9xx nm single emitter pumps for multi-kW systems

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ABSTRACT

High-power high-brightness multimode edge emitting pumps have been developed. Comprehensive development efforts have resulted in 3 mm-long cavity diodes with far-field divergence reduced down to 26°. Output in excess of 20W CW from 90 µm-wide aperture single emitter was demonstrated for the first time. Peak power was reached at 25A CW driving current and was limited by power supply. Peak CW power efficiency was as high as 67%. Two coolerless package types designed to operate up to 10W output and up to 20W output are reported. About 95% fiber coupling efficiency into NA<0.12 was demonstrated in the entire range of driving currents for both types of pumps. For packages of the later design efficiency over 50% is maintained up to 16W CW ex-fiber output. Diode junction overheat above heatsink temperature is less than 20°C up to ~ 18W ex-fiber output.

Keywords: Single emitter pumping, multimode, high power, high brightness, coolerless pumps

1. INTRODUCTION

Multimode single emitter semiconductor diodes are the most efficient and reliable pumping source presently available. They surpass monolithic laser diode arrays (bars) in efficiency, brightness and reliability in CW and QCW modes. Distributed pumping architecture based on single emitter pumps is simpler and more redundant than the bar stack architecture. Cooling requirements for high power (multi-kW-class fiber laser and direct diode) systems based on single emitter pumps are radically relaxed comparing to bar stacks; no special requirements on cooling water quality, pressure or hardness are imposed. In the past few years with increased volume of single emitter devices manufactured the cost of pumping, i.e. $/watt, has been dramatically reduced. In the nearest future the above advantages should rule out the use of bar pumping not only in the case of low power (hundreds of watts) devices but for also for multi-kW-class systems.

Recent industry efforts to further improve diode pumps were focused on performance and brightness, while maintaining appropriate reliability[1,2,3]. This paper describes further developments in highly efficient single emitter 9xx nm multimode pumps launching 10W-20W CW output range. Structure design, epitaxial growth and post-growth processing are discussed. In the conclusion the cooler-less package designs and performance are described.

2. LAYERED STRUCTURE OPTIMIZATION

2.1. Epitaxial growth of laser material

Solid State Molecular Beam Epitaxy (SS MBE) has been used for the growth of epitaxial wafers. This method yields excellent optoelectronics material quality and is the method of choice when low defect density and uniformity of optoelectronics parameters across large deposition areas are required. In our case the lasing wavelength uniformity is better than 1.5 nm across > 90% of deposition area in multiwafer epitaxial reactors.

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High-Power Diode Laser Technology and Applications IV, edited by
Mark S. Zediker, Proc. of SPIE Vol. 6104, 61040K, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.646900

Two different material systems are used to manufacture lasers emitting in 9xx nm range: traditional AlGaInAs/GaAs and phosphorus-based GaIn(Al)AsP/GaAs. Initial expectations were high for this P-based material to provide devices' higher reliability with less manufacturing steps. But the most recent data indicate bulk degradation and lower catastrophic optical damage (COD) levels in P-based laser diodes operating under high current and optical flux conditions[4]. Thus all 100 µm aperture class pumps with proven reliability and output higher than 5W are produced only with AlGaInAs-based material.

2.2. Laser structure design

To enhance efficiency of multi-kW systems reliable pumps with increased brightness and efficiency are needed. These requirements can be met in long-cavity edge-emitter pumps with improved thermal resistance. Therefore new generation pumps require layered structure design providing low internal loss ($\alpha_i < 1$ cm^{-1}). Another parameter defined by layered structure that contributes significantly to pump efficiency is narrowed fast axis divergence. This is due to the fact that modern advanced fiber coupling schemes are based on narrow beam divergence. Thus reduction of transverse far-field was another goal for the structure design. Layered structure design primarily included optimization of layers composition and doping profiles.

Unlike the fast-axis where divergence is stable with current, slow-axis divergence is known to have tendency to increase, or to "bloom". That effect often becomes the limiting factor to sustain high coupling efficiency into low numerical aperture at high driving currents. This effect results in reduced brightness of pumping power. The blooming problem was addressed in the new generation pumps by applying an appropriate stripe geometry design.

Chips with L=3 mm cavity have been selected as a good compromise between improved heatsinking capacity and manufacturability. The choice of cavity length allowed for low fast-axis divergence (FWHM = 26° versus 28° in the previous chips design[1] with L=2 mm) and efficient performance. The key material parameters dependencies for the structures of the old and the new designs are presented in the Figure 1. As one can see from the plots the internal loss for the new generation chips was reduced by about 30% without compromising other lasing parameters. That allowed high slope efficiency from 3 mm-long chips.

