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Development and thermal management of 10 kW CW, direct diode laser source

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ABSTRACT

We report on the development of direct diode laser source with high-power and high reliability. The laser source was realized by the polarization and wavelength combination of four diode laser stacks. When at the operating current of 122 A, the source was capable of producing 10,120 W output while maintaining 46% electro-optical conversion efficiency. The maximum temperature on the lens was decreased from 442.2 K to 320 K by utilizing an efficient thermal dissipation structure, and the corresponding maximum von Mises stress was reduced from 75.4 MPa to 14 MPa. In addition, a reliability test demonstrated that our laser source was reliable and potential in the applications of laser cladding and heat treatment.

1. Introduction

Diode lasers are playing a major part in the materials processing of engineering and manufacturing [1–3]. And the demand for direct diode laser sources with high output power is currently enjoying unprecedented growth in the applications of material cladding and heat treating. This is mainly driven by the significant advantages of diode lasers over their CO_2 laser counterpart, including the high material absorption and electro-optical conversion efficiency, etc. [4–6]. The output wavelengths of 9xx nm high-power diode lasers are shorter than that of CO_2 lasers. And this would increase the absorption of metal surface, improving the melting efficiency of metal powder. Furthermore, the electro-optical conversion efficiency of diode lasers is four to six times higher than that of CO_2 lasers. Thus the 9xx nm direct diode laser sources are gradually displacing the conventional CO_2 lasers in material processing applications [7]. The incomparable advantages of the direct diode laser sources are presently attracting considerable attentions. Stephen Brookshier et al. obtained a 976 nm diode laser source with electro-optical conversion efficiency of 45% by the spatial combination of diode laser stacks [8], and the output power of this laser source is 8 kW with several spot models under continuous work (CW). Baumann et al. reported the diode laser source with output power of 10 kW and electro-optical conversion efficiency of 50% by the beam shaping and wavelength combination of stacks. The spot diameter of laser source could be varied from 2 mm to 5 mm [9]. At present, much research has been focused on the design and development procedure of direct diode laser sources. However, the thermal management of 10 kW-level diode laser source is rarely investigated. Because of the large thermal stress resulting from the high radiation energy, the deformation and fracturing of optical elements in the laser sources usually appear during their operations [10,11]. As any performance degradation or failure of the laser sources is unacceptable during the laser processing, the research on the thermal management of 10 kW-level diode laser source has been of great interest.

In this paper, the development of a reliable, industrial-grade direct diode laser source was reported and the output power of 10,120 W was achieved. Two 915 nm and two 976 nm diode laser stacks were multiplexed in the diode laser source utilizing the polarization and wavelength combination. A rectangular focus beam spot with a dimension of $2.5 \times 16\ mm^2$ was realized by the focusing lens. The thermal dissipation structure was designed and optimized to reduce the thermal stress of optical elements, which could prevent the diode laser source from performance degradation or failure.

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2. Experiment design

2.1. Optical design

Diode laser stacks are chosen as the typical laser sources for laser cladding applications [12]. The output power of one diode laser stack composed by numerous diode laser bars can reach several kilowatts. To achieve high output power, we built a model based on the techniques of polarization and wavelength combination. This model comprised of two 915 nm and two 976 nm stacks, with 25 bars per stack. The operating optical power of each bar was 110 W, and thus the total optical power of four stacks was 11 kW. Due to the divergence angles of bars were $70^{\circ} \times 9^{\circ}$ (95% power content), every bar should be firstly collimated in the fast-axis by an aspheric cylindrical lens. The filling factor of bars was 50%, so the emitter pitch of bars was only 200 μm. Obviously, the common micro-lens arrays with 500 μm pitch could not be used to the slow-axis collimation of bars. In this paper, a group of double cylindrical lenses with a focal length of 200 mm was designed for the slow-axis collimation. After collimation, the divergence angle of fast and slow-axis is decreased to 7 mrad and 54 mrad (95% power content), respectively.

The diode laser source consists of two units and two stacks with the same wavelength are polarization multiplexed in each unit. The same beam combination occurs in the other unit. Generally, the polarization beam splitter is applied to combine two perpendicular polarization laser beams. In our case, we adjust the polarization state of the laser beams by the half wave plate. The beams of two diode laser stacks with perpendicular polarization state are multiplexed when they reach the polarization beam splitter. After polarization combination, two output laser beams (2 stacks $\times$ 2) are finally wavelength combined by the dichroic beam splitter, as shown in Fig. 1.

