250W QCW Conduction Cooled High Power Semiconductor Laser

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Abstract

High power diode laser arrays (HPDLAs) have increased applications in pumping of solid state laser systems for industrial, military and medical applications as well as direct material processing applications. For quasi-continuous wave (QCW) conduction-cooled-packaged high power semiconductor lasers, the operational mode is commonly at lower duty cycle (DC), such as less 2% DC. However, operating high power laser diode arrays in long pulse regime of about 200μs, and high duty cycle (such as 8% DC), which greatly limits their useful lifetime, are demanded for some special application. Finite element numerical analysis based simulations to analyze the transient thermal behavior of a conduction-cooled-packaged semiconductor laser operated in QCW mode in this paper. This work describes the performance of laser diode arrays operating in long pulse and high duty cycle mode, including the characteristics of Power-Current-Voltage (LIV), thermal, near-field, and lifetime. This paper will then offer a viable approach for determining the optimum design and operational parameters leading to the maximum attainable lifetime. Based on the numerical simulation and analysis, a series of high power semiconductor lasers with good performances were produced.

Introduction

High power diode lasers (HPDLs) offer a variety of applications due to their higher electrical-optical conversion efficiencies, compact sizes and long life-times than the most prominent types of lasers by nearly an order of magnitude. High power semiconductor lasers, whether operated at continuous wave (CW) or QCW mode, including single emitters, arrays, stacks, and two dimension area array stack have found increased applications in pumping of solid state laser systems for industrial, science and technology research, military, antiterrorism, entertainment display and medical applications as well as direct material processing applications such as welding, cutting, and surface treatment [1,2,3].The optical-to-optical conversion efficiency of diode-pumped-solid-state-laser (DPSSL) is much higher than that of lamp-pumped-solid-state-laser, as the spectral width of the diode laser is very narrow. With continuing improvement of the power, electrical-optical conversion efficiency, reliability, and manufacturability of high power semiconductor lasers, and decreasing manufacturing cost, many new applications of high power semiconductor lasers are being enabled [4].The three key performance measures of high power semiconductor lasers are power, efficiency, and reliability. For QCW conduction-cooled-packaged high power semiconductor lasers, high reliability and long lifetime are required in practical application.

To obtain higher reliability and longer lifetime, packaging plays more important role in preparing these devices. For 808nm conduction-cooled-packaged high power semiconductor lasers, the semiconductor laser die attach solder interface can significantly impact the thermal performance and reliability of a laser assembly. Fluxless soldering processes are required and solder voids should be controlled to the minimum. Large solder voids would increase junction temperature and create hot spots. Solder voids near the front facet are especially detrimental as they can significantly raise the facet temperature and cause catastrophic optical mirror damage (COMD).

Consequently, it is significant to do some researches on the 808nm diode laser which operated at QCW mode, especially in long pulse and high duty cycle mode.

Thermal Performance and Analysis

Transient thermal behavior is a crucial characteristic of the total thermal performance of a semiconductor laser. It reflects the physics of the heat propagation process inside the device. Particularly, through studying the transient thermal behavior of a diode laser array and its package, one can understand better the contribution of each constituent material layer and the interfaces to total thermal resistance, as well as the possible failure modes and mechanisms in a semiconductor laser operated in a quasi-continuous (QCW) condition.

For HPDLA devices, although the thermal is a common problem in high power diode laser array products, the thermal behavior of 250W QCW conduction-cooled-packaged HPLDAs are rarely reported. Thermal behaviors of solder interfaces are the major factors affecting the functional and structural performance of high power diode laser packages. If the accumulated heat cannot readily escape, the elevated temperatures at the location of the p-n junction adversely affect the output power, the slope efficiency, the threshold current and the device lifetime. Elevated thermal could cause spectral broadening and wavelength shift [5]. The emitting wavelengths vary, when the junction temperature of the emitters across the array is not controlled and/or is non-uniform. These circumstances make thermal management of high power devices a major challenge in the pump laser design, manufacturing and use. It is more critical to investigate and develop thermal design and optimization.

