More Efficient and Less Complex

ENHANCING THE SPECTRAL AND SPATIAL BRIGHTNESS OF DIODE LASERS

Recent breakthroughs in semiconductor laser technology have improved the laser system compactness, efficiency, power and beam quality. Simultaneously, the new developments help reduce thermal management cost and complexity in the system.

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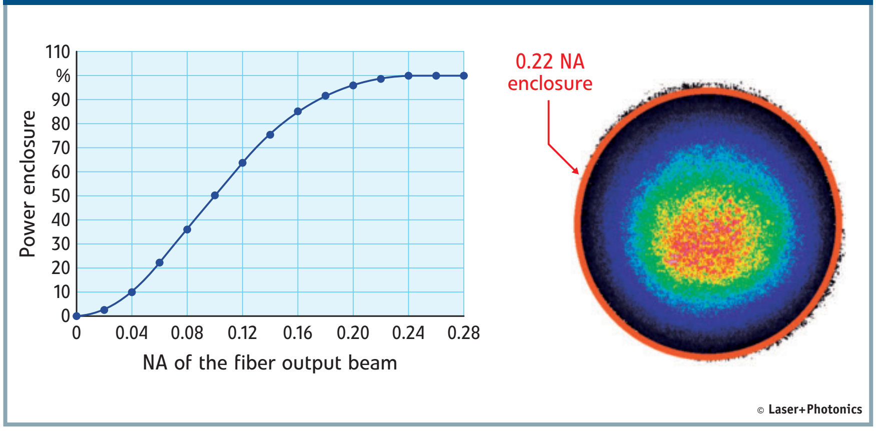
High-brightness pumping has several key advantages. First, in solid-state lasers, it allows higher gain, better beam quality and more efficient pumping by permitting a tighter focus or longer working distance for end-pumping applications. For example, pumping of Nd:Vandate crystals at 888 nm provides low and isotropic absorption, with equal coefficients for both states of polarization. This allows for reduced thermal load effects and flexible delivery of the pump light through a multimode fiber without losing conversion efficiency [1]. Given the lower absorption coefficient at 888 nm, this approach requires high spatial brightness pumps, such as the 100 W, 400 µm core fiber-coupled module available from QPC, to achieve mode-matched pumping for end-pumping of longer crystal rods.

This unprecedented spatial brightness at near-IR wavelengths is enabled by new facet protection techniques based on QPC's re-growth technology, which reduces the risk of catastrophic optical damage at short wavelengths thereby allowing QCW operation of fiber-coupled devices up to 100 W out of a 400 µm core fiber from a low fill factor single bar device at 808 nm.

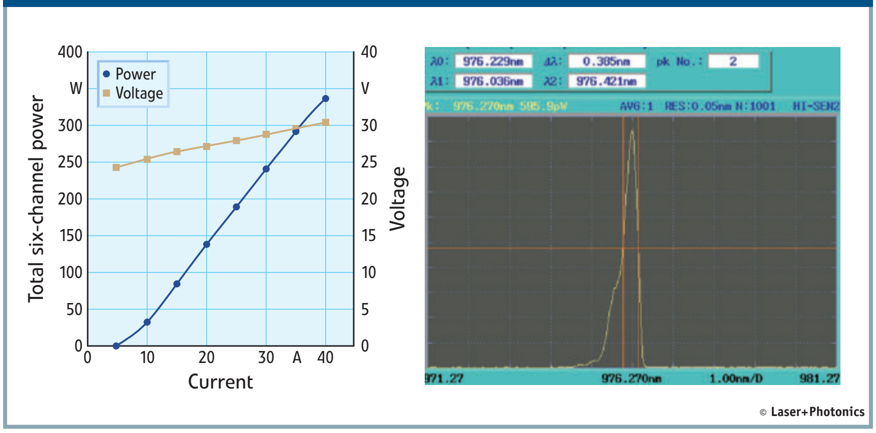
For fiber lasers and amplifiers, pumps are typically combined with pump combiners or tapered fiber bundles with a limited number of legs, increasing the de-

