High Brightness Fiber Coupled Pump Laser Development

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ABSTRACT

We report on the continued development of high brightness laser diode modules at nLIGHT Photonics. These modules, based on nLIGHT's Pearl™ product platform, demonstrate excellence in output power, brightness, wavelength stabilization, and long wavelength performance. This system, based on 14 single emitters, is designed to couple diode laser light into a 105 µm fiber at an excitation NA of under 0.14. We demonstrate over 100W of optical power at 9xx nm with a diode brightness exceeding 20 MW/cm2-str with an operating efficiency of approximately 50%. Additional results show over 70W of optical coupled at 8xx nm. Record brilliance at wavelengths 14xx nm and longer will also be demonstrated, with over 15 W of optical power with a beam quality of 7.5 mm-mrad. These results of high brightness, high efficiency, and wavelength stabilization demonstrate the pump technology required for next generation solid state and fiber lasers.

Keywords: Fiber coupled diode laser, high brightness

1. INTRODUCTION

High brightness fiber coupled diode lasers open up new applications for diode lasers in industrial applications and pumping applications. nLIGHT has demonstrated devices with excellent brightness for use in a variety of industrial and pumping applications.

nLIGHT introduced high brightness fiber coupled laser diode modules at Photonics West 2009 that demonstrated over 100W of optical power coupled into a 105 µm, 0.15 NA fiber with a corresponding brightness of over 20 MW/cm^2-str[1]. This paper focuses on the application of this technology to pump modules from 79x to 15xx nm. As always, these devices are based on nLIGHT's proprietary high power broad area single emitter architecture, that is free space combined in an elegant and inexpensive manner[2]. This approach preserves the power and high brightness of the laser diodes, resulting in a device with optimal brightness and efficiency.

2. APPLICATIONS OF HIGH BRIGHTNESS PUMP LASERS

There are several considerations in the development of high brightness laser module architectures. First, the platform and tooling must be wavelength agnostic, enabling the development of laser diodes across the spectrum. Second, the efficiency of the optical design should be as high as possible. Finally, the reliability of the laser diode module must be fully evaluated and qualified.

Originally nLIGHT's high brightness laser diode modules were developed for pumping fiber lasers. Higher brightness pump sources enable higher power fiber lasers through the ability to spatially combine a greater number of pumps and more efficiently couple them into the fiber. Pulsed fiber lasers also require high brightness pump modules to reduce the active fiber length and corresponding fiber nonlinearities. Managing nonlinearities in pulsed fiber lasers enables lasers with shorter pulse lengths and higher peak power.

Pumping applications addressed by our past year's efforts include:

- The pumping of Tm-doped fiber lasers at 795 nm
- The pumping of Er-doped fiber lasers at 1532 nm
- Pumping Yb-doped fiber lasers with wavelength stabilized devices at 976 nm
- Pumping of narrow spectral lines for Nd:YAG (885 nm), Er:YAG (1532 nm), and Ho:YAG (1910 nm) solid-state lasers

In addition to pumping applications, there are alternative applications in the consumer, materials processing, and medical areas of high brightness laser diode modules. The goal for materials processing has been the replacement of lamp-pumped solid-state lasers by direct diode laser diodes, with a corresponding improvement in efficiency from approximately 2% (for lamp-pumped devices) to over 40% for direct diode laser systems. Figure 1 shows the application space of direct diode laser diodes from 79x to 19xx nm.

