Packaging of High Power Semiconductor Laser Arrays Using a Novel Macro-channel Cooler

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Abstract

High power semiconductor laser arrays have been widely used in many fields, such as pumping solid state laser aerospace, industry, medicine and display. For many applications, high power semiconductor lasers operating quasi-continuous wave (QCW) mode are demanded. For QCW laser, the output peak power is higher and average power is low. Therefore, the transient thermal density is very high. The most common method of removing the large amounts of waste heat in a semiconductor laser package is by using commercially-available copper micro-channel coolers (MCC). However, due to the coefficient of thermal expansion (CTE) mismatching between copper and laser chip, hard-solder cannot be directly used. On the other hand, indium solder has the problem of electro-thermal migration when the temperature grads were high in QCW mode. Furthermore, copper material is susceptible to erosion and corrosion. To overcome these hurdles in many applications, a novel macro channel cooler (MaCC) was presented in this work. The thermal behavior of MaCC-packaged high power semiconductor laser arrays in QCW mode was studied using finite element analysis (FEA). A high power of >250W QCW semiconductor laser array/bar using hard solder was fabricated. The performances of laser arrays, including output power, slope efficiency, threshold, conversion efficiency, spectral width, near field, lifetime etc. were characterized. The measured results indicated that the output power of a MaCC- packaged high power semiconductor laser array was very close to that of copper micro-channel cooler. Based on MaCC-packaged single laser array/bar, multiple-bar stack and two dimension area array lasers with output powers of several kilowatts and several tens of kilowatts were fabricated.

Introduction

High power semiconductor lasers 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 lasers have found increased applications in pumping of solid state laser systems for 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]. For commercial CW high power semiconductor lasers, presently, the common output power is about 100W/bar; as for QCW lasers, the maximum output power is about 300W/bar. The conversion efficiency of 808nm high power semiconductor laser array is commonly about 50%, so half of electric energy is converted into thermal and wasted. To remove such huge thermal, MCC is most used as the heatsink for high power semiconductor laser array. Although the thermal resistance of laser array using MCC packaging technology is lower, MCC has its drawbacks. MCC is made of multiple thin copper layers. Whereas copper material is susceptible to erosion and corrosion.[5] Additionally, due to the CTE mismatch of laser chip with the MCC heatsink, it cannot use the indium-free packaging process. Although indium solder is one of the most widely used solders in high power laser die bonding due to its ductileness ability, however, results in recent years showed indium solder bonded lasers have a lower reliability than AuSn solder bonded devices due to the fast indium solder electromigration and electro-thermal migration [6]. So, it is urgent and required to develop novel micro cooler, such as ceramic micro-channel cooler [7] or other high effective thermal dissipation cooler for wide laser applications.

In this work, a hard-solder technology using the macro-channel cooler (MaCC) was developed for packaging of high power semiconductor laser arrays, as shown in Figure 1. [8]. Compared with conventional copper micro-channel cooler, the cost of our designed MaCC is lower and the damage from electric-chemical erosion is less severe. Moreover, the maintenance is much easier.

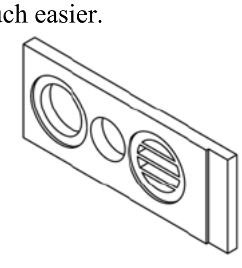

Figure 1 Schematic of a novel MaCC

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Thermal Analysis

For high power semiconductor laser array, although the thermal management is a common problem in high power diode laser array products, the transient thermal behavior of high power diode lasers in QCW mode is 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 [9].These circumstances make thermal management of high power devices a major challenge in the pump laser design, manufacturing and use. It is critical to investigate and develop thermal design and optimization.

The transient thermal behavior of high power semiconductor laser arrays packaged using our MaCC under QCW operation mode was studied using finite element analysis (FEA). The device structure of single-bar MaCC-packaged 250W QCW semiconductor laser array is shown in Figure 2. A typical semiconductor laser consists of three major parts: the laser bar, the cathode and the heat sink. The laser bar is schematically shown in Figure 3. The quantum well is the active region. It contains multiple emitters and is comprised of a cladding layer and a p-metal.