Fiber-coupled modules, far-field spatial beam profile



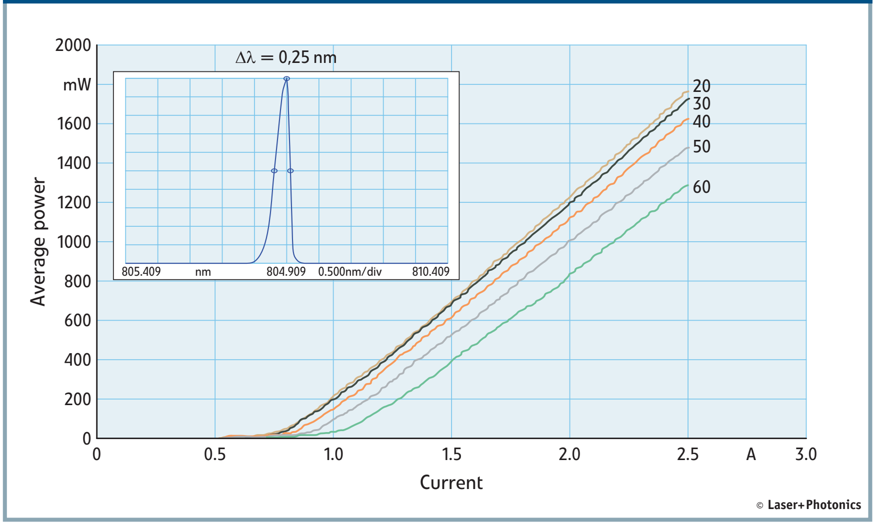
1 **Actual NA measurement from the 200 µm core fiber output of a QPC Ultra-50 high-power module at 976 nm. Measurements show that negligible power is measured outside of the specified 0.22 NA, given a 1 percent measurement error tolerance**

High-peak-power fiber laser



2 **On-chip grating stabilization of laser diodes enables high power, narrow bandwidth and reduced sensitivity to temperature. A six-channel module is shown here producing 330 W at 976 nm with < 0.5 nm bandwidth for fiber laser pumping**

Pump diodes with internal gratings



3 Performance of a wavelength-stabilized single emitter at 808 nm as a function of temperature. Locking is maintained up to 60 °C

mand for higher power per pump channel at popular wavelengths such as 792, 915 and 976 nm as demand increases for fiber lasers with higher repetition rate and average power. On the shorter wavelength side, pump diodes emitting around 792 nm have emerged as the ideal candidate for pumping increasingly popular Thulium fiber lasers for medical and defense applications. Today, high-brightness pump lasers coupled into 100 µm fibers are available from QPC with up to 40 W of ›cladding-free‹ output power at 792 nm and 45 W at 976 nm. Working with fiber laser manufacturers, QPC has set a new standard for spatial brightness from fiber-coupled modules with cladding-free power at all fiber core diameters, enhancing conversion efficiency and limiting risks of damage for pump combiners (**Figure 1**).