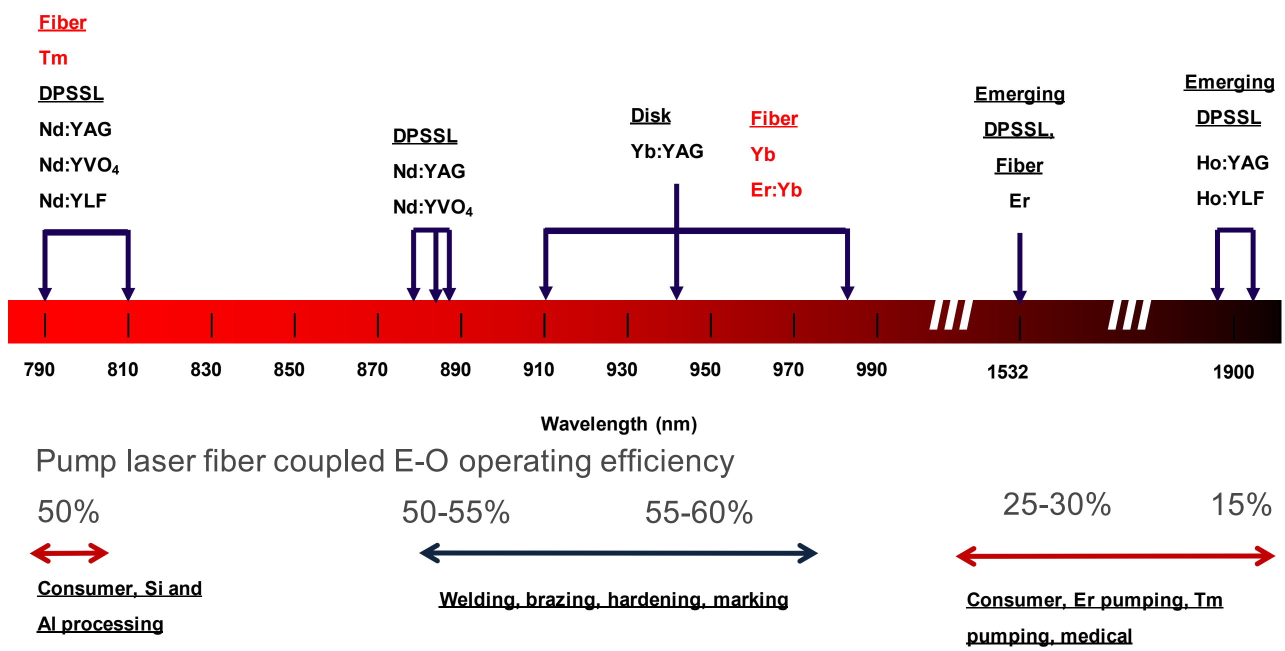


Fig. 1:*Applications of direct diode laser systems from 79x to 19xx nm. As can be seen, the efficiency of these devices is above 50% from 79x to 1000 nm. Devices from 15xx to 19xx nm have a reduced efficiency that is based on the reduced efficiency of the diodes. Optical to optical efficiency is approximately 90% across the spectrum.*

Direct diode laser modules have remarkable efficiency, with values greater than 50% for devices fabricated between 79x to 9xx nm. High efficiency fiber coupled laser devices improve module performance in several ways. First, a high optical to optical efficiency reduces diode laser count, resulting in a lower $/W cost for the module. The reduced parts count also results in a smaller package size, with fewer diodes and optics required to achieve a given optical power. The high efficiency of the system also results in simplified cooling systems with reduced waste heat dissipation requirements, as shown in Fig. 2. Finally, high module efficiency results in systems that require less electrical power, reducing the operating expenses of the laser device.

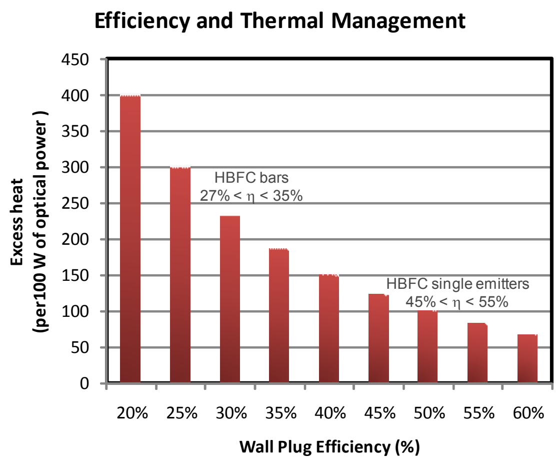


Fig. 2: *The excess waste heat per 100W of optical power generated. Historically high brightness fiber coupled bars have system efficiency in the 30% range. High brightness fiber coupled single emitters have efficiency values in the 45-55% range, resulting in a 50% reduction in waste.*

In addition to high efficiency values, diode laser systems can also be designed to show excellent reliability. Recently high power, multi-mode single emitter laser diodes have demonstrated telecom-like reliability. For instance, nLIGHT has developed high power laser diodes with a cavity length of 3.8 mm that has a failure in time (FIT) rate of under 450 failures per billion device hours at a rated power of 10W[3,4]. Additionally, nLIGHT has performed extensive reliability testing on both single emitters and fiber-coupled packages. The results indicated that the populations of individual diodes versus fiber coupled laser diode modules were statistically indistinguishable. This was determined by examining the 90% confidence levels of the plot showing unreliability as a function of time for both individual emitters and fiber coupled packages, as shown in Fig. 3. This result indicates the lack of package induced failure (PIF). These devices have a time to 10% failure of between 300,000 to 400,000 hours, at 9xx nm, providing multiple years of maintenance-free operation.

