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Going beyond the beam quality limit of spectral beam combining of diode lasers in a V-shaped external cavity

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Abstract: A novel spectral beam combining (SBC) approach based on off-axis feedback in a V-shaped external cavity (VSBC) was proposed and demonstrated. A highly reflecting mirror was used to supply the optical feedback by partial overlapping the beam. The advantages of simple setup, output coupler free, tunable beam quality and emission power over traditional SBC were presented. The beam quality exceeds single emitter with the similar energy conversion efficiency to the traditional SBC. The M^2 factors of 2.31 × 3.76 in fast and slow axes and a brightness of 122 $MWcm^{-2}sr^{-1}$ were realized at 30 A based on a commercial broad-area diode laser array.

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

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1. Introduction

High-power high-brightness diode lasers are desired in many applications, such as material processing [1], pumping of solid state lasers and fiber lasers [2], security and defense, which are typically coupled into a fiber for easy use by beam shaping and combining techniques. Spectral beam combining (SBC) [3, 4] is a simple and effective way to realize power scaling and maintain the beam quality as that of single emitter [4]. In SBC, an array of laser elements is placed in an external cavity consisting of a transform lens, a diffraction grating, and an output coupler (OC). By using this method, the high power and high beam quality diode lasers have been demonstrated [5–8], such as 4680 W diode laser with beam quality of 3.5 mm × mrad [8], mid-infrared quantum cascade lasers with M^2 of 1.5 [8]. SBC almost demonstrated the best beam quality for incoherent combining of diode lasers. In addition, SBC has also been used for the power scaling of fiber lasers with the power level of multi-kW [9, 10]. However, the beam quality limit of SBC is that of single emitter [8]. Hence, many efforts were performed to develop the high beam quality single element and then beam combining, such as the tapered diode lasers [11, 12], slab-coupled optical waveguide lasers (SCOWL) [13] and beam combining.

The reason why the beam quality achieved by SBC is limited by the single element is because that all the optical modes generated in the external cavity of SBC are reflected back indiscriminately by the OC. Off-axis SBC [14–16] is a recently developed technique, which has been used to improve the beam quality and spatial brightness of a segmented broad area laser diode (BAL). Off-axis feedback supplies an approach of beam controlling in the external cavity by the filter, the beam quality beyond the single emitters in slow axis is realized. In 2006, Jechow et al. [14], used an external cavity in an off-axis arrangement for SBC of a BAL array and achieved a beam with $M^2_{slow} < 14$ and $M^2_{fast} < 3$ at an optical power in excess of 10 W. D. Vijayakumar et al., demonstrated off-axis SBC of BAL array with a power of 9 W and M^2 value of 6.4 for slow axis, which was 5-6 times better than that of a single emitter, and the recorded brightness of 79 MW/cm^2 str^{-1} was realized [16]. However, off-axis feedback using a spatial filter often leads to the serious loss of emission power compared with the traditional SBC proposed by Lincoln laboratory [3].

In this paper, a novel off-axis SBC based on the V-shaped external cavity, called as VSBC, was proposed and the high efficiency and brightness with beam quality beyond single emitters was demonstrated. It was OC free and without any filters in this new approach, a highly reflecting (HR) mirror overlapped partially with emission beam was used to consist of a V-shaped cavity. The output power, energy conversion efficiencies and beam quality were investigated and compared with the SBC and free running. The tunable output power and beam quality were analyzed.

