

Quasi-CW Solid-State Lasers Expand Their Reach

The high peak powers, picosecond pulse durations and high repetition rates of mode-locked Nd:YVO₄ lasers provide an edge in ultrafast research, materials processing and flow cytometry.

by Andrew Held and Arnd Krueger

Flexibility may be the top selling point of mode-locked, diode-pumped Nd:YVO₄ lasers. Their 80-MHz repetition rates allow them to compete in applications typically reserved for CW sources such as argon-ion lasers. Their combination of high peak powers and picosecond pulse durations enables precision machining by incising finer and thinner cuts with almost no peripheral thermal damage. Their high peak powers also support efficient harmonic generation, providing several watts of power in the green, the UV and the deep-UV.

These Nd:YVO₄ lasers both complement and compete with conventional lasers. In micromachining ap-

plications, for example, mode-locked devices offer an operating regime complementary to high-speed Q-switched lasers in terms of repetition rate and peak power.

Ultimately, the key to mating these lasers with the right applications lies in developing an understanding of how they work.

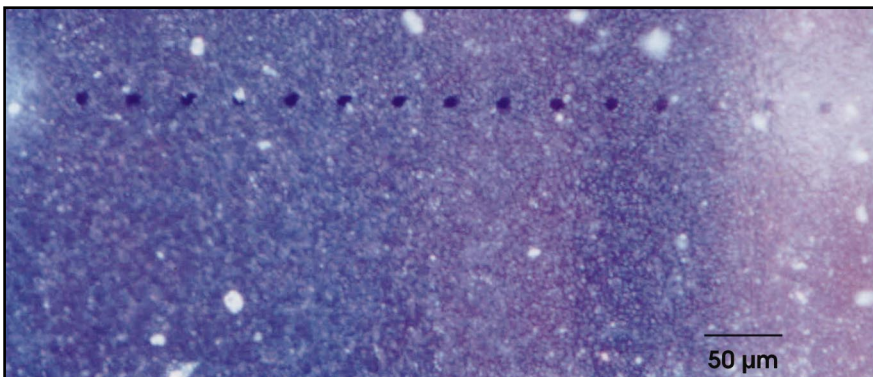
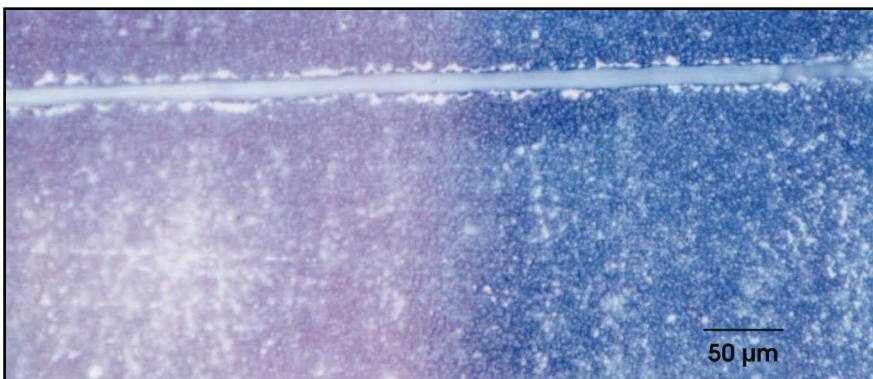
How they work

In a mode-locked laser, the phases of the longitudinal cavity modes are locked together. In the time domain, this generates one intense pulse that circulates around the cavity, producing pulsed output. Mode-locking can be active or passive in nature.

In one such laser — Spectra-Physics' Vanguard — engineers replaced the rear high reflector with a passive component, a saturable Bragg reflector. Originally developed and patented by Lucent Technologies Inc. of Murray Hill, N.J., this highly reflective cavity mirror also acts as a passive mode-locking element. Its outer layer contains a quantum well of InGaAs thick enough to absorb 1064-nm laser radiation.

When the laser operates in CW mode at low fluence, its reflector introduces significant cavity loss. The high peak powers that are characteristic of mode-locked operation, however, bleach the reflector and reduce the loss. Because a laser always seeks to operate at the highest value of gain minus loss, the saturable Bragg reflector automatically produces mode-locking that does not suffer from dropouts, unlike earlier passive techniques.

