Mode Control for High Performance Laser Diode Sources

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ABSTRACT

We report on recent progress in the control of optical modes toward the improvement of commercial high-performance diode laser modules. Control of the transverse mode has allowed scaling of the optical mode volume, increasing the peak output power of diode laser emitters by a factor of two. Commercially-available single emitter diodes operating at 885 nm now exhibit >25 W peak (12 W rated) at >60% conversion efficiency. In microchannel-cooled bar format, these lasers operate >120 W at 62% conversion efficiency. Designs of similar performance operating at 976 nm have shown >37,000 equivalent device hours with no failures. Advances in the control of lateral modes have enabled unprecedented brightness scaling in a fiber-coupled package format. Leveraging scalable arrays of single emitters, the conductively-cooled nLIGHT Pearl™ package now delivers >80 W peak (50 W rated) at >53% conversion efficiency measured from a 200-µm core fiber output and >45 W peak (35 W rated) at >52% conversion efficiency measured from a 100-µm fiber output. nLIGHT has also expanded its product portfolio to include wavelength locking by means of external volume Bragg gratings. By controlling the longitudinal modes of the laser, this technique is demonstrated to produce a narrow, temperature-stabilized spectrum, with minimal performance degradation relative to similar free-running lasers.

Keywords: Diode laser, semiconductor laser, mode stabilization.

1. INTRODUCTION

Recent advancements in commercial diode laser efficiency and power across the spectrum (635-nm to beyond 2000-nm) have enabled a wide variety of military applications including directed energy, target designation, illumination, flash- and scanning-LADAR. As a result, attention is now shifting toward the improvement of other diode performance metrics such as power, temperature performance, reliability, spectral brightness, and spatial brightness. Control of optical modes in broad area diode lasers is critical to such improvements. For example, non-uniformities in the slow-axis optical near field have been shown to reduce power conversion efficiency and may pose reliability concerns [1-4]. Many systems (such as end-pumped solid state lasers and fiber lasers) are currently limited by the brightness of the pump [5-6]. Broad area lasers offer high power but low beam quality in the slow axis; single-lateral-mode lasers provide near-diffraction limited output, but the small mode size restricts the total output. Methods to scale brightness through lateral mode control have shown promising results [7-10] though, to date, the commercialization of such devices has been less successful. In the longitudinal direction, mode control is required for efficient pumping of many solid state and fiber laser systems which require wavelength-stabilized laser diode sources.

The majority of solid-state laser systems built today use Nd:YAG crystals which are pumped by flash lamps or diode lasers. Most users currently pump at 808-nm, significantly shorter than the emission wavelength of 1064-nm, which leads to excess heat being deposited in the crystal, degrading lifetime and performance. Pumping directly into the upper level with 885-nm sources significantly reduces this effect, as shown in Figure 1, increasing efficiency by > 20% through a reduction in the quantum defect [11]. This application has generated significant commercial interest in high-performance 885-nm diode laser pump sources.

In this work, we discuss recent progress in the development of high-power diode lasers operating at and around 885-nm. Some attention is also paid to progress in similar diode lasers which operate at 940-nm and 976-nm; these wavelengths are useful in a variety of other applications including pumping Er- and Yb-doped fiber lasers. Advancements in the

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performance of high-power laser diodes have been made possible through careful design and control of the optical lasing modes. Figure 2 illustrates a typical multimode high-power broad area diode laser (drawn junction down, as usually mounted), similar to the devices discussed herein. The naming convention used in this paper is included for reference. Table 1 introduces and motivates the three independent axes of mode control, each of which is separately addressed.
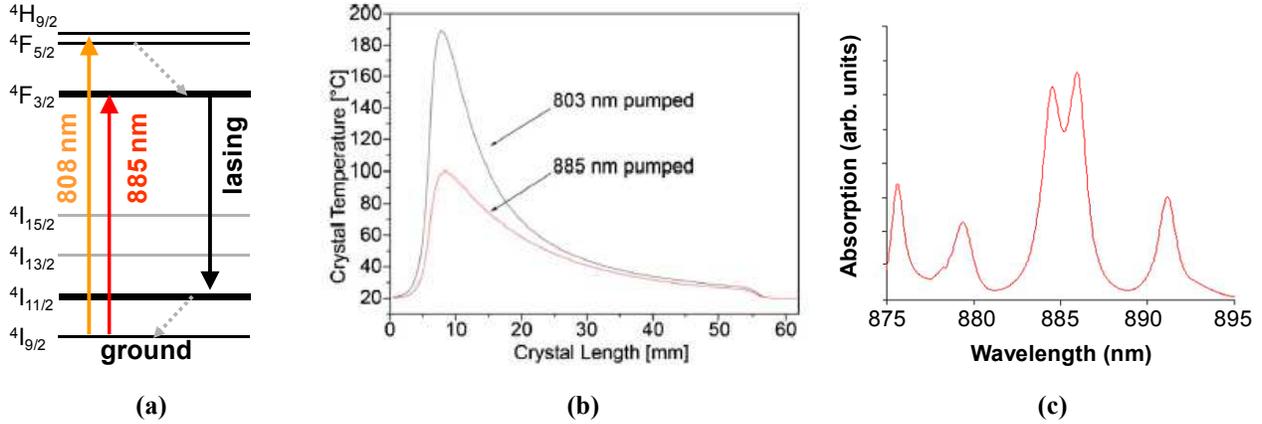