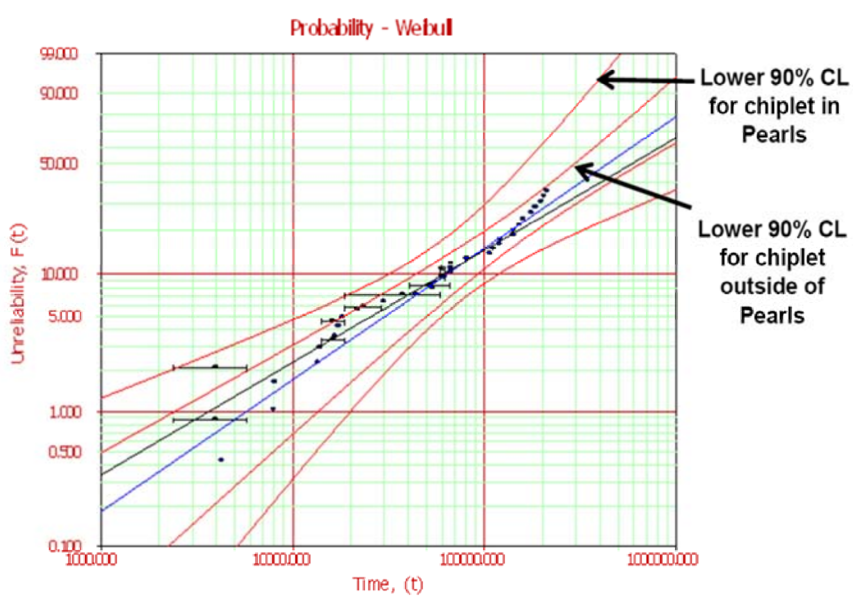


Fig. 3:*The Weibull plot for single emitters versus devices in fiber coupled packages. The two populations of devices had overlapping confidence boundaries, indicating indistinguishable populations and the absence of package induced failure (PIF).*

3. HIGH BRIGHNESS PUMP LASERS

The flexibility of nLIGHT's single emitter architecture allows for a wide variety of packages to be manufactured. These modules include diode modules specifically designed for solid state pumping, fiber laser pumping, and materials processing.

200 µm pump modules were developed for the purpose of pumping Tm fiber lasers, Nd:YAG solid-state lasers, and Yb-doped fiber lasers. Modules at 79x to 88x nm are capable of coupling over 100W CW into a 200 µm fiber with an NA of 0.15. When operated in pulsed mode, over 200W of peak power can be coupled into the same fiber, all with a spectral line below 2 nm FWHM. This result demonstrates the ability to operate nLIGHT's fiber coupled diodes in pulsed mode, with peak powers 100% higher than what is achievable under CW operation. Figure 4 (left) shows the LI characteristics of this device. 9xx nm devices are capable of coupling over 120W of optical power into a 200 µm fiber an NA less than 0.1. This result is achieved with efficiency greater than 50% over the entire operating range of the device, as shown in FIG 4 (right). Such a device has less than 2% of the light in the cladding layer, and can be fabricated with a 1 µm rejection window with over 35 dB of isolation. In addition to fiber laser pumping, this device can be used in materials processing.