The time it takes for a mode-locked pulse to circulate around the cavity determines a mode-locked laser's repetition rate. Thus, longer cavities deliver lower repetition rates and vice versa. Research has shown that 80 MHz is the optimum repetition rate for most applications. A lower rate



Cuts in epoxy glass made by high-repetition-rate, mode-locked Nd:YVO₄ UV lasers (top) are finer and smoother compared with cuts made by fast Q-switched lasers of the same average power (bottom). The devices scribed samples at a scan speed of 1000 mm/s.

Nd:YVO₄ Lasers

would not satisfy the demands of CW and quasi-CW applications. For a given average power, a faster repetition rate would reduce the peak power of the individual pulses, which could limit the advantage of these lasers for materials processing and efficient harmonic generation.

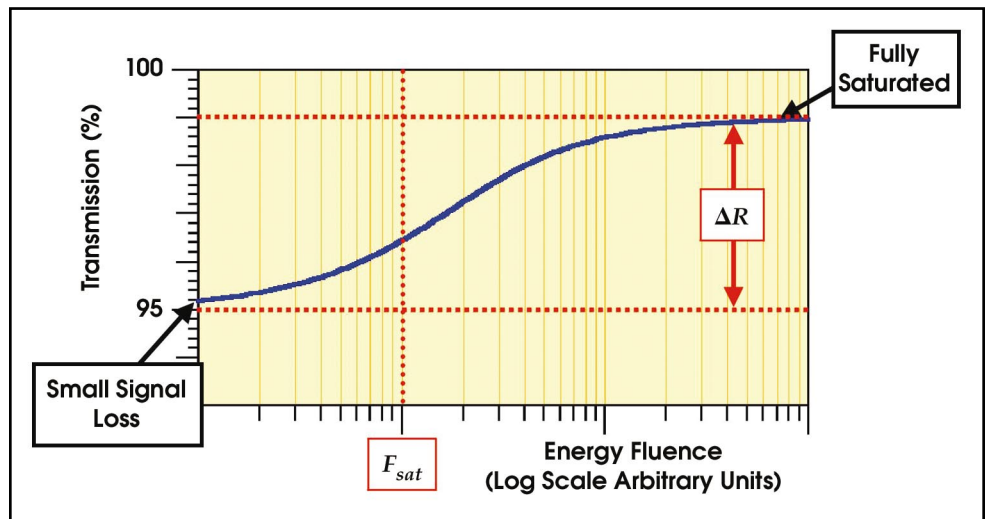
In a mode-locked laser, the shortest possible pulse is inversely proportional to the spectral bandwidth of the output. In an Nd:YVO₄ laser, the typical bandwidth of ~180 pm (~50 GHz) translates to a minimum pulse width of 6 ps. In practice, these new lasers can deliver infrared pulse widths of approximately 12 ps.

The properties of Nd:YVO₄ make it possible to extract relatively high power from a single laser rod, which simplifies the cavity design. The end-pumped rod has a single diode to maximize mode quality and TEM₀₀ power. This configuration delivers 6 W at 1064 nm, 2 W at 532 nm using an extracavity doubler module, and more than 350 mW at 355 nm with a tripler module.