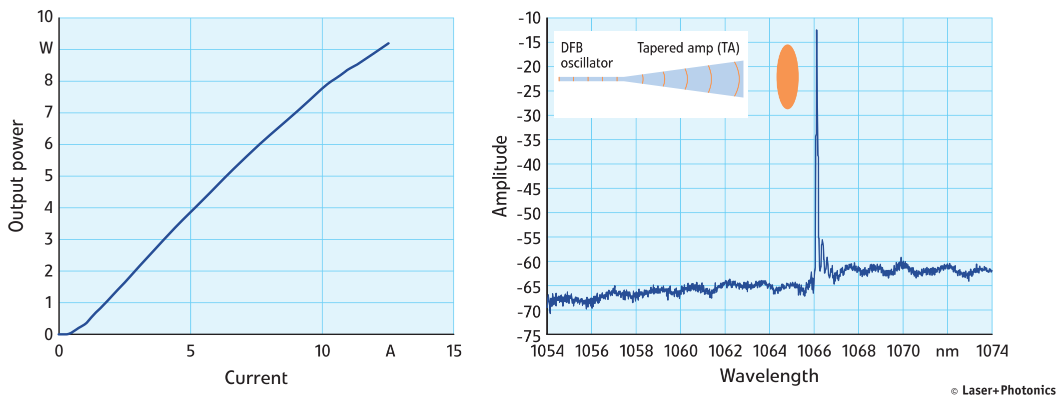
Athermal laser diode pumping

In several of today's emerging applications for solid-state and fiber lasers, it is critical to improve the stability and the spectral narrowing of the pump laser diode so the system can simultaneously deliver the efficiency associated with diode pumping and temperature stability that in the past has been possible only by lamp pumping. For example, in high-peak-power nanosecond and ultrafast lasers in Yb or Er:Yb based materials, high absorption per unit length is preferred at 976 nm to minimize nonlinearities and improve conversion efficiency [2]. However, absorption at 976 nm is narrow and requires accurate center wavelength, narrow bandwidth and stability versus temperature from pump diodes. Several very promising materials for high-power thin-disk lasers such as $Yb:Lu_2O_3$ or Alkali-vapor lasers also rely on such pump diode performance to unleash their potential.

In high -power CW applications, system designers look for a reduction of the quantum defect, defined as the difference in wavelength between laser emission and absorption wavelength. Lasers operating with a reduced quantum defect operate with less heat dissipation, lower risk of catastrophic damage, and enhanced conversion efficiency. However, it is often the case that such preferred wavelengths have narrow absorption bandwidths requiring pump lasers that have good center wavelength accuracy, narrow bandwidth and are relatively insensitive to temperature shifts.

Quasi-CW operation is also becoming more popular among high-power laser system designers for low repetition rate operation. This mode allows minimizing amplified spontaneous emission and extracting more peak power from laser diodes that otherwise would be thermally limited. However, as the current is increased at the rising edge of the electrical pulse, the spectral bandwidth of the pump diode increases due to a significant rise of the laser junction temperature. For pulses beyond several microseconds, this feature can drive the emission bandwidth of the pump diode outside of the absorption ▶

Master-oscillator power amplifier (MOPA)



4 9 W CW demonstrated from 1064 nm MOPA device. This architecture allows for single spatial and longitudinal mode, wavelength-stabilized operation at high power

bandwidth of the gain medium, reducing efficiency of the overall system.

Finally, as well known traditional diode-pumped solid-state lasers are moving into applications that require operation in severe environmental conditions for defense or portable consumer electronics applications, pump diodes are required to maintain accurate center wavelength in operation despite temperature variations as high as 80 °C.

Systems based on traditional laser diodes cannot deliver the temperature-independent performance of lamp-pumped designs. Instead precise thermal management and temperature control of the diode are needed to tune the emission wavelength precisely, and even with this control diode linewidths are insufficiently narrow, reducing overall system efficiency and increasing unwanted heat dissipation. In addition, as the number of pump diodes increases with the solid-state laser's average output power, the wide distribution of center wavelengths between pump diodes prevents a simple, unique cooling system since some diodes need to be cooled while others need to be heated to reach the desired absorption wavelength. Finally, several emerging markets including medical applications and portable laser displays prefer passively cooled solutions whenever possible to reduce cost, ambient noise and overall footprint.

It is therefore critical to improve the stability and the spectral narrowing of high-power laser diodes so that they can simultaneously deliver the efficiency promise of diode pumping and the temperature insensitivity provided by lamp pumping. If these objectives are met at a well-defined wavelength, then laser system designers can improve the system's compactness, efficiency, power and beam quality while reducing its thermal management cost.