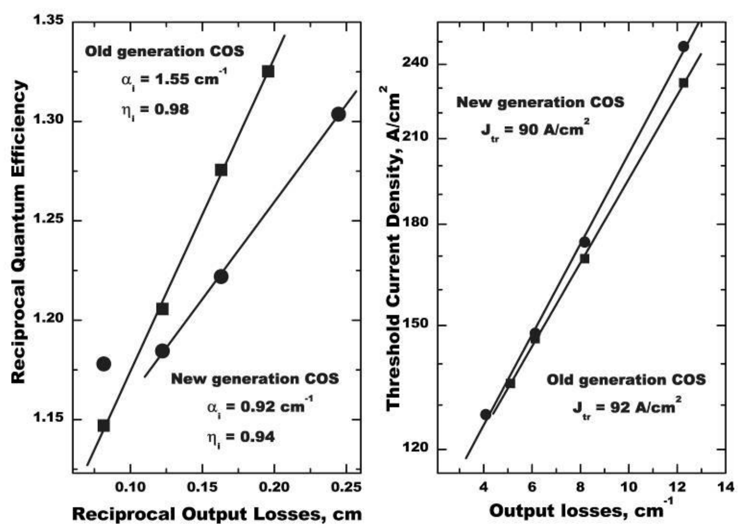

Figure 1. Dependence of external quantum efficiency and threshold current density as a function of output loss in the diodes of the new (FWHM=26°C) and the old (FWHM=28°C) designs recorded at 25°C heatsink temperature. Data presented were collected in CW mode of operation.

Another lasing parameter that has benefited from longer cavity chip, better layered structure design and improved assembly process was the temperature sensitivity of lasing. Figure 2 shows dependencies of threshold current and slope efficiency versus heatsink temperature. As one may see from the plots T_0 = 182K and T_1 = 833K were achieved in 25°C-to-85°C heatsink temperature range in CW regime of operation. It is worth mentioning that close to 90% slope efficiency was recorded at 25°C for L=3 mm COS at the lasing wavelength of λ ~ 974 nm; slope efficiency drops to 70% value when heatsink temperature is increased to 130K. High initial slope and temperature "insensitivity" of lasing make the COS of a new design ideal choice for cooler-less operation in industrial-grade multi-kW systems in which overall efficiency is a crucial parameter.

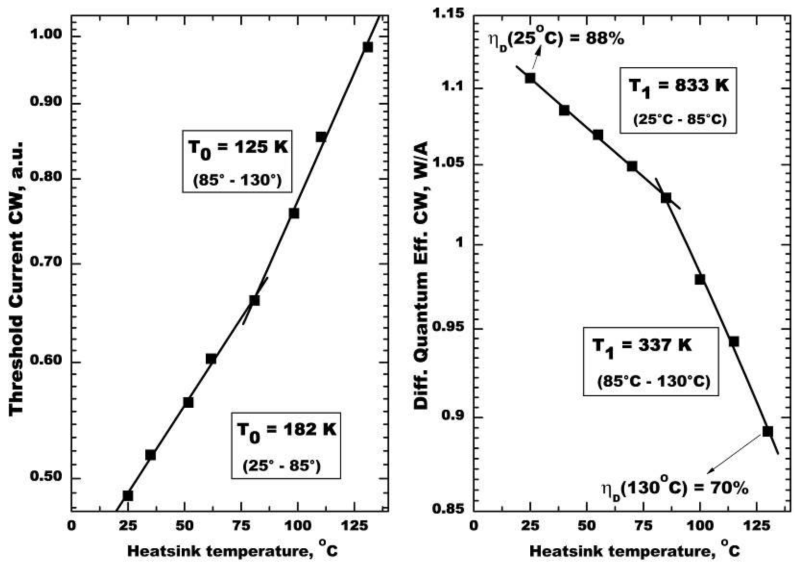

Figure 2. Dependence of CW threshold current and CW slope efficiency versus heatsink temperature for L=3 mm COS with 26° transverse divergence.

Figure 3 demonstrates an improvement of stability of far-field pattern with current. This improvement was achieved primarily due to several changes in stripe design. As one may see from the figure the far-field pattern in slow-axis is virtually free of blooming effect; divergence in lateral direction is increasing by only 0.45° with threefold driving current increase: from 3A CW to 9A CW. Such behavior ensures high fiber coupling efficiency which is stable with current and therefore allows for high brightness.

