Hard solder 20kW QCW Stack Array Diode Laser

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ABSTRACT

With the increasing applications of high power semiconductor lasers in industry, advanced manufacturing, aerospace, medical systems, display, entertainment, etc., semiconductor lasers with high power and high performances are required. The performance of semiconductor lasers is greatly affected by packaging structure, packaging process and beam shaping. A novel macro channel cooler (MaCC) for stack array laser with good heat dissipation capacity and high reliability is presented in this work. Based on the MaCC package, a high power stack array diode laser is successfully fabricated. A series of techniques such as spectrum control and beam control are used to achieve narrow spectrum and high beam quality. The performances of the semiconductor laser stack array are characterized. A high power 20kW QCW hard solder packaged stack array laser is fabricated; a narrow spectrum of 3.94 nm and an excellent rectangular beam shape are obtained. The lifetime of the stack array laser is tested as well.

Keywords: stack array diode laser, macro channel cooler, hard solder packaging, reliability

1. INTRODUCTION

With the increasing applications of high power semiconductor lasers in industry, advanced manufacturing, aerospace and medical systems, higher power, higher reliability and higher brightness semiconductor lasers are required [1-2]. For specific applications such as pumping high power solid state laser, higher power semiconductor lasers with peak output power of multi-tens of kilowatts (kW) level operating under quasi-continuous wave (QCW) mode are demanded. To scale-up the output power from kW to tens of kW, it is common to assemble the several stacks which are assembled by multiple laser bars together and form an stack array laser. Laser stacks with output power of kW level are commonly packaged using conduction cooled G-stack technology and water cooled copper micro-channel cooler (MCC) technology. For G-Stack laser, although the higher output peak power can be easily obtained and compact, it only operates at lower duty cycle (commonly less than 2%) due to its heat dissipation limitation. For QCW laser, the output peak power is higher and average power is very low. Therefore, the transient thermal density is very high. For commercially-available water cooled copper micro-channel coolers, the heat dissipation capability is more than that of G-stack, however, as a result of the coefficient of thermal expansion (CTE) mismatching between copper and laser chip, hard-solder cannot be directly used. Most of copper MCC-based laser are packaged using the conventional indium soldering technology. For indium soldering, it has the problem of electro-thermal migration when the temperature gradient are high in QCW mode. Furthermore, the copper material is susceptible to erosion and corrosion[3]. It can also use hard solder in MCC-based laser, but this will cause the pitch larger. To overcome these drawbacks and reach higher peak output power at high duty

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cycle without reliability decrease, a novel macro channel cooler for stack array laser which has both good heat dissipation capacity and high reliability is presented in this work.

In this paper, a novel macro channel cooler is designed and optimized [4]. Based on the MaCC, a high power 20kW QCW hard solder stack array laser is fabricated. The package process, spectral control and beam control are studied. The results indicated that the stack array laser has the advantages of high heat dissipation capability, high reliability and excellent beam directivity.

2. STRUCTURE DESIGN AND FABRICATION

The performance and reliability of a semiconductor laser are greatly affected by its package structure and thermal property. Since the stack array laser is assembled by single bars, the structure of the single bar has a significant impact on the performance of the stack array. Therefore, the structure of the stack array and the single bar should be both considered.

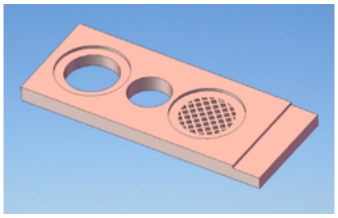

Figure 1 Schematic of the MaCC

The basic unit of the stack array laser with peak power of multi-tens of kilowatts is MaCC in this work, as shown in Figure 1. The device structure of a single MaCC-packaged semiconductor laser bar is shown in Figure 2. Compared with the conventional MCC-packaged laser, it has a CTE-matched layer, which can release the stress effectively. Hard solder is used in the die bonding process. In addition, a double-sided cooling packaging structure is developed. The heat can be conducted through both the anode and cathode; therefore, the thermal dissipation efficiency is improved significantly.