The device of single-bar conduction-cooled-packaged 808nm 250W QCW semiconductor laser array to be simulated made by the Xi'an Focuslight Technologies Co., Ltd., is shown in Fig.1. A typical semiconductor laser consists of three major parts: the laser bar (chip/die), the cathode and the heat sink. The laser bar is schematically shown in Fig.2. The

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quantum well is the active region. It contains 62 emitters and is comprised of a cladding layer and a p-metal.

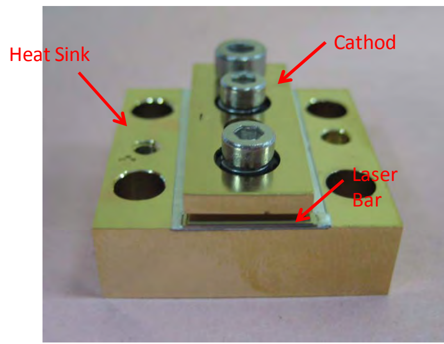


Figure 1 A sample of single-bar 808nm 250W QCW high power semiconductor laser array

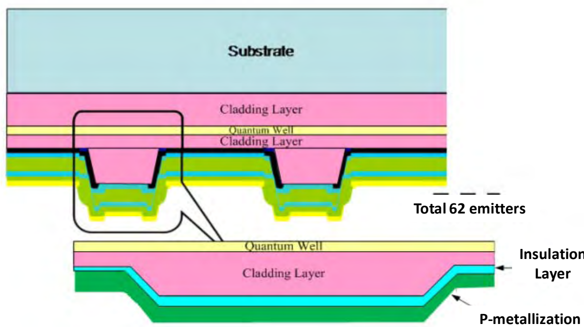


Figure 2 Schematic of semiconductor laser array

The 250W QCW high power semiconductor laser array is packaged in the conduction cooled structure, with the bottom of the heat sink fixed with a TEC (Thermal-Electric Cooler). The bottom TEC surface is kept at 25°C.

In our study the transient-state thermal behavior of a conduction-cooled-packaged semiconductor laser in QCW mode was simulated using FEA technique. Figure 3 shows the thermal behavior of 250W high power diode laser at pulse mode (400Hz, 200μs). The result shows the highest temperature in emitting region is 38.6°C when a single pulse 250A current is applied. The temperature in emitting region dropped down about 28°C within about 100μs if the drive current of 250Amp applied on 250W QCW conduction-cooled-packaged semiconductor laser is cut off.

Figure 4 (a) shows the curves of quantum well temperature versus transient time of a 250W QCW high power semiconductor laser array. During the initial 300μs, the zooming in curve of quantum well temperature versus transient time is illustrated in Figure 4 (b). From this curve, as we can see, the junction temperature rise is rapidly increased during the initial 300μs, illustrated in Figure 4 (b). The junction temperature rises from initial 25°C to 27.8°C. With the increment of operating pulse, from Figure 4 (a), the junction temperature rise is slowing down and trends flatness. The trend of temperature distribution curve via time in emitting region is like parabolic.

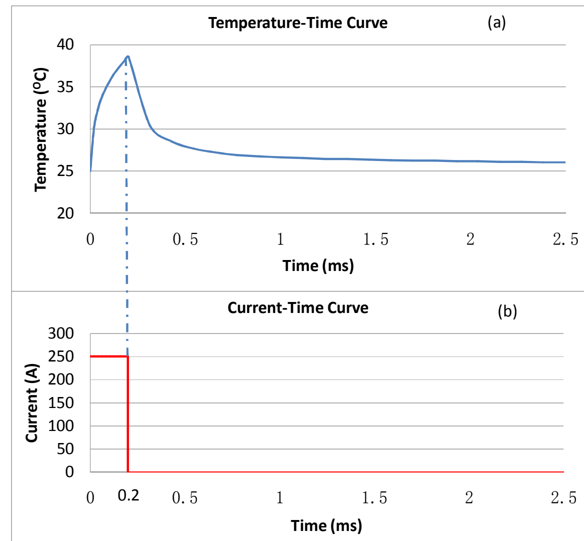


Figure 3 shows the thermal behavior of 250W QCW conduction cooled high power diode laser (a) the temperature versus time at pulse mode (400Hz, 200μs), (b) the operational current under the condition of a single pulse