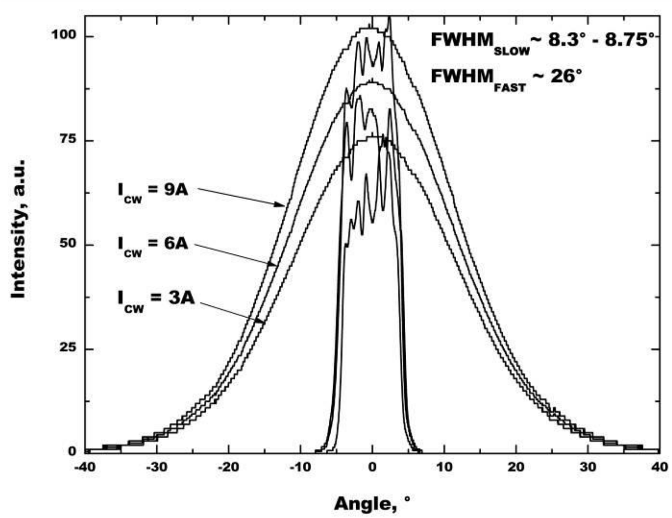

Figure 3. Evolution of far-field lasing pattern with CW driving current increase.

3. CHIP-ON-SUBMOUNT PERFORMANCE: FACET COATED DEVICES

Facet-coated Chip-On-Submount (COS) of 3 mm cavity length and W=90 μm were assembled with gold-tin eutectic alloy. The devices were tested up to 25A CW driving current; and heatsink temperature was varied from 5°C up to 75°C. To the best of our knowledge figure 4 shows the highest ever reported CW output from the single-element edge emitters with ~ 100 μm-wide aperture: over 20W CW at 25A driving current; the power-current characteristic was recorded at 5°C heatsink temperature. Over 20 W CW of free-space launched power yields optical density on the facet of > 220 mW/μm and this output value is power supply limited.

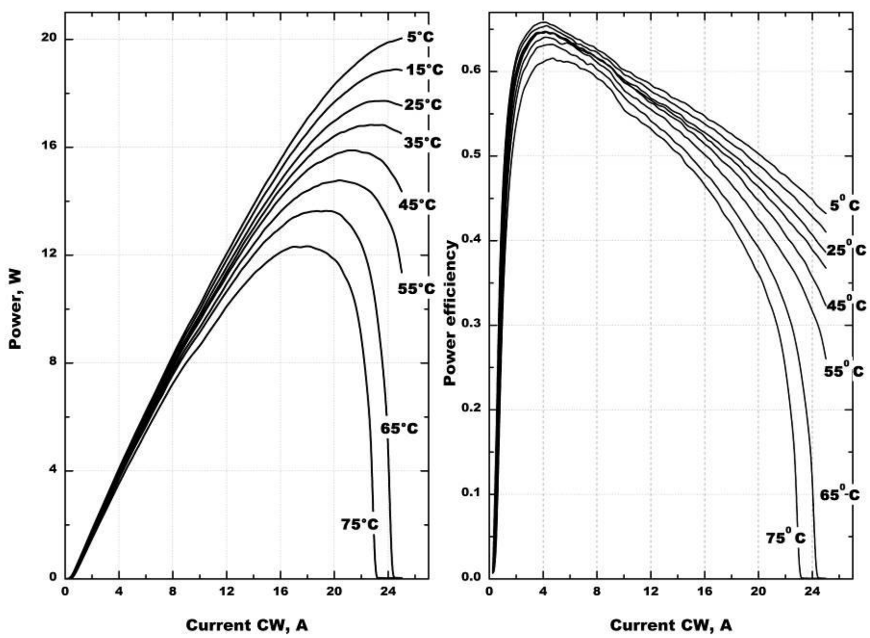

Figure 4. Power and Power Efficiency for new-generation (L=3 mm) COS at different heatsink temperatures.

In order to avoid self-focusing and to ensure absence of filamentation at high driving currents the processing optimization was implemented. The purpose of this optimization was to stabilize the near-field pattern shape in the entire range of driving current. Such improvement helps to avoid optical flux density non-uniformity that might have negative effect on facet robustness. It is worth mentioning that we had never observed COD-related failures even for the narrow-stripe (W=20-30 μm) multimode AlGa(In)As/GaAs devices in which thermally limited peak optical density on the facet was over 420 mW/μm (≥ 65MW/cm^2) [4]. Although the new generation of W = 90 μm COS operate at more than twice lower optical flux density (at the peak of LI characteristics) the filamentation can still cause "hot" spots in which the optical flux density may significantly peak over the rest of the stripe width.

Figure 5 shows the results of the optimization. As one may see from the graph the near-field profile across the stripe width indicates better than +/-10% uniformity of optical flux intensity across the aperture. Additionally, even at the highest driving current conditions, 15A CW, there is no presence of the near-field alteration: the FWHM of the near-field profile stays very stable and changes within the accuracy of the test setup. Such near-field behavior should have positive impact not only on the uniformity of the temperature across the facet but also on the stability of the far-field pattern that translates into improved and more stable fiber coupling efficiency.