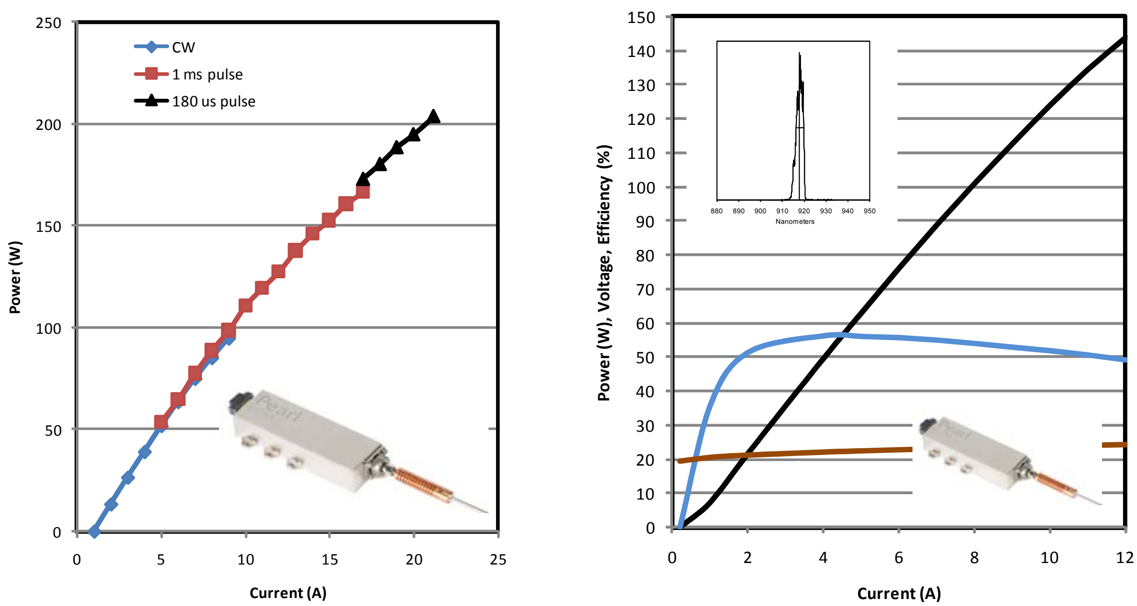
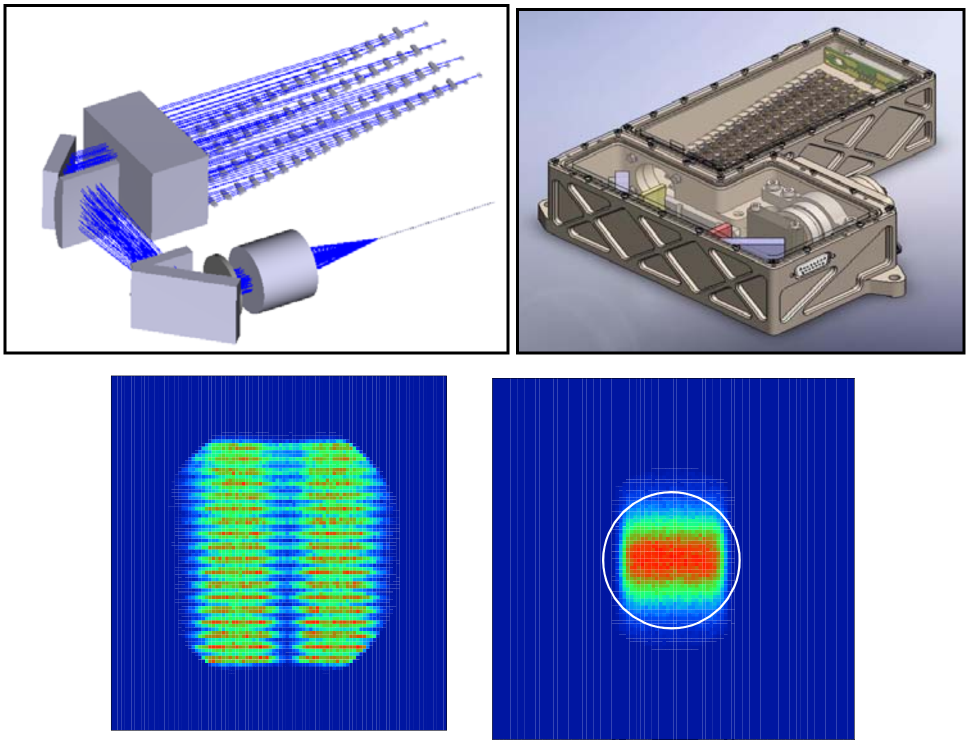


