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# High power diode laser source with a transmission grating for two spectral beam combining

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ABSTRACT

A novel laser-coupling structure is introduced, in which the same transmission grating is simultaneously employed by two spectral beams generated in identical resonant cavities. The novel structure doubles the number of coupled laser emitters and the output power. Eight 800-nm diode laser bars were coupled and combined with polarization multiplexing, achieving a continuous wavelength power of 212 W, a broad spectrum of 19.1 nm, an $M^2$ (times diffraction limited factor) beam quality of $2.2 \times 16.7$ and a brightness of 236MW/cm$^2$/sr.

High-power diode laser sources always suffer from poor beam quality [1,2]. The 800-nm diode laser matches the response peak spectrum of conventional CCDs and photovoltaics, which is beneficial for improving the detection efficiency. The 800-nm diode laser is also installed in laser illumination and laser wireless energy transmission, where it improves the illuminating effect and energy transmission efficiency. However, the poor beam quality and low brightness must be further improved. Spectral beam combining (SBC) of multiple beams through a reflection grating (R-SBC) or a transmission grating (T-SBC) reportedly maintains the beam quality of the coupling beam equal to that of a single emitter [3–9]. In R-SCB researches, Huang et al. obtained a continuous wavelength (CW) power of 30 W and $M_{x;y}{}^2 = 2$ by SBC of a 970-nm slab-coupled optical wave-guide laser composed of 100 emitters, each with a beam quality of approximately $M_{x;y}{}^2 = 1.1$ [4]. Vijayakumar et al. [5] achieved a CW power of 9.3 W and an $M^2$ value of 5.3 by SBC of a 980-nm tapered diode laser bar with 12 emitters. The individual $M^2$ values of their emitters ranged from 2.3 to 4.6 [5]. In T-SBC research, Zhu et al. obtained a CW power of 58.8 W and an $M^2$ of $1.3 \times 11.6$ by SBC of a 940-nm laser bar with 19 board-area emitters, each with a strip width of 100 µm [6]. We also demonstrated a series of 800-nm and 970-nm SBC sources with different powers and $M^2$ values of 10–15 by SBC of several board-area laser bars operated at each wavelength [7–9]. However, in the reported R-SBC and T-SBC, both the incidence and diffracted lasers are located at one side of the normal line of the diffraction grating, leaving the other side unoccupied. To increase the number of coupled laser beams and maximize the grating utilization, this paper proposes a diode laser source with two T-SBC resonant cavities (as in the conventional scheme) but only one transmission grating. The two T-SBC cavities are arranged symmetrically about the normal line of the grating. In this configuration, which is also suitable for R-SBC, the number of coupled laser emitters is exactly doubled. By exploiting polarization multiplexing, a diode laser source consisting of two T-SBC resonant cavities was achieved with a CW output power exceeding 200 W and an $M^2$ of $2.2 \times 16.7$.

Fig. 1 is a schematic of the diode laser source. The main components are two identical resonant cavities symmetrically configured about the normal of the transmission grating, a $\lambda/2$ plate, and a polarization coupler. Each resonant cavity comprises a diode laser

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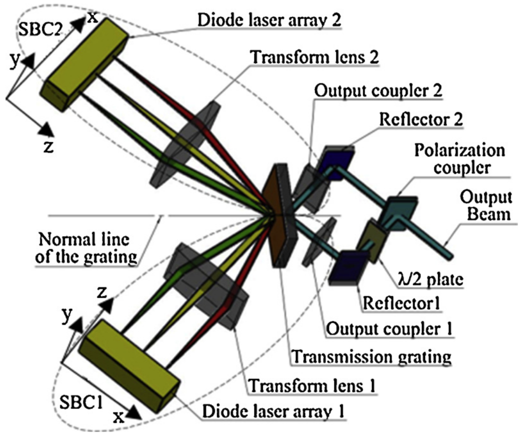


