Microchannel Heat Sink with High Thermal Conductivity Path for Diode Partially End-Pumped Slab Laser

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Abstract. The thermal effect of diode pumped solid-state laser (DPSSL) has always been a main problem limiting the further improvement of laser performance. In this paper, based on the special heat load distribution of the laser crystal of diode partially end-pumped slab (Innoslab) laser, a multi-stage manifold rectangular microchannel heat sink (MCHS) with high thermal conductivity path (HTCP) is designed. The multi-stage manifold provides the MCHS more fluid-solid heat transfer area near the heat gathering area, while the HTCP provides a path for heat transmission from pump end to the body of MCHS. According to simulation calculation, the highest temperature of laser crystal has been reduced by nearly 50℃ due to the addition of HTCP. Then the MCHS is fabricated by MEMS technology and the laser crystal is replaced by simulated heat source. Compared with the MCHS without the HTCP, the thermal resistance of the MCHS with HTCP is reduced by 6.4%, which proves the effectiveness of HTCP in heat dissipation of Innoslab laser crystal.

1. Introduction

Cooling of high-power electronic devices has always been an important research topic since the performance of integrated circuit chips and other devices is improving rapidly. For many high-power devices with traditional heat sources, many researchers have proposed different methods to reduce temperature of the devices such as heat pipe cooling \cite{1-3}, jet cooling \cite{4-6}, and thermoelectric cooling (TEC) \cite{7, 8}. Microchannel heat sink (MCHS), which was first proposed by Tuckerman, D.B. and R.F.W. Pease in 1981 \cite{9}, is an effective and stable method due to its small volume, large heat exchange area, high interface heat transfer efficiency and high thermomechanical stability \cite{10, 11}.

Diode pumped solid-state laser (DPSSL) \cite{12} is one of high-power devices. Compared with most other devices, the thermal effect of the gain medium of solid-state laser is special, because the heat load near the pump area is extremely high and decays rapidly, coupled with low thermal conductivity of most gain medium, the heat generated in pump area is not easily dismissed. So unreasonable heat transfer may lead to the thermal lens, birefringence effect and fracture damage of gain medium due to the uneven temperature distribution. Many researches have been carried out to reduce the thermal effect of laser crystal \cite{13-21}.

In this paper, taking the diode partially end-pumped slab (Innoslab) laser \cite{22} for example, a microchannel heat sink with high thermal conductivity path (HTCP) is proposed and tested.
2. Thermal Effect of Laser Crystal

In this section, before designing a reasonable microchannel heat sink, the thermal effect of laser crystal is analyzed. First of all, the working principle of Innoslab laser is necessary to be introduced. The schematic diagram of an Innoslab laser is shown in figure 1 [23]. The laser includes diode array, shaping system, resonant cavity and laser crystal. The diode array is used as pump source, and the beam shaping system composed of waveguide, cylindrical mirror and spherical mirror couples a homogeneous pumping line into the resonate cavity and further enter the laser crystal.

![Figure 1. The schematic diagram of Innoslab laser.](image1)

In the thermal load analysis, the geometric shape and spatial position of the laser crystal are shown in figure 2. The size of the laser crystal is a×L×c, and the width of the pump line is b.

![Figure 2. Schematic diagram of laser crystal.](image2)

The thermal load of the laser crystal can be described as:

\[
Q(x, y, z) = \frac{\eta P_{ab} \exp[-\frac{2y^2}{w^2(z)}-\alpha z]}{a} \int_{-a/2}^{a/2} \int_{0}^{L} \exp[-\frac{2y^2}{w^2(z)}-\alpha z] dydz
\]

where \(w(z)\) is the spot size, \(\alpha\) is the absorption coefficient of the laser crystal, \(\eta=1-\lambda_p/\lambda\), and \(\lambda_p\) is the wavelength of pump beam, \(\lambda\) is the wavelength of output beam. \(P_{ab}\) is the pump power on the pump face of laser crystal.