2. Principle and experimental setup

Figure 1 (a) shows the schematic diagram of VSBC. The components in the external cavity setup include a laser array, a beam transformation system (BTS), a slow-axis collimation

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(SAC) lens, a transform lens, a reflection grating and a sharp edged HR mirror. The BTS consists of a beam-rotated micro-lens array and a cylindrical lens for the collimation of fast-axis. The laser array is firstly collimated in the fast-axis, the beam of each element is rotated at 90° by the BTS and collimated in the slow-axis by SAC. The transform lens is placed one focal length away from the front facet of laser array and the diffraction grating. It transforms the position of an array element into the angle of incidence on the grating, thus the beams of laser array are spatially overlapped at the grating. A HR mirror is used to supply partial feedback with an off-axis reflecting angle α. α is in the order of several degree and can be optimized by tuning the angle to obtain the best output performance. HR mirror feeds the beams back to diode lasers and forms multiple off-axis external cavities for the laser array. The proposed VSBC works without OC compared with the traditional SBC, the setup becomes simple.

Figure 1 (b) shows the simplified schematic of feedback, which reveals that the HR mirror and rear facet of laser array form a V-shaped cavity at a small included angle. The combined beam emits underneath the HR mirror. Although the transform lens and grating are ignored in Fig. 1(b) for simplified understanding, it does not affect the intrinsic characteristics of V-shaped optical pathway. In contrast, the traditional SBC presents an I-shaped optical pathway [3–8]. The partial feedback is realized by the overlapping between the beam and the HR mirror, just as shown in Fig. 1(c). The beam height is l. The overlapping size l_1 can be adjusted by changing the position of HR mirror along the slow-axis direction due to the 90° rotation by BTS. Adjusting the angle α to an appropriate value, the combining is able to be realized with a single lobe emission underneath the HR mirror as shown in Fig. 1(d).

In the experimental setup, the laser array used is a standard centimeter BAL bar with 19 emitters. The SAC and BTS are the commercial products with the focal lengths of 7 mm and 0.286 mm for the collimation of slow-axis and fast-axis, respectively. The focal length of transform lens is 500 mm. The diffraction grating is 1800 lines/mm and the first order diffraction efficiency measured is about 90% at 980 nm. The HR mirror is an optical glass coated with Au.

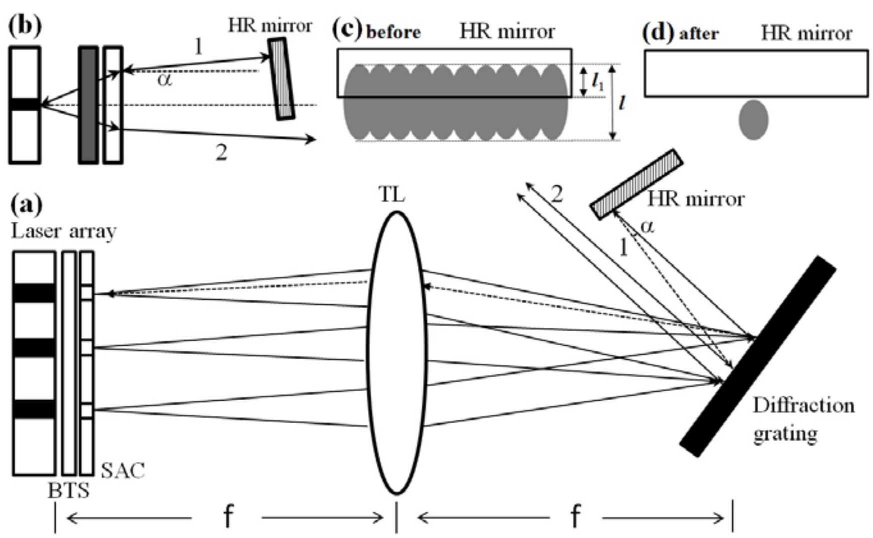

Fig. 1. (a) Schematic diagram of a VSBC setup, (b) simplified schematic of the V-shaped feedback in VSBC, (c) partial reflection by HR mirror before combining, (d) adjust the overlapping between HR mirror and the far-field spots to realize beam combining. TL: transform lens, BTS: beam transformation system, SAC: slow axis collimation.