| (a) | (b) | (c) |

Fig. 1: (a) Nd:YAG systems can be pumped at either 808-nm or 885-nm. (b) Pumping at 885-nm is predicted to significantly reduce the amount of heat built up in the YAG crystal, enhancing performance and lifetime [11]. (c) The absorption spectrum of Nd:YAG around 885-nm is narrow (< 2.5 nm FWHM).
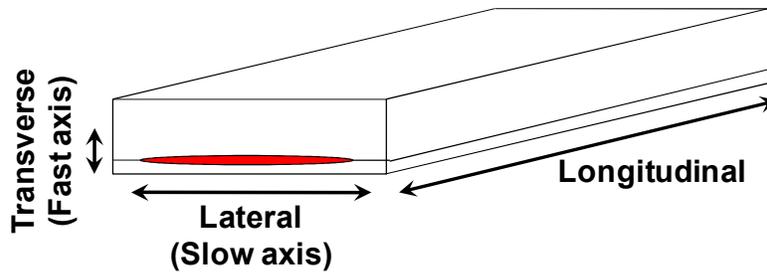

Fig. 2: Schematic illustrating the naming convention for various directions of mode control addressed in this paper. The laser is shown junction down and emitting in the longitudinal direction.

Table 1: Description of the motives and methods of controlling modes along each direction of the laser cavity.

Direction of control	Purpose of control	Methods of control
Transverse (fast axis)	Engineer loss and gain, facet loading, fast-axis beam divergence	Epitaxy design / bandgap engineering
Lateral (slow axis)	Spatial brightness, stabilization of beam filamentation, facet loading, slow-axis beam divergence	Lateral index of refraction design through planar fabrication techniques (etched ridges, regrown ridges, transverse gratings)
Longitudinal	Spectral brightness, wavelength-temperature stabilization	Surface-etched and buried Bragg gratings and Bragg reflectors, external volume Bragg gratings

2. TRANSVERSE MODE CONTROL

Control of the optical mode in the transverse direction is critical to the design of high-power, high-efficiency laser diodes. Broad area semiconductor lasers typically lase in just a single transverse mode. This is achieved through design of the laser epitaxy structure. In designing for high-power, high-efficiency operation, tradeoffs between various performance metrics must be carefully considered, and ultimately depend on the package and application of the device. In previous years, a significant development was undertaken to improve the power conversion efficiency of broad area diode lasers [12-14]. With significant strides made in demonstrating very high power conversion efficiencies, attention in now shifting towards the improvement of other performance metrics, such as power, reliability, beam quality, and temperature sensitivity.

Figure 3 details progress toward the development of high-performance 885-nm diode lasers at nLIGHT. This data was taken from single emitters; all parts were facet-passivated with nLIGHT's nXLT™ technology and bonded using AuSn solder to a coefficient of thermal expansion matched submount for reliability [15-16]. The new commercial design (still in qualification) demonstrates >25 W peak, 12 W rated, power and >61% peak power conversion efficiency. Note the designs do not fail for catastrophic optical damage, but instead roll thermally, due to the facet passivation process combined with fundamental changes to the epitaxy design. These changes focused on reducing loss and increasing mode volume through careful design of the optical waveguide and control of the transverse mode, allowing power to scale while maintaining high conversion efficiency and reliability. Figure 3 also illustrates long-term reliability data from single emitters of similar design (operating at 976 nm), indicating the merit of the approach (reliability data at 885-nm is being acquired at the time of writing). The same design also illustrates >60% conversion efficiency in 100-W cm-bar array format on copper microchannel coolers, as shown in Figure 4.
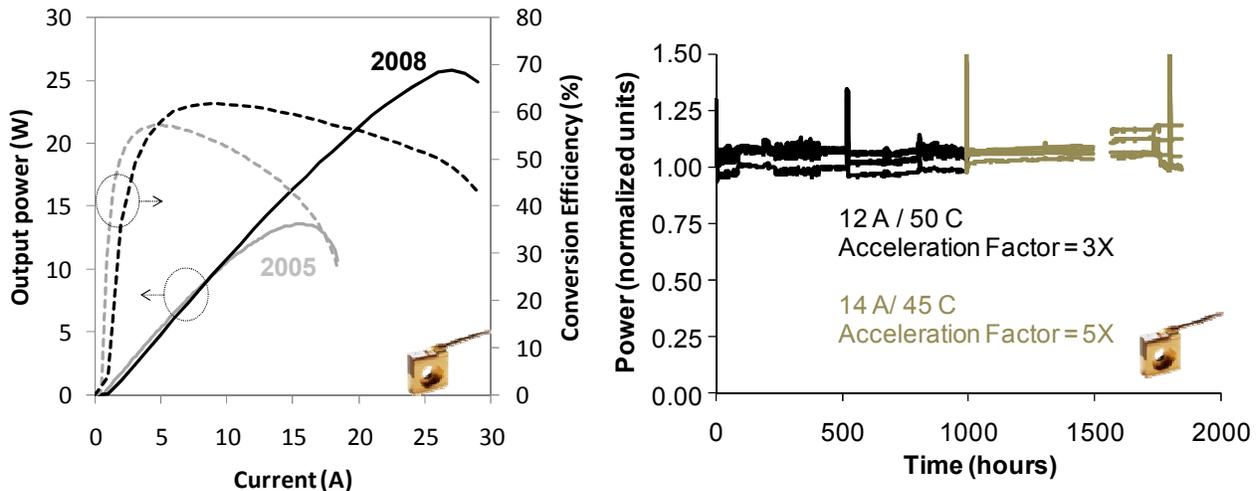

