High beam quality broad-area diode lasers by spectral beam combining with double filters

Fangyuan Sun (孙方圆)[1,2], Yufei Zhao (赵宇飞)[1,2], Shili Shu (舒世立)[1,*],
Guanyu Hou (侯冠宇)[1,2], Huanyu Lu (陆寰宇)[1,2], Xin Zhang (张 新)[1], Lijie Wang (汪丽杰)[1],
Sicong Tian (田思聪)[1], Cunzhu Tong (佟存柱)[1], and Lijun Wang (王立军)[1]

[1]*State Key Laboratory of Luminescence and Applications, 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*
**Corresponding author: shushili@ciomp.ac.cn*

Received August 10, 2018; accepted November 12, 2018; posted online December 20, 2018

A modified spectral beam combining (SBC) approach based on double asymmetrical filters was proposed. By using this scheme, the high-order lateral modes at the edge of the far-field pattern can be suppressed in the external cavity, and the beam quality in the slow-axis direction was improved from 16.1 to 13.4 compared to the conventional SBC. In the meanwhile, the electrical-to-optical efficiency from the modified SBC was more than 40% with an output power of 34.1 W, which is similar to that of the conventional SBC.

OCIS codes: 140.3298, 140.2010.
doi: 10.3788/COL201917.011401.

High-power laser sources with excellent beam quality are desirable for diverse applications, including materials processing, three-dimensional (3D) printing, and pumping solid-state lasers[1–4] and fiber lasers[5–7]. Diode lasers with small size, light weight, and high electrical-to-optical efficiency (EOE) (>50%)[8] are a particularly attractive source. Broad-area laser (BAL) diode arrays can produce continuous-wave (CW) power in excess of 50 W[9] and have applied in many applications. However, these devices typically suffer from poor beam quality in the slow-axis direction due to the inherently large lateral dimension.

Spectral beam combining (SBC) with high EOE has proven to be an effective technique to improve the beam quality of BAL arrays[9–11], whereas the beam quality obtained by SBC is limited by that of a single emitter. For further improving the beam quality of the beam combining system, one approach is optimizing that of the laser chip, including the reduction of the ridge waveguide extent and introducing special microstructures in the waveguide layer. Tapered[12] and slab-coupled optical waveguide[13] diode lasers can provide excellent beam quality coherent emission due to a single-mode ridge structure. However, the output power of these lasers remains limited to the watt level[12,13]. In addition, the fabrication process of these lasers is complicated and difficult.

The other approach for improving the beam quality of the beam combining system is changing the configuration of the external cavity of SBC to suppress the high-order lateral modes of the BAL array. It has been demonstrated that off-axis SBC, employing a sharp edge D-shaped mirror and a spatial filter (SF), can improve the beam quality of BAL arrays in excess of that of a single emitter[14–17]. However, this external cavity technique reduced the EOE (~18%)[15,17] due to the one lobe serving for feedback and the geometrical mismatch between the gain and mode profiles. This approach is also unstable at a high injection current. Therefore, developing a simple, stable, and high-efficiency beam combining approach with high beam quality is crucial. Herein, we propose a modified SBC approach with double asymmetrical intracavity SFs, which are used to filter the higher-order lateral modes at the edge of the beam spot. The beam quality of the BAL array has been improved observably on the basis of this configuration. In the meantime, compared to the conventional SBC, the EOE of this modified SBC was not significantly reduced.

The BALs with a wide waveguide tend to produce high-order lateral modes, which is undesirable due to the formation of a high-divergence, multiple lobe far-field profile and poor lateral beam quality. This is the reason why the BALs have high output power. However, the beam quality of these devices is unsatisfactory in practical applications. Furthermore, for the BALs with SBC, the high-order lateral mode still exists in the external cavity, because all of the optical modes generated in the external cavity of SBC are reflected back indiscriminately by the output coupler (OC). In other words, the beam quality of the conventional SBC is limited by the poor beam quality of the single BAL. Double SFs are able to effectively suppress the edged high-order modes in the semiconductor chip to improve the beam quality of the output beam. Because of the asymmetrical distribution of lateral modes, the double SFs are nonparallel, requiring accurate and respective adjustment. Comparing the SBC with a single SF, twofold higher-order lateral modes at the edge of the beam spot can be suppressed by using double SFs in the external cavity; meanwhile, the beam quality of the slow axis can be further enhanced.