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3. Results and analyses

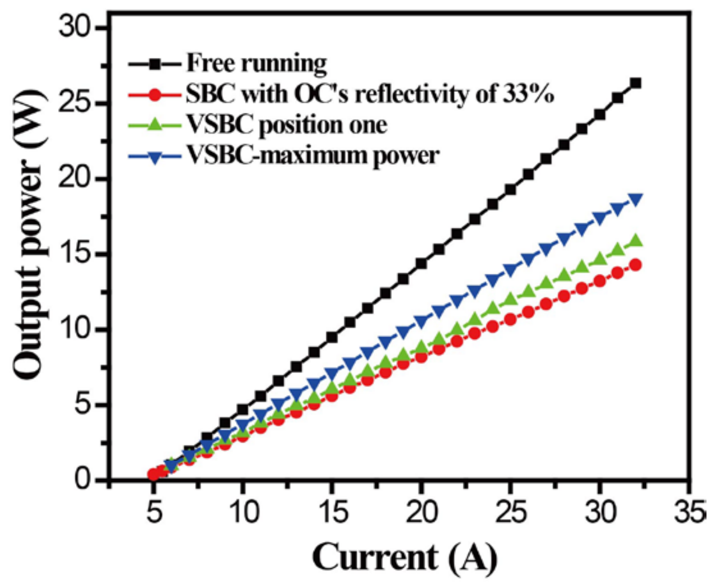

Fig. 2. Output power of diode array combined by VSBC (triangles) and SBC with OC's reflectivity of 33% (circles) as a function of driving current. The squares represent the power of free running. The curve of upper triangles is the VSBC with the similar power as SBC (circles) for the purpose of beam quality comparing. The curve of downward triangles is the maximum power realizable by adjusting the position of HR mirror in VSBC.

Figure 2 shows the output power of VSBC as a function of driving current. The power curves of free running (solid squares) and SBC (solid circles) at an OC's reflectivity of 33% were also shown for comparison. The power was measured by Ophir FL500A at the coolant temperature of 18 °C. Two VSBC curves were shown with different overlapping sizes l_1. Curve of downward triangles is the maximum power realizable by adjusting the position of HR mirror in VSBC. Too small overlapping leads to an unstable combining, large overlapping reduces the combined power. It is found that a stable combining can be realized when the value of l_1 is larger than 3.32 mm, and the power performance is also the best at l_1 of 3.32 mm. The measured beam height l is 9.0 mm. The slope efficiency of free running is 0.95 W/A, and the maximum slope efficiency of VSBC is 0.69 W/A, which is about 1.8 times higher than that of off-axis SBC based on the filter and D shape mirror [16]. The continuous wave (CW) power for VSBC is 18.7 W at 32 A (downward triangles), and there is no any sign of thermal roll-over. The corresponding power of free running at 32 A is 26.4 W, hence the combining efficiency is about 71%. This efficiency is also comparable to SBC [3, 11]. The SBC at an OC's reflectivity of 33% was performed and power curve was depicted as solid circles in Fig. 2. For reasonable comparing the performance of VSBC and SBC, such as beam quality and lasing spectrum, the VSBC with the similar power as SBC (solid circles) was carried out by adjusting the position of HR mirror. The position was called as position one, and the corresponding light-current curve is plotted as upper triangles in Fig. 2.

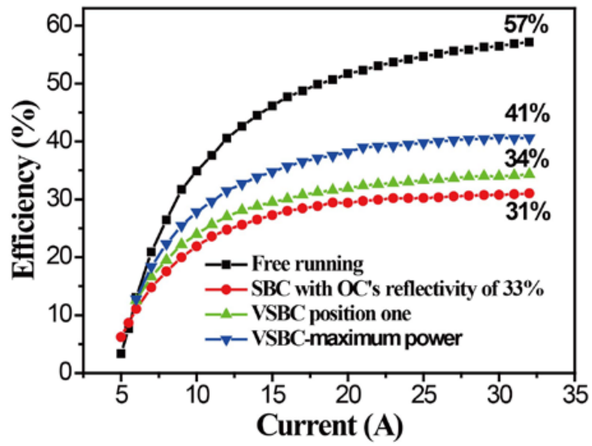

Fig. 3. Energy conversion efficiencies of VSBC, SBC and free-running.