Fig. 3: (Left) Light and E/O efficiency as a function of drive current for 885-nm single emitter laser diode designs. These emitters were bonded using AuSn 'hard' solder to CTE-matched submounts. The parts were tested to rollover/COD following a burn-in at elevated temperature. The devices were operated CW at 10 °C. nLIGHT's next-generation commercial design has focused on reducing loss and increasing the modal volume to increase power while maintaining high conversion efficiency. This has been achieved through careful design and control of the transverse optical mode profile. As a result, the peak power attainable from a single emitter has been increased twofold from previous designs and efficiency > 61% is maintained. (Right) Single emitter laser diodes of a similar design operating around 976-nm have shown >37,000 equivalent device hours with no observed failure (reliability data at 885-nm is still being acquired at the time of publication). The spikes in the plot are due to electrical isolation issues with the photodetectors which directly correlate with the energizing of adjacent test modules, and do not represent true power spikes in the diode lasers themselves.
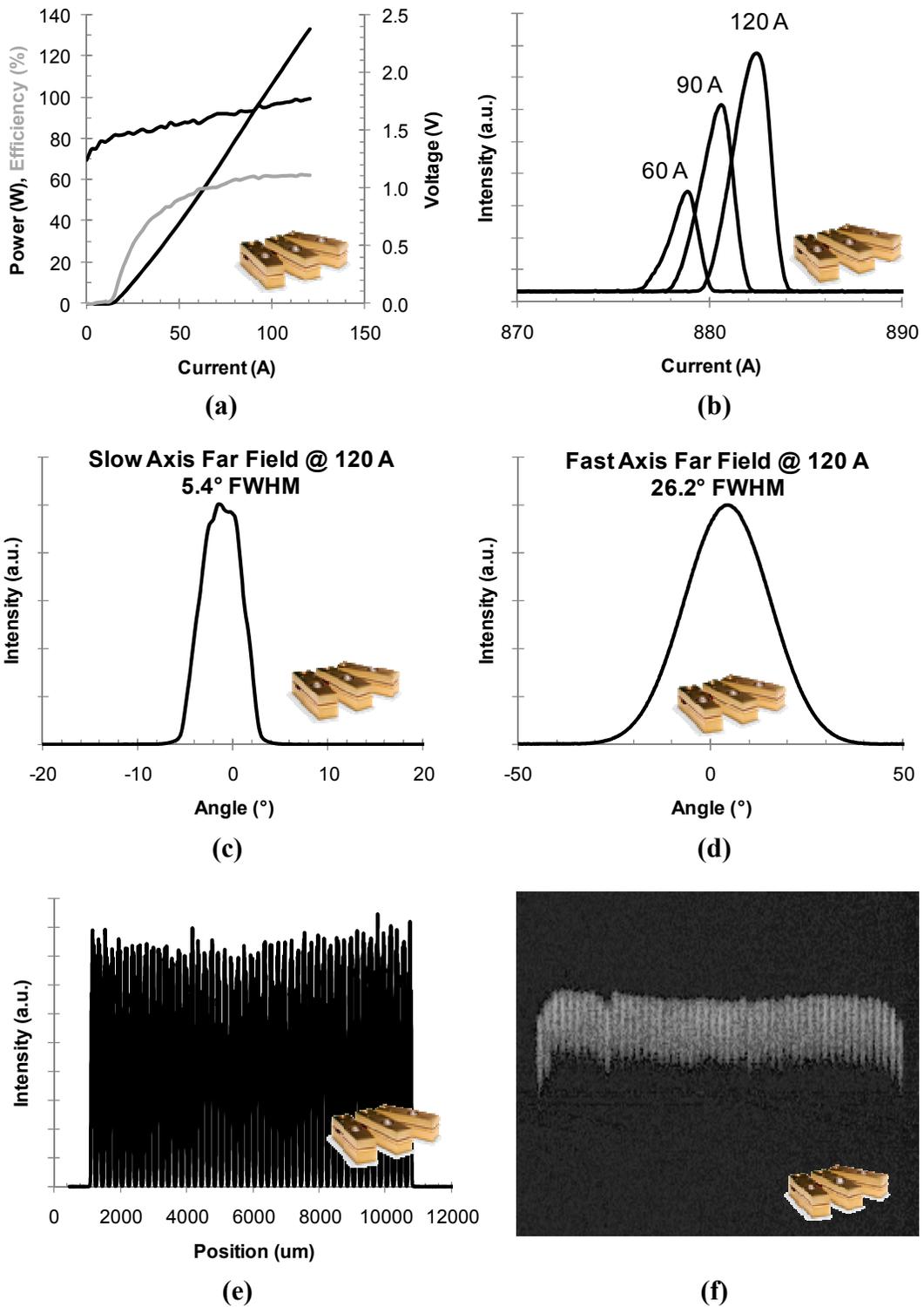
Fig. 4: Diode characteristics for the new high performance laser design in a 50% fill factor, 1.5 mm cavity length bar. The bar was bonded using In solder to a copper microchannel-cooled heatsink. Testing was done at 25 °C, 0.2 lpm flow. (a) LIV curve showing >60% conversion efficiency at 100W. (b) Lasing spectra taken at 60, 90, and 120 A illustrates < 2.2 nm FWHM spectral width. (c) Slow- and (d) fast-axis far field measurements. (e) Optical near field and (f) spatially-resolved emitter spectra taken at 120 A drive current.