In this Letter, a novel off-axis SBC based on double filters was proposed, and it demonstrated the high beam quality beyond single emitters. By using this modified

SBC scheme, the high beam quality and efficiency were achieved. Compared with the conventional SBC, the output power, EOE, and beam quality were further investigated.

A 976 nm high-power BAL array with 19 emitters and a pitch of 500 μm was utilized in our experiment. The waveguide width of a single emitter is 100 μm. There is an anti-reflection coating with a reflectivity of 5% on the front facet and a high-reflection coating (>95%) on the rear facet of the laser arrays. Figure 1(a) shows the schematic of the experimental setup of a modified SBC with double filters, including the fast and slow axes collimating structures, Fourier transform lens (FTL), reflection grating (RG), double SFs, and OC. Collimation of the fast axis was performed by a beam-transformation system (BTS), which consists of a fast-axis collimation lens (FAC) with a focal length of 365 μm and a diagonal lens array for rotating the beams by 90°. The focal length of the slow-axis collimation lens (SAC) is 22 mm. Subsequently, a plano-convex FTL with a focal length of 400 mm was utilized to image the collimated beams from each emitter onto an 1800 lines/mm RG. The diffraction efficiency of the first-order RG is approximately 86% at 980 nm. The emitting beam from the center emitters of the laser array was incident on the grating with an angle of approximately 53°. Compared to the conventional SBC, two separated SFs were employed in front of the OC. Figure 1(b) shows the diagrammatic sketch of the beam spot function with the double SFs. It can be seen that the double SFs were nonparallel and asymmetrical due to asymmetrical distribution of the beam spot. Two six-axis alignment stages were utilized to adjust the position of double SFs. The resolution of the manual stage alignment unit in the x, y, z and θ_x, θ_y, θ_z directions is approximately 0.5 μm and 33 in. for each scale, respectively. This manual stage is satisfied with the requirement of the accuracy of the adjustment. The beam quality of the slow axis can be controlled effectively by adjusting the degree of θ_z and the y axis. If the accuracy of the adjustment is coarse, it will have a significant influence on the beam quality in the slow-axis direction and the output power. In our experiment, the position of each SF was adjusted when the beam quality in the slow-axis direction had the best value and the external cavity could be locked stably. All of the optical modes that transmit to the OC, including higher-order lateral modes, were fed back to emitters in the conventional SBC. Not all of the reflected modes contribute to the improvement of the beam quality. The OC that forms the external cavity locking has a suitable reflectivity of 16%.

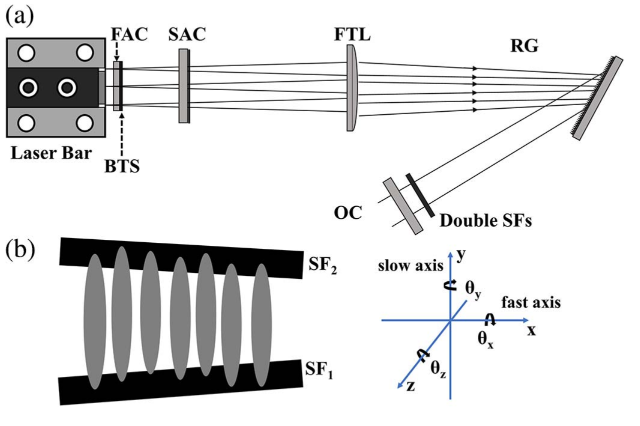

Fig. 1. (a) Schematic of the SBC with double filters and (b) the filtering schematic by nonparallel double SFs before combining.

