CW 50W/M^2 = 10.9 diode laser source by spectral beam combining based on a transmission grating

Jun Zhang,[1,2] Hangyu Peng,[1,*] Xihong Fu,[1] Yun Liu,[1] Li Qin,[1] Guoqing Miao,[1] and Lijun Wang[1]

[1]*State Key laboratory of Luminescence and Application, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China*
[2]*University of Chinese Academy of Sciences, Beijing 100049, China*
[*]*imphy@163.com*

Abstract: An external cavity structure based on the −1st transmission grating is introduced to spectral beam combining a 970 nm diode laser bar. A CW output power of 50.8 W, an electro-optical conversion efficiency of 45%, a spectral beam combining efficiency of 90.2% and a holistic M^2 value of 10.9 are achieved. This shows a way for a diode laser source with several KW power and diffraction-limited beam quality at the same time.

OCIS codes: (140.2010) Diode laser arrays; (140.3298) Laser beam combining; (050.1950) Diffraction gratings.

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1. Introduction

For high power diode lasers, how to improve the beam quality is a key technology problem to be solved [1]. Beam shaping is generally employed, like step-mirrors [2], parallel plate arrays [3], etc. However, the final beam quality is much larger than that of a single emitter [4, 5]. Spectral beam combining (SBC) has been proven to an effective way to keep the beam

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quality of the diode laser source the same with that of a single emitter [6], and improves the output characteristic. R. K. Huang et al. obtained a continuous wavelength (CW) power of 30 W and $M_{x;y}^2 = 2$ by spectral beam combining of a 970 nm slab-coupled optical wave-guide laser (SCOWL), which consisted of 100 emitters and beam quality of each emitter is about $M_{x;y}^2 = 1.1$ [7]. D. Vijayakumar et al. yielded an power of 9.3 W and an M^2 value of 5.3 by spectral beam combining of a 980 nm tapered diode laser bar with 12 emitters whose M^2 in the range of 2.3 to 4.6 [8]. All the gratings of the above structures are 1st order reflective gratings, and the efficiency of spectral beam combining is not the best [9], generally not more than 85% [7, 8], because both the incidence angle and the diffractive angle are deviated from the Littrow angle of the grating. In addition, the number of the combined lasers is limited, resulting in a limitation of the output power, because the optical paths of both the incidence and the diffraction are in the same side of the deflective grating and their intersection angle generally does not exceed 15°. A −1st order fused silica transmission grating is usually used for pulse compression of high power pulse laser [11, 12], providing a CW damage threshold and high diffractive efficiency. We find it suitable for spectral beam combining and can solve those problems of the reflective grating. First, both of the incidence angle and diffractive angle are allowed to equal to the Littrow angle of grating and provides a better diffractive efficiency. Then it is easy to couple more lasers leading to higher power, thanks to the abundant combining space, because the output plane is on the opposite side of the transmission grating from the input plane and the angle of the incidence and the diffraction maybe exceed 90°. An easier optical adjusting is also achieved.

In this letter, a −1st order transmission grating is used to spectral beam combining (T-SBC) of a 970nm centimeter diode laser bar with 19 emitters, 100 μm emitter width, and 500 μm pitch. The incidence angels of the central emitter and the diffraction angel of all emitters are strictly equal to the Littrow angle of the grating. A CW power of 50.8 W, a holistic M^2 of 10.9, an electro-optical conversion efficiency of 45%, a spectral beam combining efficiency of 90.2% and a spectrum span of 24.1 nm are demonstrated.