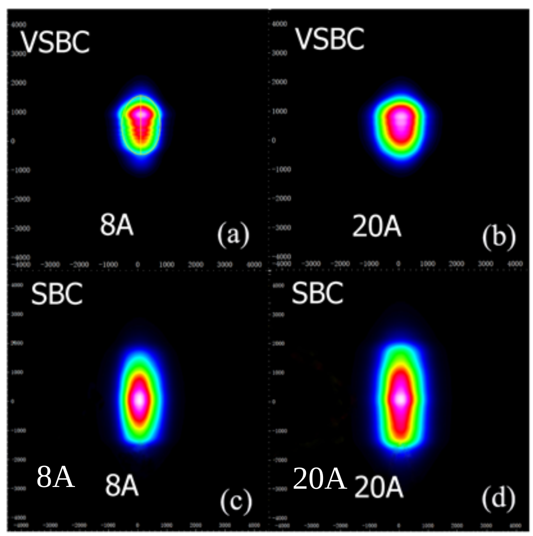

Fig. 4. Far field patterns of VSBC at driving currents of (a) 8 A and (b) 20 A, (c) and (d) are the far field patterns of SBC at 8 A and 20 A, respectively.

The corresponding energy conversion efficiencies were shown in Fig. 3. The efficiency of VSBC with maximum power is as high as 41%, which is almost same as the SBC with OC reflectivity of 14.4% [17]. It is also the lowest OC reflectivity for the stable SBC using the same grating as this work, and the achieved efficiency is also the highest value by optimizing the OC reflectivity in SBC. The energy conversion efficiency of laser array under free running is 57%, hence the efficiency ratio of combining is about 72%. Adjusting the position of HR mirror to position one, the efficiency of VSBC drops down to 34%. The efficiency of SBC with OC's reflectivity ~33% is 31% at 32 A. Using the overlapping between HR mirror and beam to control the feedback intensity in VSBC is just like that adjusting the feedback with different OC in SBC. One of significant advantages of VSBC over SBC is that the emission efficiency and power can be tuned by one cheap HR mirror, no need many piece OCs with different reflectivities.

To clearly show the difference of beam quality, the far field of VSBC and SBC were measured and compared. The VSBC is corresponding to the position one, and SBC is the SBC with OC's reflectivity of 33% as shown in Figs. 2 and 3. Figures 4(a) and (b) are respectively the far field spots of VSBC at 8 A and 20 A, (c) and (d) are the corresponding far field patterns of SBC. It can be seen that the shape of VSBC's far field pattern is asymmetric and likes a shield, the top part broadens because of the feedback of HR mirror. With the increase of driving current, the far field pattern becomes larger, however, the far field pattern of VSBC is noticeably smaller than that of SBC at the same current.

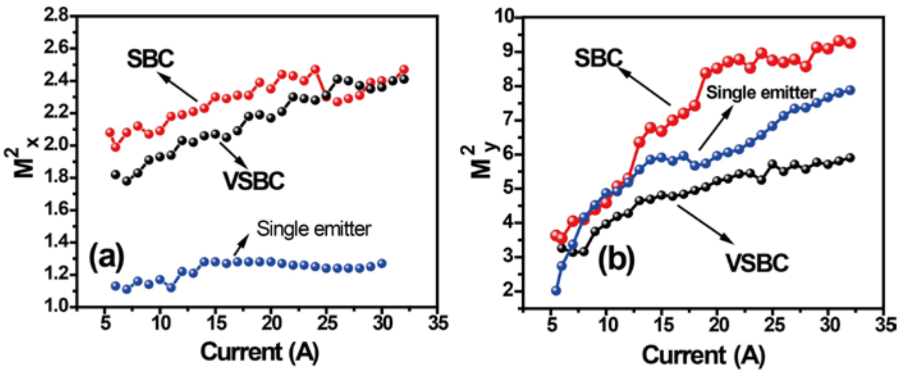

Fig. 5. Current dependent M^2 factors in (a) fast-axis and (b) slow-axis.

