Research on Heat Dissipation of Diode Laser Array with Sharp-angle Sink

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Abstract: The project is designed and analyzed for the heat sink of the semiconductor laser array, and the heat dissipation performance of the heat sink with a sharp-angled channel is simulated by the finite element method. The results show that: compared with the traditional cylindrical cavity, the sharp-angle shape cavity has a stronger heat dissipation capacity. By designing a gradual flow channel inlet and outlet size, the flow channel inlet and outlet two of the large-size and multi-bar array laser are significantly reduced. The chip junction temperature difference at the end makes the array chip wavelength difference controlled within 1.9nm, which effectively improves the absorption uniformity and efficiency of the Nd:YAG crystal in this type of pump module.

1. Preface
High-power semiconductor lasers are widely used in fiber laser and solid-state laser pumping, industrial processing and other fields due to their advantages in conversion efficiency, reliability, volume, weight, and lifespan. LD pumping methods mainly include end face and side pumps. Compared with end pumping, side pumping is easier to achieve high continuous pump power and is suitable for high average power output. However, due to the extremely large amount of waste heat generated, the temperature of the laser medium increases, which affects the conversion efficiency of the laser [1-3]. In addition, Nd: YAG has good thermo mechanical properties, with strong absorption near 808nm, as shown in Figure 1. It has a large gain cross section and a high damage threshold near 1064nm [4]. Therefore, ND:YAG is still the mainstream laser working medium for solid-state lasers.

![Figure 1 The relationship between wavelength and absorption coefficient](image)

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At present, there are few studies on the consistency of the working parameters of the Nd:YAG crystal pump source multi-Bar high-power semiconductor laser array, and it needs to be solved urgently. The traditional circular cavity channel semiconductor laser array, due to its limited heat dissipation capacity, can no longer meet the heat dissipation requirements of the large-scale multi-bar linear array laser array. The temperature difference between the first and last chips of the horizontal array laser array is obvious, and the wavelength difference is large. Therefore, an extended channel heat sink is proposed in this study. The uniformity of heat dissipation performance of the channel is related to factors such as fluid-structure coupling area and the gradual change of the flow channel size at the inlet and outlet ends, which has been recognized by users [5-7].

This paper uses finite element simulation software to simulate the specially designed sharp-angle shaped inner cavity laser array, analyzes the improvement effect of the model compared with the conventional circular cavity channel heat sink and the thermal stress of the chip package, and conducts experiments and tests to verify.

2. Theoretical analysis [8,9]

When the current is injected into the active area and is less than the threshold current, the laser chip emits spontaneously and no laser is generated. This part of the injected current mainly generates waste heat, and the thermal power density is:

\[ Q_{\text{Nh}} = \frac{1}{d} U_j (1 - \eta_i) \]  

(1)

In the formula: \( d \) is the thickness of the active region, \( U \) is the semiconductor voltage drop, \( j \) is the current density, and \( \eta_i \) is the internal quantum efficiency.

When the current injected into the active area exceeds the threshold current, the output power of the laser increases sharply with the increase of the threshold current, and the waste heat generated by the energy loss, the thermal power density \( Q_{\text{act}} \) calculation formula is:

\[ Q_{\text{act}} = \frac{V_j (1 - \eta_{sp} f_{sp})}{d_{\text{act}}} [j_{th} + (j - j_{th}) (1 - \eta_i)] \]  

(2)

Where: \( Q_{\text{act}} \) is the thickness of the active region, \( V_j \) is the voltage drop across the PN junction, \( j \) is the injection current density, \( j_{th} \) is the threshold current density, \( \eta_{sp} \) is the spontaneous emission internal quantum efficiency, \( \eta_i \) is the stimulated emission internal quantum efficiency, and \( f_{sp} \) is the spontaneous emission photon escape factor.

Except for the active area, the loss of each layer of epitaxial material and the heat generated by the resistance of the electrode layer.

\[ Q = j^2 p_i \]  

(3)

\( Q \) is the thermal power density and \( p_i \) is the resistivity of each layer of material.

For this reason, the above heat needs to be conducted and dissipated in time to avoid serious impact on the working efficiency and life of the semiconductor laser chip. Channel semiconductor lasers mainly exchange heat through direct contact between fluid and solid wall. Heat transfer refers to it as "convection heat transfer". Because of the temperature difference, heat convection is accompanied by heat conduction, based on the basic formula of convective heat transfer process, which is:

\[ \phi = h(t_w - t_f) A = h \nabla t A(W) \]  

(4)
In the formula, $t_w$ is the solid wall surface temperature, unit °C; $t_f$ is fluid temperature, unit °C; $\nabla t$ is wall surface and fluid temperature difference, unit °C; $h$ is the convective heat transfer surface heat transfer coefficient, its meaning refers to the unit area, the same fluid The amount of heat that the unit temperature difference between the walls can transfer per unit time.

3 Thermal simulation

3.1 Modeling and setting of boundary conditions

In this paper, finite element software is used for simulation calculation. The model first selects a conventional circular cavity channel laser array, as shown in Figure 2, and then improves the design of fluid-structure coupling cavity area extension according to the simulation results, and compares the improvement effects. Due to the limitation of space structure, the circular cavity channel adopts a semicircular cavity design, and the structure is shown in Figure 2.