**Fig. 1.** Experimental setup of two SBC cavities using a common transmission grating.

array with an antireflection (AR) coated output facet, a transform lens, a transmission grating, and an output coupler. In each cavity, the output facet of the diode lasers and the transmission grating are located in the front and rear focal planes of the transform lens, respectively. All beams from the laser array are collimated and redirected by the transform lens, and overlapped on the grating. Only the beams perpendicular to the output coupler are fed back into the emitters to generate an effective resonance oscillation. Thus, each emitter receives feedback signals with a unique wavelength induced by the different incident angle and the same diffractive angle on the grating, and emits a beam with a unique wavelength. Finally, all beams are superposed at the output coupler and emitted as a broad spectrum along the same direction, maintaining the beam quality of a single emitter while scaling the output power by the number of emitters. Exploiting the linear polarization property of the laser beam, the two SBC beams are coupled by polarization multiplexing, which doubles the output power without compromising the beam quality.

To maximize the diffractive efficiency, the grating incidence angle of the center emitter $\alpha_0$ of the diode laser array was set to the Littrow angle of the grating, given by $arcsin(\lambda/2/\Lambda)$, where $\Lambda$ is the grating period. According to the $-1^{st}$ grating equation, the diffractive angle $\beta_0$ also equals the Littrow angle of the grating. Because the diffractive angle is common to all beams, the output wavelength $\lambda_i$ depends on the position of the beam source, and is a function of $\beta_0$ and the incidence angle $\alpha_i$ as follows:

$$\lambda_i = \Lambda\cdot(\sin\alpha_i + \sin\beta_0) \tag{1}$$

In this work, two diode laser arrays, each including four 800-nm laser bars, mounted on passively cooled heat sinks, were spatially arranged in their specified SBC directions (x axis). The laser bars were fabricated by standard processes but with less than 1% reflective coating on the output facet. Each bar consisted of 19 transverse electric (TE) polarization emitters with a pitch and width of 500 µm and 100 µm, respectively. The emitter sub-beams emerging from the bar were collimated in the vertical fast axis (FA) direction (y axis) by an FA collimation microlens. The beams were combined in the fundamental-mode FA direction using commercial micro-optic beam rotators. This micro-optic beam transformation system consists of an array of tilted cylindrical microlens telescopes, each of which rotates an individual emitter beam by 90°. In this way, the FA and slow axis (SA) directions are interchanged and the beam combining in FA is performed along the horizontal dimension (x axis) of the cavity architecture. Along the beam-combining direction, the far fields of the collimated and coaxially propagating emitter sub-beams were imaged onto a $-1^{st}$ transmission grating by a cylindrical Fourier transform lens. The period $\Lambda$, wavelength (designed for S polarization) and Littrow angle of the transmission grating were 1/1765 mm, 800 nm and 44.91°, respectively. To simplify the laser path adjustment, both $\alpha_0$ and $\beta_0$ were set to 45° and the central wavelength $\lambda_0$ was set to 801.3 nm. After these adjustments, the $-1^{st}$ diffractive efficiency of the transmission grating remained high (˜92%). The reflectivity of the output coupler, after testing from 6% to 20% for wavelength locking, was set to 9%. The transform lens was composed of an expander with a magnification of 1/10 (from 150 mm to 15 mm), and a cylindrical lens with a focal length of 100 mm. Its equivalent focal length was 1 m. This structure decreases the size of the laser source, which is desired. The diffraction grating was approximately 400 mm from the laser chip, and 100 mm from the external cavity mirror. The length of the entire outer cavity was about 500 mm. The total size of the setup was around (450 × 450) $mm^2$, excluding the cold plate.