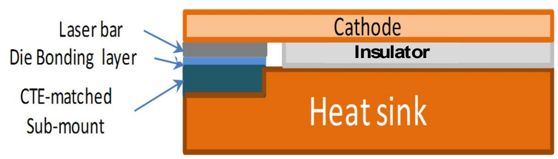


Figure 2 Structure of a MaCC-packaged high power semiconductor laser array

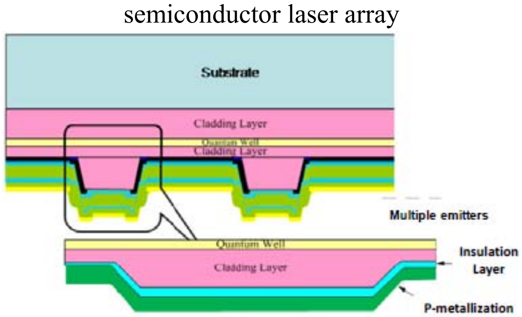


Figure 3 Schematic of semiconductor laser array

The simulation condition is shown as follows: The liquid temperature is 25℃. The flow of liquid is 0.5L/min.

In our study the thermal behavior of a MaCC-packaged semiconductor laser with the heat of 250W was simulated using FEA. Figure 4 shows the thermal behavior of 250W high power diode laser. From this curve, as we can see, the junction temperature rise is rapidly increased during the initial 300μs. The junction temperature rises from initial 25℃ to 33.8℃. With the increase of operating time, the junction temperature rise is slowing down. The trend of temperature distribution curve via time in emitting region is like parabolic.

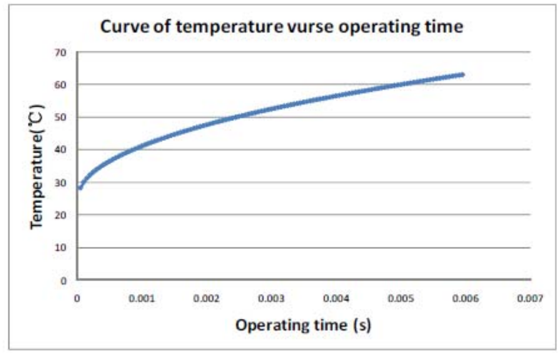


Figure 4 Thermal behavior of 250W QCW MaCC-packaged high power diode laser

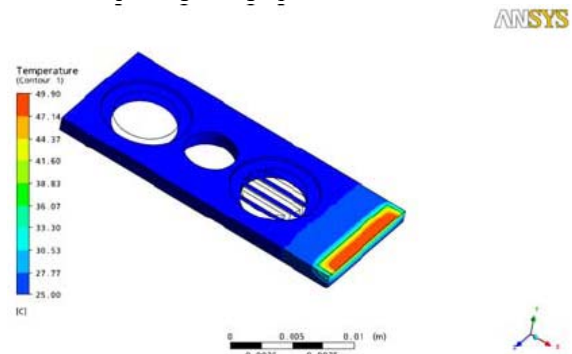


Figure 5 Thermal behavior of a single bar 250W QCW MaCC-packaged high power diode laser

The simulation result indicates that the junction temperature rise is up to 50℃ when the pulse width is 2450μs. The temperature distribution of a QCW 250W high power semiconductor laser array reaches a steady state after it working for a couple of seconds. To achieve high reliability and long lifetime, to reduce the junction temperature rise below 50℃ is required. Thus, high power semiconductor laser operating short pulse duration could improve the reliability and lifetime of high power laser.

Device fabrication

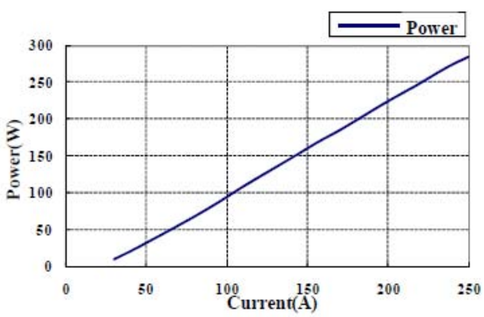
Based on the thermal analysis, the structure of a single bar MaCC-packaged is designed, illustrated in Figure 2. A series of QCW 250W MaCC-packaged high power semiconductor laser array were fabricated by using the indium-free packaging process. Figure 6 shows a sample of a single-bar QCW 250W MaCC-packaged high power semiconductor laser array.

