> 360W and > 70% Efficient GaAs-Based Diode Lasers

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ABSTRACT

High power GaAs-based high power diode bars produce wavelengths in the range of 780 to 980 nm and are widely used for pumping a broad range of rare earth doped solid-state lasers. As the markets for these laser systems mature, diode lasers that operate at higher power levels, greater overall efficiency, and higher reliability are in high demand.

In this paper we report efficiencies of over 70% in the 9xx-nm band, continuous wave power levels over 340 Watts in the 8xx-nm band, and reliability data at or above 100 Watts. We will also review the latest advances in performance and detail the basic physics and material science required to achieve these results.

Keywords: diode, laser, conversion, efficiency, peak, optical, power, reliability, GaAs, 980, 808

1. INTRODUCTION

There are two major device performance metrics for high power diode laser material: the maximum optical output power achievable and the power conversion efficiency. We report major advances in both peak power and peak efficiency from GaAs based diode lasers, without any compromise in reliability. We have focused on improving peak power in 1-cm 8xx-nm laser bars, and peak efficiency in 1-cm 9xx-nm laser bars.

A typical high power commercial diode laser bar is packaged using a water-cooled micro-channel heatsink. The maximum power delivered from these bars is important for two reasons:

1) higher power means higher on-target power density is achievable (W/cm^2 increases), especially when these bars are integrated into stacked arrays and combined with multiplexing optics [1]

2) higher power means that the overall cost of ownership can be reduced – the cost per watt of optical output power decreases overall ($/W decreases).

Achieving the highest powers without compromising product reliability relies on extremely high quality diode laser material and packaging—defects in process or design will quickly lead to failure. We demonstrate high power 8xx-nm diode bars with peak optical powers in excess of 360W. The electrical input power to deliver these output powers is in the range of 2-10kW/cm2. Most of this input is immediately converted to optical output—however at such high power densities and peak currents, defects will rapidly lead to device failure.

Although increased peak output power enables new high power-density applications and reduces overall cost of ownership, there is a further critical parameter to consider - the power conversion efficiency (*PCE*) of the diode bars (commonly termed wall-plug efficiency). *PCE* is defined by the equation:

PCE = Useful Optical Output Power ÷ (Input Current x Voltage Dropped across Device) (1)

In other words, the PCE tells you how much useful optical power is extracted for a given electrical input power. The power left behind is deposited in the device as “waste” heat.

Increased *PCE* leads to two crucial benefits:

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1) Increased output power for a fixed input power (more watts out for same power supply)
2) Reduced waste heat – less heat is left behind in the laser material, so the user will only need a small, simple cooling system.

Using careful diagnostic experiments, we have identified many of the key mechanisms limiting the efficiency of a 9xx-nm diode laser bar and have increased the efficiency of diode laser material in the 9xx-nm band to > 70%.

2. HIGH POWER 8XX-NM DIODE LASER BARS

Very high power 1-cm diode laser bars depend on high-grade laser material and high-grade low thermal resistance packaging, as reviewed in [1]. A single 150-µm stripe diode laser at 8xx-nm can deliver typically between 2W and 5W of reliable optical output, with peak powers in excess of 10W [1]. Higher powers are more demanding and require more advanced facet passivation techniques. 100W of optical output therefore requires between 20 and 50 150-um wide emitters in 1-cm bar format. This corresponds to a fill factor (proportion of active region) of between 30% and 80% in a 1-cm diode laser bar.

Figure 1 shows the optical output power and power conversion efficiency for a 790-nm 1-cm laser bar with 80% fill factor, mounted on a water-cooled micro-channel heatsink. Details of the laser construction are given in [1]. The de-ionized cooling water was held at 6C throughout the test. A peak power of 364W is achieved, with a power of 346W reached at 20C cooling water. Typical bars to the same design have been placed on extended lifetest at 100W per bar for over 5000 hours without failure. These powers are a significant advance over previous publications - previous authors have reported high powers from 1-cm laser 8xx-nm diode bars diodes in the range of ~ 240W [2], when attached to high efficiency water-cooled micro-channel heatsink.

