Numerical simulation of thermal distribution in quasi-heat-capacity fiber lasers

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Abstract. In this paper, a quasi-heat-capacity fiber laser is designed, which uses a heat sink to store heat during the operation time, and uses a low-energy cooling system to cool down slowly. Compared with conventional water-cooled or air-cooled fiber lasers, this quasi-heat-capacity fiber laser has a compact structure with low-energy consumption, which might be useful for platforms that have strict requirements for volume, weight and energy consumption. By using the finite element analysis (FEA) method, a detailed quantitative thermal analysis of the proposed quasi-heat-capacity fiber laser is investigated. The laser heat source consists of two pumping laser diodes (LDs), gain fibers, and an electronic power source. During operation, the heat is stored only through an aluminum heat sink with a limited mass of 5 kg. The lasing-on-time of the laser is defined as the time when the temperature of LD bottom plate increases from 20 ℃ to 30 ℃ for the first time in a certain period of working time, which is the best working temperature range of the wavelength stabilized LDs. Numerical simulation results show that when the fiber laser works in heat capacity mode, the lasing-on-time can be effectively improved.

1. Introduction
With the continuous improvement of the performance of fiber lasers, its applications have gradually expanded to scientific research, industrial, medical, and special environment[1, 2]. As the main pump for solid-state lasers and fiber lasers, semiconductor lasers inevitably have quantum defect and various losses, which means that a certain portion of the injected electric power will be converted into heat, which will cause the LD temperature to rise. And the temperature rise will lead to a series of problems such as LD output power reduction, working wavelength drift[3, 4], which will adversely affect laser systems. In order to ensure the safe and stable operation of the system, effective heat dissipation measures must be taken to reduce the thermal effects[5].

Reported heat dissipation methods include air cooling, water cooling, thermoelectric cooler (TEC), phase-change refrigeration and conduction cooling (such as micro-channel cooling and heat pipe conduction technology)[6-8]. Due to the particularity and harshness of special environment, traditional air cooling and liquid circulation cooling methods are not practicable[9, 10]. Although phase change refrigeration technology has the advantages of large energy storage density, good controllability, and high reliability, the requirements for phase change materials are more stringent and the cost is
higher[11]. In contrast, conduction cooling technology is easier to apply and is considered as an effective way of laser cooling for special environment[12].

Based on the conduction cooling technology, a quasi-heat-capacity fiber laser is designed in this paper, which uses a heat sink to store heat during the operation time, and uses a low-energy cooling system to cool down slowly. In our work, the experimental data and simulation results are firstly compared and analysed to verify the validity of numerical simulation. Based on this, the finite element model of the quasi-heat-capacity fiber laser was established, and a series of numerical simulations were carried out by changing the geometry of the heat sink, the distribution of laser elements in the heat sink and the duty cycle of the quasi-heat-capacity laser. Finally, it is found that when the fiber laser works in heat capacity mode, the lasing-on-time can be effectively improved. Particularly, when the duty cycle is smaller than a critical value, the laser can work without time limitation.

2. Numerical simulation feasibility verification
In order to verify the validity of the finite element model used in this paper, an experimental platform was built. In the experiment, two LDs are closely attached to the aluminium heat sink, and a layer of thermal grease was applied between the LD and the aluminium heat sink. A number of temperature sensors were placed in close proximity to the outer wall of the LD and the surface of the aluminium heat sink, and a paperless recorder was used to record the temperature change. The experimental setup was wrapped with thermal insulation material to simulate the adiabatic environment. The schematic diagram of the experimental setup was shown in figure 1.

![Figure 1. Schematic diagram of the experimental setup.](image)

The solid model of the LDs and the aluminium heat sink was used for transient thermal analysis. Among them, the LD shell and COS (chip on submount) are made of pure copper, the collimating lens are made of glass, the outer shell is made of rubber, and the heat sink is made of pure aluminum. The thermal performance parameters of the materials are shown in table 1.

| Material | Density (Kgm⁻³) | Isotropic Thermal Conductivity (Wm⁻¹K⁻¹) | Specific Heat Capacity (Jkg⁻¹K⁻¹) |
|----------|----------------|------------------------------------------|-----------------------------------|
| Copper   | 8933           | 400                                      | 385                               |
| Aluminium| 2719           | 202.4                                    | 871                               |
| Rubber   | 1010           | 0.25                                     | 1700                              |
| Glass    | 2500           | 1.4                                      | 750                               |

The initial temperature of the system was set as 20 ℃, and the boundary condition was assumed as heat insulation. The thermal load power 9W was added to the chip. The size of the aluminium heat sink is 120mm×100mm×80mm. Based on the heat conduction theory in solids, it is necessary to set the heat transfer coefficient of the interface between the LD and the aluminum block in the simulation...
calculation. The thermal conduction coefficient of the thermal grease used in the experiment is 1.2 (Wm⁻¹K⁻¹), and the thickness is 0.1 mm, according to the basic formula of the thermal resistance and heat transfer coefficient of the single-layer flat wall:

\[ r_t = \frac{1}{k} = \frac{\delta}{\lambda} \]  

(1)

Where \( r_t \) is the thermal resistance per unit area, the heat transfer coefficient \( k \) is used to characterize the intensity of the heat transfer process, and \( \delta \) is the wall thickness. According to the formula, the heat transfer coefficient between the LDs and the aluminium heat sink is \( 1.2 \times 10^4 \) (Wm⁻²K⁻¹). In general, the heat transfer coefficient of the copper-copper interface is approximately \( 5.55 \times 10^4 \) (Wm⁻²K⁻¹)[10], and the heat transfer coefficient of the copper-rubber and glass contact interface is low, which is 1000 (Wm⁻²K⁻¹). After working 800 seconds, the temperature distribution was calculated as shown in figure 2. It can be seen that the temperature difference between the outer wall surface of the LD and the aluminium heat sink is about 6 °C, indicating that the heat transfer is insufficient.