***Fig. 4**: (left) The LI curve for a 200 µm, 0.15 NA pump module for 79x to 88x nm. The device can be operated in pulsed mode to achieve approximately double the CW available power. (right) The LIV characteristics of a 9xx nm 200 µm, pump module with 0.1 NA. These devices can be used as pump laser modules as well as for materials processing applications.*

Where higher powers are required, a large format package based on single emitters is under development at nLIGHT. This package is designed for optical power coupling capacities of over 600W into a 400 µm, 0.2 NA fiber, or over 500W into a 200 µm, 0.2 NA fiber. The device is also designed to be highly configurable, with separate optics and laser modules and capable of coupling into either a 200 µm 0.2NA fiber or a 400 µm, 0.1 NA fiber. The laser module is partially populated with 56 emitters, which are polarization combined into two columns. Two cylinder lenses form a telescope to symmetrise the beam, which is then focused with a multi-element objective lens. A raytrace of the system is shown in Figure 5. This device is expected to achieve cost reduction through lowering the fixed cost of housings, optics, and fibers. nLIGHT estimates that the $/W reduction for such a system can be in excess of 40% when coupled with high brightness single emitter laser diodes.



OPTICAL	
Wavelength, nm	940.4
Output Power, watts	700
Spectral Width, FWHM	4.3
Spectral Width, 1/e^2	6.8
Slope Efficiency, W / A	77.0
Divergence, NA (90% power incl.)	0.13
Wavelength Temp. Coeff., nm / °C	0.35
ELECTRICAL	
Total Conversion Efficiency (ηWP)	58%
Threshold Current, amps	0.60
Operating Current, amps	9.63
Operating Voltage, volts	125.98
Series Resistance, ohms	2.60
THERMAL	
Operational Temperature, °C	25.0
Thermal Resistance, °C / W_{heat}	0.05

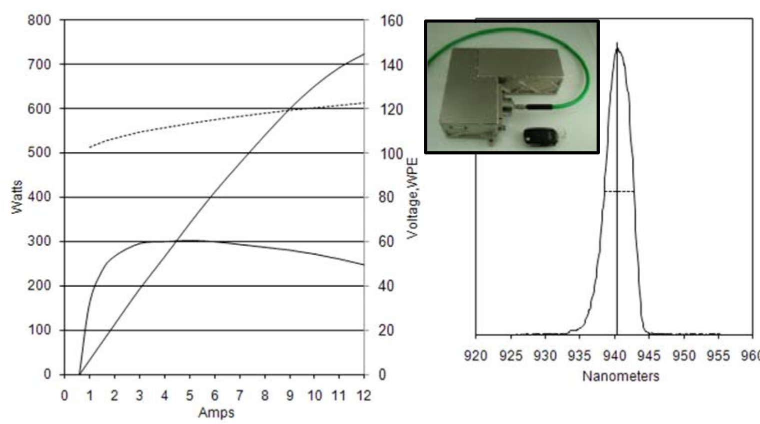
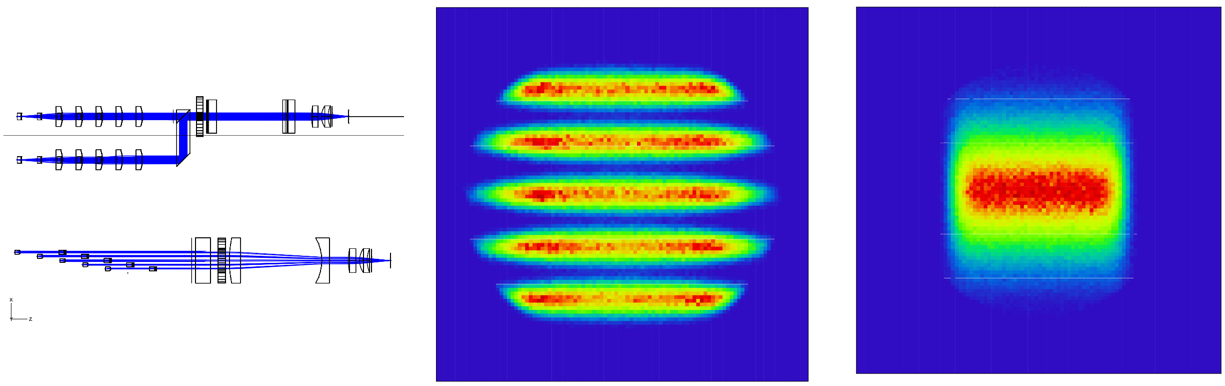


