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Hundred-watt diode laser source by spectral beam combining

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Abstract

A diode laser source with a continuous wavelength (CW) power of 106 W and the beam quality M^2 of 14.6 is demonstrated by spectrum beam combining (SBC) of three 800 nm LDAs. With the help of relay optics, a wavelength interval of 0.21 nm and a whole spectrum span of 13.9 nm are achieved, which is almost 10 times narrower than those of the structure without the relay optics. This presents a method to obtain a high power and high beam quality SBC laser source with a narrow spectrum.

Keywords: diode laser, spectral beam combining, transmission grating, relay optics

(Some figures may appear in colour only in the online journal)

1. Introduction

Spectral beam combining (SBC) has been proven to be an effective way for improving the beam quality of a high power diode laser source [1–5]. Previously, 970 nm and 800 nm diode laser sources by SBC with –1st order transmission grating (T-SBC) have been demonstrated [6, 7]. However, for the SBC source, the improved beam quality comes at the expense of increased spectral width, leading to a spectrum span of up to several tens of nanometers. As a result, the SBC source is not suitable for application of the narrow bandwidth required such as with pumping fiber lasers [8]. In addition, the wavelength interval of neighbor laser emitters is too large to combine multiple laser units at the specified wavelength range, leading to a limitation of output power. A transform lens with a large focal length is generally used to decrease the wavelength interval and the spectrum span but results in a long cavity of several meters [5, 9], which is difficult for assembly and practical application. In this letter, the relay optics was introduced to image the output facet of the bars into a small image and achieved the purpose of shortening the spatial interval of neighbor emitters and decreasing the entire size of the output facet in the direction of SBC. Consequently, the wavelength interval and the spectrum span were respectively reduced to 0.21 nm and 13.9 nm, when a short focal length transform lens was used. A diode laser source that consisted of three 800 nm laser bars, each of which included 19 emitters, 100 μm emitter width and 500 μm pitch was achieved with a continuous wavelength (CW) output power of 106 W and beam quality M^2 of 14.6. An effective method of compressing the spectrum bandwidth of the SBC source was demonstrated.

2. T-SBC experimental setup based on three 800 nm laser bars

Figure 1 shows a schematic diagram of a typical T-SBC setup, including a diode laser array (LDA), a transform lens, a –1st order transmission grating and an output coupler. The combining principle can be thought of as the spatial superposition of many independent diode laser external cavities with different wavelengths in the direction of SBC. All of the emitters are spatially overlapped at the output coupler, maintaining the output beam quality of a single emitter while scaling output power by the number of emitters. Every oscillation wavelength satisfies the grating equation with the same diffraction angle due to the corporate transmission grating and output coupler, which can be expressed as:

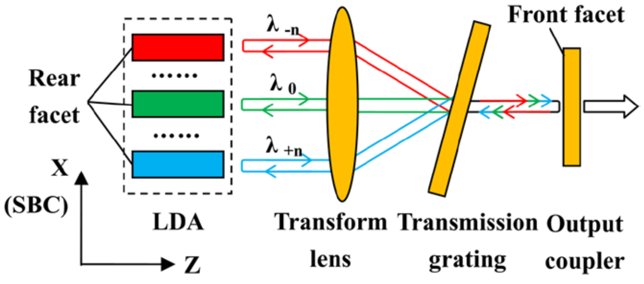

Figure 1. Basic sketch of T-SBC with external cavity feedback based on transmission grating.

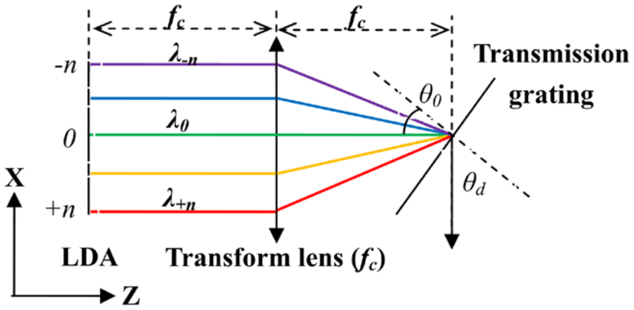

Figure 2. Equivalent optical path of the primary laser beam incident on the grating in the direction of SBC.

$$m \cdot \lambda_i = \Lambda \cdot (\sin \theta_i + \sin \theta_d) \,, \tag{1}$$

where $m = -1$ for the -1st order transmission grating, θ_i and θ_d are the incidence angle and the diffractive angle of the grating, respectively. Λ is the grating period and λ_i is the oscillation wavelength of the laser emitter in the position i. When $\theta_i = \theta_d = \theta_{\text{littrow}} = \arcsin(\lambda/2/\Lambda)$, the highest diffraction efficiency is obtained.