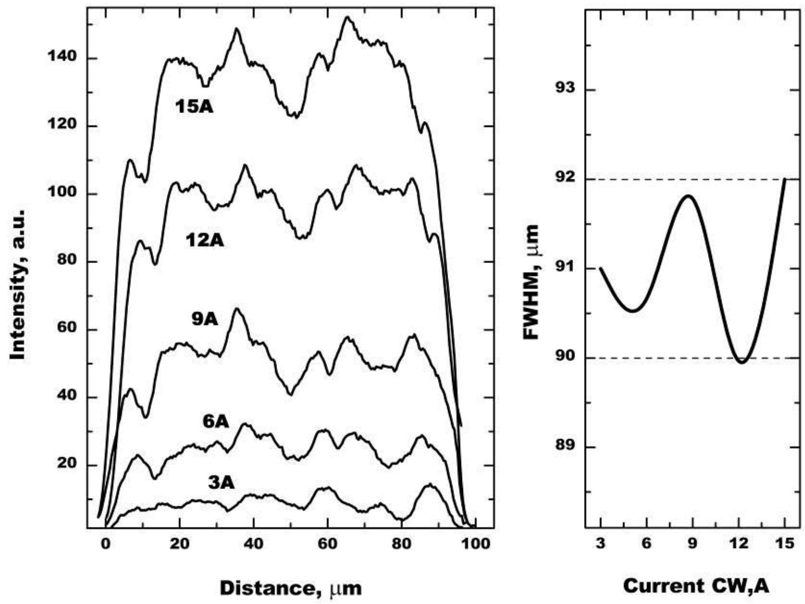

Figure 5. Evolution of the near-field profile of new-generation (L=3 mm) COS and near-field FWHM dependence on driving current

Figure 6 is included for the sake of comparison of the two generation COS performance. It demonstrates the power and power efficiency from the old generation 2 mm-long W = 90 μm COS recorded at different heatsink temperature, while figure 7 presents side-by-side comparison of power characteristics recorded at 15°C. As one may see from these graphs the longer cavity COS have clear advantage over the older generation devices when operated in stressed regimes: ultimate power, i.e. brightness, and power efficiency are sustained up to much higher currents and elevated heatsink temperatures. This advantage is due to improved thermal resistance intrinsic to longer cavity COS as well as the changes implemented into layered structure and submount designs for the 3 mm-long COS. These modifications allowed over 12W CW peak free-space power with heatsink temperature maintained at 75°C (which means heating the heatsink), see figure 4. This optical output value compares favorably with ~7W CW free-space power launched that was reported earlier[1] for previous generation 2 mm-long COS at the same T_{HS}=75°C, see figure 6.

For 3 mm-long COS peak power efficiency over 60% was demonstrated in the entire range of heatsink temperature, up to T_{HS}=75°C. At T_{HS}=25°C power efficiency (free-space-launched over electrical supplied to COS) in excess of 50% was maintained up to > 18A CW driving current. Although power efficiency values reported in this paper are comparable with the record peak values presented elsewhere[5], the authors believe present data were recorded under much more practical operating conditions (high current and high temperature), i.e. coolerless operation. These stressed conditions are much closer to the real-life end-user environment which is realized during in-field multi-kW systems operation with no cryogenic heat-removal setups[6] involved. Furthermore, multi-kW systems pumped by single element pumps do not need high-pressure and ultra-high-purity micro-channel cooling whose presence negatively affects overall system efficiency, reliability and boosts cost.

In addition to "temperature insensitivity" of power and power efficiency parameters there is another key advantage of the new generation COS, which is a lower junction overheat with current, i.e. with output power. This feature of the longer cavity diodes is translated into lower thermal resistance of the packaged pumps and ensures better reliability. This advantage will be discussed in more detail in the next paper section on packaged devices.