Fig. 5*: (top left) The optical ray trace of a 56 emitter module designed to couple over 500W of optical power into a 200 µm, 0.2 NA fiber (top right) A mechanical design implementing this system. (center) The NA and spot diagrams of the laser module, showing the possibility of highly efficient fiber coupling of these 56 emitters into this BPP. (bottom) A data sheet showing the afocal characteristics of this package as implemented with over 72 emitters. Peak efficiency of 60% is achieved with a peak power of over 700W of optical power.*

nLIGHT has also developed a 10-emitter fiber coupled unit based on the Pearl architecture for coupling 80W of optical power into a 105 µm, 0.15 NA fiber. The optical model and ray trace and data sheet are shown below in Fig. 6. There is excellent agreement between the optical model and the fabricated device, with fiber coupling efficiency measured above 90%.



OPTICAL	
Wavelength, nm	979.0
Output Power, watts	80
Spectral Width, FWHM	3.6
Spectral Width, 1/e^2	6.0
Slope Efficiency, W / A	7.8
Divergence, NA (90% power incl.)	0.12
Wavelength Temp. Coeff., nm / °C	0.35
ELECTRICAL	
Total Conversion Efficiency (ηWP)	50%
Threshold Current, amps	0.43
Operating Current, amps	9.83
Operating Voltage, volts	16.30
Series Resistance, ohms	0.27
THERMAL	
Operational Temperature, °C	25.0
Thermal Resistance, °C / W_{heat}	0.35

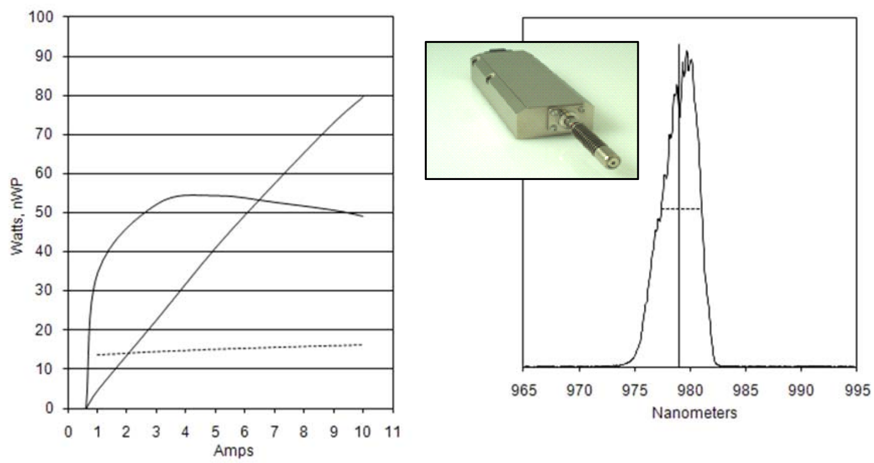


Fig. 6: *(top) The ray trace, NA diagram, and spot diagram for a 10-emitter Pearl module capable of coupling over 80-W of optical power into a 105 µm fiber at 0.12 NA. The two columns of light are combined using polarization multiplexing. (bottom) The data sheet for this laser module. The efficiency is above 50% over the entire operating range of the device.*

nLIGHT has also fabricated devices based on 14 emitters into a 105 µm, 0.15 NA fiber at 79x-808 nm, 9xx nm, and 15xx nm. The optical ray trace is shown below in Fig. 7. The 79x nm devices are designed for pumping Tm-doped fiber lasers, enabling the KW scaling of eye-safe fiber lasers. These devices coupled over 70 W of optical power into this fiber, with an efficiency greater than 40% and a corresponding brilliance of 13 MW/cm^2-str. 15xx nm devices were also demonstrated for the purpose of medical applications (wrinkle removal), Er:YAG pumping, and the pumping of Er-doped fiber lasers. We achieved over 15 W of optical power, using only 7 devices and a single polarization. This device had a corresponding brightness of >3.5 MW/cm^2-str. We suspect that over 30W of optical power will be achieved when we use polarization beam combination in conjunction with these laser diodes. Finally, over 100W of optical power were achieved at 9xx nm with efficiency values approaching 50% and brightness values of 20 MW/cm^2-str.