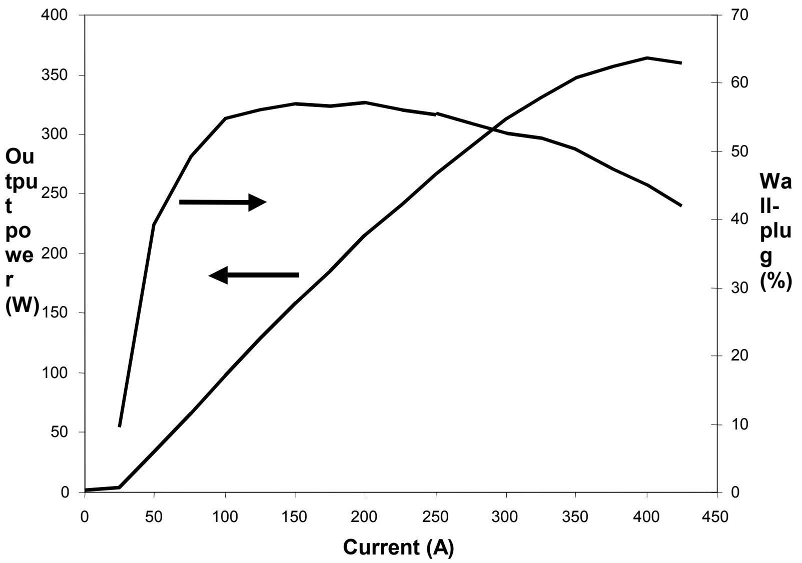

Figure 1: Power and Wall-plug Efficiency of a 1-cm 8xx-nm diode laser bar optimized for high powers

1-cm bars to the same design were placed on long-term endurance at 100W output power per bar, with cooling water held at 30C. The change in operation current for 100W output was tracked as a function of time, assessed via periodic re-test. In figure 2, the relative change in 100W operation current is shown as a function of time. Only small changes are seen in 5000 hours of continuous test.

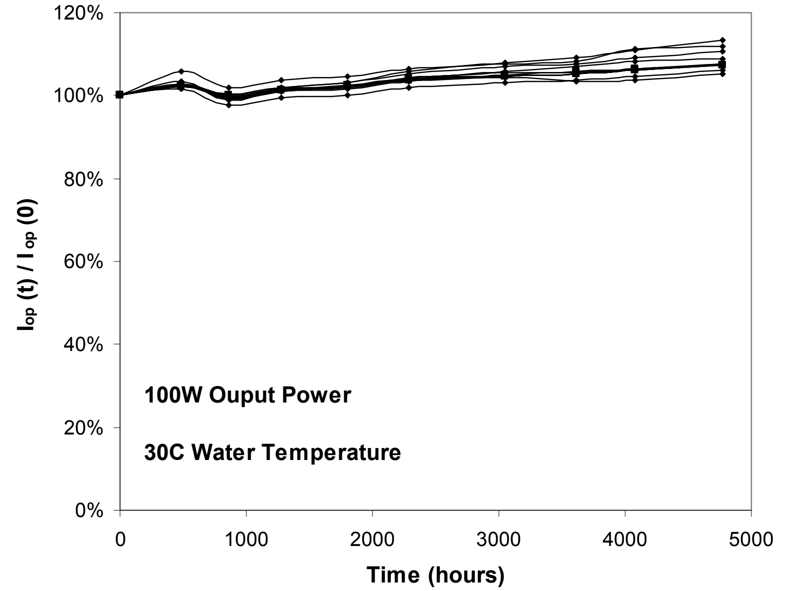

Figure 2: Long-term endurance performance of 1-cm 8xx-nm diode laser bars at 100W operation power and 30C water temperature.