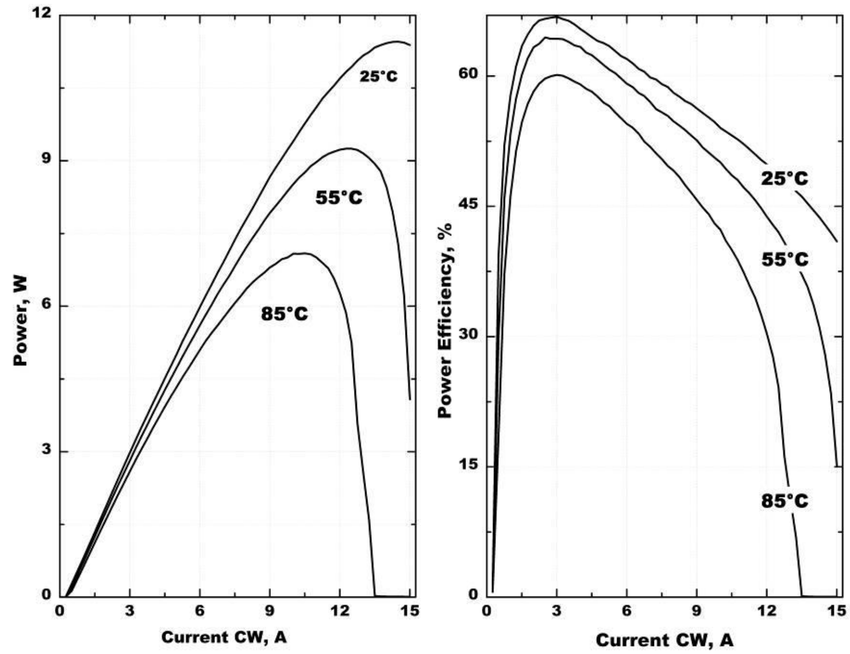

Figure 6. Power and Power Efficiency for the previous-generation (L=2 mm) COS recorded at different heatsink temperatures[1].

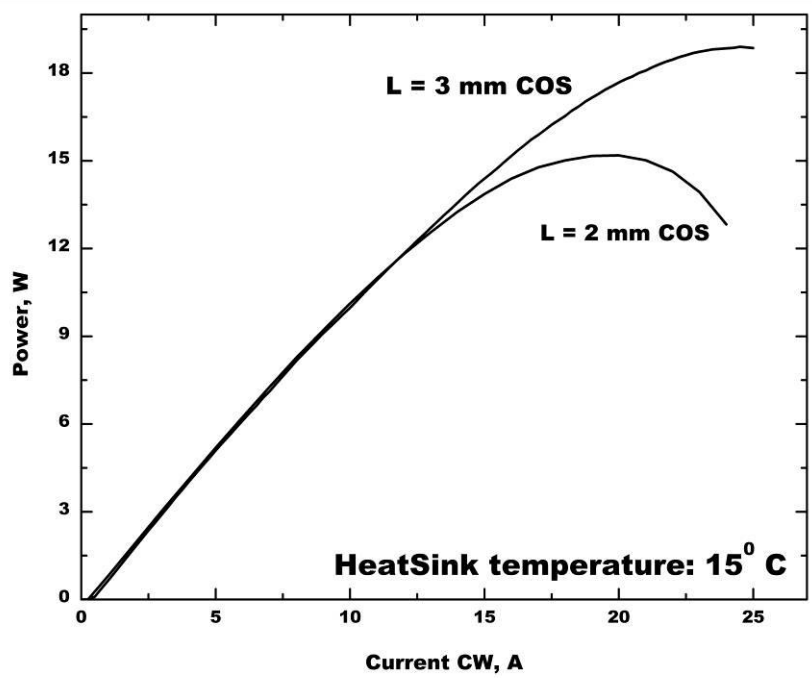

Figure 7. High power CW performance of COS of the new (L=3 mm) and the old (L=2mm) generation recorded at 15°C heatsink temperature

4. FIBER COUPLED PACKAGED PUMPS

This section focuses on fiber coupled packaged multimode pumps manufactured at IPG Photonics for fiber lasers and direct diode systems; i.e. for non-telecom applications. All ex-fiber outputs reported here are recorded for the fiber of ~ 100 μm dia. Figure 8 shows the photograph of two different types of pumps: T1 and T2. T1 coolerless-pumps type reported earlier elsewhere[1] and are the devices of medium pumping power range (up to 10W CW). T2-coolerless-type pump were designed for applications that require higher power and higher brightness of pumping. Presently the power rating of T2 production devices is up to 20W, although newer laboratory prototypes demonstrate 30W ex-fiber power and higher without increase in pump size. Unlike other commercially available high-brightness ex-fiber solutions scaling-up power in T2 pumps did not involve significant increase of device footprint. As one may see in the figure T1 and T2 pump's footprint would compare favorably with industry-standard open heatsink passively cooled CS-type laser diode bar mount.