Wavelength combination is a common technique that is used to scale to higher power in the diode laser source. In generally, the common dichroic beam splitter is used to combine the two laser beams with different wavelengths. The two wavelengths being combined are typically separated by tens of nanometers. The idea of wavelength combination is to precisely place the transition region edge of dichroic film between two wavelengths, so that the 915 nm laser is reflected and the 976 nm laser is transmitted [13], as shown in Fig. 2. The combining efficiency can be as high as 96% for the transmitted beam and 99% for the reflected beam, or an average of 97.5%. To avoid the spectrum of stacks mismatching to the dichroic film, the stacks with a spectrum of $\pm$5 nm are acceptable in the wavelength combination. This is not a strict demand for the commercially available stacks.

According to the actual work distance of laser processing, a group of triple lenses with 300 mm focal length was designed to focus the output laser beams. The calculated beam spot at the focal plane of lenses was a rectangular spot of 2.5×16 mm^2, which could meet the need of large area processing in the laser cladding.

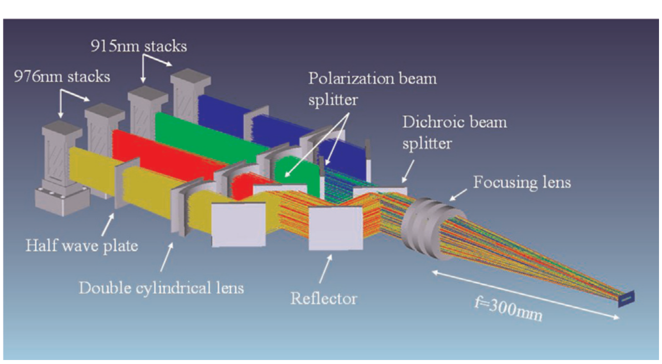

Fig. 1. Layout of beam combination in diode laser source.

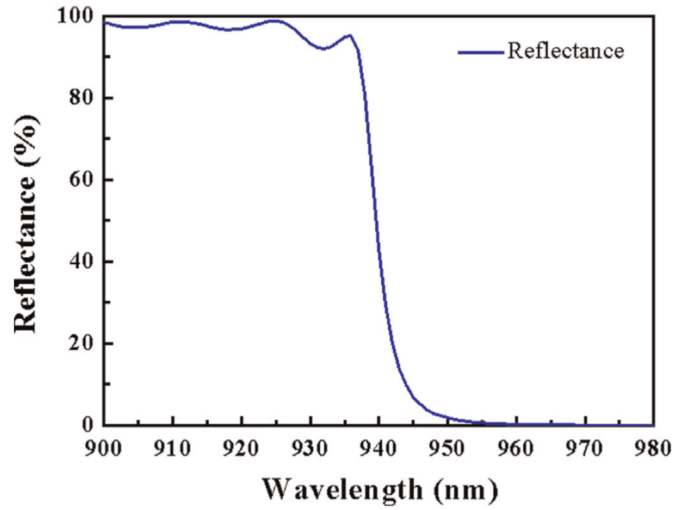

Fig. 2. Efficiency of dichroic beam splitter.

2.2. Design of thermal dissipation structure

Since the output power of this diode laser source is up to 10 kW, it is very necessary to investigate the thermal dissipation of all the elements including diode laser stacks and optical elements. The diode laser stacks are usually cooled by the mature technology of microchannels thermal dissipation, hence, we only discuss the cooling of the optical elements in this paper [14,15]. The local temperature of the lenses will be increased under the powerful laser radiation. Correspondingly, the thermal stress caused by temperature gradient may lead to the fracturing of the lenses. In all the lens elements, the last one of the focusing lens group sustains the highest laser power density, so we select this one as an example to illustrate. The finite-element analysis software called COMSOL has been applied to simulate and calculate the thermal stress of this lens. The heat on the lens is the result of absorbing the laser energy by the substrate material of lens. The substrate material of lens is fused silica and its absorption coefficient α to diode laser energy is 0.05 m^{-1}. However, the heat conductivity of fused silica is only 1.3 W/(m K). Thus it tends to generate serious thermal stress on the lens. The heat source function is given as the following equation:

$$q(x, y, z) = \frac{P\alpha}{S} e^{-\alpha z}$$

where P denotes the total power of laser after combination and S denotes the radiation area of laser on the lens.

Under the free convection thermal dissipation, the thermal stress of lens was simulated by COMSOL. The coefficient of free convection and the environment temperature were set to be 10 W/(m^2 K) and 293 K, respectively. After meshing the finite-element module, the distribution of temperature and thermal stress were calculated using the classical method. Fig. 3 illustrates the simulation results. The maximum temperature on the lens reaches 442.2 K and the maximum thermal stress (von Mises stress) exceeds 75.4 MPa, which can induce the fracturing of lens.