Delivering increasingly high powers is not simply a case of integrating more emitters into a bar- there are several technical challenges that must be overcome. The three most significant requirements are:

1. Control of device temperature
2. Defect Free, Low Stress Soldering
3. High Peak Optical Output Power

2.1. Control of device temperature

Driving a high power diode laser bar inevitably means a large amount of heat and current is concentrated in a very small area. The performance of diode laser material degrades at higher temperature, reducing peak achievable power. Also, package and diode failure modes depend strongly on temperature and excessive temperatures will quickly lead to failure. In Figure 3, the total electrical energy delivered to the diode is plotted, along with the "waste heat" left behind. At 100W of optical output, ~ 80W (~ 0.8kW/cm^2) is delivered to the diode, and at 360W of optical output, 500W (~ 5.0kW/cm^2) of waste heat is left in the diode. Three approaches are taken to minimize the impact of this waste heat.

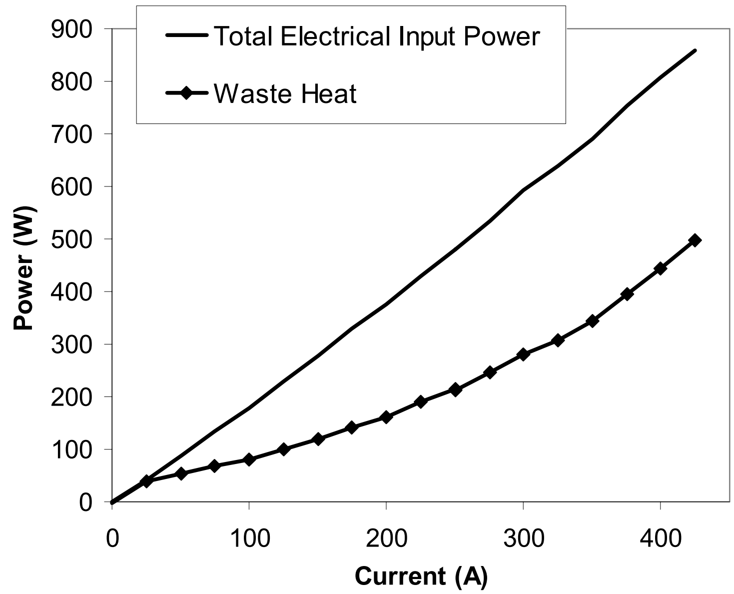

Figure 3: Electrical input power (IV) and waste heat left in the diode bar in figure 1.

2.1.1. Temperature insensitive diode laser material

Through careful design optimization, the temperature sensitivity of the diode laser material can be minimized, as reviewed in [1] to ensure output powers are not compromised under high temperature operation. The laser material used here has characteristic temperatures of T_0 ~ 150K and T_1 ~ 2000K, reflecting very small performance degradation with increasing temperature. As further evidence of minimal temperature sensitivity, similar material was tested over temperature in bar format, demonstrating PCE in excess of 50% even up to 70C package temperature [1].

2.1.2. High cooling power package

Single emitters deliver high power densities and high reliability. However, when integrated into a bar, much more heat is concentrated in a small area, potentially leading to thermal run-away. Water-cooled micro-channel heat-sinks are essential: they provide a high cooling rate and the ability to cope with high total heat loads. Thermal resistances (R_{therm}) as low as 0.2C/W can be achieved in optimized configurations – a detailed development program in its own right. With such low thermal resistance, no compromise in performance of bonded devices is seen in bar format when compared to single emitters, even up to ~kW class stacked arrays [1].

2.1.3. High efficiency material

High efficiency diode laser material will leave less waste heat behind in the laser packaging, reducing the overall temperature of the device, minimizing degradation in performance and lifetime. The laser material used in this high power application has been optimized for high efficiency and delivers ~ 60% peak wall-plug at ~ 200W of output power. High efficiency 8xx-nm diode lasers can only be delivered based on optimized low loss, low threshold material with low resistance, as reviewed in [1].