The equivalent optical path of the primary ray of each emitter incident on the grating in the direction of SBC is shown in figure 2. Making the incidence angle of the center emitter θ_0 the same as θ_{littrow}, the common diffraction angles of all emitters θ_d are equal to θ_{littrow}.

The incidence angle of emitter i $\theta_i = \theta_{\text{littrow}} + \arctan(i{\cdot}p/f_c)$, correspondingly the oscillation wavelength λ_i, can be described as:

$$\lambda_i = \Lambda \cdot \left(\sin\left(\theta_{\text{littrow}} + \arctan\frac{i \cdot p}{f_c} \right) + \sin\theta_{\text{littrow}} \right), \tag{2}$$

where $i = -n, -(n-1)\ldots\ldots -1, 0, +1\ldots\ldots +(n-1), +n$, p is the pitch of the LDA.

Therefore, wavelength interval $\Delta\lambda_i$ can be written as

$$\Delta\lambda_i = \Lambda \cdot \left(\sin\left(\theta_{\text{littrow}} + \arctan\frac{(i+1) \cdot p}{f_c} \right) - \sin\left(\theta_{\text{littrow}} + \arctan\frac{i \cdot p}{f_c} \right) \right), \tag{3}$$

where f_c is much larger than $(i+1){\cdot}p$,

$$\Delta\lambda_i = \frac{\Lambda \cdot p}{f_c} \cdot \cos\theta_{\text{littrow}}, \tag{4}$$

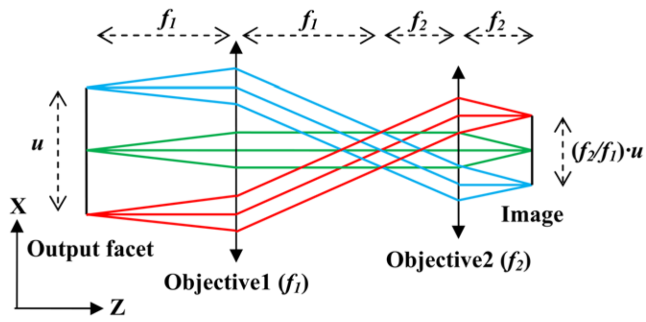

Figure 3. Structure of the relay optics.

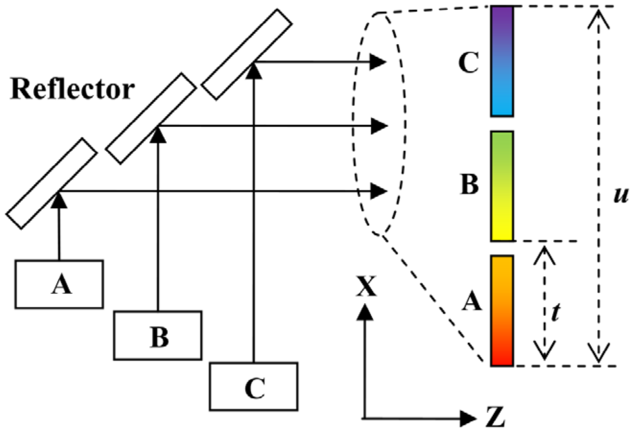

Figure 4. Sketch of spatial arrangement of three LDAs in the direction of SBC.

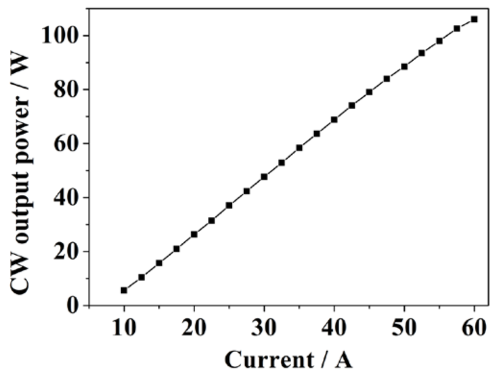

Figure 5. Curve of CW power versus current after SBC of three 800 nm LDAs.