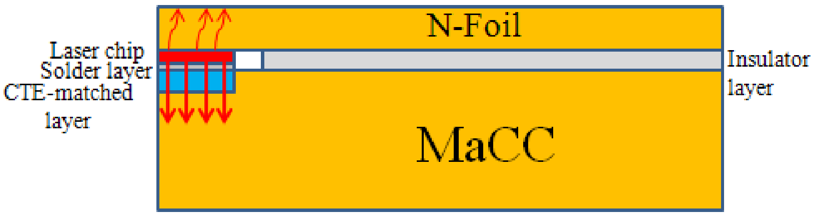

Figure 2 Structure of a MaCC-packaged high power semiconductor laser array

The MaCC has the advantages of low thermal resistance, and it is not easily corroded and easily maintained [5]. A series of transient thermal behaviors of high power MaCC-packaged semiconductor laser array at QCW mode are simulated using finite element analysis (FEA), as shown in Figure 3. The liquid temperature is 25℃ and the flow of liquid is 0.5L/min. Compared with traditional copper micro-channel cooler, the MaCC has less heat dissipation capacity, but the hard solder can be used and the damage from electric-chemical erosion is less severe. Therefore, MaCC-packaged semiconductor laser is more suitable for the QCW mode application.

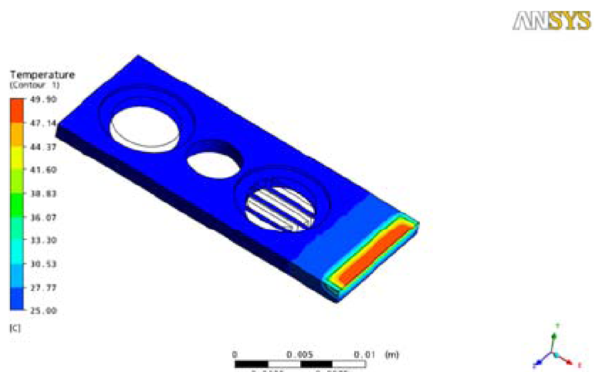

Figure 3 Thermal behavior of a single bar 250W QCW MaCC-packaged high power diode laser

The structure of the stack array laser is optimized from MaCC pitch, cooling fluid velocity, flow distribution and other aspects. The heat can be taken away as quickly as possible by the cooling water, which can ensure that less thermal accumulation exists between the bars. The temperature distribution of the stack array laser with 80 bars is simulated and calculated for the thermal design and the structure optimization, as shown in Figure 4. The liquid temperature is 25℃. The flow of liquid is 20 L/min. The simulated result indicates that the maximum temperature is 53.28℃, in which the maximum temperature difference is 6.22℃ between the bars.

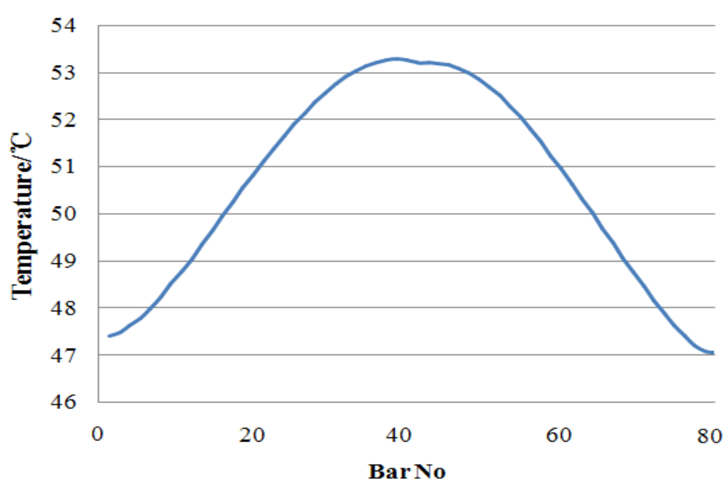

Figure 4 The temperature distribution of half part of the stack array laser.