The main mechanism of this proposed SBC with double SFs to control the lateral modes and improve the beam quality is as follows. The BALs generally have a large number of lateral modes, and the far-field profiles of high-order lateral modes are with two lobes[18]. The divergence and separation angles between two lobes increase with the increase of the mode order. Many lateral modes with different optical intensities form the far-field spot. The high-order lateral modes with the highest allowed mode order are located at the outermost edge of lateral far-field pattern. When the double SFs were put in the setup, the modes with a higher order will be filtered first. The decrease of the mode order and number will improve the divergence and beam quality. In addition, the output beam generally presents a super or flat-top Gaussian distribution, and the center area of the beam spot with several-order modes has the largest optical intensity[18,19]. In contrast, the higher-order modes at the edge of the beam spot have the relatively weak optical intensity but significant impact on the beam quality. When these higher-order modes were filtered by the double SFs, the output power and EOE would not be reduced significantly, but the beam quality can be obviously improved.

To clearly show the improvement of beam quality, the far-field pattern is measured at a distance of 400 mm from the OC. The far-field pattern of the conventional SBC was shown in Fig. 2(a). The elliptical beam spot was approximately 2 mm × 4.3 mm in the vertical and lateral directions. Compared with that of the modified SBC shown in Fig. 2(b), the spot was narrowed in the slow-axis direction, and the size was approximately 1.8 mm × 3.6 mm. The nearly circular beam is beneficial to coupling into a fiber with a low numerical aperture for applications[20].

The beam quality of both of the external cavity configurations was measured in accordance with ISO11146

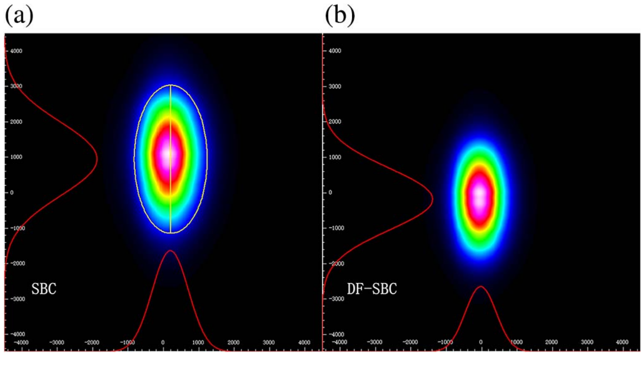

Fig. 2. Far-field spots of (a) the conventional SBC and (b) the modified SBC.

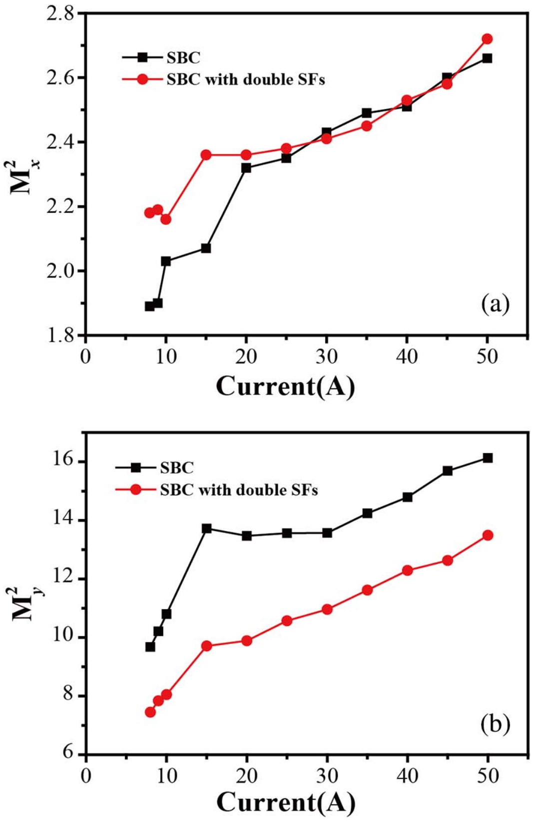

Fig. 3. M^2 factors of the BAL arrays with the conventional SBC and the modified SBC in the (a) fast and (b) slow axes.