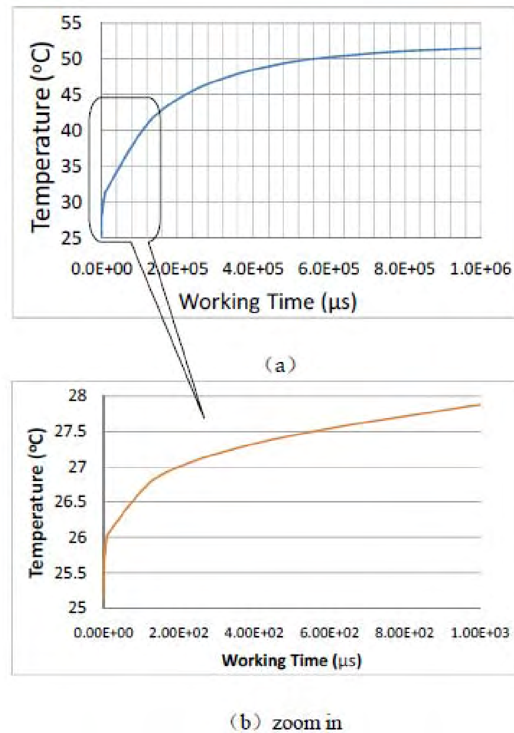


Figure 4 Curves of quantum well temperature versus transient time of a 250W QCW high power semiconductor laser.

Zhenbang Yuan's research paper indicated that if the pulse width is longer than 37μs, the working condition is the same as in CW mode. [6] It can be seen from Figure 4 that the increment of junction temperature rise is become smaller after a single-bar 250W QCW conduction-cooled-packaged high power semiconductor laser array operates 2500 pulse. That is to say, when the pulse width is longer than 37μs, the temperature distribution of a QCW high power semiconductor laser array comes to the steady state after it works for a couple of seconds.

Consequently, for a single-bar 250W QCW conduction-cooled-packaged high power semiconductor laser array operating in high pulse width, the failure analysis could be considered from the aspect of continuous wavelength mode.

Based on the above analysis, one of the major challenges in single bar packaging is thermal management. Thermal management includes thermal design and process control to achieve voids "free" in bar bonding interface. Xingsheng Liu's work showed that voids in bar bonding interface can affect the performance of a laser bar including power and reliability significantly. Two process approaches are used to reduce solder voids in the bonding interface. One is to bond a laser bar using die bonders with controlled pressure, and protected environment under a designed temperature profile. The other approach is to use a vacuum solder reflow system. [7]

LIV testing

Based on the numerical simulation and analytical results, a 250W QCW conduction cooled high power semiconductor lasers using hard solder (Gold-Tin) bar bonding process were produced. Moreover, the performance parameters, including the optical and electrical parameters as well as thermal resistance, are tested and characterized by means of our home-made testing instruments.

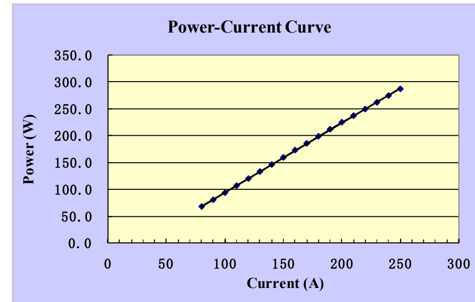
A single-bar 250W QCW conduction-cooled-packaged high power semiconductor laser array is not collimated. The bottom of copper block heat sink is fixed on a cool end plane of TEC (Thermal-Electric Cooler). The TEC is set up to maintain at 25°C.