2.2. Defect free, low stress soldering

1cm bars have an extended bond area, meaning very tight control is required of both the solder used and the metallization of bar and package to prevent any defects from occurring. It is essential for the high power bar supplier to have internal control of these materials to enable low defect manufacture and process optimization. For example, solder voids are a very important defect to understand and minimize. Voids lead to local hot-spots under the diode bar which lead to rapid device failure. Even small voids can grow over time, leading to eventual failure. Void growth can be driven simply by current flowing (electro-migration) or via stress built into the diode laser material [3]. The rate of material movement (mass transport) is a strong function of the microstructure of the solder used in deposition – again emphasising the importance of internal control of solder properties. Through careful control of process and materials, the amount of bonding stress can be minimized, as reviewed in [1].

2.3. High peak power

GaAs based diode lasers can fail at high output powers due to degradation of the facet due to a process known as COMD, potentially limiting peak operation powers. Achieving high output powers in 8xx-nm diodes are more challenging than 9xx-nm diodes, due to the higher energy of each emitted photon. However, if appropriate precautions are taken, the device failure point is many times operation current and this failure mode is not seen. Even at 100W operation, each emitter in the 1-cm bar is delivering < 3W, at least 4x below the maximum operation power for this material [1].

3. HIGH EFFICIENCY 9XX-NM DIODE LASER BARS

The power conversion efficiency for a diode laser can be written in terms of laser parameters as:

$$PCE = \frac{E_{ph} \times \eta_{ext}^{(d)} (I - I_{th})}{I \times (V_{BG} + V_D)} \qquad (2)$$

Where I_{th} is threshold current, E_{ph} is the energy per photon, $\eta_{ext}^{(d)}$ is the external differential quantum efficiency (photons out per electron in), I the current, V_{BG} is the voltage corresponding to the emission wavelength and V_D is the voltage "defect" showing the excess voltage above the band-gap. A laser device would deliver 100% *PCE* if it had zero threshold, no voltage defect and if every injected electron was converted into a photon.

By careful optimization of the device parameters, we have delivered material with PCE in excess of 70% at both 940-nm and 980-nm, as shown in figure 4. Previous authors have reported single emitter PCE ~ 66% at 980-nm and 808-nm [4, 5].

The results presented are for 150-µm stripe single emitters bonded junction down to industry standard c-mounts. All testing was performed CW. All devices are optically coated, with 93% on the back facet, 5% on the front facet. Laser material was grown using MOCVD and is constructed from the AlInGaAsP material system. Optical power was measured using a Labsphere SC5500 integrating sphere system which was calibrated against a standard Molectron EPM1000 meter connected to a PM150-50C thermopile head, itself referenced to NIST power standards.

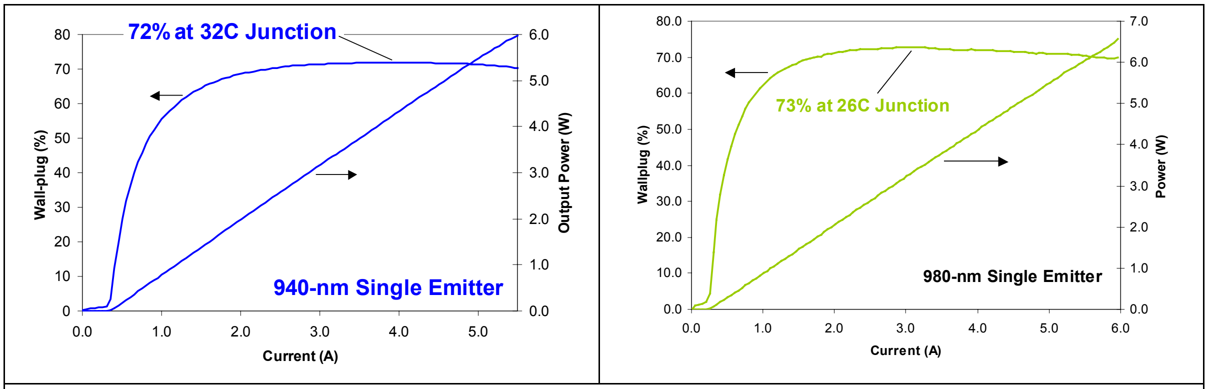

Figure 4: Peak Wall-plug Efficiency from 940-nm and 980-nm 150-µm stripe Single Emitters