For thermal management, a water-cooled lens holder was designed so that the thermal stress of lens was optimized to prevent any fracturing of lens. As shown in Fig. 4, 12 precise machined water channels with the diameter of 3 mm are equally spaced on the side wall of lens holder. The coolant water inflows from the cooling inlet, then injects into the water channels through circular cooling groove. Finally, the coolant water is converged together

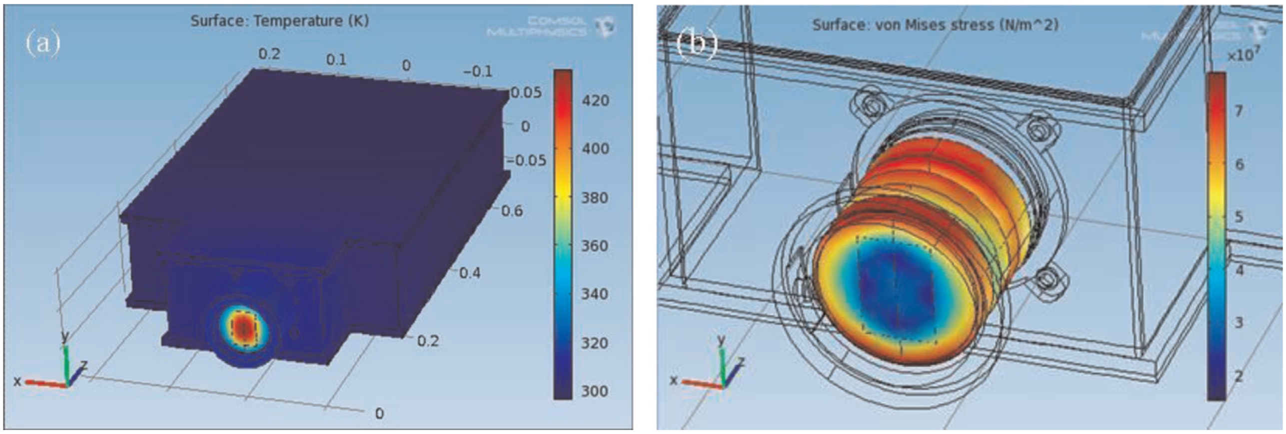

Fig. 3. Simulations of temperature and thermal stress distribution under free convection thermal dissipation.

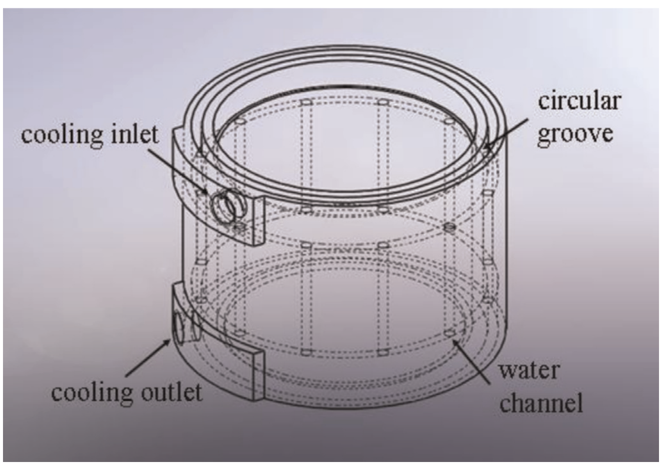

Fig. 4. Thermal dissipation structure of focusing lens holder.

and outflow from the cooling outlet. The flowing coolant water can remove the heat of lens efficiently and decrease the thermal stress.

The number of water channels is an important parameter influencing the cooling effect. Fig. 5 depicts the temperature and thermal stress of lens versus the number of water channels. The flux and temperature of cooling water are set to be 5 L/min and 293 K, respectively. Judging from Reynolds number, the cooling water flows with a turbulence pattern. After the fluid calculation, the thermal stress and temperature distribution are gained by defining the velocity as the boundary condition.

As shown in Fig. 5, the temperature and thermal stress

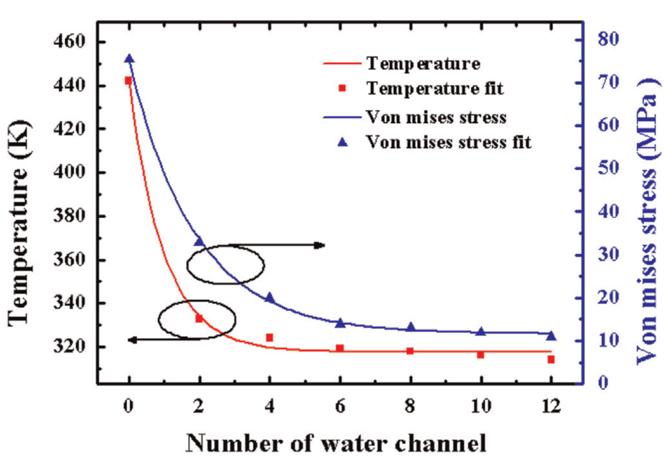

Fig. 5. Temperature and thermal stress with varying water channels.