and plotted in Fig. 3 as a function of injection current. The beam quality in the fast-axis direction is not noticeably improved for the modified SBC, and the measured M^2 values in the fast axis are 1.7–2.7, as shown in Fig. 3(a). It can be seen that the M^2 factors in the fast axis for both of the external cavity configurations increase with the current and show a weak current-dependent property. Without double filters, the M^2 values in the slow axis are 9.5–16, as shown in Fig. 3(b). Because of the strong current-dependent property of the beam quality in the slow-axis direction, the M^2 factors in the slow axis for both of the cavity configurations degrade quickly with the increase of the current. By using the double filters in the external cavity, the M^2 values in the slow axis can be improved from 16.1 to 13.4 at 50 A. Although the modified SBC shows a power loss of 3.4 W, the beam quality of the slow axis was improved by 17% compared to that of the conventional SBC cavity without double SFs. The M^2 values in the slow axis are expected to achieve the beam quality beyond that of the single device.

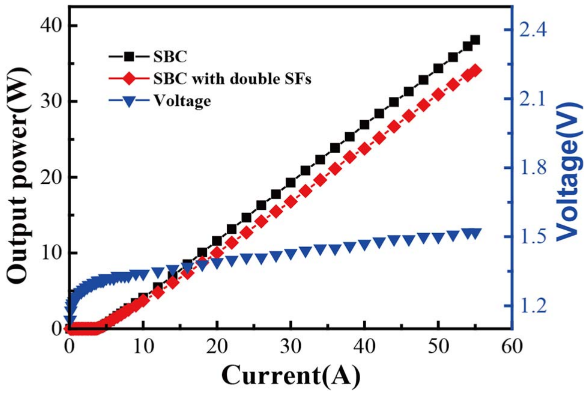

Fig. 4. L–I–V characteristics of the diode laser array combined with off-axis SBC with selective feedback. The inset graph shows the efficiency characteristics of the off-axis SBC.

Figure 4 shows the light–current–voltage (L–I–V) curves of the BAL array combined by the modified SBC with double SFs. For comparison, the characteristics of the BAL array combined by conventional SBC were also measured and plotted in Fig. 4. All data received from both of the SBC cavity configurations were measured under the water-cooling system at the temperature of 25°C. As shown, the two cavities have the same threshold current of approximately 4.5 A. At the injected current of 55 A, the measured maximum output powers from the conventional SBC and the modified SBC are 38.1 and 34.1 W, respectively. Both the maximum output power and the slope efficiency of the modified SBC decrease by 10% compared with the conventional SBC.

Figure 5 shows the EOE curves of both external cavity configurations. Both of the external cavity configurations show similar trends for the measured EOE with the increase of the injected current. At a high injection current of 50 A, the EOEs of the conventional and modified SBCs are approximately 45% and 41%, respectively. The EOE of the modified SBC is in excess of 40%, which is slightly lower than that of the conventional SBC. By increasing the diffraction efficiency of the RG and decreasing the reflectivity of the OC, the EOEs were supposed to be further improved. It can be seen that the SBC with double SFs has an attractive efficiency for realistic applications.

An output spectrum from the modified SBC, measured by Yokogawa AQ6370B at 50 A is shown in Fig. 6, which is the same as that from the conventional SBC. It can be observed that there are nineteen emission peaks in the measured spectrum, and no crosstalk occurs between the adjacent emission peaks[21]. The measured wavelength

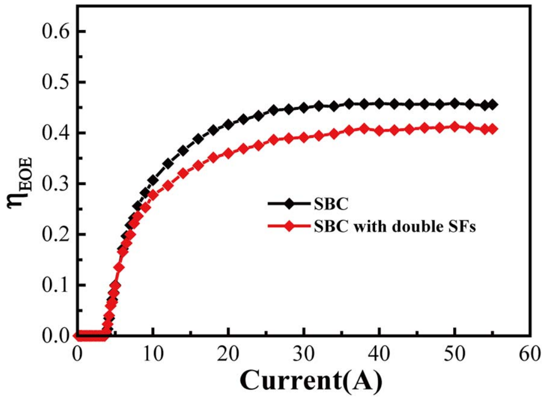

Fig. 5. Electrical-to-optical efficiency η_{EOE} for both external cavity configurations as a function of driving current.