3. LATERAL MODE CONTROL

For pumping of the solid state, efficient lasing is achieved by efficient absorption of the pump light in the solid state crystal and good overlap of the cavity optical mode with the pumped regions of the crystal [5]. The laser cavity eigenmode is TEM_{00}; circularly symmetric with a Gaussian lateral profile. Ideally, the laser designer would like the pump optical mode profile to be close to that of the cavity eigenmode. This is best achieved through end-pumped configurations. Figure 5 illustrates the importance of pump brightness in end-pumping solid state laser rods. High brightness is also critical for pumping double-clad fiber lasers, where output powers are often limited by pump power, and the maximum launched pump power is directly proportional to the pump brightness [6].
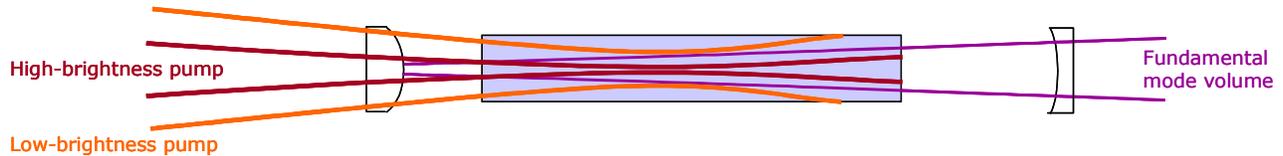

Fig. 5. High brightness pumps have distinct advantages in the end pumping of solid state laser rods. Thermal lensing sets strict limits on pump power and linear absorption. Lower-doped, longer rods allow for higher pump powers. Longer rods require pumps with large Rayleigh range to overlap with TEM_{00} mode volume.

Because high-power broad area diode lasers support and lase on many lateral modes, the beam quality in the slow-axis is quite poor. Beam quality (M^2) is defined by the ratio of the beam divergence to the divergence of a diffraction limited laser beam of the same wavelength and waist size (A perfect diffraction-limited beam would have $M^2 = 1$). This figure of merit is inversely proportional to brightness. Diode brightness can therefore be scaled in two ways:

1. Increase emitter power (which is directly proportional to brightness)
2. Decrease M^2 (which is inversely proportional to brightness)

For a diode laser, the beam qualities in the transverse (fast) axis and lateral (slow) axis are very different (typically $M^2 \sim$ 1 in the fast axis and ~ 15 in the slow axis). This is further exacerbated in bar format where 20 to 50 emitters are fabrication adjacent to one another, resulting in $M^2 \sim 2$ in the fast axis (due to bar smile) and ~ 1000 in the slow axis. This asymmetry makes it very difficult to efficiently end pump solid state lasers with good overlap between the gain region and laser resonator mode.

At the *emitter level*, a variety of techniques have shown promise towards improving the beam quality (reducing M^2) in the slow axis. Two techniques are the tapered laser amplifier [7-8] and the slab-coupled optical waveguide laser (SCOWL) [9]. While both techniques have made excellent progress, these approaches are still relatively immature - relying on more difficult fabrication processes which may affect long-term device reliability.

nLIGHT has been actively working to improve brightness at the *array level*. To this end, nLIGHT has developed a new package [17-18] based on arrays of singles emitters which offers the following advantages:

1. *Higher brightness*: Single emitters can be reliably operated at higher powers than emitters in a bar array. Fewer emitters are required to achieve similar operating powers to bars, improving M^2.
2. *Conductively cooled*: The physical separation of the emitters as compared to a bar eliminate neighbor heating and the requirement for water cooling
3. *Enhanced reliability*: AuSn hard solder permits higher operating powers without the creep associated with low melting point In solder. Active regions run cooler at a given output power compared to on a bar.
4. *Low cost*: Screening/qualification of individual 'chiplets' increases yield and leads to lower cost and higher reliability.
5. *Flexibility*: Any wavelength diode laser nLIGHT currently produces (from 600 to 2100 nm) can be packaged in this way. Multiple wavelengths from a single box are possible. Emitters can be wavelength-locked using volume Bragg gratings for spectral stabilization. The unit can be fiber-coupled or collimated for easier coupling to the solid state.