Figure 6 A sample of single-bar 250W QCW MaCC-packaged high power semiconductor laser array

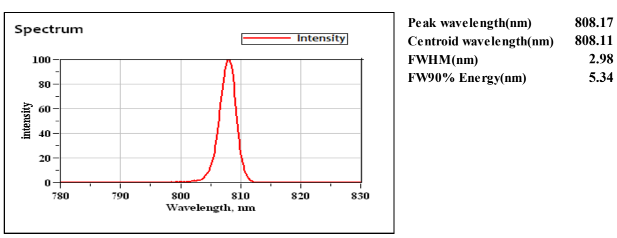
Packaging process is the key to improve the performances of a MaCC-packaged laser bar. A "no voids" die bonding technology is developed and used. The process minimizes the voids in bar bonding interface. It was reported that voids in bar bonding interface can affect the performance of a laser bar including output power and reliability significantly.[10]. Two process approaches were used to reduce solder voids in the bonding interface. One is to bond a laser bar using die bonders with controlled pressure and under a designed temperature profile environment. The other approach is to use a vacuum solder reflow system. [11]

LIV testing

The LIV curves were obtained through the integration of integrating spheres, spectrometer and power meter. Figure 7 shows the LIV testing results of a QCW 250W MaCC-packaged high power semiconductor lasers array. It can be seen that the higher power of 284W and slope efficiency of 1.28W/A at 250amps were obtained at 8% duty cycle. The full width of half maximum (FWHM) and full width of 90% energy (FW90%E) of spectrum is 2.98nm and 5.34nm, respectively. These tested results are very close to that of copper micro-channel cooler [12].The measurement results indicate that the performance of 808nm QCW 250W MaCC-packaged high power semiconductor lasers array is pretty good.



(a)



(b)

Figure 7 P-I curve and spectrum of a QCW (400Hz, 200μs) high power semiconductor laser

Near-field measurement

The schematic of near-field test system is illustrated in Figure 8. In measuring a laser bar, the output light of driven by a laser pulse diver went through the optical imaging system, making the intensity of output light image 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 were captured on a digital camera at a low drive current.

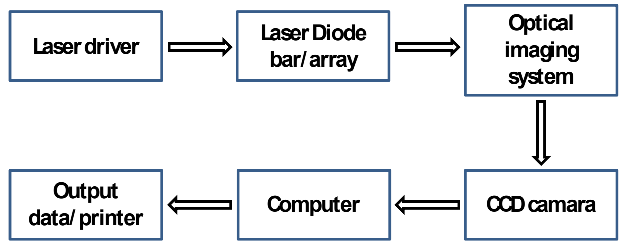


Figure 8 The Schematic of near-field test system

Figure 9 Near-field image of an 808nm QCW 250W MaCC-packaged high power semiconductor laser array

As it is seen from Figure 9, the output light intensities of each emitter in a laser bar are uniform. It indicated the distribution of drive current on individual emitter in a laser bar/array is homogeneous. Carriers in active region are fully excitated simultaneously which leads to the output light homogeneity of high power semiconductor laser bar.

Our experimental results exhibit that the near-field performance of an 808nm QCW 250W MaCC-packaged high power semiconductor laser is relatively good.

The non-linearity of the near-field ("smile" measurement)

The non-linearity of the near-field of emitters (or the so called "smile") in a laser diode array poses significant challenges in optical coupling and beam shaping and has become one of the major roadblocks in broader applications of laser arrays. Figure 10 shows a magnified "smile" image of a typical good diode-laser array. As can be seen from Figure 10, a typical good laser diode array is nearly linear.

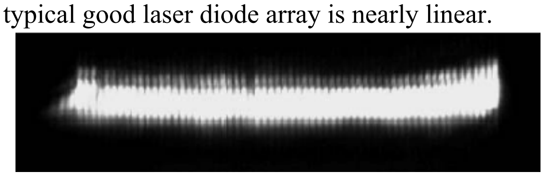


Figure 10 Enlarged "smile" image of a typical good laser diode array

The smile of a laser diode array is caused by the coefficient of thermal expansion (CTE) mismatch among the different layers of a bare bar, the packaging process and CTE mismatch between the laser bar and the bonding heat sink [13]. Low smile of a laser bar will be obtained by choosing packaging material and using advanced packaging process.

Nearly 120 single bars were tested. It was found that the smile of 85.3% laser bars were less than 1μm, as shown in Figure 11. The result exhibits that the linearity of near-field of the laser bars and its uniformity are both good.

