. This shaping of the pump light can be performed using conventional optics or fiber bundles. Since this configuration maximizes efficiency and beam quality, many low- to medium-power lasers (up to 50 W) use end-pumped configurations. Moreover, because this configuration requires only a small rod of laser crystal, it has enabled the widespread use of Nd:YVO$_4$, which is difficult to grow in large crystals.

End pumping creates power limitations, preventing the use of the technique in higher-power lasers. The end facets of a rod are only a few millimeters in diameter or less. When the pump light is focused into these small facets, it causes intense local heating that can induce a refractive index gradient, i.e., thermal lensing. In addition, expansion of the crystal material actually causes slight bulging of the facet. This causes additional lensing and also strains the crystal and its coated facet. In fact, producing the antireflection coatings on the crystal facets requires complex designs and sophisticated fabrication procedures, since they must withstand high power as well as this thermomechanical strain without cracking or delaminating.

In the case of YVO$_4$ and YAG, the thermal lensing ultimately destabilizes the laser output as the power is increased. Crystals of YLF have a lower fracture threshold and will actually crack at higher power levels. One way to limit thermal problems is to use a thin disk of laser crystal with efficient heatsinking. However, the thin disk does not absorb all the pump light in a single pass, requiring the use of elaborate multi-pass schemes.

This thermal limitation can also be circumvented by pumping the laser crystal through a large surface area. Laser engineers accomplish this goal by either end pumping a slab-shaped crystal, which has large end facets, or by side pumping a rod-shaped crystal. In both cases, the pump light fills an extended volume of the crystal, resulting in multi-mode output. Although they offer power in the kilowatt range, most of these lasers have poor mode quality with very high $M^2$ values, however.

Many important applications need a combination of high power and good mode quality, however. A typical exam-
therapy (LLLT and MLLT), spider-vein removal, teeth whitening, and rubidium and potassium vapor pumping techniques used for spin exchange in next-generation MRI systems. This medical market totaled about $80 million in 2000. Photodynamic therapy (PDT) has recently been commercialized for treatment of age-related macular degeneration (ARMD), a leading form of blindness. But unlike previous market predictions, which suggest that PDT would be the largest diode medical application, the aesthetics market, which includes hair and spider-vein removal, has grown the most. Less expensive diode-laser-based hair removal systems are now finding their way not just into dermatologists offices but also into day spas.

New applications for diode lasers continue to emerge, including materials processing, pumping of next-generation military and avionics platforms, and imaging. The automotive market may be the next high-growth commercial area with applications in taillight assemblies and collision avoidance systems. Both technical and market advances have contributed to the ubiquitous presence of diode lasers. Just as cost per watt is decreasing, output power is increasing, along with reliability and lifetime. With compact, inexpensive 100 W diode lasers soon to be commercially available on the market, there is no telling just what the next great diode-laser application may be.

—Merrill Apter, Coherent Inc.

Reference
1. Courtesy of Strategies Unlimited
are arranged in a zig-zag configuration so that their outputs are added to yield double the output power with very high beam quality (see figure 4).

For many applications, however, laser cost is more important than laser efficiency. Interestingly, the most costly component in any of these lasers is the packaging of the diode laser. Consequently, high-power large stacks offer much lower cost per watt than multiple arrays or several medium-power stacks. One way to produce high power and low $M^2$ at a reasonable cost is therefore to side pump a rod with a high-power stack. Internal apertures (spatial filters) then trim the beam and sacrifice efficiency for beam quality.

sealed laser heads

The most dramatic impact of diode pumping has been in low- to medium-power lasers, in which it has enabled designers to build the sealed laser head. Traditionally, lasers are constructed using discrete macroscopic components, including the gain medium and the optics. The optical elements are held in adjustable mounts in an open cavity (with a dust cover), allowing free access for service and optical adjustments. In high-vibration environments, lasers may require correction of the optical alignment on a weekly or even daily basis.

The purpose of the sealed-laser concept is relatively simple—to take full advantage of the inherent stability of solid-state technology. There are several elements to this approach: Remove the only consumable (the diode array) from the laser head, use robust optical components, apply permanent mounting to assemble the components in a monolithic structure, design the structure for thermal stability, build the laser in a cleanroom atmosphere, and then factory seal it.

The approach offers a number of benefits. The diode array is permanently fiber coupled, with each output facet coupled into an individual fiber. These fibers are then reformed into a circular bundle. This arrangement serves two important purposes. First, the pump light is now in the form of a circular beam that can be efficiently end-coupled into the laser rod. Moreover, with appropriate focusing optics in the laser head, most of the pump light is coupled into the $TEM_{oo}$ mode of the laser cavity, resulting in a very high-quality output beam (typical $M^2 = 1.1$). The fiber-coupled design allows the diode array to be remotely located in the laser power supply. A diode can be field replaced within minutes without requiring realignment of the laser or any downstream optics in the system. Remote location of the pump diodes also enables the laser head to be much more compact than a lamp-based laser, which saves valuable space in applications performed in cleanrooms and laboratories, as well as simplifies integration into OEM equipment.

The sealed laser head has had a dramatic impact on the throughput, work quality, and economics of precision applications for near-IR laser light, including marking metals and trimming electronic components. However, they are having an even more significant impact in green and UV applications, such as marking plastics and semiconductors, micro-via drilling, wafer inspection, and FBG production. Lamp-pumped UV lasers have been notoriously unstable, requiring constant attention and replacement of damaged optics. In contrast, the latest sealed UV laser can be operated for weeks and months at a time without the need for any maintenance.

Diode-pumped solid-state laser technology has more than fulfilled its initial promise. It has increased the performance and reliability of solid-state lasers over a wide range of powers and wavelengths. In the low- to medium-power range in particular, it has allowed the development of the sealed laser head and has set new standards in output stability, beam quality, laser reliability, and ease of use.