Brightness scaling in this format can be achieved through three independent approaches – increasing the number single emitters in the array, increasing the coupled power per single emitter in the array, and moving toward smaller diameter fiber / improved collimated beam quality. Continued innovation in the areas of diodes, optics, and packaging will enable ever-brighter products. Figure 6 illustrates a photograph of nLIGHT's fiber coupled package and the three independent paths toward brightness scaling.
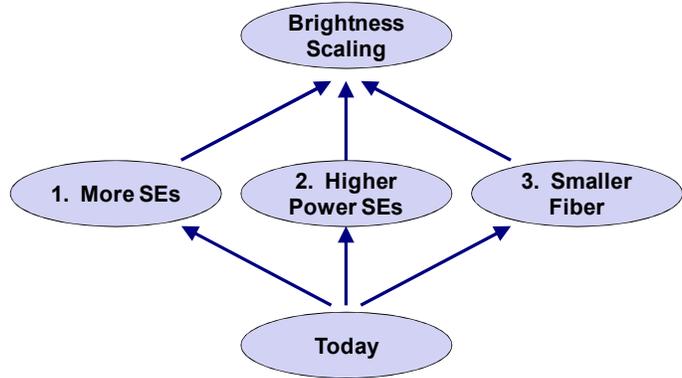

Fig. 6: (Left) Photograph of an nLIGHT Pearl™ fiber-coupled pump module. The unit is photographed adjacent to an ink pen to emphasize its relative size. (Right) Module brightness can be scaled in three independent ways.

The Pearl™ approach has enabled rapid brightness scaling (>25 X) in just 18 months, as depicted in Table 2. Most recently, we have demonstrated a prototype units operating at 80 W peak, 50 W rated, coupled into 200-µm core fiber and at 45 W peak, 35 W rated, coupled into a 100-µm core fiber. These units operate CW at 25 °C and are conductively cooled. The peak conversion efficiency (power measured at the fiber) is measured to be in excess of 53% for the 200-µm design and 52% for the 100-µm design. These advances have been made possible through high optical-to-optical coupling efficiencies in excess of 92%. This eases cooling considerations as the fiber need not be actively cooled. See Figure 7.

Table 2: Rapid pump module brightness scaling (in the 8xx-9xx band) has been enabled through this approach

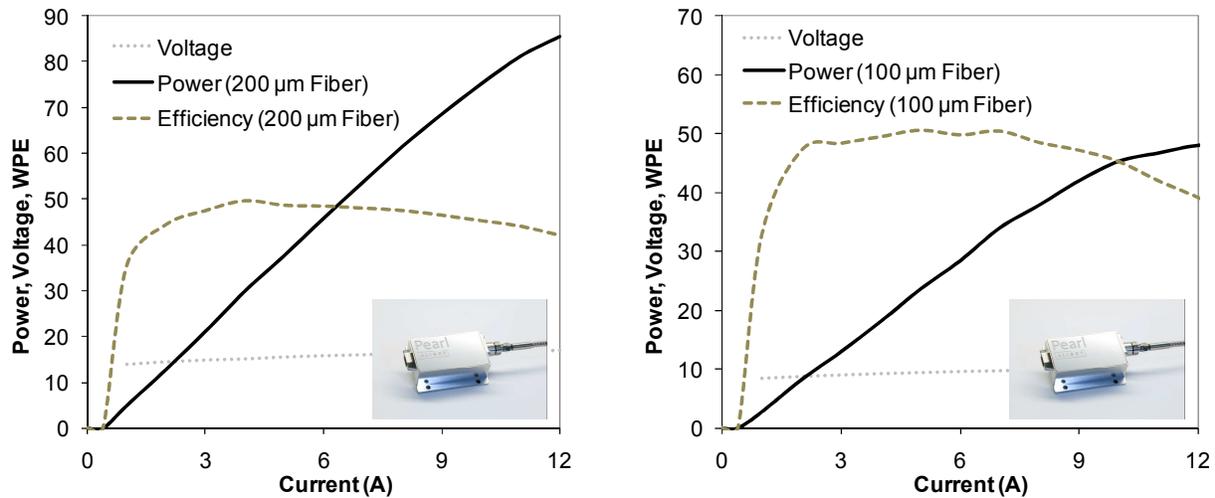| Year	Power	Fiber Diameter	Relative Brightness
2006	25 W	400 um	1
2007	50 W	400 um	2
2007	100 W	400 um	4
2007	40 W	200 um	6.4
2008	80 W	200 um	12.8
2008	45 W	100 um	28.8
Late 2008	80 W (Projected)	100 um	51.2

Fig. 7: Output power, conversion efficiency, and voltage as a function of drive current for two prototype fiber-coupled pump module designs. (Left) A 200-um core diameter fiber-coupled unit demonstrates >80 W peak, 50 W rated, power and >53% conversion efficiency (measured from the fiber). (Right) A 100-um core diameter fiber-coupled unit demonstrates >45 W peak , 35 W rated, power and >50% conversion efficiency (measured from the fiber). These 976-nm units are conductively cooled and operating CW at room temperature.