The LIV curves were obtained through the integration of integrating spheres, spectrometer and power meter. Measurement instruments are definitely calibrated before all of the performance parameters, including the optical and electrical parameters, are measured.

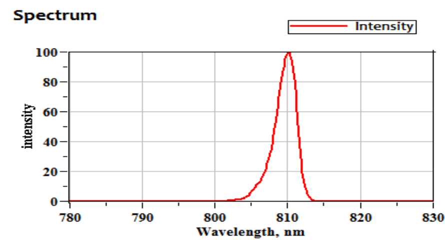
Figure 5 shows a practical example of the LIV testing of a single-bar 250W QCW conduction-cooled-packaged high power semiconductor laser array operating in high duty cycle (8%, 400Hz, 200μs).

Figure 5 Example of the LIV testing of a single-bar 250W QCW conduction-cooled-packaged high power semiconductor laser array operating in high duty cycle (8%, 400Hz, 200μs)

The results of a 250W QCW conduction cooled high power semiconductor lasers array with good performances were illustrated in the Figure 6. It can be seen that the higher power of 287W and slope efficiency of 1.3W/A at 250amps under the condition of pulse mode of 8% Duty Cycle were obtained. The full width of half maximum (FWHM) and full width of 90% energy (FW90%E) of spectrum is 3.2nm and 6.1nm, respectively. The measurement results indicate that the performance of 808nm 250W QCW conduction cooled high power semiconductor lasers array is pretty good.



(a)



(b)

Figure 6 P-I curve and spectrum of a QCW (400Hz, 200μs) high power semiconductor laser

Near-field measurement

Our experimental setup schematic of near-field test system is illustrated in Figure 7. When measuring 250W QCW high power semiconductor laser array in the near-field test system, the output light of driven by a laser pulse diver went through the Optical Imaging System, making the intensity of output light imaged onto the photo-sensitive surface of the CCD camera. The signals from the photo-sensitive surface through the image grabbing card were converted to data signals and delivered to the analyzing software. Images are captured on a digital camera at a low drive current.

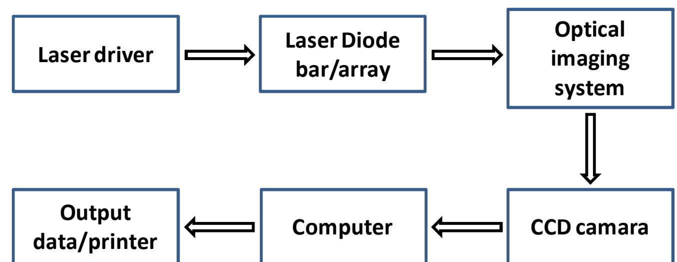


Figure 7 The block diagram of smile test system

Figure 8 Near-field image of QCW 250W conduction- cooled-packaged high power semiconductor laser array

The measurement conditions of near field are 40Amp, degraded the intensity of the order of magnitude of 1E8. As it

is seen from Figure 8, there are light and black laser spots in the near field imaging. The output light intensities of each emitter in a laser bar are not uniform. Possibly, this is caused by the inhomogeneous distribution of drive current on each emitter in a laser bar/array. Carriers in active region are not fully excited simultaneously. This leads to the output light inhomogeneity of high power semiconductor laser bar.

Our experiments result exhibits that the near-field performance of a 250W QCW conduction-cooled-packaged high power semiconductor laser is relatively good.

Lifetime testing

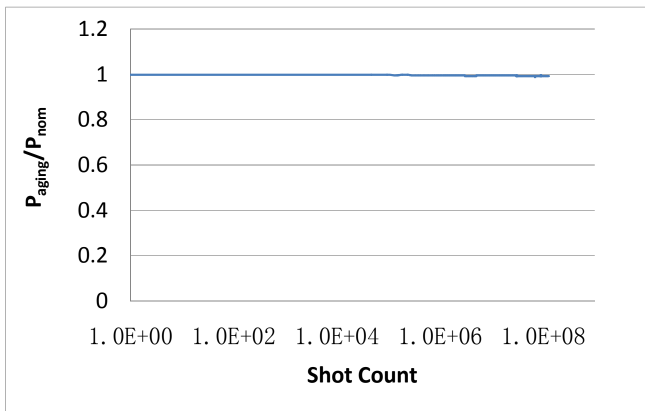
Compared with low-power CW counterparts, these HPDLAs suffer from shorter lifetimes and are more susceptible to degradation and premature failure. This is mainly due to the excessive localized heating and substantial pulse-to-pulse thermal cycling of the laser active regions. The thermally-induced stresses are even more dramatic when the required pump pulsewidth is increased from 200μs. [8]