The detailed beam quality M^2 factor were measured and plotted in Fig. 5. The M^2 factors were measured by THORLABS LA4158-UV, and the beam width was determined by the second order moment according to ISO11146. Figure 5(a) shows the current dependent M^2 factors of VSBC, SBC, and single emitters in fast-axis (M^2_x) from 5 A to 32 A. The M^2_x values of single emitters are in the range from 1.1 to 1.28. After the combining, M^2_x is around 2, and becomes sensitive to the injection current. At a low driving current, M^2_x of VSBC is slightly better than that of SBC, but they are not noticeably different at high current. The reason why M^2_x values of SBC and VSBC are higher than that of single emitter is most likely because of the imperfect overlapping of beams on the grating due to the position errors. In contrast, it is totally different for the M^2 factors of slow axis (M^2_y) shown in Fig. 5(b). The M^2_y achieved by SBC is about 9.3 at 32 A and it is 7.8 for single emitter. For VSBC, M^2_y decreases to 5.9 at this injection current, which shows 37% and 24% improvement in beam quality of slow axis compared with SBC and single emitter, respectively. In addition, it was also demonstrated that the influence of current on M^2_y was improved in VSBC as shown Fig. 5(b). In principle, the beam quality of the combined output of a laser array can at most be as good as that of a single emitter using SBC. By using the VSBC, the beam quality of the combined beam can be improved even further, i.e., to a quality exceeding the beam quality of a single emitter. Although off-axis SBC by a filter and D shape mirror can also realize the beam quality exceeding the single emitter, the efficiency is much lower than VSBC and the setup is also complex. For the beam combining of BAL array, the beam quality in the slow-axis determines the final beam quality of the whole laser. Therefore, VSBC supplies a high efficient approach to go beyond the beam quality limit in SBC.

Different from the SBC, the feedback is realized by the partial reflection of HR mirror in VSBC, not the OC. To evaluate the feedback effectiveness, the lasing spectrum was measured and compared with that of SBC. Figure 6 shows the lasing spectra of VSBC and SBC measured by Yokogawa AQ6370B at 25 A. As can be seen in Fig. 6, the lasing spectrum of VSBC shows the behavior similar to SBC. Both here are clear nineteen peaks and the intensity distribution is almost same. There is no split in any single peak, which means no crosstalk occurs between the adjacent emitters [18]. The wavelength spread Δλ are respectively 5.67 nm and 5.69 nm for SBC and VSBC, this difference is comparable to the measurement resolution of 0.01 nm. Δλ is determined by the focal length of transform lens, the distance between adjacent emitters in laser array, the line spacing and dispersion of

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grating [6]. The laser array, grating and transform lens used in the VSBC and SBC are the same, so it is not strange for the same wavelength spread.

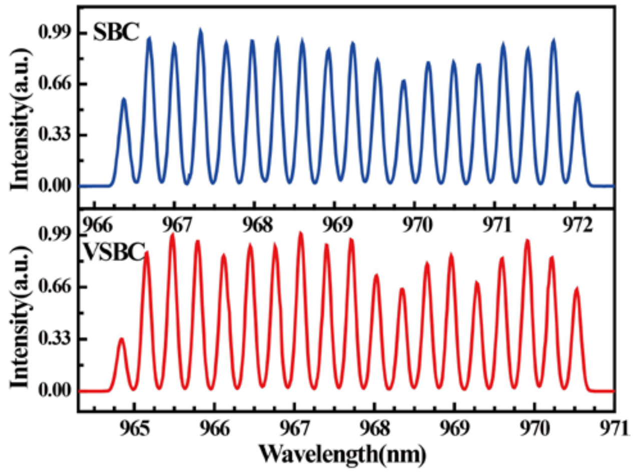

Fig. 6. Lasing spectra of lasers combined by SBC and VSBC.