4. LONGITUDINAL MODE CONTROL

As was shown in Figure 1, the absorption feature around 885-nm for Nd:YAG is narrow (around 2.5 nm FWHM). Efficient laser systems require that the diode pump source be equivalently narrow to ensure uniform absorption of the pump beam. The drift of operating wavelength with temperature of conventional diode lasers also sets strict requirements on thermal control of the diode pump source. Figure 8 illustrates the operating spectral width and wavelength temperature coefficient of nLIGHT's single emitter diode laser products across the spectrum. As shown, there is a clear quadratic dependence of spectral width on wavelength. This dependence is understood as follows: The cavity length of broad area edge emitting laser diodes is many times the wavelength of light, resulting in a structure that can support many longitudinal modes. Each of these cavity modes is resonant at a slightly different wavelength (each corresponding to a different integer number of half-wavelengths in the cavity). Standard broad area semiconductor diode lasers do not employ wavelength-selective feedback or longitudinal mode suppression mechanisms, resulting in lasing on any and all modes which experience sufficient round-trip gain within the spectral gain bandwidth of the active region. The envelope spectral width of the lasing modes is therefore predominantly dependent on the spectral width of the optical gain, which is itself proportional to the square of the emission wavelength [19]. The wavelength temperature coefficient is similarly related. As a result, the spectral performance of broad area diode lasers is intimately linked with the gain material, and hence lasing wavelength.

Reducing these two parameters can be achieved by controlling the longitudinal modes of the laser. Two methods which are actively employed for this are 1) internal and 2) external locking through the use of a wavelength-selective feedback source, such as a Bragg grating. This approach effectively increases the threshold for all undesired longitudinal modes such that they can never begin to lase. As a result, power is efficiently diverted into just one (or a few) desired longitudinal modes. Furthermore, because the laser operates in modes selected by the cavity, rather than material gain, the wavelength temperature drift coefficient is also controlled.
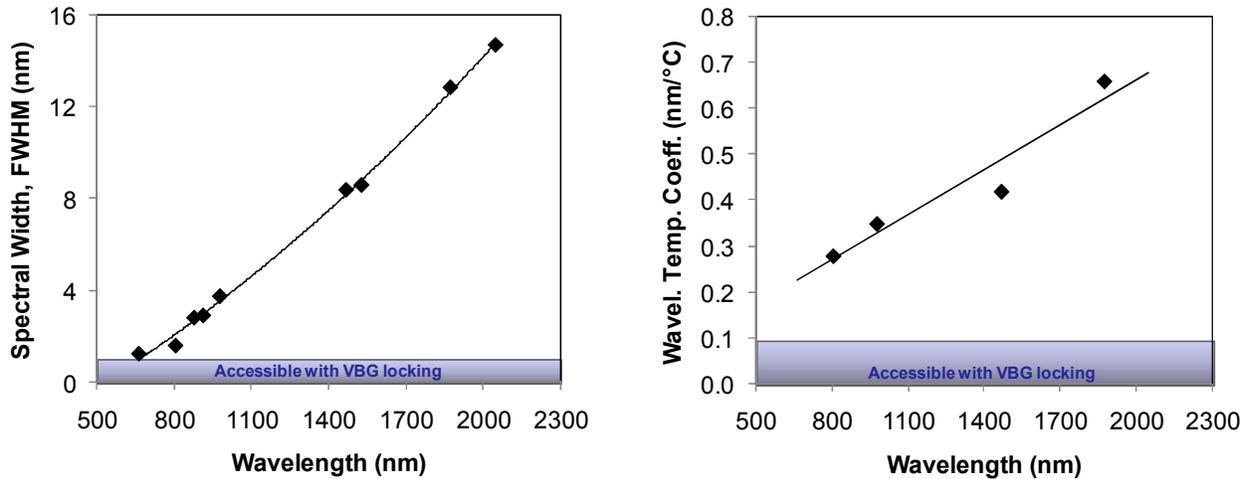
Fig. 8: (Left) Spectral width and (Right) wavelength temperature coefficient are strongly correlated with the operating wavelength of the diode laser. Longitudinal mode control, such as that introduced by locking with an external volume Bragg grating can dramatically reduce each of these.

Each approach offers a unique set of advantages and disadvantages, as summarized in Table 3. Monolithic surface-etched and buried internal gratings have long been the de-facto standard for the stabilization and control of longitudinal modes. The approach was particularly well-suited for telecommunication applications where very narrow linewidth / true single-mode operation was required [20]. More recently, a number of commercial vendors have begun to offer high-power products based on the technology. Unfortunately, in the 8xx-nm to 9xx-nm wavelength band, second order gratings are required for low cost fabrication. These designs are inherently lossier than first order gratings, and the incorporation of the grating into the epitaxy design may be at odds with other design priorities. As a result, high efficiencies (comparable to those obtained herein) have yet to be demonstrated.

Volume Bragg gratings (VBGs) are an external optic component in which a periodic variation in index of refraction has been written into the photorefractive glass [21]. These VBGs can then be mounted and aligned externally to selectively feed-back a narrow range of wavelengths, locking the wavelength of the diode laser as previously described. This approach is now gaining traction in the high-power diode arena for the following reasons:

1. External locking decouples diode-self-heating from the wavelength detuning of the feedback structure, further improving the wavelength-temperature coefficient.
2. Recent advances in volume manufacture capabilities and competitive pricing pressures have reduced the cost of the optics. Alignment and mounting of the optics leverages the same well-developed techniques used in lensing.
3. The approach offers greater flexibility in wavelength, because longitudinal lasing modes are selected by an external optic.
4. The epitaxy design can be optimized for high performance without the additional restrictions that the incorporation of a buried grating places on the design.
5. External locking avoids yield and reliability losses associated with complex epitaxy regrowth methods required for buried gratings.
6. The emission linewidth can be tailored to the application.