Narrow bandwidths and stabilized wavelengths

Various methods have already been used to improve the spectral brightness, stability and consistency of laser diodes. These approaches include various external techniques using either volume Bragg gratings, or external lenses and bulk gratings. Emission based on external volume Bragg grating stabilization typically offers very narrow linewidth (< 0.1 nm) and very low wavelength temperature coefficient, typically on the order of 0.01 nm/°C.

However, approaches based on external components require sensitive and high-precision alignment, costly additional lasers and/or optics and specially designed coatings which can become a source for reliability concern. Also, because the diode gain continues to shift at a rate of about 0.3 nm/°C in external cavity configurations, the operation of the laser diode is restricted to a narrow current range to maintain wavelength locking over the entire laser bandwidth [3]. Finally, although the great wavelength stability versus ambient temperature (~ 0.01 nm/°C) and very narrow bandwidth (~ 0.1 nm) of a diode locked with external component is attractive for some spectroscopy and low noise applications, these features are not always desirable for standard pumping applications if the emission is too narrow or fine-tuning is needed.

Recently, QPC has overcome these challenges and demonstrated a range of high-power lasers operating at 808, 976, 1064, 1470, 1532 and 1550 nm, which are fabricated at the company's headquarters in Sylmar, CA [4]. Labeled ›BrightLock‹ for their unique combination of spectral brightness and wavelength stabilization properties, these MOCVD grown GaAs-based and InP-based lasers feature internal gratings that narrow the spectral linewidth down to less than 0.5 nm, reduce wavelength-temperature sensitivity by 400 percent and ensure that the device operates at the required wavelength. These devices are fabricated in a similar way to conventional laser diodes, with the gratings defined by optical lithography into a photoresist, followed by etching, then formed during a growth and regrowth process. High spectral brightness from on-chip wavelength stabilization can also be combined with QPC's ›Brightlase‹ technology for unmatched brightness performance from laser diodes.

High-performance diodes for demanding applications

For high-peak-power fiber lasers, wavelength-stabilized high-brightness fiber-coupled modules at 976 nm are now available from QPC Lasers. Several of these modules can be combined with a pump combiner to achieve unprecedented spectral brightness for Yb and Er:Yb laser pumping applications. An example of such a module is shown in **Figure 2**, demonstrating 330 W of optical power with a bandwidth of less than 0.5 nm. The combined output offers a dramatic reduction of the wavelength temperature coefficient from 0.3 to 0.074 nm/°C. Similarly, the center wavelength accuracy as a function of applied current is measured at 0.089 nm/A, showing great promise for QCW operation of these devices.

Internal gratings also enable high temperature operation of pump diodes with center wavelength tuning at only 0.07nm/°C up to at least 60 °C, as shown in **Figure 3**.

High-power single-mode laser chips

The next logical step in laser diode evolution consists in pushing the spectral and spatial brightness performance towards single spatial and longitudinal mode from a monolithic chip. Today, technology developed by QPC enables this unique performance combination via improved chip technology: a wavelength stabilized single-mode oscillator followed by a flared amplifier on a monolithic device. Such a chip architecture, also referred to as master-oscillator power amplifier or MOPA, maintains the single spatial mode and purity of the longitudinal mode created by the DFB (distributed-feedback) laser section while enabling record CW and peak power from a single chip. Independent control over current of the oscillator and the amplifier sections of the chip allows control over power and spectral characteristics depending on the application requirements.

QPC has recently demonstrated record power from MOPA devices at various wavelengths, with up to 9 W CW at 1064 nm with a single spatial and longitudinal mode, and up to 40 W peak power, single spatial mode, with 20 ns pulses at 1 MHz repetition rate (**Figure 4**). These devices are an excellent replacement source for Nd:YAG lasers in marking applications, as well as visible laser engines based on their excellent frequency-doubling characteristics at 532 nm and possible direct modulation at high repetition rates.