2. T-SBC experimental setup

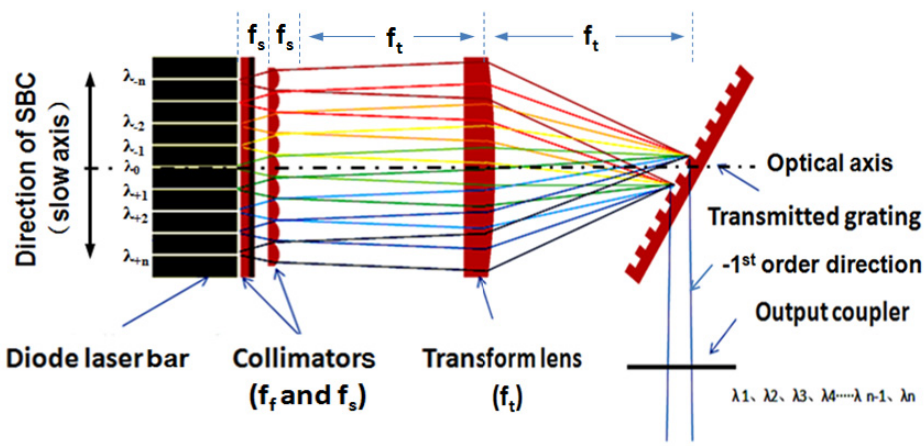

Fig. 1. Schematic diagram of a T-SBC setup based on a diode laser bar.

Figure 1 shows a schematic diagram of a typical T-SBC setup, including a diode laser bar, collimators, a transform lens, a −1st order transmission grating and an output coupler. The principle of combining is thought as the spatial superposition of many independent diode laser external cavities with different wavelengths in the direction of SBC. The cavity of each laser diode emitter is formed between the back facet of the laser bar and the output coupler. Due to the dispersion characteristic of the grating, each emitter in the bar is feedback and

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oscillated at a particular wavelength and the wavelength increases or decreases along the direction of SBC. As a result, all of the emitters are spatially overlapped at the output coupler, maintaining the output beam quality of a single emitter while scaling the output power by the number of emitters.

The structural parameters of the 970 nm laser bar are shown in Table 1. The bar is firstly collimated in the fast-axis (f_f) and in the slow-axis (f_s), respectively. Then a cylindrical transform lens with a focal length (f_t) of 150 mm is used to image sub-beams from emitters onto a transmission grating with a period of 1600 lines/mm in the direction of SBC (slow axis of laser bar), and the −1st diffractive efficiency of the grating is over 92% to the TE polarization from 930nm to 1000nm. At last, the diffractive beams of grating impinge on the output coupler with a reflectivity of 20% and an anti-reflection coated back side. Only the beams perpendicular to the output coupler can be fed back into the emitters and oscillated to form laser.

Table 1 Structural parameters of the 970 nm diode laser bar

Parameter	Values
Chip width	10 mm
Cavity length	2 mm
Number of emitters	19
Emitter pitch	500 μm
Emitter width	100 μm
θ_{slow}(95% power content)	7°
θ_{fast}(95% power content)	45°
Front facet reflectivity of bar	<1%
Rear facet reflectivity of bar	95%

In order to keep beam quality of the laser bar the same with that of a single emitter, besides the spots of all the sub-beams from each emitter overlap on the grating, their diffractive angles must be the same. To obtain the best diffractive efficiency, the diffractive angle is equal to the Littrow angle of the grating to the designed wavelength.

According to the −1st grating equation, as Eq. (1),

$$\Lambda \cdot \left(\sin\theta_i + \sin\theta_d\right) = \lambda \tag{1}$$

Where θ_i and θ_d are the incidence angle and diffractive angle, respectively, Λ is the grating period and λ is the grating designed wavelength. $\theta_{littrow} = \theta_d = \theta_i = 50.6°$, when λ = 966 nm and $\Lambda = 1/1600$ mm. So the angle between the grating and the output coupler is strictly equal to 50.6°. In addition, defining the incidence angle of central emitter in the bar θ_0 equal to $\theta_{littrow}$, the dispersion of grating is 0.144°/nm, decided by Eq. (2).

$$\frac{d\theta}{d\lambda} = \frac{1}{\Lambda \cdot \cos\theta_0} \tag{2}$$

Corresponding, wavelength interval is shown in Eq. (3),

$$\Delta\lambda = \frac{d\theta}{d\lambda} \cdot \frac{\Delta d}{f} \tag{3}$$

where Δd is the interval of emitters along the slow axis and f is the focal length of the transform lens. So the calculated wavelength interval of neighbor emitters is 1.33 nm, and the whole spectrum span of the laser bar is 23.9 nm.