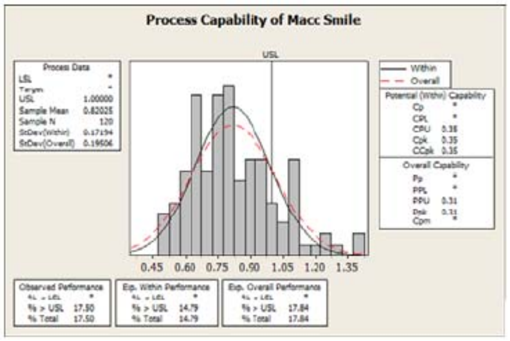


Figure 11 Smile statistics of the single bar QCW MaCC-packaged semiconductor laser

Lifetime testing

Compared with low-power CW counterparts, these high power semiconductor laser arrays 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. [14]

The lifetime test of a MaCC-packaged vertical stack was conducted. The condition is at 8% duty cycle (400Hz, 200µs). The lifetime result is illustrated in the Figure 12.

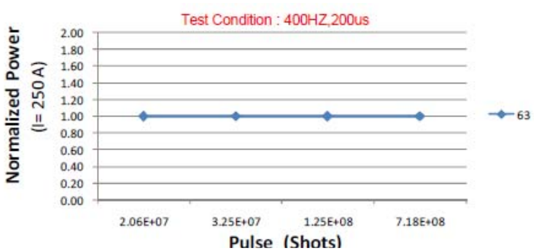


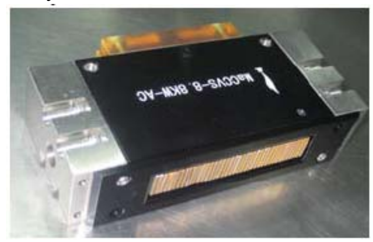
Figure 12 Lifetime curve of a MaCC-packaged multiple bar vertical stack operating in 8% duty cycle (400Hz, 200µs)

The curve in Figure 12 exhibits that the power degradation of the MaCC-packaged multiple bar vertical stack is less than 2% after working 7.18×10^8 shots, which indicates a good reliability. The lifetime test is still ongoing.

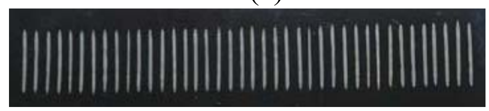
Stack and Area array lasers based on MaCC-packaged bars

Many new applications require ever increasing output power of a semiconductor laser. To further increase the output power, several packaging technologies have been developed including multiple single-emitter modules, horizontal bar arrays, vertical bar stacks, and area bar arrays. With the demand of higher output power, vertical bar stacks becomes the choice.

To achieve higher power in actuarial application, multiple bar series structure are designed. Based on the MaCC laser array unit, a QCW 8.8KW and 20KW Indium-free laser stack were produced by Xi'an Focuslight Technologies Co., LTD, as shown in Figure 13, and Figure 15. For a vertical bar stack in configuration Figure 13, the output power can be as high as 250W bar par and up to 40 bars can be packaged together. This kind of high power semiconductor laser using indium-free packaging process has advantage of long storage time and high reliability.



(a)



(b)

Figure 13 An examples of vertical MaCC-packaged stacks (40bar-808-QCW-8.8kW) (a) and laser beam spot (b)

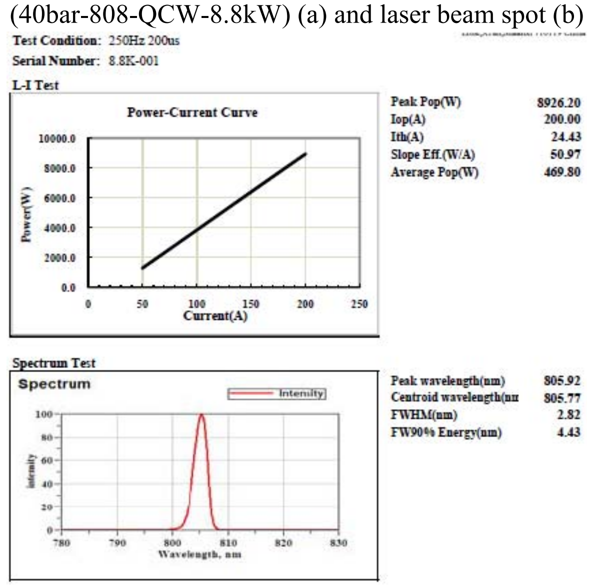
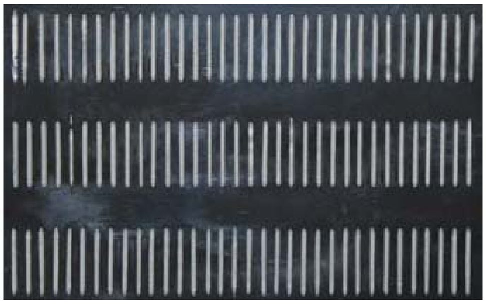