Based on the water cooled MaCC-packaged laser array, two 40 bar vertical stacks are fabricated, and then assembled into the two-dimensional stack array laser. Finally, a 2*40 bars stack array laser is fabricated. The whole process of the stack array laser fabrication is shown in Figure 5.

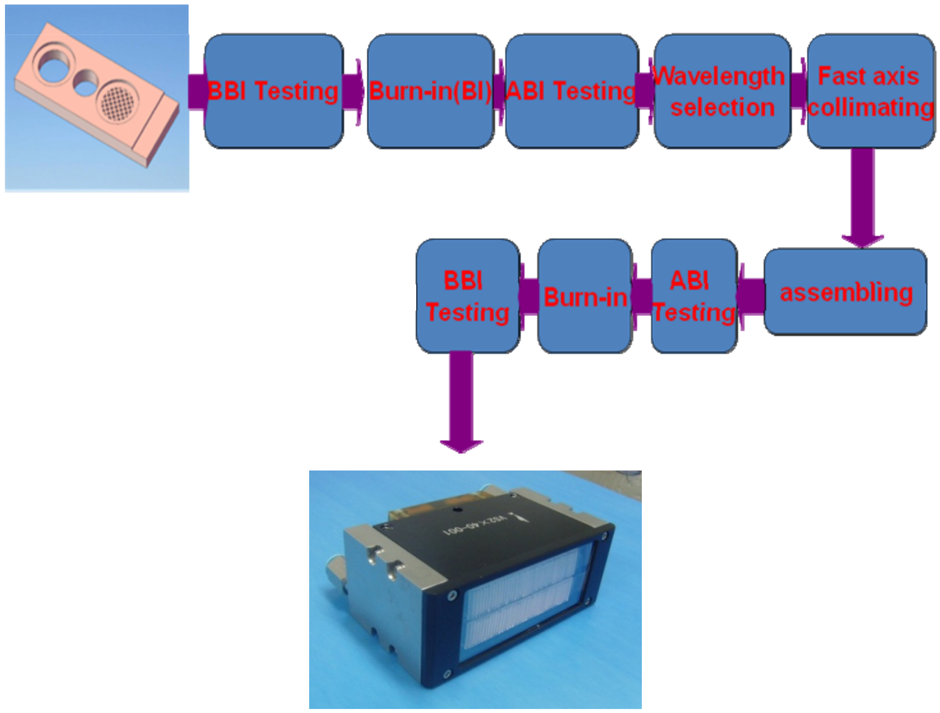

Figure 5 The whole process of the stack array laser fabrication

3. PERFORMANCE CHARACTERIZATION

The performance of the semiconductor stack array lasers is characterized under the condition of QCW mode at room temperature, as shown in Figure 6. The high output power over 20kW and the slope efficiency of 86.23 W/A at 250 amps are obtained at 5% duty cycle (500µs, 100Hz).

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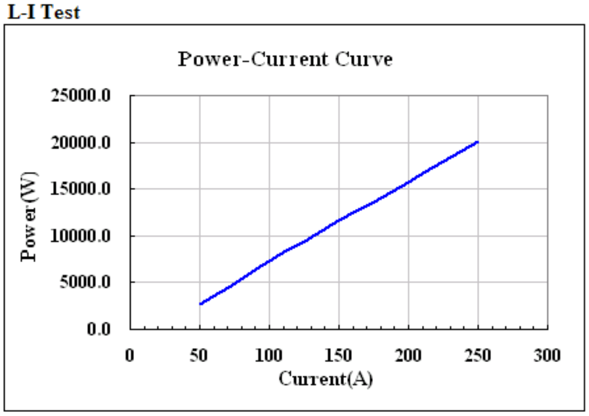
L-I Test



Peak Pop(W)	20088.00
Iop(A)	250.00
Ith(A)	19.38
Slope Eff.(W/A)	86.23
Eff.@Iop(%)	54.49
Average Pop(W)	251.10

Figure 6 LIV testing result of the QCW 20kW stack array laser

The major challenges for stack array laser packaging are the spectrum control and beam control. In this work, we used advanced packaging process to maintain temperature distribution uniform, which can effectively control the spectrum broadening, as shown in Figure 7. The Full Width at Half Maximum (FWHM) spectrum width is only 3.94nm, and the 90% energy width is 5.45 nm.

