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Fiber-coupled Diode Laser Flexible Processing Source for Metal Sheet Welding

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Abstract: A high power fiber-coupled flexible source is fabracated in which 20 conduction cooled diode laser bars were intergrated in manner of linear array coupling. Under the macrochannel cooling with industrial water, a CW output power of 907 W, a beam parameter product of 47 mm · mrad, an optical power density of 3.21×10^5 W/cm^2 and a maximum wall-plug efficiency of 39% on the work piece are demonstrated from a 600 μm, *NA* 0.2 fiber. This source has a great potential to be directly adapted in materials processing, especially in metal sheet welding.

Key words: diode laser; linear array coupling; fiber-coupled; flexible processing source
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适用于金属薄板焊接的柔性光纤耦合半导体激光加工光源

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摘要: 研制了一种单光纤耦合的柔性半导体激光加工光源,该光源由20个传导热沉封装的激光列阵以线阵合束方式耦合而成,在大通道工业水冷条件下,从600 μm芯径、*NA*为0.2的光纤中连续输出907 W功率,输出光束质量为47 mm · mrad,最终达到工件表面的功率密度为3.21×10^5 W/cm^2,最大插头效率达39%。该激光光源具有直接应用在金属薄板焊接的潜力。

关 键 词: 半导体激光; 线阵合束; 光纤耦合; 柔性加工光源

1 Introduction

High power diode laser systems are gaining substantial interest in materials processing because of the benefits of high wall-plug efficiency, high reliability, long lifetime, relatively low investment costs and a small footprint. However, a practical problem for a direct diode laser system is its low reliability,

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such as the heating effect and splatters due to the short interval between the laser source and the work piece. A fiber-coupled diode laser system effectively improves the reliability by introducing a fiber output to increase the distance, meanwhile offering an effective transmission, a flexible operation and other advantages. In recent years, great progresses on this research have been gained in many countries, especially in the USA and Germany [1-7]. The domestic development is relatively slow and the output power from a fiber is not more than 500 W from the reported papers [8-9], which cannot meet the requirement of materials processing, like metal sheet welding. In addition, conventional microchannel cooling stacks, a main package pattern of high power diode laser sources, have the inherent defects of easy corrosion, poor maintainability, low filling factor and so on.

In this paper, a novel method of linear array coupling is adopted to develop a high power fiber-coupled diode laser flexible processing source by coupling 20 conduction cooled bars. Under the macrochannel cooling, a CW output power of 907 W, an optical power density of 3.21×10^5 W/cm^2 and an overall electro-optical conversion efficiency of 39% was fabricated.

2 Experiments

Beam parameter product (*BPP*) is used to evaluate the beam quality of diode lasers, defined as the product of the beam waist radius w_0 and the beam divergence half angle $\theta/2$ of far field [10]. The smaller the *BPP* is, the better the beam quality. Correspondingly, *BPP* of the optical fiber is calculated by multiplying the core radius r and its numerical aperture (*NA*). To totally couple a laser beam into a predefined fiber, the following requirements should be met:

$$BPP_{\rm laser} \leqslant BPP_{\rm fiber}, \tag{1}$$

$$\theta/2 \leqslant NA, \tag{2}$$

$$w_0 \leqslant r, \tag{3}$$

Where $BPP_{\rm laser}$ represents the whole *BPP* of the laser source, and there are two methods to describe it: $BPP_{\rm laser1} = \sqrt{BPP_{\rm f}^2 + BPP_{\rm s}^2}$ [10]; $BPP_{\rm laser2} = BPP_{\rm f} + BPP_{\rm s}$ [11], in which $BPP_{\rm f}$ and $BPP_{\rm s}$ are the *BPP* of fast axis and slow axis, respectively. $BPP_{\rm laser1}$ is the common way of calculating the whole *BPP*, only considers either the maximum beam width or the maximum divergence angle. Taking the reliability of optical fibers into account, it is easy to make the maximum divergence angle of laser beam smaller than the *NA* of the fiber. As a result, the maximum beam width would be larger than the fiber core diameter, and its four corners would be lost. $BPP_{\rm laser2}$ includes both the maximum beam width and the maximum divergence angle, theoretically making the laser beam totally coupled. But the fiber diameter required by $BPP_{\rm laser2}$ is larger than $BPP_{\rm laser1}$.