To simplify the expression, the pump beam can be regarded as Gaussian beam, and the crystal pump length is not too long so the size of light spot is always approximately equal to the waist size, and assuming that the length of the x-axis is long enough and the pump intensity in the x-direction is
equal. So the equation 1 can be simplified as [17]:

$$Q(y, z) = \eta \alpha P_{ab} \exp(-\alpha z)$$  \hspace{1cm} (2)

According to equation 2, the thermal load of the middle section under specific parameters is shown in figure 3. It can be seen that the thermal load of laser crystal has obvious distribution effect, it concentrates on the pump end and decays exponentially with the change of crystal depth. In addition, the thermal conductivity of laser crystal is not very high, for instance, $k = 14 \text{W/(m·K)}$ for YAG crystal and $k = 5.10 \text{W/(m·K)}$, $k = 5.23 \text{W/(m·K)}$ for YVO₄ crystal. As a result, serious temperature unevenness may occur without sufficient heat dissipation. So designing a heat sink capable of dissipating heat from pump face efficiently is an urgent issue to be solved.

![Figure 3. Distribution of thermal load with depth in pumping area.](image)

3. Simulation of Heat Sinks with HTCP or not

According to the exponential thermal load obtained above, for Nd:YVO₄ crystal with a size of 22mm×12mm×1mm, a microchannel heat sink with enhanced heat dissipation at pump end is designed, as shown in figure 4(a). The MCHS is made by cooper with a size of 23.5mm×20mm×1mm and a mass of 3.659g. Based on traditional MCHS with rectangular channel, a multi-stage shunt structure of rectangular microchannel is arranged at the corresponding position of the pump face to get a larger fluid-solid heat transfer area and further enhance the heat dissipation at the pump end. Each main channel is divided into secondary heat dissipation channels at the pump face, and the length of the secondary channels is 3 mm, 1mm in front of the pump face and 2mm behind. The best channel height, substrate thickness channel width and space between two secondary channels have been verified at 500um, 250um, 300um and 900um by simulation. And the MCHS is symmetrically installed on the upper and lower cooling face of the laser crystal, as shown in figure 4(b).

Considering the low thermal conductivity of laser crystal, on another MCHS, for some laser crystals that work with high-reflection film and anti-reflection film coated on the end face of the crystal as a resonant cavity, a cooper layer is added as a high thermal conductivity path to transfer heat from pump end to the main body of MCHS, as shown in figure 4(c). The cooper layer is processed on the pump face but does not cover the pump area, and the thickness of copper is 50um.
Figure 4. Schematic diagram of MCHS. (a) Structure of microchannel. (b) Schematic diagram of the installation. (c) Schematic diagram MCHS with HTCP.

Figure 5 shows the curves of the maximum temperature of crystal and pressure drop with the flow rate of the working fluid, in which MCHS2 is the heat sink added with a cooper layer as high thermal conductivity path (HTCP) while MCHS1 is not. It can be seen from figure 5(a) that MCHS with cooper layer has better performance than the other one, the maximum temperature drops nearly 50°C after adding HTCP.

Considering the high external power consumption caused by excessive pressure drop, select the flow rate of 0.2L/min to compare the temperature distribution. Some typical nephograms are shown in the figure 5(b-e), comparing the temperature distribution in figure 5 (b) and (d), it can be seen that the addition of copper HTCP significantly reduces the temperature of the pump face of the crystal, and there is no obvious temperature gradient at the place where crystal is covered by cooper, and the temperature rises sharply in the pumping area. Inside the crystal, it can be seen from the comparison of figure 5(c) and (e) that the temperature near the pump face have been reduced and the highest temperature point has been moved inward, it indicates that a large amount of heat near the pump end has been transferred into the MCHS through the HTCP, and the thermal load away from the pump face is much smaller due to its exponential decay, so the maximum temperature can be greatly reduced even if the lower thermal conductivity restricts the heat relatively far away from the pump face from being conducted to the heat sink.

Figure 5. Simulation result. (a) Flow rate- maximum temperature and pressure drop. (b) Nephogram of pump face with MCHS1. (c) Nephogram of side view section with MCHS1. (d) Nephogram of pump face with MCHS2. (e) Nephogram of side view section with MCHS2.
4. Fabrication of Microchannel Heat Sinks and Simulated Heat Source

To test the difference of these two MCHSs in practice, both of them are fabricated by MEMS process. And considering the system complexity and difficulty of testing an Innoslab laser, a simulated heat source using ZrO₂ ceramics (k≈3 W/(m·K)) as material and heating by Ni resistance wire is made to replace the laser crystal. Due to the symmetry of the simulated model, half of the models were processed and tested.