Taking the 940-nm device as an example, in figure 5 the contributions of the three major empirical terms to the peak efficiency point are broken out. The data in figure 5 was derived by numerically assessing how much the efficiency is increased if in turn, the DQE is set to 100%, the voltage defect is set to zero and the threshold current set to zero. The threshold, DQE and voltage defect all limit the efficiency by approximately the same amount and are each the subject of intensive further optimization.

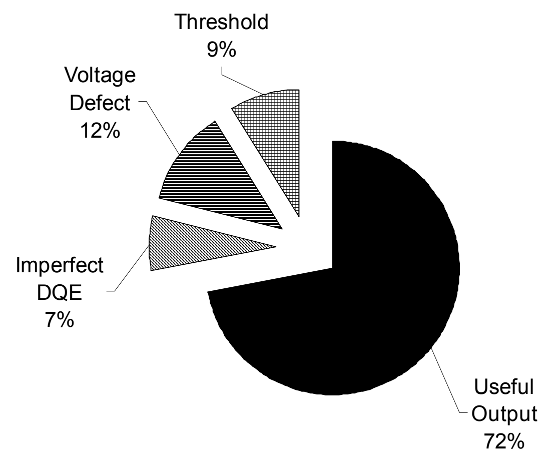

Figure 5: Contributions of main empirical terms to wall-plug of an example 940-nm diode laser

3.1. Voltage defect improvement

For carriers to reach the quantum well and recombine into photons, they must pass through many different material junctions, from the metal contact into the semiconductor then across the semi-conductor junctions themselves. Each of these junctions can lead to a voltage drop, adding to the overall device voltage. By careful material choices, and appropriate grades, doping spikes and ramps, reduced voltages can be delivered [6]. The voltage improvement is wavelength independent: voltage defect reduced to ~ 0.15V at peak efficiency point (~ 1.5kA/cm2) for both 980-nm and 940-nm material, as shown in figure 6. Further improvements are possible through materials optimization or via more radical design approaches, such as injecting current into the edges of the active region, avoiding the hetero-barriers [7].

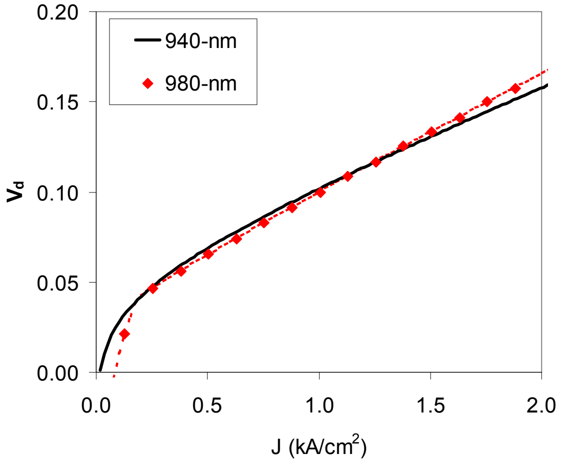

Figure 6: Voltage defect for 940-nm and 980-nm single emitters

3.2. Improvements to external differential quantum efficiency

The External Differential Quantum Efficiency (*DQE*) is the number of useful photons generated above threshold for every additional electron-hole pair injected to the laser. It is limited by the loss of carriers and the loss of photons. High quality low defect material limits the loss of carriers. Photons can be lost by absorption in highly doped regions, absorption in the quantum well or at imperfect semiconductor interfaces. All of these terms have been studied extensively in the literature and will not be reviewed here. All laser designs assessed here make use of the Large Optical Cavity approach [4], which minimizes the overlap of the light with the highly absorbing doped regions. Fine tuning the doping profile to minimize absorption gives > 90% DQE for both 940-nm and 980-nm single emitters, as shown in figure 7.