In this system, the linear array coupling source is combined by 20 diode laser bars, of which ten 808 nm and ten 870 nm laser bars are adopted, with 10 mm width and 20% filling factor, soldered on conduction cooled heat sinks. The *P-I-V* cures and the divergence distributions of the 808 nm and 870 nm laser bars are shown in Fig. 1. At the current of 70 A, the output power of both bars are up to 70 W, and their efficiencies are about 58%. 95% of the optical power are fed at a transverse angle of 48° and at a lateral angle of 7°.

The optical procedure of every bar consists of four steps, including fast axis collimation, beam symmetrizing with beam transformation systems from the Limo, slow axis collimation and reflection. Every 5 bars with the same wavelength are mounted in a stair-step manner, leading to optically stacking in the slow axis, shown in Fig. 2. Because of the separation of laser bars without any overlap, only macrochannel coolers with industrial water are required. The filling factor of almost 100% is achieved in the stack direction. Beam widths and divergence angles of fast axis and slow axis are 10.5 mm, 6.98 mrad and 10.2 mm, 6.96 mrad, respectively, measured by a Spiricon CCD camera. The resulting $BPP_{\rm s}$ are 18.3 mm·mrad and 17.7 mm·mrad, respectively [12], and $BPP_{\rm laser1}$ = 25.5 mm·mrad, $BPP_{\rm laser2}$ = 36 mm·mrad.

Then all of the laser units are combined with polarization multiplexing and wavelength multiplexing.

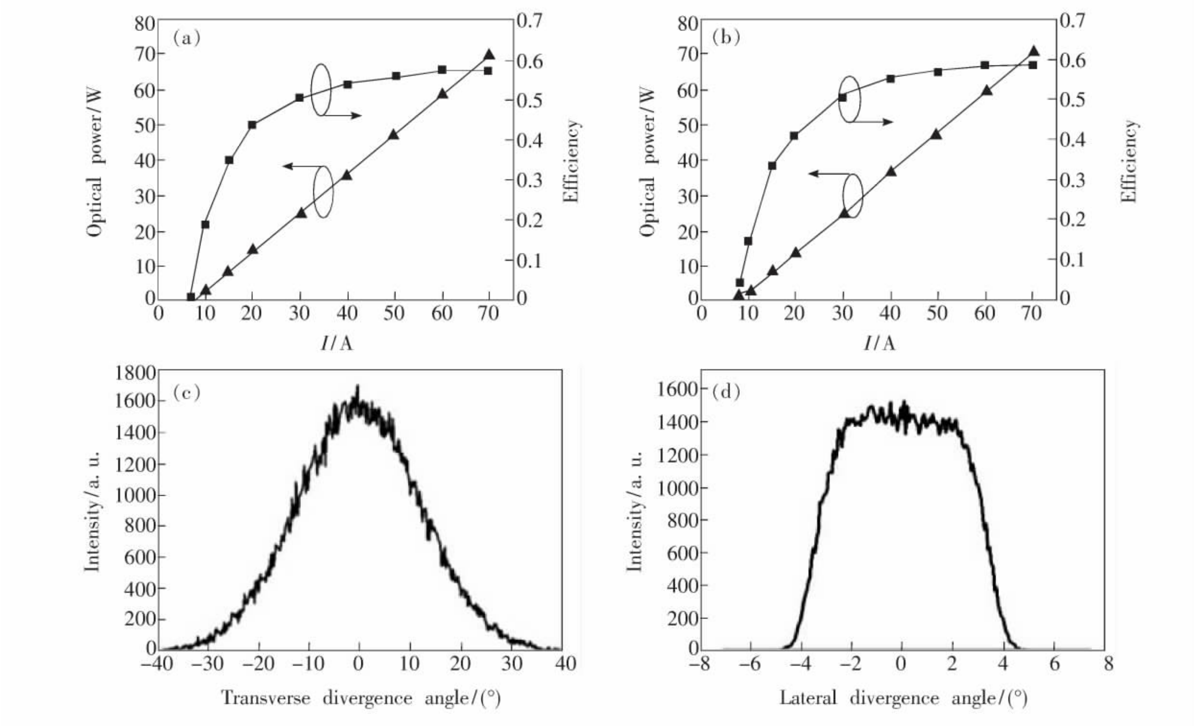

Fig. 1　*P-I-V* cures and divergence distributions of the 808 nm and 870 nm laser bars. From (a) and (b), at the current of 70 A, the output power of both bars are up to 70 W, and their efficiencies are about 58%. 95% of the optical power are fed at a transverse angle of 48° and at a lateral angle of 7°, shown in (c) and (d).