From equation (4), decreasing the pitch p can also reduce $\Delta\lambda_i$ in addition to the increase of f_c. Considering that the pitch of an off-the-shelf LDA is generally 500 μm or larger, it is difficult to obtain a small $\Delta\lambda_i$ when using a short focal length transform lens. The relay optics is introduced into the combining structure and is located between the LDA and transform lens, which consists of two aberration corrected objectives with focal lengths of f_1 and f_2, respectively, as shown in figure 3. With the help of the relay optics, the output facet of an LDA is first imaged into a reduced and inverted image and the width and the pitch are reduced to $(f_2/f_1){\cdot}u$ and $(f_2/f_1){\cdot}p$, respectively. Then, the image, considered as a virtual LDA, is imaged onto the grating by the transform lens. Correspondingly, the wavelength interval becomes

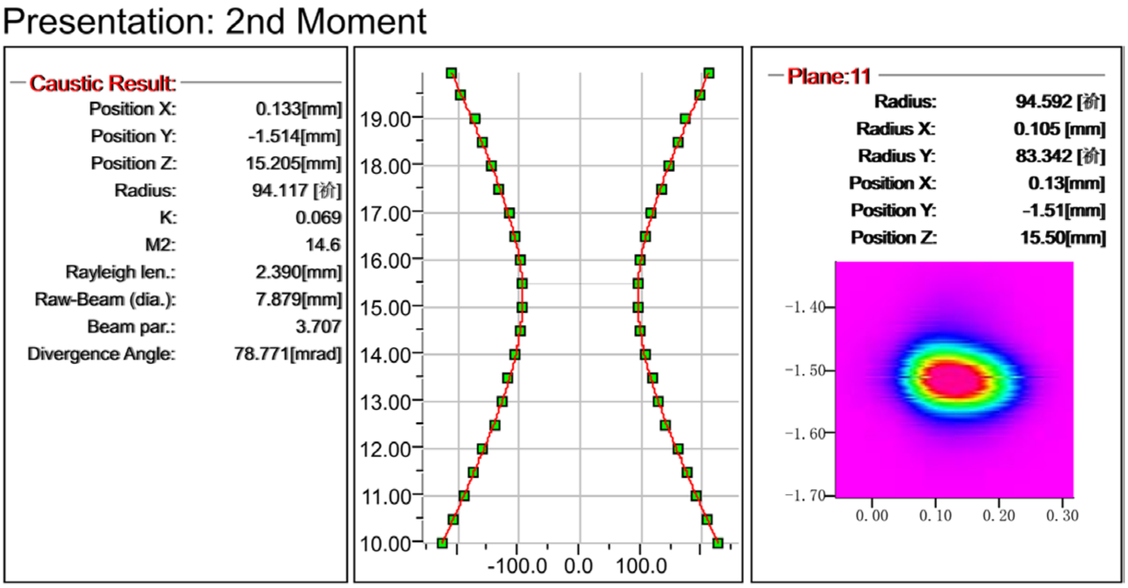

Figure 6. Beam quality after SBC of three 800 nm LDAs.

$$\Delta\lambda_i = \frac{\Lambda}{f_c} \cdot \frac{f_2 \cdot p}{f_1} \cdot \cos\theta_{\text{littrow}}, \tag{5}$$

Obviously, $\Delta\lambda_i$ can be adjusted by the ratio of f_1 and f_2 and the larger the ratio, the smaller $\Delta\lambda_i$.

In this work, three 800 nm LDAs, named A, B and C, are spatially arranged in the direction of SBC, as shown in figure 4. The LDA is fabricated by standard processes but coated with anti-reflection coating (R < 1%) at the output facet. One LDA consists of 19 TE polarization emitters with pitch of 500 μm and width of 100 μm. The spatial period of LDAs t is 12 mm and the whole width u is 34 mm.The relay optics components with f_1 of 140 mm and f_2 of 15 mm and the transform lens with f_c of 100 mm are used. The transmission grating with a period of 1/1765 mm, a designed wavelength of 800 nm for S polarization and the littrow angle of 44.91° is employed. A half-wavelength plate is used to change the polarization of the laser beam to match with the grating. The optimized reflectivity of the output coupler is selected as 9% by the test from a range of 6% to 20%. Hence, the designed wavelength interval and the span of the entire spectrum are ~ 0.21 nm and 14.61 nm, respectively, which are almost 10 times narrower than the structure without the relay optics.