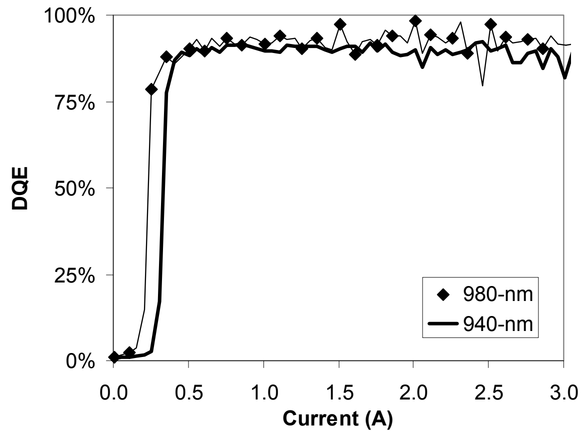

Figure 7: Differential Quantum Efficiency of 940-nm and 980-nm single emitters

3.3. Improvements to threshold current

Gain in these structures is provided by a single quantum well and fine-tuning the well characteristics can significantly reduce the device threshold current. For example, applying the correct strain is known to reduce threshold current significantly.

3.4. Reliability

The improvements seen here in device efficiency come without any degradation in device reliability. As an example, five single emitters were put through a step stress reliability test, as shown in figure 8. These devices were 150-um stripe devices mounted to commercial c-mounts junction down. The test was performed at a fixed heatsink temperature of 55C, and current was increased from 5.5A to 7.5A over a 1500 hour period. No degradation was recorded, confirmed by testing the devices before and after reliability testing. The low degradation shows the bulk laser material and output facets do not suffer from defects.

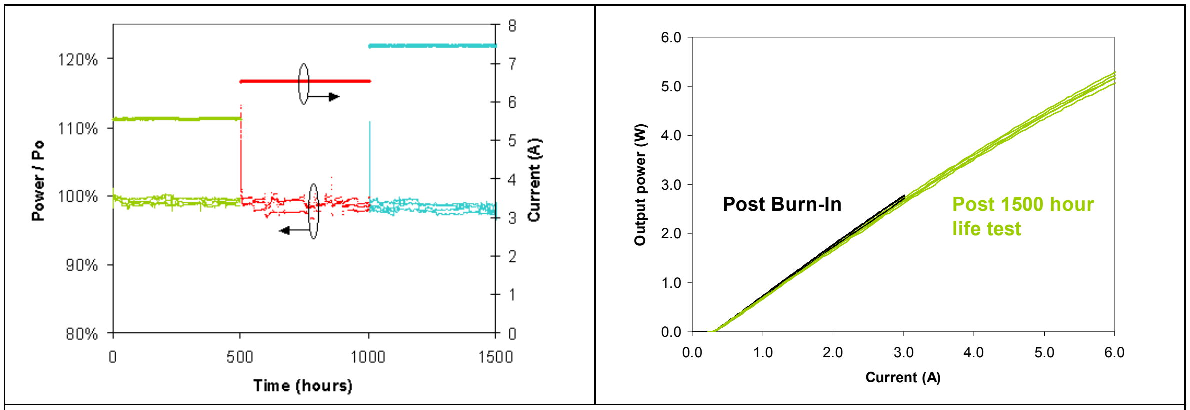

Figure 8: Step stress reliability assessment of 940-nm single emitter material, and pre and post-test results showing minimal degradation.