Figure 2a, model 1 horizontal sharp-angled channel heat sink
Figure 2b Model 2 Horizontal angular shape channel heat sink

Figure 2. Two types of heat sink models for simulation

Figure 2a is a semi-cylindrical heat sink, and Figure 2b is a new-designed sharp-angle heat sink. The heat sink uses 7 800nm band centimeter Bar chips for horizontal array discharge packaging, a "sandwich" core group design, the core group is connected to the copper base through the ceramic chip, and the flow channel is water as the cooling medium. Model it 1:1, as shown in Figure 3, the simulation boundary conditions are as follows (the boundary condition settings of the sharp-angle heat sink are the same):
Figure 3 Simulation of the circular cavity horizontal array laser array model

Heat source: body heat source 30W/Pcs, total 7Pcs; inlet: volume flow V=6L/min; outlet: ambient pressure; initial temperature: liquid and solid are both 298K; flow mode: laminar flow and turbulent flow. The physical parameters of the array material thermal simulation are shown in Table 1.

Table 1. Material parameter form for the laser module

| Part name            | Materials | Density (g/cm³) | Elastic Modulus (Mpa) | TEC (10⁻⁶·℃⁻¹) | Thermal conductivity (W·m⁻¹·k⁻¹) | Specific heat (J/kg·k) | Poisson’s ratio |
|----------------------|-----------|-----------------|-----------------------|-----------------|----------------------------------|------------------------|----------------|
| low temperature solder | In52Sn48  | 7.29            | 16                    | 20              | 34                               | 230                    | 0.45           |
| high temperature solder | Au80Sn20  | 4.52            | 68                    | 16              | 57                               | 150                    | 0.405          |
| conduction heat sink | WCu10     | 17              | 315                   | 6.5             | 180                              | 161                    | 0.3            |
| ceramic              | ALN       | 3.05            | 310                   | 4.5             | 180                              | 600                    | 0.36           |
| semiconductor chip   | GaAs      | 5.32            | 88.5                  | 6.4             | 44                               | 330                    | 0.31           |
| heatsink with water  | Cu        | 8.9             | 110                   | 16.5            | 398                              | 390                    | 0.34           |

3.2 Comparison before and after optimization

Based on the above model, a numerical simulation is performed on the heat dissipation of the circular cavity laser array, and the final heat dissipation effect can be displayed by the chip junction temperature. Figure 4a is a schematic diagram of the position of the circular cavity channel laser array chip in the array and its temperature field distribution. Fig. 5a is a schematic diagram of the position of the angular shape channel laser array chip in the array and its temperature field distribution. Figure 4b is a schematic diagram of the temperature field distribution of a single chip in a circular cavity channel laser array, and Figure 5b is a schematic diagram of the temperature field distribution of a single chip in a sharp-angle channel array laser.

It can be seen that the following situations: 1. The highest temperature of the chip junction temperature is 54.6°C, which exceeds the normal operating temperature limit of semiconductor laser chips within 50°C, thus affecting its working efficiency and lifespan. 2. The temperature difference
between the high and low temperature of the chip is 12.8°C. According to the relationship between the wavelength of the 800nm semiconductor chip and the temperature of 0.28nm/°C, the wavelength difference between the first and last chips of the horizontal array laser array is nearly 4nm, which is not conducive to the absorption of Nd: YAG in side pump applications effectiveness.

Fig. 4 The distribution diagram of the fluid temperature field of the channel horizontal array laser array

a. Circular cavity  
b. Sharp-angle shape cavity

Figure 5 Diagram of the temperature field of a laser array chip with a circular cavity channel horizontal array

The fluid-structure coupling inner cavity area of the channel laser array is improved, and the fluid-structure coupling surface of the original semicircular cavity is extended and designed into a sharp corner shape, which increases the convective heat conduction area in the limited space of the channel. As shown in Figures 4b and 5b, in order to reduce the temperature difference between the front and rear sections caused by the accumulation of heat along the flow channel, the size of the inlet end of the flow channel is relatively small, and then gradually increases to the outlet end.

It can be found that after the improved design, the maximum temperature of the chip is reduced from 54.6°C in model 1 to 45.6°C, which is lower than the 50°C normal operating temperature limit of the semiconductor laser chip, and the temperature field distribution of the inner cavity fluid is more uniform, as shown in Figure 5b. The temperature difference between the first and last chips is reduced to 6.8°C, which is the same as above, converted to a wavelength difference of 1.9nm, and the wavelength difference is reduced by more than 50%. As shown in Figure 5a, b, observing the temperature field of the fluid area of the sharp-angled cavity channel, a relatively uniform distribution is also obtained.
Figure 6 Test results of sharp-angle channel array laser

4 Experimental results

Experiments show that the PVI index of this type of laser meets expectations, the power can be output linearly, and there is no saturation or bending, and the half-width of the wavelength is 2.5nm, which meets the needs of users.

5 Conclusion

The conventional circular cavity and the horizontal array laser array of the fluid-structure coupling area extended sharp-angle shaped cavity channel are simulated numerically, and the heat dissipation performance of the two is compared with the junction temperature of the horizontal array chip as an indicator. When using conventional circular cavity channel horizontal array array heat sink. The highest chip junction temperature is as high as 54.6°C, the temperature difference is 12.8°C, and the wavelength difference of each chip of the laser array is 4nm. After the improvement to the sharp-angle shaped cavity and the gradual flow channel volume design, the maximum chip junction temperature is 45.6°C, the chip junction temperature difference is reduced to 6.8°C, and the wavelength difference is 1.9nm, which is reduced by more than 50%, which can improve the crystal absorption efficiency of side pump applications.

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