Fig. 2　Mechanical setup of 5 bars mounted in a stair-step manner

To obtain a higher efficiency, an effective improvement introduced is that the transmitted lasers propagate in a Brewster's angle (θ_B) at the wavelength beam combiners (WBC), making the coupling efficiency a 5% enhancement.

Due to the symmetrization of beam widths and divergence angles of both of the axes, the laser beam is directly focused by an objective with a focal length of 35 mm, determined by the maximum beam width and the fiber *NA*. Accounting for the adjusting errors

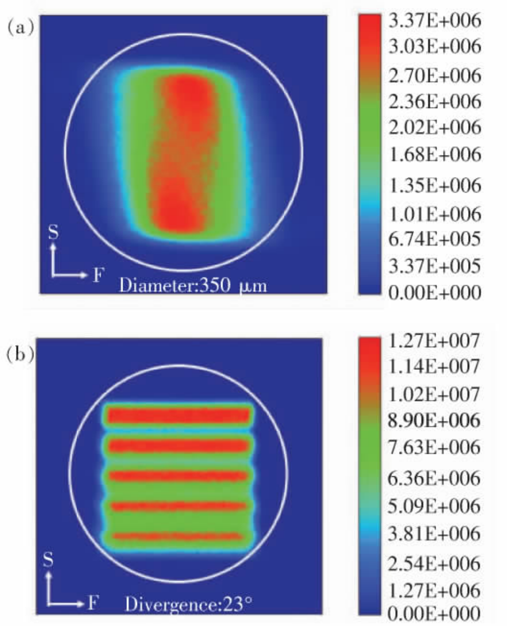

Fig. 3　Simulated distributions of (a) spot at the focus and of (b) divergence angle after focused by ZEMAX. The sizes of two detectors are 400 μm × 400 μm and 30° × 30°, respectively, in which the diameters of the white circles are 350 μm and 23°, respectively. F and S represent the fast axis and slow axis of laser beam, respectively.

of the fast axis collimators, the simulated beam spot at the focus and divergence angle are shown in Fig. 3, which can be theoretically coupled into a 350 μm, *NA* 0.2 fiber. Limited by the existing optical fiber in our laboratory, a water cooled 600 μm, *NA* 0.2 QBH-fiber from Optoskand is used to couple the laser beam, whose *BPP* is 60 mm · mrad, larger than both BPP_{laser1} and BPP_{laser2}. To ensure the coaxial characteristic of laser beam, focusing lens and fiber input end, an effective way is to introduce a combination of reflectors to precisely adjust the direction of the laser beam. A processing head with the magnification of 1∶1, is finally assembled at the output end of the optical fiber. Sketch of the diode laser coupling source is shown in Fig. 4.

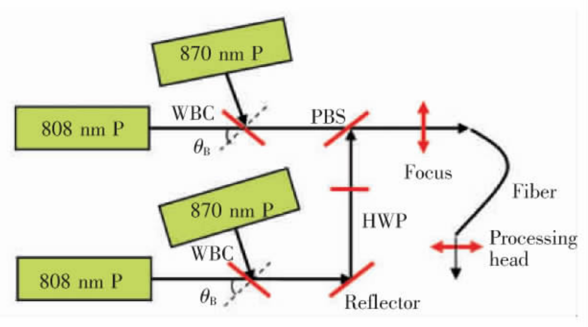

Fig. 4 Sketch of the diode laser coupling source (WBC: wavelength beam combiner; HWP: half-wave plate; PBS: polarization beam splitter).

3 Results and Discussion

Under the macrochannel cooling, the CW output powers are tested at three different positions including after focused, output from the optical fiber and behind the processing head, as shown in Fig. 5. The corresponding efficiencies are calculated and fitted. At the current of 70 A, the three powers of 1 000 W, 935 W and 907 W are achieved, respectively, leading to the overall electro-optical conversion efficiency of 37%. The maximum electro-optical conversion efficiency is up to 39% at the current of 45 A.