Two of these devices were left on extended test at 7.5A to assess performance on much longer timescale. After a further 2000 hours of continuous test at fixed current of 7.5A, there has still not been any significant degradation. Figure 9 shows the total collected life data on these parts: the first 1000 hours were at 5.5A and 6.5A, the final 2500 hours at 7.5A. Minimal degradation is seen, confirmed in re-test data.

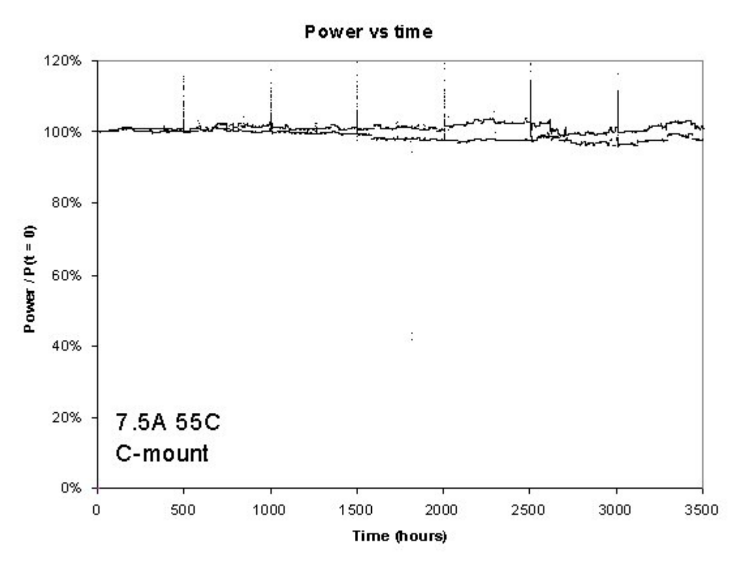

Figure 9: Extended life-test performance on two c-mounts at constant current and 55C package temperature.

3.5. Testing in bar format

Figure 10 shows the efficiency of a 980-nm bar in 100W bar format (50% fill factor), also mounted on a passively cooled CS mount. QCW testing under 200-µs, 100Hz leads to a power conversion efficiency of 73% at 100W of QCW output power and at approximately 25C junction temperature. Optical power was measured using a Labsphere SC5500 integrating sphere system which was calibrated against a standard Molectron EPM1000 meter connected to a PM150-50C thermopile head, itself referenced to NIST power standards. QCW powers were measured directly into the thermopile head.

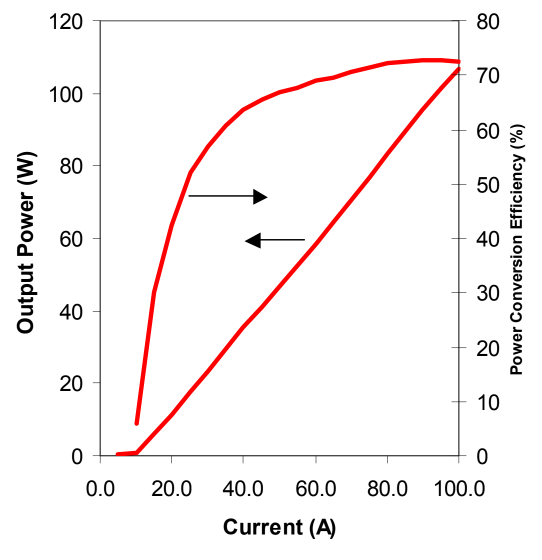

Figure 10: Power and Wall-plug efficiency for a 50% fill factor 975-nm diode laser bar.

2. SUMMARY

Significant advances in both peak power and power conversion efficiency have been achieved for high power 1-cm diode bars in 8xx-nm and 9xx-nm material. 8xx-nm bars with peak powers in excess of 360W and 980-nm material with peak power conversion efficiency of 73% have been demonstrated. The performance progress has been delivered through a combination of diode laser material improvements, and optimization of diode packaging and soldering.

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