Figure 14 LIV testing result of MaCC-packaged laser stack in Figure 13

Based on the MaCC-packaged stacks, a 940nm QCW 20KW Indium-free MaCC-packaged area array laser was fabricated as well, as shown in Figure 15. The LIV testing result was illustrated in Figure 16.

(a)



(b)

Figure 15 A 940nm QCW 20KW Indium-free MaCC-packaged area array laser (a) and laser beam spot (b)

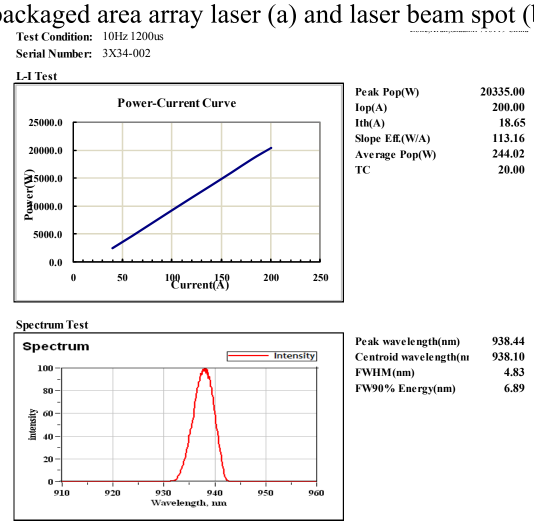


Figure 16 LIV testing result of MaCC-packaged laser stack in Figure 15 (a)

Figure 16 shows that the output power of 20335W high power area array laser in QCW mode was obtain. The FWHM and FW90%E of this area array laser is 4.83nm and 6.89nm, respectively. Compared with MCC, MaCC can be a good candidate for high power semiconductor lasers operating in low duty cycle, such as less than 5%.

The major challenges in vertical bar stack packaging are the spectrum control and beam control. Although the laser bars in the vertical stack are cooled by macrochannel liquid cooled configurations, there remains temperature non-uniformity among the bars due to thermal crosstalk and/or liquid flow non-uniformity. This would alter the wavelength of the bars and broadened the spectrum of the stack. In this work, advanced packaging process was used to obtain the narrow spectrum. First of all, total temperature distribution was simulated and calculated. Secondly, the wavelength of each single bar was chosen to match the temperature distribution based on the simulation results. On the other hand, by optimizing packaging technology, the very close output wavelength between bar and bar was achieved. Using this method, the spectrum broadening of vertical stack can be effectively controlled.

As for beam control, it includes beam size, intensity uniformity and pointing direction control. To obtain a good beam, a beam shaping optical systems need to be designed and installed to achieve beam control. First, fast-axis collimation components are demanded to be mounted in front of each bar to make pointing direction consistent. Additionally, an advanced real-time monitoring setup is necessary to keep each bar fine-tuned in vertical and horizontal orientation to ensure accurate positioning. It was found that the output beam spot of each bar was very uniform and the directivity was excellent.

Conclusions

In conclusion, a novel packaging technology of high power semiconductor laser array using macro-channel cooler was developed. A high power of QCW 250W semiconductor laser array, QCW 8.8KW laser stack and QCW 20KW area array laser using indium-free packaging process was fabricated. Although the thermal dissipation ability of MaCC is not higher than that of conventional copper micro-channel cooler, the testing results indicated that the performance of a MaCC-packaged laser arrays in QCW mode was similar to that of copper micro-channel cooler. More important, MaCC enables the indium-free packaging process in fabricating high power semiconductor laser array, multiple-bar vertical stack and area array laser. The MaCC can be a good candidate in high power semiconductor laser array/bar, stack and area array.

Acknowledgments

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