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3. T-SBC experimental results and analysis

At the coolant temperature of 18 °C, flow of 10 L/min and CW operating mode, the output characteristics under free running and T-SBC are measured by Ophir FL500A, shown in Fig. 2. After T-SBC, the threshold current drops to 5 A from the initial 10 A, and a CW power of 50.8 W and an electro-optical conversion efficiency of 45% are measured at 72.5 A, and the corresponding slop efficiency is 0.753 W/A. Under free running, the extrapolated power is about 56.3 W at 72.5 A, according to the slop efficiency of 0.9 W/A tested from 10A to 25A. As a result, a spectral beam combining efficiency of 90.2% is demonstrated, defined as the ratio of the T-SBC power to the free running power at the operating current (72.5A).

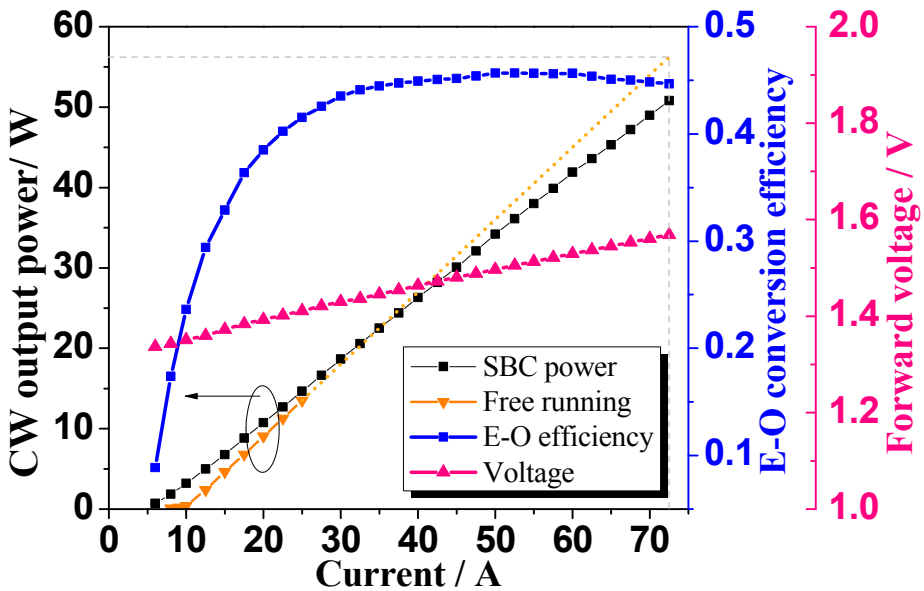

Fig. 2. Curve of CW power and efficiency of the laser source as function of current. 56.3W is estimated at 72.5A under free running.

Figure 3 demonstrates the beam quality of the combining laser focused by an objective with a focal length of 100mm at 60A. The laser beam is directly measured by Primes focus monitor without any attenuation, and the beam width is determined by the second order moment, referring to ISO 11146 [13]. To gain the accurate measurement result, the range of over six times Rayleigh-length around focus along the optical axis is scanned. A holistic M^2 of 10.9 is observed, a little larger than 9.98, which is the calculated value M^2 of a single emitter, calculated by the RMS of the fast axis M_x^2 and the slow axis M_y^2, where $M^2 = w_0 \cdot \theta/2 \cdot \pi/\lambda$, where w_0 is the spot radius and θ is the divergence angle.

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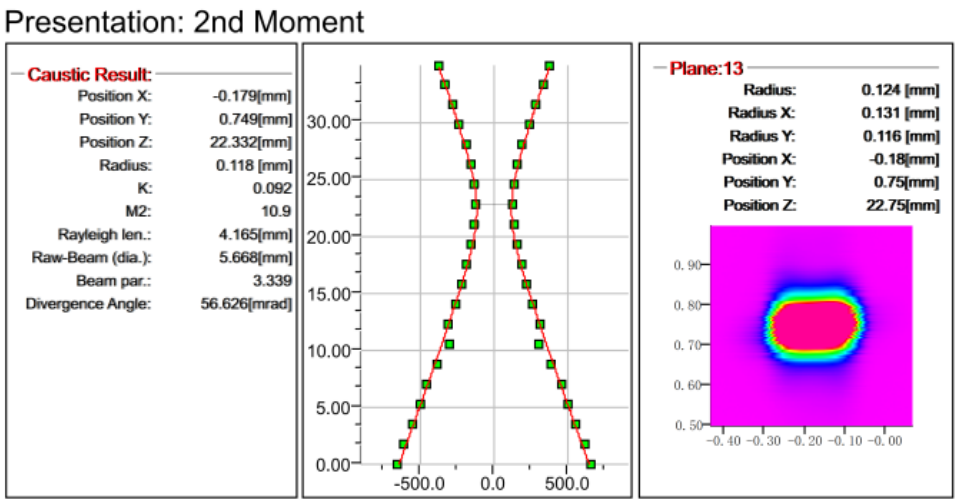

Fig. 3. Beam quality measured by Primes focus monitor at I = 60A.