The lifetime testing setup is automated using a single computer to set operational and environmental parameters, acquire and archive data, flag anomalous readings, and generate a number of warning and status alert messages when necessary, such as the over-temperature of laser bar and the shortage of cooling water. All the HPDLAs performance parameters are continuously monitored and recorded using a set of instruments for consistency and accurate comparative analysis and evaluation.

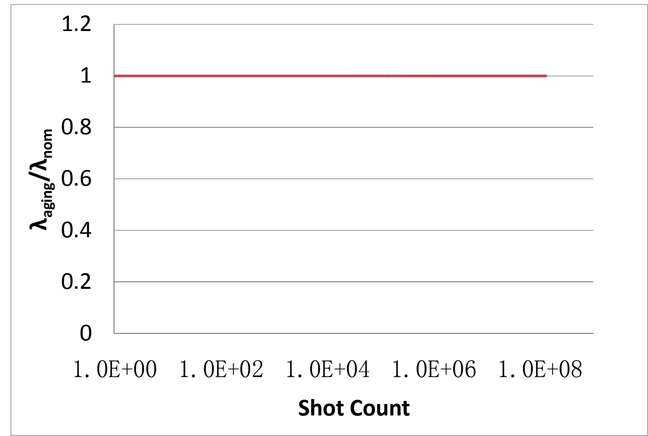
High power semiconductor laser arrays are tested under the general operational parameters chosen below:

- Drive current: 250 A
- Pulse duration: 200μs
- Rep. rate: 400Hz
- Heatsink temp. 25°C

An example of lifetime test data of single-bar 250W QCW conduction-cooled-packaged high power semiconductor laser array operating in 8% duty cycle (400Hz, 200μs) is illustrated in the Figure 9.



(a)



(b)

Figure 9 Example of lifetime test data of a single-bar 250W QCW conduction-cooled-packaged high power semiconductor laser array operating in high duty cycle (8%, 400Hz, 200μs)

As it is seen from Figure 9 (a) that the normalized ratio of output light power is almost constant after operating 1.2×108 pulse. The curve exhibited that the value of power reduction of the single-bar 250W QCW conduction-cooled-packaged high power semiconductor laser array is less than 2%. The wavelength shift is same to power; the shift difference is less 0.2nm. Results showed in Figure 9 indicate that the lifetime of single-bar 250W QCW conduction-cooled-packaged high power semiconductor laser array we prepared are acceptable. These devices have a high reliability.

Discussion

The current HPDLAs have an electrical to optical efficiency of about 50%. Therefore, when running a single bar 808nm 250W QCW high power semiconductor laser, about close to 300 W of peak power is generated in the form of heat, (24W average at 200μs pulse duration and 400 Hz prf). This excess energy primarily generated in the active area of the bars (light emitting surface), is quite substantial. Given that the total active area at the surface of each bar is on the order of 1.5 mm wide by 10 mm long (0.15cm2), yields a thermal density on the order of 160W/cm^2. If the accumulated heat cannot readily escape, the elevated temperatures at the location of the p-n junction adversely affect the output power, the slope efficiency, the threshold current and the device lifetime.