Figure 6 shows the process flow of the MCHS with simulated heat source. The process flow of microchannel corresponds to (1-a) to (1-d), the cover plate with input and output corresponds to (2-a) to (2-b), and the simulated heat source, (3-a) to (3-c). First, the positive photoresist of AZ-4620 was spin-coated on the silicon wafer, patterning by ultraviolet lithography and development, and etching by NMC ICP deep silicon etching system, the complementary structure of microchannel is fabricated on the silicon wafer (1-b). The Cr-Cu seed layer is deposited on wafer by magnetron sputtering and then electroplating cooper as the body of heat sinks (1-c). After that, the silicon is dissolved in KOH solution so the microchannel is released and the back of the channel is polished to flat(1-d), after that, cutting the cooper into individual units. As for cover plate, two circular holes are fabricated on the cooper by laser drilling (2-b). The simulated heat source is manufactured on ZrO₂ ceramic wafer, patterning the resistance wire and electroplating nickel after sputtering the seed layer on ZrO₂ ceramic (3-b), then cutting the wafer into units. For the heat source with HTCP, coating the photoresist on end face while other faces are coated by polyimide tape, the rectangle with the same width of cooper layer is patterning on the simulated pump face, and then sputtering the seed layer and growing cooper layer on it by electroplating (3-c). Finally, bonding these 3 pieces together by Cu-Sn intermetallic bonding technology before welding the inlet and outlet on the MCHS. The pictures of these three pieces and the bonded devices are shown in figure 7.
Figure 7. Picture of the devices. (a) Microchannel. (b) Cover plate. (c) Simulated heat source. (d) The bonded device. (e) MCHS with inlet and outlet.

5. Experimental Test and Data Analysis

Setup a test system in figure 8(a) to evaluate the performance of MCHSs. Including a worm pump, a DC power, a pressure gauge and the infrared camera. Before testing, the MCHS should be welded the conducting wire and sprayed black paint to reduce reflect, as shown in figure 8(b). For each MCHS, adjust the current and voltage to control the thermal power under the flow rate of 50mL/min, 100mL/min, 150mL/min, 200mL/min respectively, record the temperature of the heating area, figure 8(c) shows the image on infrared camera during testing. The result is shown in figure 9.

Figure 8. (a) The test system. (b) Devices to be tested. (c) Image of thermal infrared camera.

It can be seen from figure 9(a) and (b) that there is a linear relationship between temperature and thermal power, and the thermal resistance can be given by the slope of linear fitting of data points (figure 9(c)), the MCHS2 with cooper layer as HTCP has a significantly lower thermal resistance than MCHS1 at a given flow rate, the thermal resistance has dropped 6.4% when the flow rate is 200mL/min. Figure 9(d), (e) and (f) show the temperature rise relative to room temperature at a given power, it can be seen that the temperature difference between the two MCHSs increases with the increase of thermal power, which means that for heat source with similar heat load distribution, adding
the cooper layer is an effective way to enhance the heat dissipation, especially for high power heat source, and layer crystal is undoubtedly one of them.

![Figure 9](image-url)

**Figure 9.** Testing result. (a) Testing result of MCHS1. (b) Testing result of MCHS2. (c) Comparison of thermal resistance (d) Temperature comparison at power of 3W. (e) Temperature comparison at power of 6W. (f) Temperature comparison at power of 12W.

### 6. Conclusion

In this paper, the thermal load in the laser crystal of diode partial end-pumped slab(Innoslab) laser is analyzed, and according to the special heat load distribution of the laser crystal, a multi-stage manifold rectangular microchannel heat sink(MCHS) with cooper layer as high thermal conductivity path(HTCP) is designed, the multi-stage manifold provides the MCHS more fluid-solid heat transfer area near the heat gathering area, and the HTCP provides a path for heat transmission from pump end to the body of MCHS, and the comparison between MCHS with HTCP or not have been taken by simulation calculation, the simulation results verify the effectiveness of the microchannel, the maximum temperature of laser crystal has been reduced by nearly 50℃ due to the addition of HTCP. The MCHS is fabricated by MEMS process, and the simulated heat source is adopted to replace the laser crystal, and the result of testing shows the MCHS with the cooper layer has better heat transfer performance than the other, the thermal resistance of the whole device consists of the MCHS and simulated heat source is 6.4% lower than that of the MCHS without the HTCP.

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