decrease rapidly with the increasing of water channels' number at first. And this is mainly benefited from the increased total flux of cooling water. However, no obvious change of cooling effect is observed when the number of water channels exceeds six. And it indicates that the heat diffusion is limited by the thermal conductivity of lens. Thus the number of water channels is set to be six. Fig. 6 shows the simulation results of cooling effect on the lens with six water channels. It is observed that the maximum temperature decreases from 442.2 K to 320 K, and the corresponding maximum von Mises stress is reduced from 75.4 MPa to 14 MPa. Therefore, the thermal dissipation structure improves the stability of lenses in this diode laser source efficiently.

3. Results and analysis

The polarization and wavelength combination of four diode laser stacks were carried out following the model described in Section 2.1. Fig. 7 illustrates the power and efficiency curve of the diode laser source operating at the coolant water temperature of 293 K. The diode laser source is capable of providing an output power of 10,120 W while maintaining an overall electro-optical conversion efficiency of 46% at the operating current of 122 A.

As can be seen from Fig. 7, the PI curve shows an almost linear distribution, which indicates that diode laser stacks cooled by microchannels can yield a stable output and the power drop caused by heat accumulating does not occur at the maximum power.

The original efficiency of diode laser stacks is about 50%, but the efficiency at the maximum power of diode laser source decreases to 46% after the combination, which can be explained by following aspects. Firstly, the beams of diode laser stacks are linear polarization with the purity of 98%, which leads to the power losses in the polarization combination [16]. Furthermore, the efficiency of dichroic film is hard to achieve a perfect condition because of the coating technology. Usually, the transmittance to *P* polarization beams and reflectance to *S* polarization beams are about 96% and 99%, respectively, which induce an average efficiency drop of about 2.5% at the step of wavelength combination. The last but not least, the antireflection film of each lens also has a residual reflectance of 0.3–0.5%, the accumulation of small imperfections in the coating lead to a relatively large impact on the percentage of laser transmission.

As shown in Fig. 8a, a rectangular focus beam spot with a dimension of 2.5×16 mm^2 is realized by the focusing lenses, which is consistent with the simulated result. Then a 24 h reliability test on the diode laser source was carried out. The focusing spot was monitored in the test by Spiricon laser beam profiler. We directed 99.99% of the 10 kW laser beams away from the laser beam

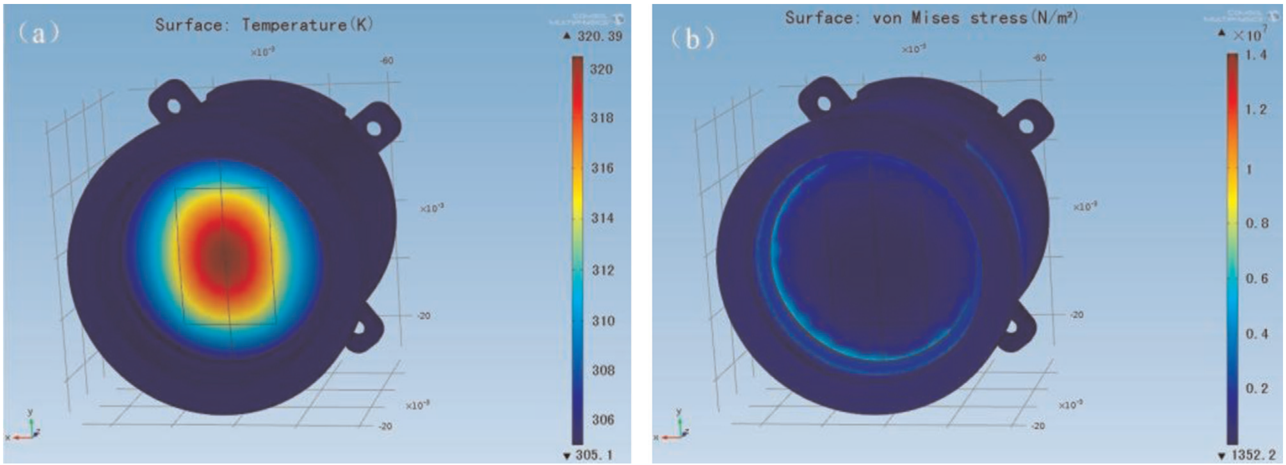

Fig. 6. Temperature and thermal stress distribution with six water channels.