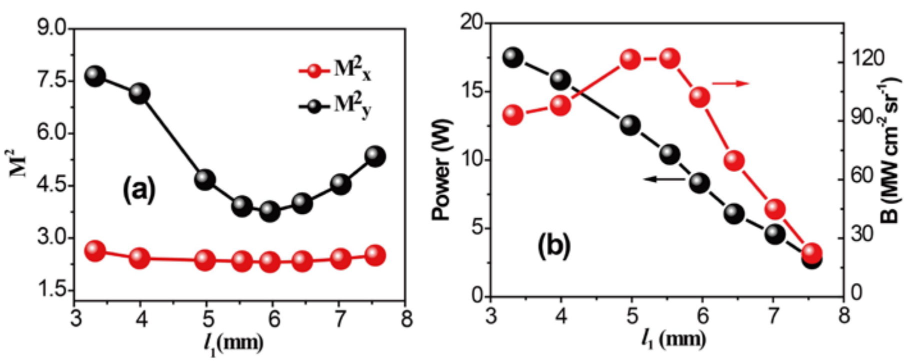

Fig. 7. Dependences of (a) M^2 factors and (b) power of VSBC on the overlapping size l_1 at 30 A.

Considering the overlapping size between the beam and HR mirror affects the performance of the VSBC, the dependences of power and beam quality on the overlapping size l_1 were investigated. The measured beam height l is 9.0 mm. It is worth note that the beam is not a regular pattern, so it cannot estimate the intensity of feedback by the ratio of l_1/ l. Fig. 7 plots the dependence of M^2 factors and output power on l_1 at 30 A. Obviously, the variation of M^2_x is small, but it is significant for M^2_y. When l_1 increases from 3.32 mm to 5.96 mm, M^2_x reduces from 2.63 to 2.31 and M^2_y decreases from 7.64 to 3.76. To our best knowledge, this is the best beam quality achieved by SBC based on the commercial BAL bar with a power level of ten watts. Continuing to increase l_1, the beam quality becomes poor. The output power decreases with l_1, which shows a trade-off between the power and beam quality. In many cases, the higher beam quality is desired, and the decreased power can be compensated by putting more laser emitters in combination. Of course, the power can also be increased by increasing the driving current. Figure 7(b) shows also the brightness, B, of combined lasers defined by [19]

$$B = \frac{P}{\lambda^2 M_x^2 M_y^2}. \tag{1}$$

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Where P is the output power, λ is the center wavelength. Although the power drops with l_1, the brightness B increases and reaches peak values in excess of 122 $MWcm^{-2}sr^{-1}$ at l_1 of 5.54 mm. Then the brightness starts to decrease. The brightness of 122 $MWcm^{-2}sr^{-1}$ is 54% higher than that achieved by the off-axis SBC by using a filter at the same driving current [16].

4. Conclusions

In summary, a simple and efficient SBC in a V-shaped external cavity was demonstrated. It shows the noticeable advantages over the traditional SBC, including the high beam quality exceeding a single emitter, OC free, tunable power and beam quality. Compared with the off-axis SBC using a filter, the VSBC presents the characteristics of simple setup, high efficiency and high brightness. It was found that the beam quality and brightness of VSBC can be adjusted by changing the overlapping area between HR mirror and beam. The slope efficiency of 0.69 W/A and energy conversion efficiency of 41% were demonstrated. The M^2 values of 2.31×3.76 in fast and slow axes and a brightness of 122 $MWcm^{-2}sr^{-1}$ were realized at 30 A. These results will contribute to the development of beam combining techniques.

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