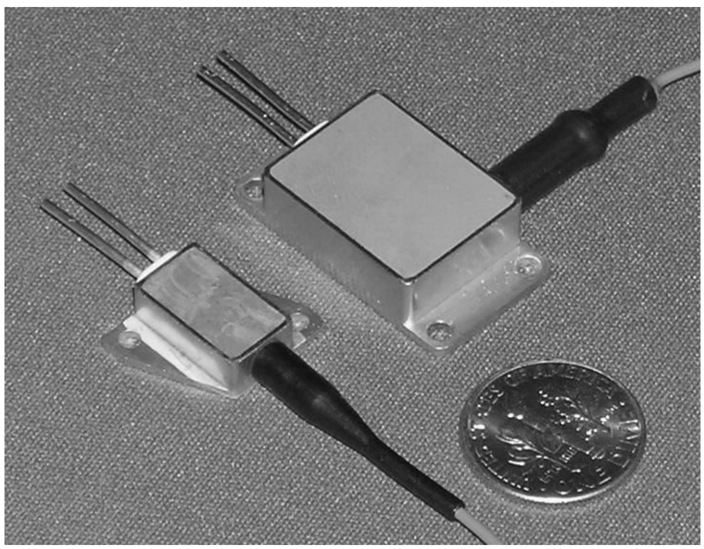

Figure 8. Photograph of the two types of packaged coolerless pumps manufactured at IPG Photonics: T1 (on the left) and T2 (on the right). One dime coin is placed alongside for scale purpose.

Figure 9 depicts typical ex-fiber output for T1 coolerless pumps; the data was recorded for regular devices extracted from IPG manufacturing line. The two sets of curves were recorded for T1 pumps built with the old COS and the new generation COS. As one can see from the figure the two sets of light-current characteristic are virtually indistinguishable up to ex-fiber output of approximately 5W-6W. Beyond this power level the T1 pumps built with long-cavity COS demonstrate clear advantage. L-I curves appear to be almost linear with current up to 10W (at ~12A) output with L=3 mm diodes. Such efficient power performance is delivered without sacrifice in numerical aperture; NA < 0.12 is maintained in the entire range of driving currents. The thermal properties of T1 packages differ noticeably for the pumps built with the new and the old generation devices, as is depicted in figure 10. Diode junction temperature increase of about 30ºC, i.e. lasing wavelength shift of ~ 10 nm, occurs at 3A to 4A higher driving currents in T1 pumps with the COS of the new design. The set of data presented in figures 9 and 10 qualifies T1 devices with L=3mm COS as efficient coolerless pumping source for up to 10W pumping power.

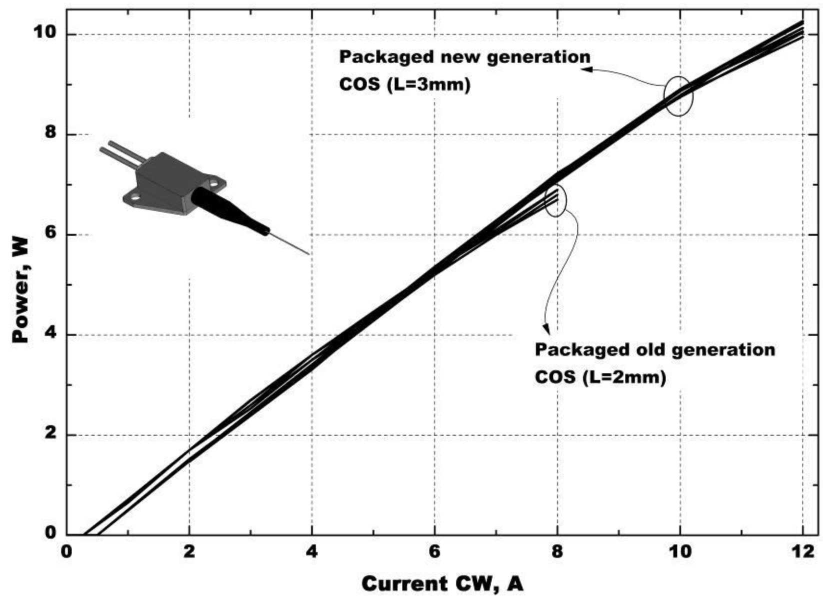

Figure 9. T1-type pumps CW performance comparison: with new generation COS (L=3mm) vs. old generation COS (L=2 mm); heatsink temperature was set at 25°C.