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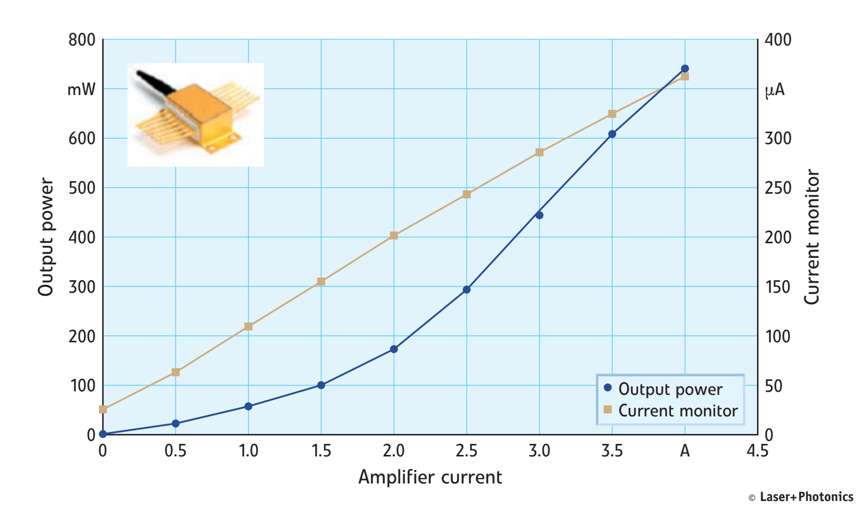

5 Performance curve from a 14-pin butterfly device coupled into a 9 µm core diameter single-mode fiber at 1550 nm. Pulse operation is also possible with peak power in excess of 2 W at megahertz repetition rates

At 1550nm, as high as 700 mW CW is obtained from the output of a single-mode fiber, a power that rivals commercial Raman fiber amplifiers for telecom EDFA pumping (Figure 5). These devices are also excellent seed lasers for CW and pulsed fiber lasers, eliminating the need for additional pre-amplifier stages and allowing flexible and independent control of parameters such as pulse width and repetition rate. They are also an excellent laser source for eye-safe LIDAR applications. When translated to pumping wavelengths such as 1532 or 976 nm, these devices will enable kilowatt average power from CW and high-peak-power solid-state lasers. ■

Summary: Breaking brightness barriers

Semiconductor laser diodes continue to break spectral and spatial brightness barriers, enabled by Brightlase and Brightlock technologies recently introduced into several pumps and direct-diode products. This performance improvement culminates in single-spatial-mode, single-frequency MOPA devices producing close to 10 W CW at near-IR wavelengths and over 700 mW CW from a single-mode fiber at 1550 nm.

AUTHORS

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OPTICAL FIBERS

Maintain polarization

Nufern announced further expansion of its ›NuPower‹ line of active fibers. The new fibers include an Erbium/Ytterbium co-doped (›PM-EYDF-17/200‹) and Ytterbium-doped large-mode-area (LMA) fibers (›PLMA-YDF-10/125‹ and ›PLMA-YDF-25/400‹). All three fibers are polarization-maintaining (PM), double-clad fibers and are complemented by the availability of matched passive fibers for component and pigtail development. The launch also includes a non-PM variant, ›LMA-YDF-10/130‹.

▶ **www.nufern.com**

DIODE LASER ARRAYS

Water-cooled

The diode laser manufacturer Dilas introduces a new series of high-power, water-cooled diode laser arrays used in scalable stack designs that deliver up to 80 W CW per bar at standard wavelength of 808, 940 and 980 nm for industrial applications. Dilas' stack designs are available up to 12 bars horizontally side-by-side or vertically stacked with up to 70 diode laser bars. Tested under CW and on/off-operating conditions, according to the manufacturer, these products offer ›superior lifetime characteristics, high reliability (assuring highest productivity) and lower total cost of ownership‹. The water-cooled diode laser arrays are a suitable solution as a line source for side pumping of diode-pumped solid-state (DPSS) lasers, for direct materials processing, hair removal and line-beam-applications.

▶ **www.dilas.com**