New pumps for old lasers

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A technology based on advanced semiconductor lasers promises to reduce the cost and improve the reliability and performance of the work-horse of the laser industry.

The first laser was demonstrated more than 50 years ago at Hughes Research Laboratories by Theodore H. Maiman on May 16, 1960. The laser consisted of a solid-state flashlamp-pumped synthetic ruby crystal that produced red laser light. Such lasers, in which a light source is used to pump a solid gain medium located within a resonant cavity to produce stimulated emission (lasing), are known as optically pumped solid-state lasers. Today they are among the most widely used lasers, covering a wide array of applications such as materials processing (cutting, drilling, welding, and marking), semiconductor fabrication (annealing, and wafer cutting), industrial printing, laser-based displays, medical and surgical procedures, rangefinders, instrumentation, and scientific research. One of the primary advantages of the solid-state laser over other types is that it enables very high energy output in a very high-quality, low-divergence beam.

One of the most crucial components of the optically pumped solid-state laser is the light source that pumps the solid gain medium. The pumping source primarily employs two different technologies, lamps and semiconductor laser diodes. The lamp in a solid-state laser system, although straightforward and inexpensive, is generally inefficient and must be replaced often. Laser diodes are very efficient, narrow-band, low-divergence, and low-cost light sources, which makes them highly compact and efficient for pumping purposes as compared to lamps. Solid-state lasers that use semiconductor lasers as pumps are often referred to as diode-pumped solid-state lasers (DPSSLs).

Edge-emitting lasers are currently the dominant pump technology for DPSSLs. Although they provide superior brightness and efficiency, they suffer from drawbacks, such as complex coupling optics, strongly temperature-dependent emission wavelengths, and limited reliability at high operating temperatures. The complexity of the coupling optics increases the system costs (the edge-emitting pump modules are often fiber-coupled), and the strong wavelength dependence on temperature requires a cooling mechanism to keep the emission wavelength of the pump within the generally narrow absorption spectrum of the solid-state gain medium, increasing costs further.

Novel high-power semiconductor lasers based on the vertical-cavity surface-emitting laser (VCSEL) technology emerged recently as potential candidates for solid-state laser pumps. Their key advantages over the existing edge-emitter technology are simpler coupling optics, reduced wavelength sensitivity to temperature, and increased reliability, especially at high temperatures. In addition, they benefit from low-cost manufacturing and two-dimensional planar scalability. As my colleagues and I have demonstrated, a single VCSEL chip can contain several hundreds or thousands of low-power single elements in a planar 2D array configuration in order to scale up the power. Several of these 2D VCSEL arrays can be combined for even higher power. Furthermore, because the positions of the single elements within an array are photolithographically defined, the elements can be arranged in any user-defined layout. Therefore, although the VCSEL array chip has a square or rectangular shape, the emission area within the chip can be of any shape.

This advantage is illustrated in Figure 1, which depicts a high-power VCSEL module that we designed for end-pumping

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of solid-state lasers. The module comprises four VCSEL arrays electrically connected in series. Each array has a quarter-circular emission area consisting of thousands of single elements. The four arrays are arranged to provide a circular emission area approximately 1cm in diameter. The light is emitted perpendicular to the plane of the arrays. This module can provide a peak output power of up to 800W around the 808nm emission wavelength in quasi-continuous-wave (QCW) operation. It emits a uniform circular beam with a divergence of $19^\circ$ (full-width, $1/e^2$). The emission spectrum of the pump is less than 2nm wide (full width at half-maximum).

Figure 2 shows a Nd:YAG solid-state laser in an end-pumping configuration using our VCSEL module as the pump. The light from the VCSEL pump is focused into one end of the Nd:YAG rod using a simple focusing lens. The Nd:YAG rod is located between two mirrors that form the resonant cavity. The back mirror is highly reflective at 1064nm and is anti-reflective at the pump wavelength. The output mirror is partially reflective at 1064nm and highly reflective at the pump wavelength. In an earlier demonstration of a similar VCSEL-based end-pumping configuration, a Q-switching element in the cavity was added in order to obtain 18mJ of very short pulse output energy from the solid-state laser. The results from the set-up described in Figure 2 are shown in Figure 3. We obtained more than 250W of peak power from the solid-state laser at a peak pump power of 700W under QCW operation (250µs pulse width and 4Hz duty cycle).

We have also successfully demonstrated high-power VCSEL modules in side-pumping configurations with very simple coupling optics. Such configurations are advantageous for scaling up the power of solid-state lasers. However, although the VCSEL technology offers many benefits as a pump source for solid-state lasers, it still lags slightly behind the edge-emitting technology in terms of power density and efficiency. We are working to address these shortcomings.

**Figure 2.** The VCSEL-based solid-state laser consists of (left to right) the high-power VCSEL pump, simple focusing lens, first highly reflective mirror, Nd:YAG gain medium, and second partially reflective mirror. The focusing lens focuses the pump light directly into one end of the solid-state gain rod.

**Figure 3.** The solid-state laser light peak output power (1064nm) as a function of the VCSEL pump peak output power (808nm). The pump module is operated under quasi-continuous-wave conditions at a pulse width of 250µs and a duty cycle of 4Hz.

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**References**

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