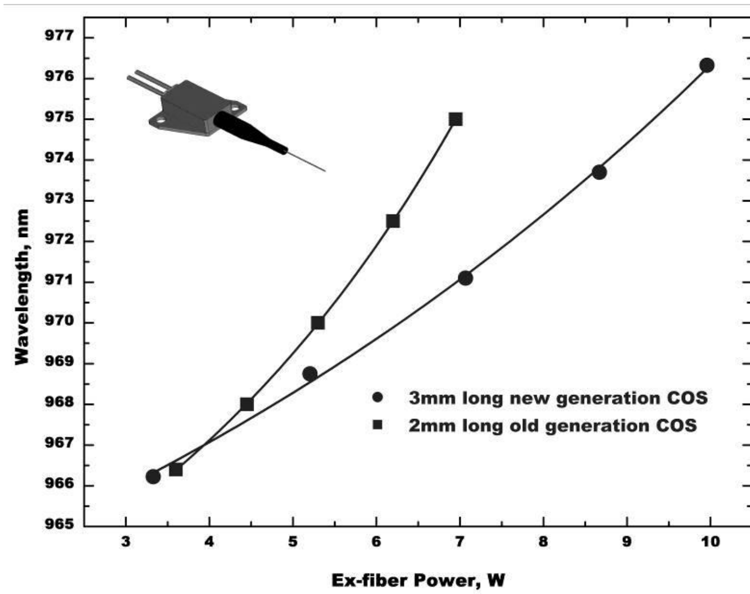

Figure 10. Typical shift of the pumping wavelength versus ex-fiber output for T1-type pumps recorded at 25°C in CW mode of operation; heatsink temperature was set at 25°C.

The next two figures depict data recorded for the T2 high-power high-brightness coolerless pumps. This generation packaged pumps are designed for higher range of pumping power: the data are presented up to 20W ex-fiber output. Despite the transition to higher powers there was no penalty in the brightness of pumping; ex-fiber output is contained within less than 0.12 numerical aperture.

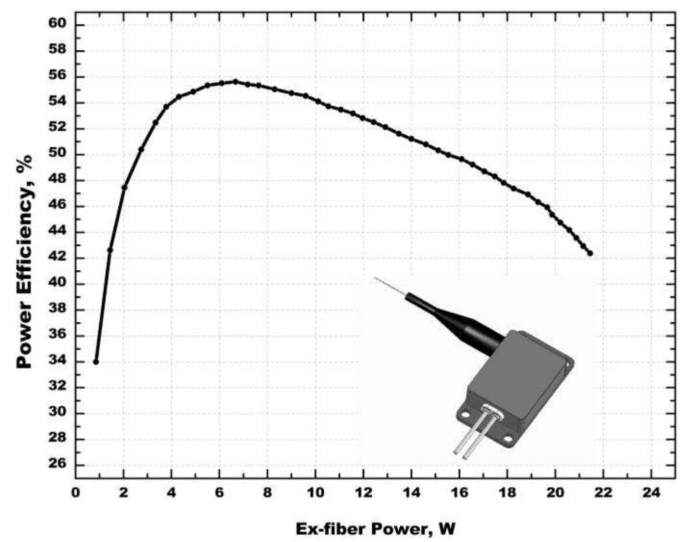

Figure 11. Power efficiency (electrical into ex-fiber) recorded for a T2-type pump with COS of L=2 mm design at 25°C heatsink temperature in CW mode of operation.

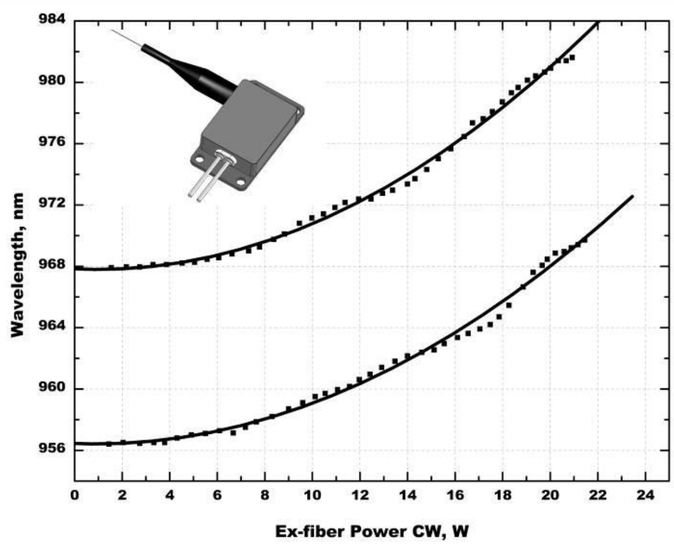

Figure 12 Shift of the pumping wavelength versus ex-fiber output for a T2-type pump (COS of 2 mm design) recorded at 25°C in CW mode of operation; the data for two T2 packages operating at different wavelengths are plotted.

Figure 11 represents power efficiency (electrical into ex-fiber power) of T2 type coolerless pumps. Power efficiency in excess of 50% is maintained up to 16W CW ex-fiber (NA<0.12) output; efficiency does not decrease below 42% with output increase up to ~ 22 W. Junction temperature rise is about 40ºC at output power of >20W and is about 30ºC at about 18W output (as seen from the graph in figure 12). Authors are unaware of a pumping source demonstrating comparable quality of ex-fiber pumping power and brightness available commercially or even ever reported.