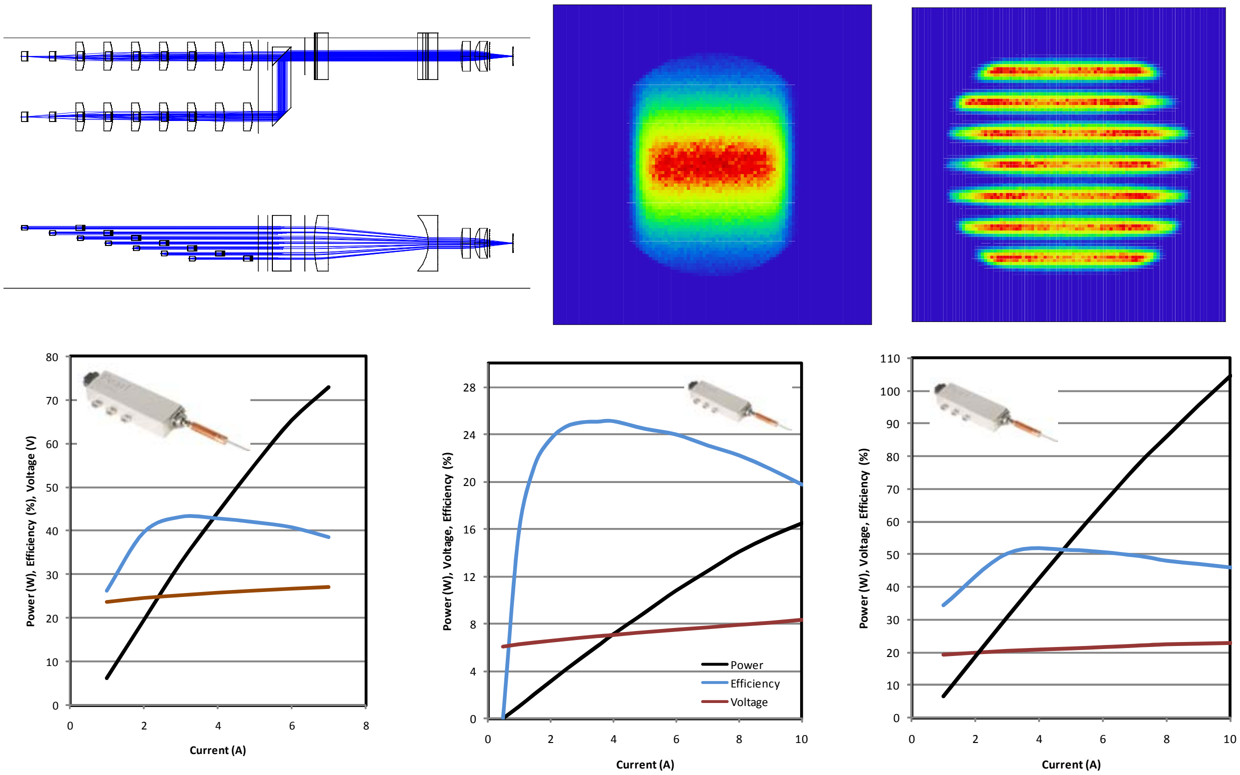


***Fig. 7**: (top) The ray trace, NA diagram, and spot diagram for a 14-emitter Pearl module at 9xx nm. (bottom) LIV curves for various devices coupled into a 105 µm, 0.15 NA fiber. (bottom left) Device characteristics for an 808 nm, showing over 70W of optical power into a 105 µm, 0.15 NA fiber. (bottom center) 15xx nm results of over 15 W of optical power into a a 105 µm, 0.15 NA fiber. (bottom right) 9xx nm device results of over 100W of optical power into a 105 µm, 0.15 NA fiber, for a measured brightness of over 20 MW/cm^2-str.*

4. CONCLUSIONS

In conclusion, we have demonstrated high brightness diode laser modules from 80x to 15xx nm. These devices can be used in a broad range of applications including: fiber laser pumping, solid state laser pumping, medical, and materials processing.

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