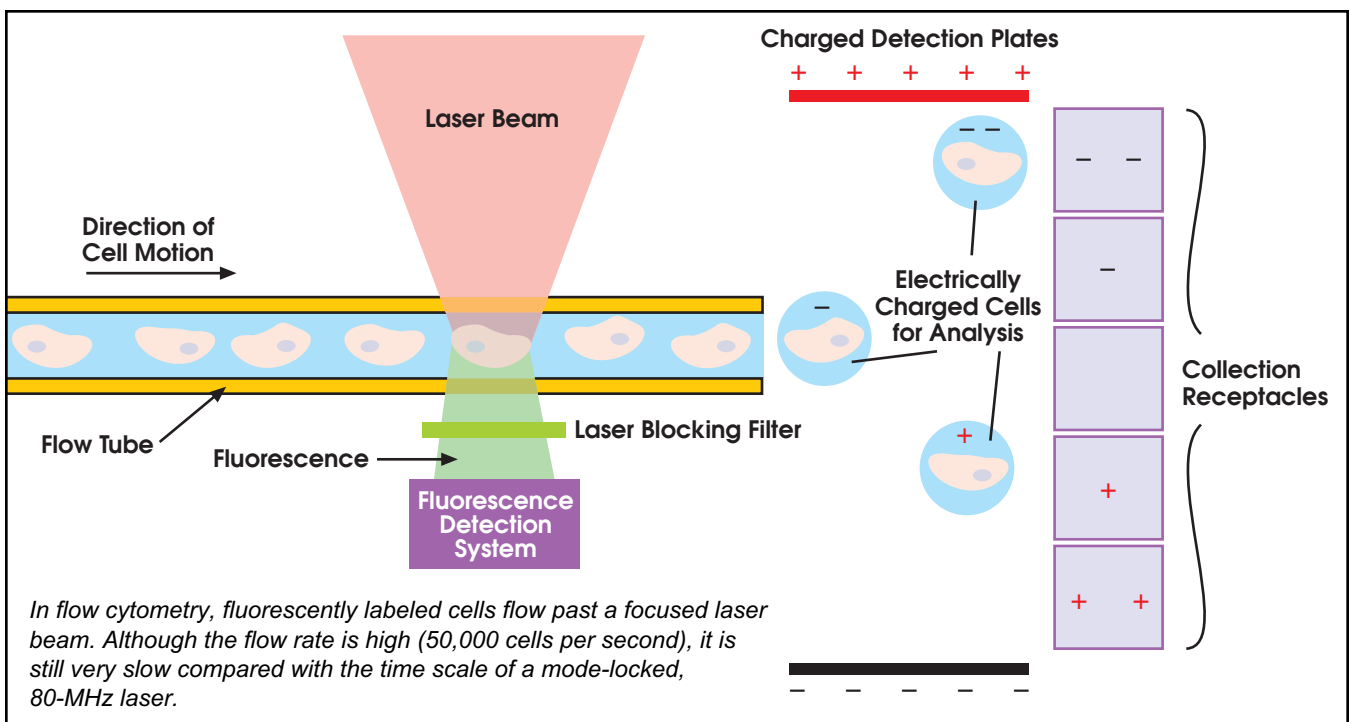
A higher-power version uses

a simple, double-pass amplifier, wherein the laser pulse passes twice through a second Nd:YVO₄ rod that is pumped by diodes at both ends. This produces more than 20 W at 1064 nm, 10 W at 532 nm and 4 W at 355 nm. Because of the short pulse duration, the peak power is several kilowatts, making this laser suitable for materials processing applications.

Diode-pumped Nd:YVO₄ lasers are also compact: Although an 80-MHz repetition rate requires a cavity length of 1.8 m, these lasers have a folded cavity that reduces the head size. They require no external cooling water, operate from conventional line voltage and do not need a three-phase power installation. Because they rely on diode-pumping and permanently aligned components, diode



In a saturable Bragg reflector, the absorption saturates at higher intensities, thereby increasing its reflectance. End users can tailor both the absorption and the saturation fluence for individual applications.



In flow cytometry, fluorescently labeled cells flow past a focused laser beam. Although the flow rate is high (50,000 cells per second), it is still very slow compared with the time scale of a mode-locked, 80-MHz laser.

lifetimes exceed 10,000 hours. Also, because the pump diodes are produced as fiber-coupled modules and are located in the power supply, no optical realignment is necessary during diode replacement.

For micromachining, mode-locked lasers offer an operating regime complementary to high-speed Q-switched lasers in terms of repetition rate and peak power. In a performance comparison reported at the October ICALEO conference in Scottsdale, Ariz., both a mode-locked UV laser and a Q-switched laser produced 4 W of 355-nm UV output. However, the mode-locked device delivered repetition rates of 80 MHz and pulse widths of 10 ps, whereas the Q-switched laser operated at 30 kHz with pulse widths of 35 ns.