Based on these considerations, external locking by means of volume Bragg gratings provide the most attractive solution for wavelength stabilization of high power diode lasers. Figure 9 illustrates the performance of a VBG-locked nLIGHT diode bar operating around 940 nm. As shown the broad spectral width is reduced from 2.7 nm FWHM to under 0.3 nm FWHM. This device suffered less than 3% decrease in optical power and efficiency as a result of the VBG locking. This figure also demonstrates locking over a wide temperature range. The effective wavelength temperature coefficient is much less than 0.1 nm/°C.

Table 3: Advantages and disadvantages of various methods of longitudinal mode stabilization in high-power diode lasers

| Technique	Advantages	Disadvantages
Surface-etched Bragg gratings or Bragg reflectors (DBR laser)	• Monolithic • Does not require epitaxy regrowth • Reliability • Very narrow linewidth possible	• Generally incompatible with high power laser designs • Cost • Reduced locking temperature range
Buried internal Bragg grating (DFB laser)	• Monolithic • Very narrow linewidth possible	• Reduced conversion efficiency due to increased loss • Reduction in diode lifetime due to regrowth process • Possible yield loss • Laser spectral width limited by facet reflectivity • Cost-effective fabrication techniques limited to lossy second-order grating designs
External volume Bragg grating (VBG laser)	• Minimal loss • Epitaxy can be independently optimized for high performance • Easy wavelength changes	• Laser spectral width limited by facet reflectivity • Not monolithic
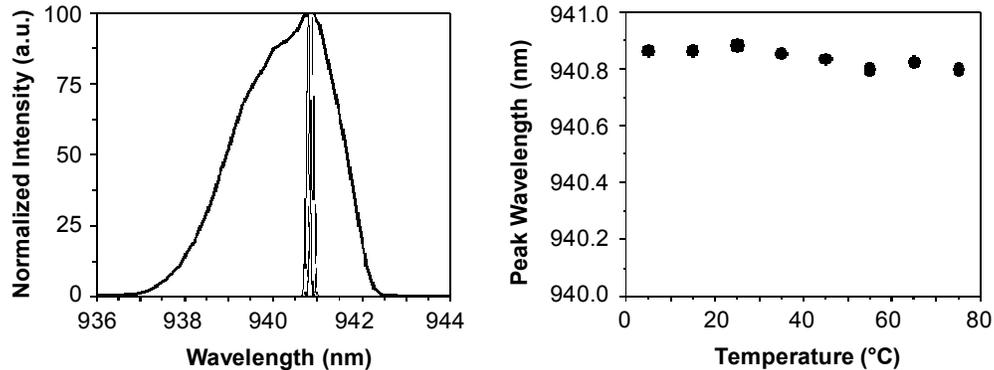
Fig. 9: (Left) Comparison of an unlocked and locked (the locked data is taken at a temperatures between 10C and 70 °C, and the plots overlaid on top of one another). (Right) Peak wavelength as a function of temperature. Locking is observed between 10 and 70 °C.