At the coolant temperature of 18° C, a flow of 10 L/min and in CW operation mode, the output power and electro-optical (E-O) efficiency of the laser source were measured as functions of the driven current. The results are plotted in Fig. 2. At 40 A, the total power was 212 W (112 W from $SBC_1$; 100 W from $SBC_2$), and the E-O efficiency was 39.5%. The power difference between $SBC_1$ and $SBC_2$ was caused by the alignment requirements and the optical path design. The $SBC_1$ cavity was adjusted first, and the transmission grating was fixed after aligning its position with the optimal position of $SBC_1$. The $SBC_2$ cavity was then modulated with $SBC_1$ fixed, reducing its coupling efficiency. Moreover, the reflection efficiency of the beam from $SBC_1$ on the polarization coupler exceeded 99%, but the transmission efficiency of the beam from $SBC_2$ through the coupler was only 96%.

Fig. 3(a) presents the spectrum of the beam from the output coupler after SBC of the four laser bars under a current of 40A, measured by a fiber spectrophotometer (ANDO AQ6317, Yokogawa, Japan). The whole spectrum spanned approximately 19.1 nm,

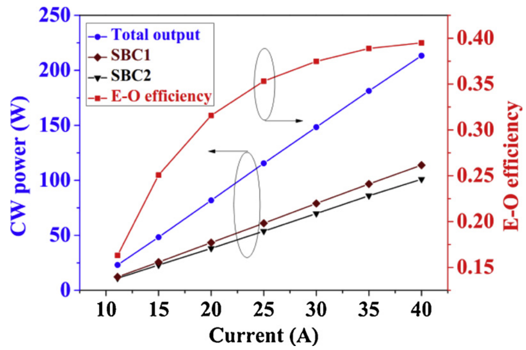


**Fig. 2.** CW power and electro-optical (E-O) efficiency as functions of driving current.

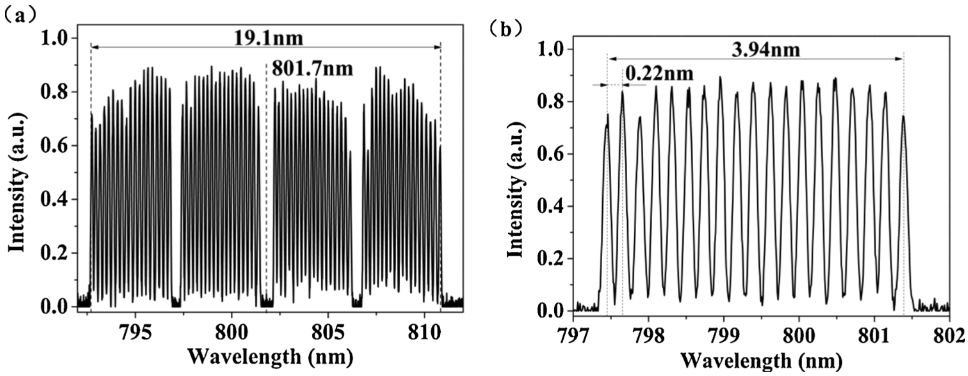


**Fig. 3.** Spectral distribution of the laser beam after SBC of **(a)** four laser bars and **(b)** one bar.

with a central wavelength of 801.7 nm (slightly larger than the designed value). In addition, four group wavelengths were easily observed, each featuring nineteen distinct peaks. In the SBC structure, each group and each wavelength peak corresponded to one of the laser bars and a single emitter, respectively. No redundant wavelengths were observed, meaning that all emitters of all four laser bars were locked at their unique wavelengths. Fig. 3(b) shows the beam spectrum of one bar under the same current. The wavelength spanned only 3.94 nm, and the interval between neighboring peaks was approximately 0.22 nm (due to the enlarged focal length). Both the wavelength span and peak-to-peak interval were smaller than in previous reports. [3–8]