Figure 2. (a)Temperature distribution of the system calculated by FEA. (b)Temperature distribution inside the LD.

The experimental results are shown in figure 3 (a). Figure 3 (b) is the temperature data obtained by performing time post-processing on the simulation results.

Figure 3. Comparison between experimental data and simulation results of temperature changes at different positions. (a) Experimental data. (b) Simulation results.

Comparing the experiment results with the simulation results, it can be found that the temperature trends of the detected positions are basically consistent. The slope of the curve in the experiment is \( 8 \times 10^{-3} \) °C/s, and the slope of the curve calculated by simulation is \( 7.3 \times 10^{-3} \) °C/s, they are nearly the same.
3. Calculation results and discussion

The heat source of the fiber laser is mainly composed of two LDs, gain fiber and an electronic power source, and the thermal power of these three heat sources is 18 W, 5.4 W and 15.4 W respectively. During the operation time, the heat is stored only through the aluminum heat sink with a limited mass of 5 kg. The lasing-on-time of the laser is defined as the time when the temperature of LD bottom plate increases from 20 ℃ to 30 ℃ for the first time in a certain period of working time, which is the best working temperature range of the wavelength stabilized LDs. Assuming that the initial temperature of the fiber laser is 20 ℃, the numerical simulation results under different conditions are given below.

Figure 4 shows the temperature distribution map of the system when all heat sources of the fiber laser are located on the same side of the heat sink. It can be seen that when the temperature of LD bottom plate reaches 30 ℃, the heat sink temperature is only about 26 ℃, indicating that the heat conduction process cannot be fully carried out in this process. The temperature change curve of LD with time is shown in figure 5. It can be seen from the figure that the lasing-on-time of the fiber laser in this mode is about 13 minutes.

Since the power supply and optical fiber can withstand temperatures far exceeding the LDs, changing the relative positions of the three heat sources and the structure of heat sink can increase the lasing-on-time of the laser to some extent. However, the improvement of working time in this way is much limited, mainly by the total mass of the heat sink. After a series of numerical simulation, it is found that when the laser is in continuous working state, the lasing-on-time of the fiber laser can be increased by 1 minute with only changing the geometry of the heat sink and the distribution of laser
elements in the heat sink. Even if the heat pipe with an power of 2 W is added to the system, the improvement is not remarkable. Figure 6 and figure 7 show some numerical simulation results. It can be seen that the lasing-on-time of the laser does not increase significantly. As can be seen from figure 7, the lasing-on-time of the fiber laser is less than 15 minutes.

Figure 6. The temperature distribution after changing the geometry of the heat sink and the distribution of laser elements in the heat sink.

Figure 7. The temperature change curve of LD with time.

When the laser works in the heat capacity mode, we assume that the laser works for 10 seconds and rest for 90 seconds, which is one working cycle. In one working cycle, the heat sink is used to store heat when the laser is running, and a 2 W heat pipe conducts the waste heat of the system to the external radiation cold plate when the laser is suspended. It should be noted that, for the quasi-heat-capacity fiber laser, the heat pipe works continuously in a cycle, which is different from the conventional solid-state heat capacity lasers. Figure 8 shows the temperature distribution map of the laser at a certain moment under the heat capacity working mode. It can be seen that the temperature difference of each part of the laser decreases compared with the continuous working mode, and the heat transfer is more sufficient. Figure 9 shows the change curve of the temperature of LD with time. Combined with the numerical simulation data, we can get that the laser can be turned on for about 33 minutes in a period of 328.4 minutes before reaching the maximum temperature at a duty cycle of 10 %, which is greatly improved compared to the non-heat capacity working mode.
Figure 8. The temperature distribution of the laser under the heat capacity working mode.

Figure 9. (a) The temperature change curve of LD with time. (b) The temperature change curve when the temperature of LD bottom plate reaches 30 °C.

In fact, when we constantly adjust the duty cycle of the laser working time, it is not difficult to find that with the duty cycle decreases, the lasing-on-time and total working time of the laser gradually increase, as shown in figure 10. When the duty cycle is reduced to a certain critical value, the laser can theoretically run forever. And the critical value can be calculated as 5.15 % by the power of the heat pipe and the total power of the heat source. If the duty cycle is lower than the critical value, the temperature of the laser decreases gradually instead of rising. Figure 11 shows the temperature change curve of LD when the duty cycle is 2 %, 5.15 %, respectively. Of course, in practical applications, once the duty cycle is lower than this critical value, we should control the heat dissipation efficiency to ensure that the temperature of the laser is in a normal range.

Figure 10. (a) Lasing-on-time. (b) Total working time.
4. Conclusion
Numerical simulation results show that when the fiber laser works continuously, only by changing the geometry of heat sink and the distribution of laser components in the heat sink, the improvement of working time in this way is much limited, mainly by the total mass of the heat sink. Even if a heat pipe with an power of 2 W is used to assist the heat dissipation of the laser, the improvement is not remarkable. However, if the laser is in the heat capacity mode, the lasing-on-time and total working time of the laser can be greatly improved. What’s more, it is possible to keep the laser working when the duty cycle is smaller than a critical value. The design of this kind of quasi-heat-capacity fiber laser might be useful for improving the performance of fiber laser in special environment.

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