The flexibility of the VBG approach lends itself to nearly any packaging format. Figure 10 illustrates data from a VBG-locked 885-nm microchannel-cooled stacked diode array. This 6-bar stack is operated CW with 25 °C water at a flow rate of 0.2-lpm. LIV and spectral data are shown before and after VBG locking. As shown, the array suffers virtually no power penalty as a result of the locking. The slight deviation in optical power observed the locked stack (relative to the free-running stack) at high powers is due to the martial gain spectrum spectrally shifting out of spectral alignment with the peak reflectivity of the VBG. In this case, complete locking is purposely not achieved. Regardless, the spectral width is still reduced by >35% to 2.48-nm $FW1/e^2$. For a Nd:YAG laser system, this would result in a >10% improvement in overall efficiency, greatly reducing the need for costly/bulky temperature control systems. nLIGHT has also demonstrated VBG-locking in the Pearl package format. Figure 11 illustrates the LIV and spectral data before and after VBG-locking, respectively. In this case, the conversion efficiency is reduced by approximately 5%, and reducing the spectral width by a factor of four to 0.6 nm FWHM and the wavelength temperature coefficient by a factor of three to 0.1 nm/°C.
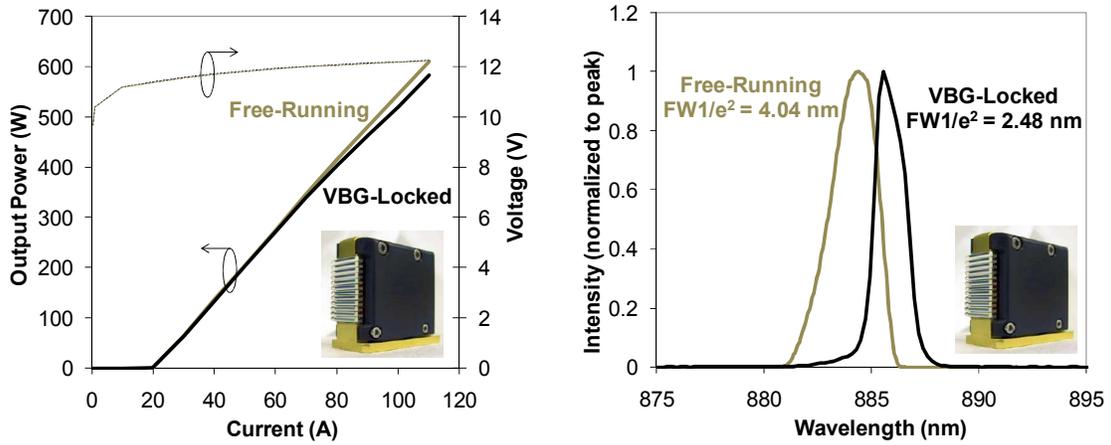
Fig. 10: (Left) LIV and (Right) spectrum of a 6-bar vertically-stacked array of 885-nm diode laser bars before and after VBG locking. The array is operated CW with 25 °C water at a flow rate of 0.2-lpm. As shown, the unit suffers virtually no degradation in optical power as a result of wavelength locking. The spectral width is reduced by 35% to 2.48 nm FW1/e^2.
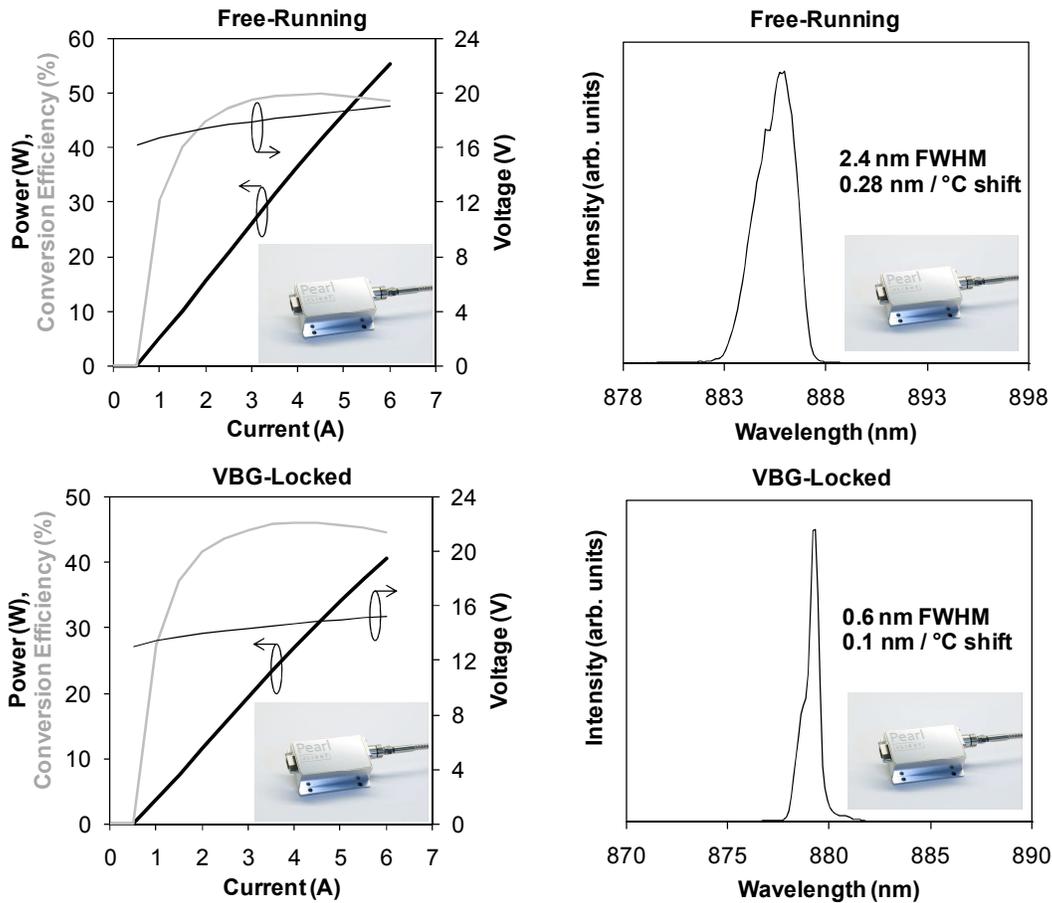

Fig. 11: LIV and spectra of a free-running (top) and VBG-locked (bottom) 885-nm fiber-coupled pump module (different modules). The output is taken from a 400-μm-core fiber. As shown, the VBG-locked device operates with a 0.6 nm FWHM spectral width and the wavelength temperature coefficient is noted at 0.1 nm/°C.

5. CONCLUSION

In this work, we reviewed the motivation, techniques, and progress in control of optical modes in all dimensions of diode lasers. Through scaling to larger optical mode volume, peak power from newly released commercial designs have been improved by a factor of two relative to previous designs. Leveraging the Pearl™ platform, based on scalable arrays of highly-reliable, conductively-cooled single emitters, we have demonstrated a >25 times improvement in pump module brightness in just 18 months. For applications requiring narrow spectral width and/or wavelength stabilization, nLIGHT has expanded its product portfolio to include grating-stabilized laser modules (Cascades™ bars and stacks, and Pearl™ fiber-coupled pump modules). This technology is enabled by the use of external locking by volume Bragg gratings, with minimal penalty to operating power and efficiency.

6. REFERENCES

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