The distribution of wavelengths after spectral beam combining is shown in Fig. 4, measured by ANDO AQ6317. From the result, nineteen distinct peaks can be easily distinguished, and each one is associated with the individual emitter on the laser bar, which means that all of the nineteen emitters are perfectly locked. The total wavelength span is approximately 24.1 nm, and the interval between neighbor peaks is 1.337 nm, a little larger than the previous calculated values, the reason is maybe that the focal length of the transform lens is smaller than 150mm. In addition, the intensity of the centered emitters is obviously higher than that of the two edges, related to both the material gain of the laser bar and the diffractive efficiency of the grating. The actual output wavelength, the material gain wavelength and the grating design wavelength are demanded to mutually match as much as possible.

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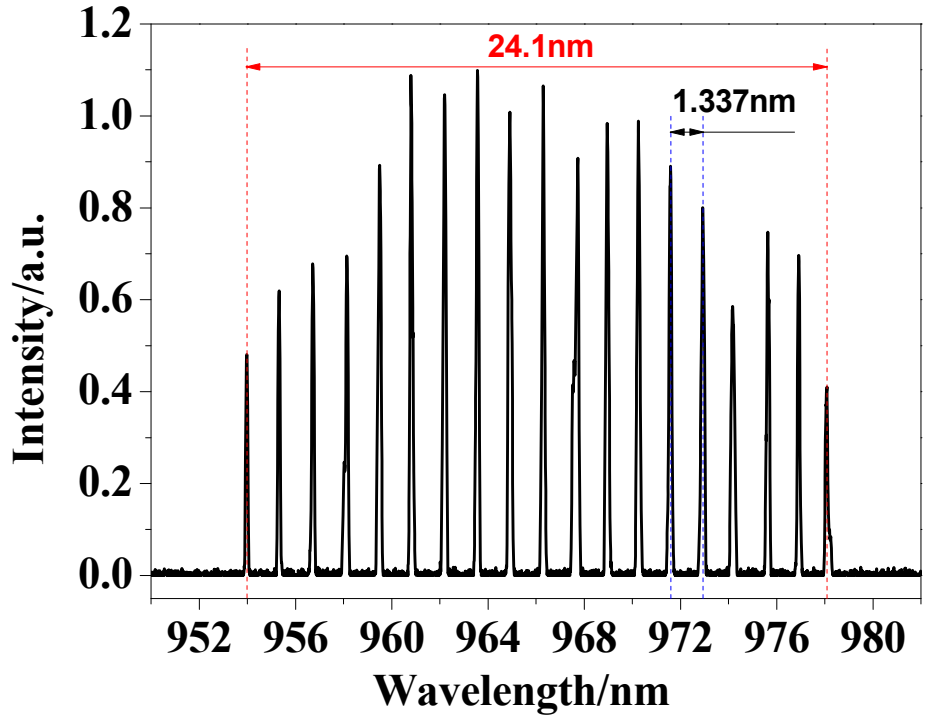

Fig. 4. Distribution of wavelengths after spectral beam combining.

4. Conclusion

In summary, a novel structure of spectral beam combining based on the transmission grating is demonstrated. By using a 970nm commercial centimeter bar, a CW power of 50.8W, an electro-optical conversion efficiency of 45% and a holistic M^2 of 10.9 are achieved. The power will further increase with the same beam quality by increasing the number of emitters in the direction of SBC. T-SBC must be an effective way to gain a CW several thousand watts diode laser source with beam quality close to that of solid state lasers. Accompany with the advantage of high efficiency and long lifetime, diode laser based on T-SBC would be widely used as a direct source in defense, material processing, etc.

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