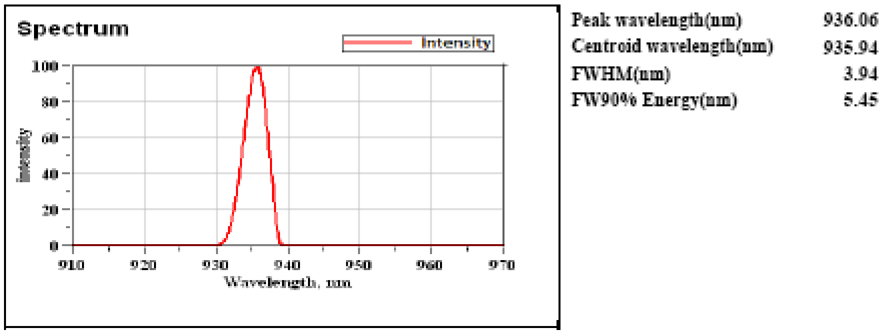


Figure 7 Spectral curve of the stack array laser

Figure. 8 shows the laser beam spot of the stack array laser after beam collimation and directivity correction. It is found that the output beam spot of each bar is very uniform and the directivity is excellent.

Figure 8 Laser beam spot of the stack array laser

The lifetime test of a MaCC-packaged vertical stack is shown in Figure 9. The curve shows that the power of the MaCC-packaged stack array laser is still stable after working 7.18×10^{8} shots under the condition of 250A, 200μs and 400Hz without failure, which indicates a good reliability. The lifetime test is still ongoing.

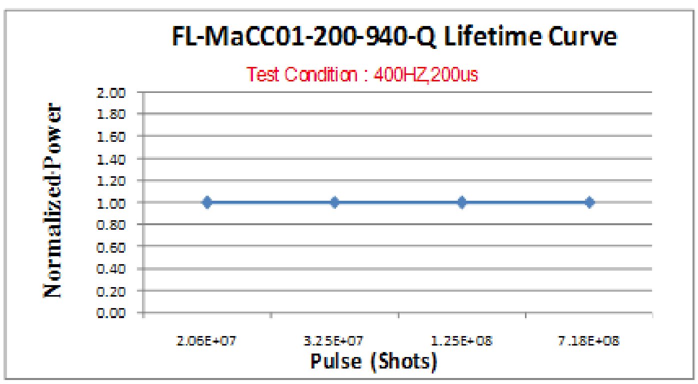


Figure 9 Lifetime curve of the stack array laser

4. DISCUSSION

With the increasing demand on the high power laser performance, narrow spectrum and high beam quality are required, which are also the major challenges for stack array laser packaging. Although the laser bars in the stack array laser are cooled in both conduction cooled and MaCC configurations, there still exists temperature non-uniformity among the bars. This would alter the wavelength of the bars and broadened the spectrum of the stack. On the other hand, since the stack array laser is assembled by two vertical stacks with a large initial beam size, beam shaping optical systems should to be designed and assembled to control beam size.

4.1 Spectrum control

The spectral broadening of stack array laser results from nonuniform emitting wavelength from individual bars. In order to achieve the spectral control, we should control the spectrum of the single bar first. The emitting wavelength of individual emitters is affected by wafer uniformity as well as packaging related thermal and thermal stress effects[6]. The use of the CTE matched materials as submount reduces the thermal stress effects significantly. Effective heat dissipation structure MaCC is designed and the advanced packaging process such as "void free" packaging technology and vacuum solder reflow system are used to reduce the thermal effect. Finally the very close output wavelength from the bars and narrow spectrum are achieved.