There is a clear advantage in T2 pump thermal performance with transition from the “L=2 mm” to “L=3 mm” device design. The example of this is presented in figure 13 which depicts peak wavelength position shift with ex-fiber output.

As one can clearly see from the graph the junction temperature overheat is much less in the case of longer cavity devices especially at high ex-fiber output: at 20W output junction temperature rise does not exceed 25°C.

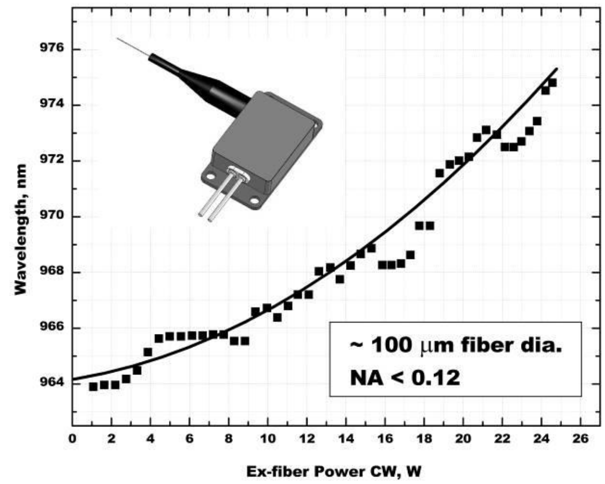

Figure 13. Shift of the pumping wavelength versus ex-fiber output for a T2-type pump (COS of 3 mm design) recorded at 25°C in CW mode of operation.

5. COS RELIABILITY ASSESSMENT

AlGa(In)As/GaAs-based single emitter multimode pumps manufactured by Solid Source MBE possess reliability[1] unsurpassed by any other pumping source. This data was obtained from extensive multi-cell stress test experiments performed on L=2 mm COS. We do not expect any deterioration of reliability for the new generation pumps with L=3mm. As of today we have not accumulated enough device-hours from multi-cell tests to provide data on MTBF with sufficient accuracy and confidence level, but preliminary data obtained even for the most stressed burn-in conditions indicate that improved performance did not compromise the reliability of the diodes. One example for that is presented in figure 14. These burn-in conditions (I=10A, T_{HS}=75°C) drive the COS junction temperature in excess of 120°C.

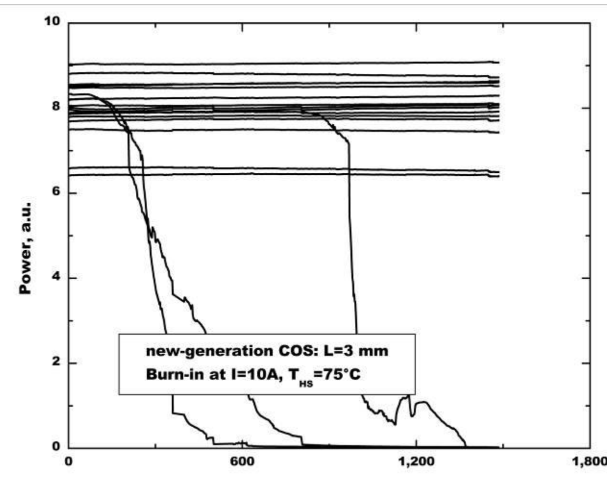

Figure 14. Sample of burn-in data for a lot of 18 COS: burn-in at 75ºC heatsink temperature and driving current of 10A, COS were not screened prior being put on test.

6. CONCLUSION

We have demonstrated record-high CW free-space output in excess of 20 W and record-high brightness of over 200 mW/μm from 90 μm aperture AlGaInAs/GaAs MBE-grown laser diodes. COS operating in 9xx nm range maintain highly efficient performance at elevated heatsink temperatures: over 60% power efficiency was demonstrated at T_{HS}= 75°C; and 50% efficiency is maintained up to 18A driving current at T_{HS}=25°C. Packaged pumps based on the new generation devices exhibit excellent thermal resistance and demonstrate unsurpassed brightness of pumping power (ex-fiber output). Coupling efficiency is maintained at ~ 95% value in the entire range of driving currents. Combination of the above features makes these pumps the ideal choice for any pumping application. These pumps provide very cost effective pumping for direct laser diode systems and fiber lasers: from mid-power class devices (hundreds watt) to multi-kW systems (tens of thousands of watts). They enable numerous new applications in which brightness and overall system reliability and power efficiency are the key factors.

7. ACKNOWLEDGEMENT

Authors would like to thank numerous people at IPG Photonics Corp. who have assisted this work in many different ways.

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