After focusing by an objective with a focal length of 100 mm (following the second-order moment ISO 11146 standard [10]), the quality of the coupling beam after polarization multiplexing was directly measured by a focus monitor (Primes Inc) with no attenuation. The measured result at 40 A is shown in Fig. 4. The beam quality was assessed by the beam parameter product (BPP), determined by multiplying the waist radius ($w_0$) and the far-field half divergence ($\theta_0/2$) of the beam. The $M^2$ was also taken. Finally, the BPPs of the fast and slow axes were determined as 0.56 mm·mrad and 4.23 mm·mrad, respectively. And the corresponding $M^2$ was $2.2 \times 16.7$. The total BPP was 4.269 mm·mrad and the $M^2$ was 16.8, slightly larger than 13.8 (the calculated $M^2$ of a single emitter of width 100 μm and divergence angle 8°). Due to the excellent beam quality, it has the ability to be coupled into a 50 μm/0.22 NA fiber (with a $BPP_{fiber}$ of 5.5 mm·mrad).

The brightness $B$ of a diode laser beam is given by $B = P/(16BPP_f \times BPP_s)$ [2], where $P$ is the output power. With a power of 212 W and a $BPP$ of 0.56 mm·mrad × 4.23 mm·mrad, the brightness of the laser source was 236 MW/cm$^2$/sr, an order of magnitude higher than 8.37 MW/cm$^2$/sr, which is the brightness of commercial 800-nm 100 μm/0.22 NA fiber coupled diode lasers with a power of 100 W.

In summary, this paper demonstrated the laser-coupling structure of a transmission grating intercepted by the spectral beam combination of two resonant cavities. This structure is suitable for reflection-grating-based SBC of any spatial capacity. Polarization multiplexing was incorporated with a diode laser source comprising two T-SBC resonant cavities, each including four 800-nm diode laser bars. The system achieved a CW output power of 212 W, a broad spectral range of 19.1 nm, an $M^2$ of $2.2 \times 16.7$, and a brightness of 236 MW/cm$^2$/sr. With the improvement of beam quality and brightness, the 800-nm diode laser source can be more effectively applied in laser illumination and laser wireless energy transmission.

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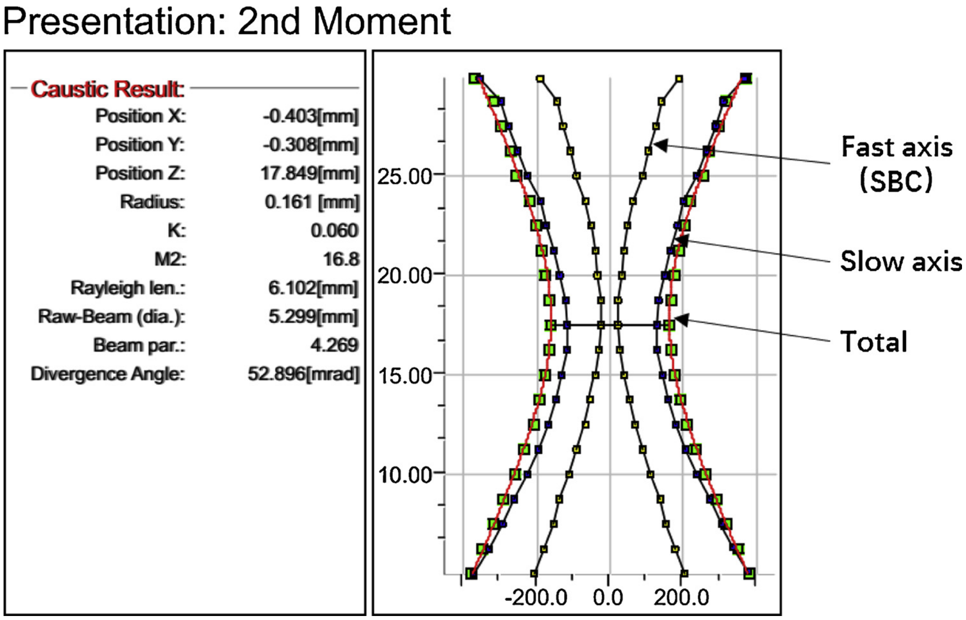


**Fig. 4.** Beam quality of the laser beams after polarization multiplexing of two SBCs.

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