The level of impact of the long pulse operation may be roughly estimated by an Arrhenius relationship written as:

$$\text{Lifetime}\ (\tau) \propto (Ta-Tb)^{-N} \text{Exp}(Ea/kTa)$$

Where lifetime (τ) is expressed as a function of junction temperatures Ta and Tb measured immediately after and before the generated pulse, the activation energy (Ea) and Boltzmann's constant (k). The leading term accounts for the thermal cycling fatigue due to mismatch of thermal expansion coefficients of different package materials and various layers of the laser bar. The power N in the expression above can have a value between 2 and 5 depending on the materials properties.

It is obvious from this Arrhenius equation that reducing the temperature difference before and after the pulse is the key for increasing the lifetime to an acceptable level. This may be

achieved through careful selection of the HPLDA package type, specifications of the array considering the pumping requirements, and defining its operational parameters.

Many failures in high power diode laser packages are directly related to packaging technology, especially to the solder interfaces [9,10]. Thermal behavior in solder interfaces is a major factor affecting the functional performance of high power diode laser array packages. To provide a cost-effective and high performance HPDLAs, thermal management and optimization are needed. During practical manufacturing process, optimizing packaging design, thermal and thermal mechanics, thermal stress design and packaging process, such as the solder layer material, mounting substrate/heatsink material and thickness, and die bonding process, could improve the performance.

Conclusions

A 250W QCW conduction-cooled-packaged high power semiconductor laser array under the condition of 8% duty cycle (400Hz, 200μs) was presented in this paper. These devices were characterized using home-made measurement setup, and optical imaging techniques to study the performance of high power diode laser bar or array, including the LIV characteristics, near-field, and lifetime. The thermal behavior of the semiconductor laser was simulated by means of the finite element numerical analysis. Strategies in improving the performance of HPDLAs in terms of package architecture design and bar bonding process are proposed in the paper. Based on the numerical simulation and analytical results, 250W QCW conduction cooled high power semiconductor lasers using hard solder bar bonding process were produced.

Acknowledgments

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References

1. Uwe Brauch, Peter Loosen, and Hans Opower, "High-Power Diode Lasers for Direct Applications", *Springer-Verlag (Berlin Heidelberg)* 2000, pp.1-2.
2. Brian Faircloth, "High-brightness high-power fiber coupled diode laser system for material processing and laser pumping", *Proceedings of SPIE* Vol. 4973, 2003, pp. 34-41.
3. E. Rugi, P. Mueller, P. Lambelet,"Scalable high brightness laser pump for aerospace applications", *IEEE*, 2003, pp81.
4. Michael A. Bolshov, Yuri A. Kuritsyn, "Laser Analytical Spectroscope", Ullmann's Encyclopedia of Introdustrial Chemistry, Six Edition, *Wiley (Weinheim, Germany)*, 2001, pp18-23.
5. X. Liu, J. Wang, and P. Wei,"Study of the mechanisms of spectral broadening in high power semiconductor laser arrays", *Electronic Components and Technology Conference,* IEEE, 2008, pp1005-1010.
6. Zhenbang Yuan, Jingwei Wang, Xu Chen, Di Wu, Xingsheng Liu, "Study of Steady and Transient Thermal Behavior of High Power Semiconductor Laser array," *Proceedings of 59th Electronic Components and Technology Conference (ECTC)*, 2009, accepted.
7. Xingsheng Liu and Wei Zhao, "Technology Trend and Challenges in High Power Semiconductor Laser Packaging", *Proceedings of 59th Electronic Components and Technology Conference (ECTC)*, 2009, accepted.
8. J. Yu, A. Braud, and M. Petros, "600mJ, Double pulsed 2 micron laser," Opt. *Lett.*, 28, 540-542, 2003.
9. X. Liu, R.W. Davis, L. C. Hughes, M. H. Rasmussen, and C.-E. Zah, "A Study on the Reliability of Indium Solder Die Bonding of High Power Semiconductor Lasers," *Journal of Applied Physics*, Vol. 100, Issue 1, 013104, 2006.
10. E. Suhir, "Interfacial Thermal Stresses in a Bi-Material Assembly with a Low-Yield-Stress Bonding Layer", *Modeling and Simulation in Materials Science and Engineering*, vol. 14, 2006, pp.1421-1432