3. Experimental results and analysis

At the coolant temperature of 18 °C, flow of 10 L min^{-1} and under CW operation mode, the output power versus current was measured by an Ophir FL500A power meter, shown in figure 5. A CW power of 106 W was obtained at the injected current of 60 A and limited by the measurement equipment. The corresponding slope efficiency is 2.1 W A^{-1}. From 50 A to 60 A, the slope efficiency has a slight decrease due to the self-heating effect.The beam quality was directly measured by a Primes focus monitor with no attenuation after focus by an objective with a focal length of 100 mm at 40 A. The beam

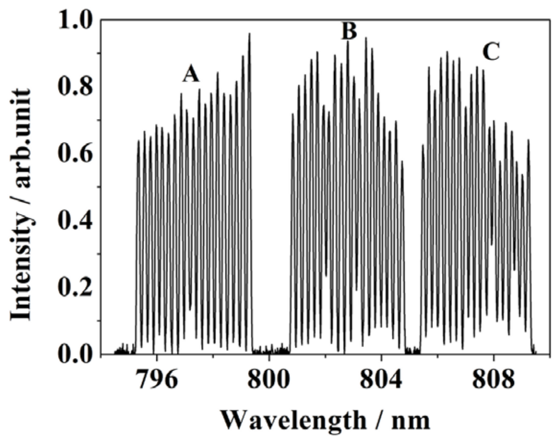

Figure 7. Wavelength distribution after SBC of three 800 nm LDAs.

width was obtained on the basis of the standard of the second order moment, referring to ISO 11146 [10]. The result is shown in figure 6. The beam quality M^2 of 14.6 was observed as slightly larger than 12.0. The M^2 of a single emitter was calculated by the root mean square (RMS) of the fast axis M_f^2 and the slow axis M_s^2 [11]. A possible reason for this is that the laser spots do not absolutely overlap on the grating.Figure 7 demonstrates the SBC wavelength distribution, measured by ANDO AQ6317. Three group wavelengths were observed, each of which includes nineteen distinct peaks. Refering to the SBC structure, each group and peak of wavelength correspond to one LDA and a single emitter, respectively and no redundant wavelength exists, which means that all three LDAs are perfectly locked in wavelength. In addition, LDA A is close to the shorter wavelength and LDA C is the longer wavelength. Respectively, the wavelength widths of A, B and C are 3.94, 3.89 and 3.76 nm and are almost identical to the designed values of 3.92, 3.87 and 3.82 nm. The measured interval between neighbor peaks is also about 0.21 nm. However, the entire

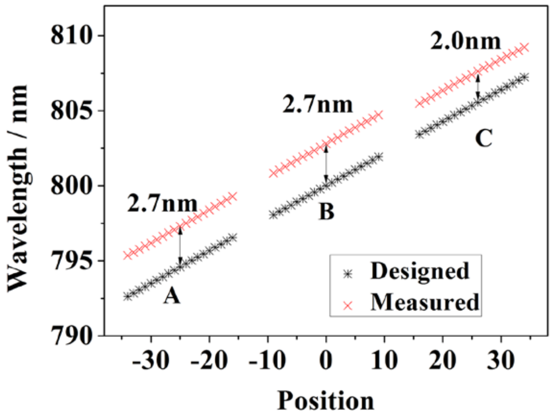

Figure 8. Dependence of peak wavelength on position *i*.

spectrum span is approximately 13.88 nm, which is smaller than the designed span. Moreover, the interval of neighbor wavelength-group is not uniform and the center wavelength is not 800 nm.To detemine the reason for this, the dependence of peak wavelength on position *i* is plotted in figure 8. Compared with the designed values, the respective deviation is 2.7 nm larger for LDA A and LDA B, but 2.0 nm larger for LDA C. In addition, the deviation of every emitter in the same bar is constant. Firstly, from this result, a smaller deviation of LDA C means that a distance error between LDA B and LDA C in the SBC direction has occurred that is smaller than the designed one, which is the main reason for a smaller spectrum span of 13.88 nm and a non-uniform interval. Secondly, an angle error of the output coupler indicates that the angle between the grating and the output coupler is larger than the designed one, resulting in a larger center wavelength. Both of the above errors can be corrected by the precise adjustment and the come closer to the theoretical design values.

4. Conclusions

In summary, we demonstrated a diode laser source with CW power of 106 W and M^2 of 14.6 by spectrum beam, combining three 800 nm LDAs in the direction of SBC. Thanks to the introduction of relay optics, wavelength interval of 0.21 nm and the whole spectrum span of 13.9 nm are achieved, which is almost 10 times narrower than that of the structure without relay optics. Moreover, if relay optics with a larger ratio of f_1 and f_2 is chosen, a narrower spectrum span can be obtained. This demonstartes an effective way to achieve a high power and high brightness diode laser source with a narrow wavelength width.

Acknowledgments

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