The peak wavelengths of the laser source measured at current of 60 A are 807.3 nm and 869.2 nm, respectively, and the corresponding spectrum widths of FWHM are 2.7 nm and 3.4 nm, as described in Fig. 6.

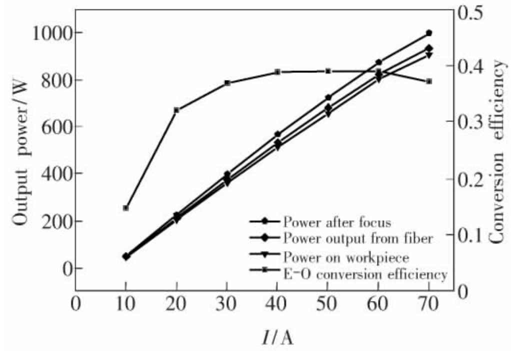

Fig. 5 Various powers and efficiencies verse current of the flexible processing source. All of the measurements are performed using a commercial power meter of Ophir 5 000 W at the coolant temperature of 20 ℃, the flow of 13 L/min and in CW operating mode.

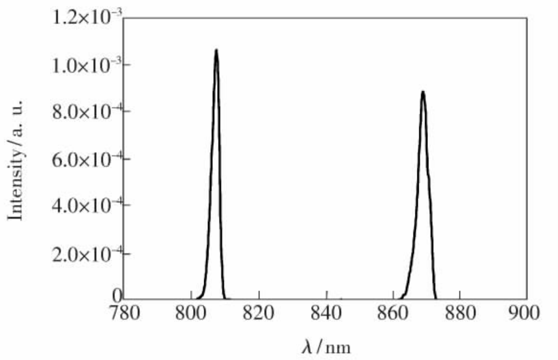

Fig. 6 Centre wavelengh measured at the current of 60 A are 807.3 nm and 869.2 nm, respectively, and the corresponding spectrum widths of FWHM are 2.7 nm and 3.4 nm.

The beam quality of the flexible processing source is measured by PRIMES Focus Monitor F35 at the current of 20 A, shown in Fig. 7. Determined by the second moment, the radius of the beam waist is 0.3 mm and the divergence angle is 312.6 mrad are observed, which leading to a *BPP* of 46.96 mm · mrad and a Rayleigth length of 1.92 mm. The tested *BPP* is smaller than the BPP_{fiber}, which are most likely to that the focal length of the focus lens is larger than the expected.

From the above data, a power density of 3.21×10^5 W/cm^2 at the waist is achieved and all of the power densities are larger than 1×10^5 W/cm^2 along the propagation axis of ±2 mm around the waist, a great potential to be directly adapted for metal sheet welding[13-15]. The power density of about 1.28×10^6 W/cm^2 would be achieved supposing that the

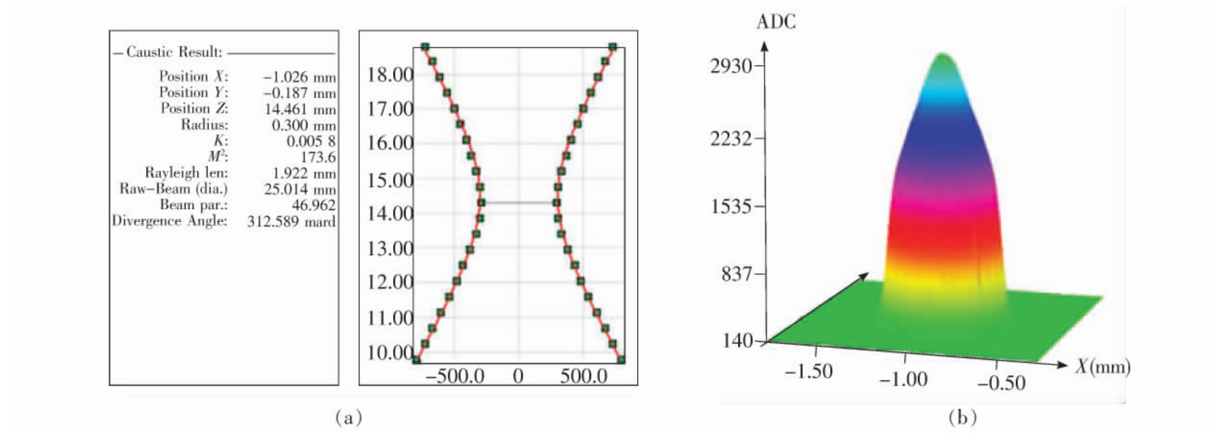

Fig. 7　Tested results of (a) beam quality measurement of the laser system and (b) intensity distribution of the spot at the waist. The radius of the beam waist of 0.3 mm and the divergence angle of 312.6 mrad are observed, leading to a *BPP* of 46.96 mm · mrad and a Rayleigth length of 1.92 mm.

magnification of the processing head is 2∶1.