In the case of metal (copper) samples, the Q-switched laser proved more effective for drilling and scribing because of its higher energy per pulse. However, in the case of several nonmetallic samples, such as epoxy glass and thin films of polyimide, the mode-locked laser delivered higher cutting speeds and produced more finely detailed cuts. Furthermore, the thinner the film, the bigger the maximum speed difference between the two laser types.

In 50- μ m polyimide, for example, the mode-locked laser was 7.5 times faster and produced much thinner cuts than the Q-switched laser. In addition, the high repetition rate of the mode-locked device produced smooth cuts, with no evidence of individual pulses.

Flow cytometry

One application for CW UV laser radiation is flow cytometry, in which the source excites multiple fluorophores that emit in different characteristic spectral regions. In this application, prediluted cells pass a focused laser beam one at a time in the form of a stream or tiny droplets. The system detects the fluorescence using a series of photodetectors, each of which features its own spectral filter. This allows counting or sorting of cells using an electric field to deflect the cells according to their fluores-

cence profile.

In a high-performance flow cytometer, the typical flow rate is approximately 50,000 cells per second. In that time frame, an 80-MHz, mode-locked laser seems to be CW. Recent research by scientists at the Laboratory for Cell Analysis at the University of California, San Francisco, and colleagues at Becton Dickinson BioSciences in San Jose, Calif., confirmed the suitability of these lasers in a project using a 355-nm, oscillator-only device that produced 350 mW.

A key question answered by this study was whether the high peak power would kill or damage the sorted cells. In fact, with its power attenuated to below 260 mW, the laser appeared to have no effect on cell viability.

As a result, the scientists concluded that this laser works well in research and clinical laboratory applications of flow cytometry and that it could replace UV argon-ion lasers in many cases.

Circuit boards

Direct imaging of printed circuit boards also requires CW or quasi-CW UV laser radiation. The traditional board fabrication process relies on light to polymerize a photoresist, followed by a wet-chemistry photoetch process and copper plating. Engineers usually create the design for exposing the photoresist as a negative image, but this introduces several limitations, especially with the trend to push line densities ever tighter to meet the demand for miniaturization and increased functionality in consumer products.

First, the plates may distort slightly as a function of temperature and humidity. In fact, most circuit board manufacturers keep several plates for different ambient conditions. Second, layer-to-layer registration becomes increasingly important and difficult at high line densities, requiring the use of oversize copper pads on each layer to ensure that the vias form good electrical connections between the layers. In addition, the plates are not robust, having a finite lifetime. Fixed artwork

also limits flexibility and increases the cost of short, prototype production runs.

One solution is to create the desired pattern in the photoresist with a scanning UV laser beam. Ion lasers are not good choices for this application because of their high power and water consumption and because of the limited lifetime of their plasma tubes. Q-switched solid-state UV lasers also will not work because their pulse rates could potentially limit process throughput. At the high scan speeds delivered by the polygon mirrors, the scanned laser beam would produce a broken line rather than the desired continuous line.

Thus, the high-repetition-rate, mode-locked quasi-CW laser becomes a good choice to meet the needs of this growing application. Moreover, with up to 4 W at 355 nm from an oscillator/amplifier model, beta testing in this application indicates that the output power is sufficient to support economically attractive throughput rates.