From Fig. 4, it is obvious to see that there is temperature non-uniformity among the bars. This would alter the wavelength of the bars and broaden the spectrum of the stack, as shown in Figure 10 (left).

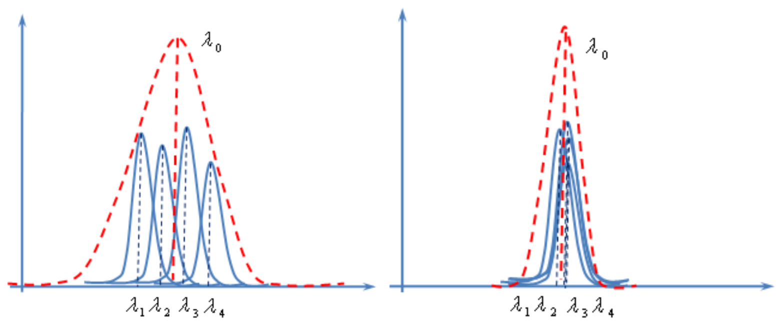


Figure 10 The broadened wavelength of semiconductor laser vertical stack before (left) and after (right) wavelength selected

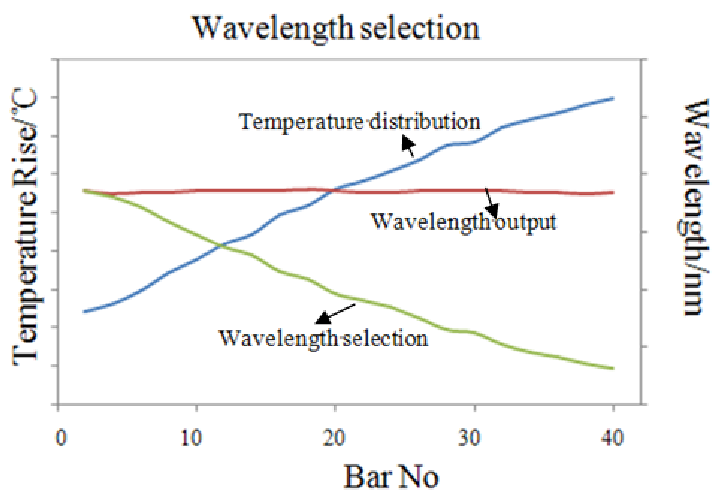


Figure 11 The schematic of the wavelength selection

The wavelength of each single bar is chosen to match the temperature distribution in order to get the same wavelength output shown in Figure 11. With this method the spectrum broadening of vertical stack can be controlled effectively, as shown in Figure 10 (right) and Figure 6. The FWHM width of the stack array laser is only 3.94 nm and the 90% energy width is 5.45 nm.

4.2 Beam control

For most applications, it is very useful to control the beam from the semiconductor laser in a relatively small stack. Beam control includes beam size, intensity uniformity and pointing direction control.

To obtain a good beam of stack array laser, the divergence angle and the beam pointing direction of the unit bar should be collimated within a certain range. The collimation are influenced by the near-field non-linearity effect (also called “smile” effect). The increase of the near-field linearity of a pumping laser diode array enables the laser system manufacturer to improve the compactness of laser system optical coupling efficiency, power, and beam quality while at the same time reducing manufacture cost in the laser system. The smile effect is mainly caused by the CTE-mismatched issue between the heatsink and the laser chip. We use the following methods to reduce the smile effect: the first is using CTE matched material, the second is using the substrate and solder with sufficient thickness and the last one is optimizing the reflow process. In addition, using the advanced packaging technology, a good near-field linearity of the laser bar is obtained, as shown in Figure 12.