4　Conclusion

A high power and high efficiency fiber-coupled diode laser source is demonstrated by adopting a linear array coupling source composed of 20 conduction cooling bars. Under the marcochannel cooling with industrial water, a CW output power of 907 W, a optical power density of 3.21×10^5 W/cm^2 and a wall-plug efficiency of 39% on the work piece are demonstrated from a 600 μm, *NA* 0.2 fiber. Improvement of performance and enhancement of reliability endows this source with a great potential in metal sheet welding.

References:

[1] Huang R K, Chann B, Burgess J, *et al*. Direct diode lasers with comparable beam quality to fiber, CO_2, and solid state lasers [J]. *SPIE*, 2012, 8241: 824102-1-6.

[2] Matthews D G, Kleine K, Krause V, *et al*. A 15 kW Fiber-coupled diode laser for pumping applications [J]. *SPIE*, 2012, 8241: 824103-1-6.

[3] Huang R K, Chann B, Glenn J D. Ultra-high brightness wavelength-stabilized kW-class fiber coupled diode laser [J]. *SPIE*, 2011, 7918: 791810-1-9.

[4] Timmermann A, Bartoschewski D, Schlüter S, *et al*. Intensity increasing up to 4 MW/cm^2 with BALB's via wavelengths coupling [J]. *SPIE*, 2009, 7198: 71980X-1-10.

[5] Koenning T, Alegria K, Wang Z L, *et al*. Macro-channel cooled high power fiber coupled diode lasers exceeding 1.2 kW of output power [J]. *SPIE*, 2011, 7918: 79180E-1-8.

[6] Havrilla D, Brockmann R, Strohmaier S, *et al*. Dramatic advances in direct diode lasers [J]. *SPIE*, 2010, 7583: 75830B-1-6.

[7] Price K, Karlsen S, Leisher P, *et al*. High-brightness fiber-coupled pump laser development [J]. *SPIE*, 2010, 7583: 758308-1-7.

[8] Gao X, Bo B X, Qiao Z L, *et al*. Single fiber coupling of multi-linear-array-diode-lasers [J]. *Acta Photonica Sinica* (光子学报), 2010, 39(7): 1229-1234 (in Chinese).

[9] Wang X W, Ma X Y, Fang G Z, *et al*. 808-nm fiber coupled module with a CW output power up to 130 W [J]. *Chin. Opt. Lett*. (中国光学快报), 2007, 5(8): 466-467 (in English).

[10] Bachmann F, Loosen P, Poprawe R. *High Power Diode Lasers: Technology and Applications* [M]. New York: Springer, 2007: 166-168.

[11] Wang Z L, Segref A, Koenning T, *et al*. Fiber coupled diode laser beam parameter product calculation and rules for

optimized design [J]. *SPIE*, 2011, 7918: 791809-1-9.

[12] Zhang J, Shan X N, Liu Y, *et al.* KW-output high and beam quality diode laser linear array coupling source [J]. *Chinese J. Lasers* (中国激光), 2012, 39(2): 0202010-1-5 (in Chinese).

[13] Peng H Y, Liu Y, Shan X N, *et al.* 2 600 W high efficiency laser diode source with polarization coupling [J]. *Chin. J. Lumin.* (发光学报), 2011, 32(10): 1036-1040 (in Chinese).

[14] Yang Y, Liu Y, Qin L, *et al.* Near diffraction limit highbrightness taper 850 nm laser diodes [J]. *Chin. J. Lumin.* (发光学报), 2011, 32(10): 1064-1068 (in Chinese).

[15] Salminen A, Jansson A, Kujanpää V. Effect of welding parameters on high-power diode laser welding on thin sheet [J]. *SPIE*, 2003, 4973: 106-115.

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