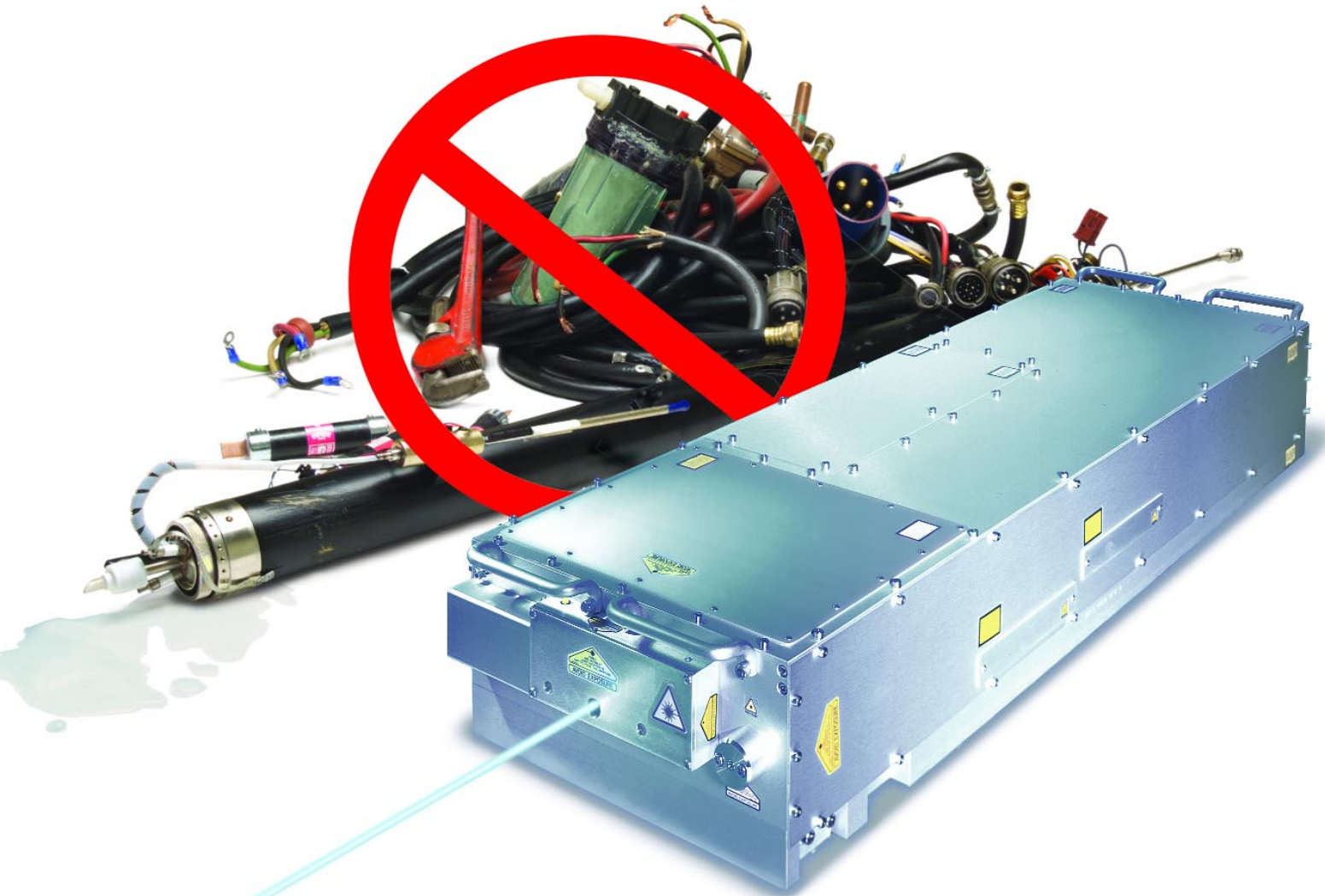
What's ahead

Mode-locked, diode-pumped lasers also offer potential benefits to other applications. For example, the research community has a large installed base of synchronously pumped dye lasers supported by a generation of failing lamp-pumped, ultrafast Nd:YAG lasers. These lasers perform multiphoton spectroscopy and time-resolved photochemistry at "difficult" wavelengths. The Nd:YVO₄ systems can serve as a replacement pump source for these dye lasers — an application that represents a sizable potential market in the near term. In fact, a 2-W green model has a cavity length optimized to deliver a choice of 76- or 80-MHz outputs, the typical repetition rates for commercial ultrafast dye lasers. □

Meet the authors

Andrew Held is marketing manager for the diode-pumped Q-switched lasers at Spectra-Physics in Mountain View, Calif.

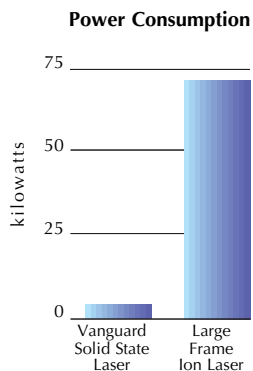
Arnd Krueger is marketing manager for the company's diode-pumped continuous-wave and ultrafast lasers.



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