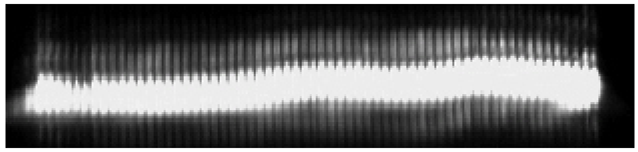


Figure 12 The “smile” image of a typical good semiconductor laser bar

A beam shaping optical systems is designed to achieve beam control in the fast axis collimation process. More than 2000 single bars are tested after fast axis collimation. It is found that about 98.77% divergence angle (fast axis) are less than 0.5 degree and 96.87% beam pointing direction are within ±0.06 degree, as illustrated in Figure 13. This results show that the beam quality of the single bars are pretty good after fast axis collimation.

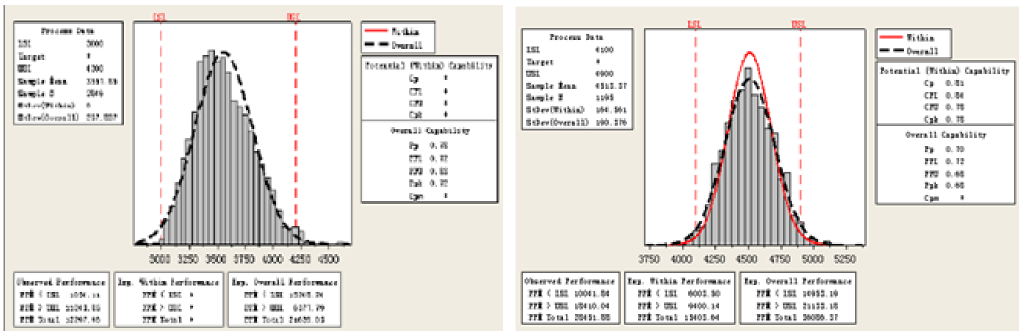


Figure 13 Fast axis detergency angel (left) and beam pointing direction (right) statistics of the single bars

Before assembling stack array laser, the bars in the same stack are selected for close beam divergence angle and pointing direction for better beam control. We also simulated the laser beam spot of the stack array laser after beam collimation at z=0mm and 300mm, respectively. The results are shown in Figure 14. The pitch of the MaCC and the interval between the two stacks are optimized according the simulation result.

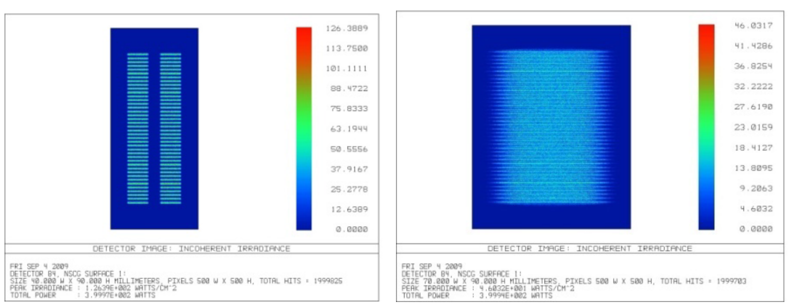


Figure 14 The simulation of light intensity of the stack array laser at z=0 mm (left) and 300mm (right)

During the assembling process, the advanced real-time monitoring equipment and the advanced beam shaping process are used to ensure accurate positioning of each bar. Figure 8 shows the actual laser beam spot of the stack array laser after beam collimation and directivity correction. It is found that the output beam spot of each bar is very uniform and the directivity is excellent.

5. SUMMARY

In summary, a novel macro channel cooler for stack array laser which has both good heat dissipation capacity and high reliability is presented in this work. Based on the MaCC, a new high power and high reliability stack array laser of 20kW at QCW mode with excellent beam directivity is designed and fabricated. The package process and beam shaping method are also optimized. The peak output power of stack array lasers has reached 20kW at 250A at 5% duty cycle, the

FWHM spectrum width is only 3.94nm and an excellent beam output is obtained. The lifetime test result shows a good reliability.

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