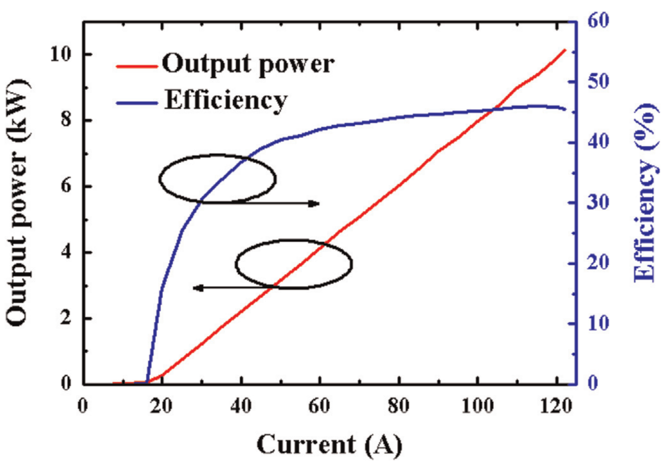

Fig. 7. Output power and efficiency versus operating current.

profiler using reflective mirrors so that only 0.01% of power transmitted through to the laser beam profiler. The profiles of the focusing spot before and after the reliability test are shown in Fig. 8. The focusing spot have no obvious variation after the long time continuous operation, which indicates that the thermal dissipation structure prevents the lens from distortion caused by the thermal stress. The diode laser source showed a stable output power during the full operation. It is proved that our direct diode laser source is reliable and suitable for the applications of laser cladding and heat treatment.

4. Conclusion

We have demonstrated a reliable, industrial-grade, 10 kW-level direct diode laser source based on water-cooled stacks. Polarization and wavelength combination were used in the diode laser source. The total output power of 10,120 W at current of 122 A, an electro-optical conversion efficiency of 46% and a focus spot of $2.5\times16\ \text{mm}^2$ were realized. A 24 h reliability test on the laser source was carried out in this work, and the degradation of the output power and focusing spot of diode laser source was not observed, which was benefited from the well-designed thermal dissipation structure of optical elements. We believe that the high-power diode laser source promise wide application prospects in the field of laser cladding and heat treating.

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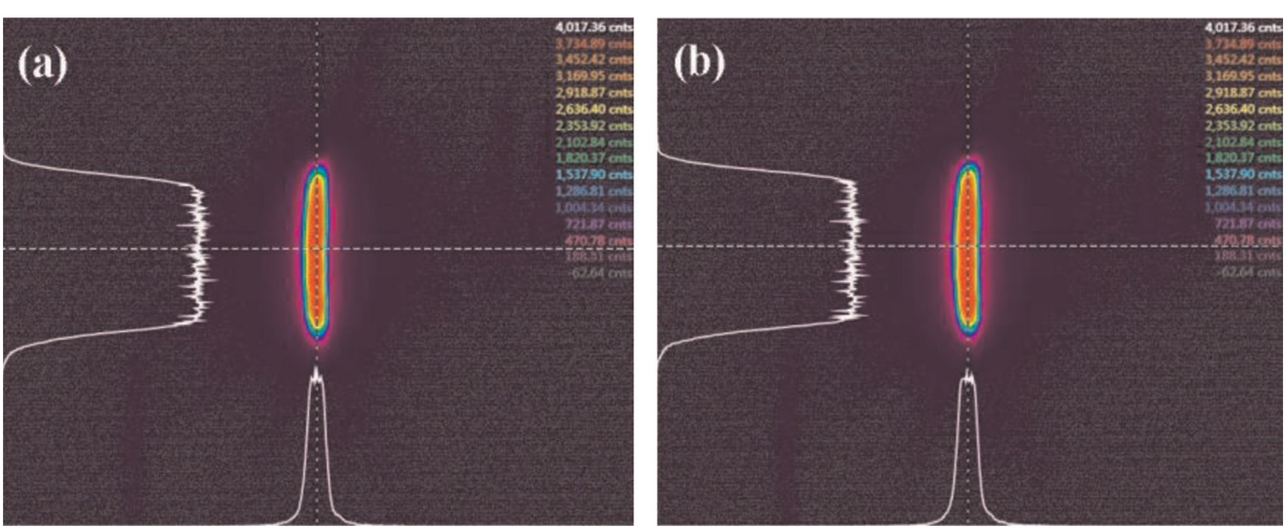

Fig. 8. Profiles of focusing spot before (a) and after (b) the reliability test.

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