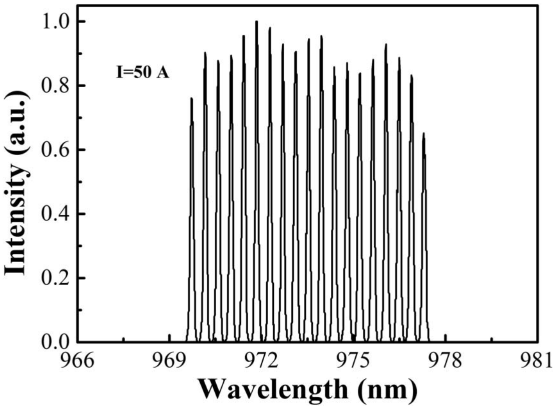

Fig. 6. Lasing spectrum of BAL array by modified SBC with double SFs measured at 50 A.

space of the whole spectrum and the interval between the adjacent emission peaks are about 7.7 and 0.43 nm, respectively. The wavelength spread $\Delta\lambda$ and the wavelength interval $\Delta\lambda_{ij}$ can be defined as[9]

$$\Delta\lambda = \frac{(n-1)p\Lambda \cos\alpha}{f}, \quad (1)$$

$$\Delta\lambda_{ij} = \frac{p\Lambda \cos\alpha}{f}, \quad (2)$$

where n is the number of laser-array elements, p is the pitch spacing between the adjacent elements, f is the focal length of the FTL, Λ is the grating period, and α is the angle of incidence relative to the grating for the center element. According to Eqs. (1) and (2), the calculated wavelength spread $\Delta\lambda$ and the wavelength internal $\Delta\lambda_{ij}$ are 7.5 and 0.42 nm, respectively, which are in agreement with the measured values. Because the double filters just suppress the high-order modes in the external cavity, it has no effect on the output spectrum.

In summary, a simple and efficient SBC technique was proposed to dramatically improve the beam quality produced from BAL arrays. By using the double SFs in SBC, the high-order lateral modes with higher mode order in the external cavity were suppressed. The beam quality of the slow axis has been improved by 17%. This external cavity configuration provides a possibility to exceed the beam quality of a single emitter, and the output power decreases by only a few watts compared to the conventional SBC. In addition, the EOE of the modified SBC was in excess of 40% and can be further improved via increasing the diffraction efficiency of the RG. For diode lasers, the output power can be easily increased by combining more light-emitting units or laser arrays. Therefore, it is possible to obtain a high-power diode laser source with excellent beam quality by using the method demonstrated in this Letter to combine more arrays.

This work was supported by the National Natural Science Foundation of China (Nos. 61790584 and 617741s53).

References

1. Y. Tzuk, A. Tal, S. Goldring, Y. Glick, E. Lebiush, G. Kaufman, and R. Lavi, IEEE J. Quantum Electron. **40**, 262 (2004).
2. Q. Zhou, C. Zhou, N. Yu, C. Wei, W. Jia, and Y. Lu, Chin. Opt. Lett. **15**, 091403 (2017).
3. X. Wu, Z. Ye, Z. Lu, Y. Takiguchi, Y. Wang, and H. Kan, Chin. Opt. Lett. **1**, 93 (2003).
4. M. Hemenway, Z. Chen, W. Urbanek, D. Dawson, L. Bao, M. Kanskar, M. DeVito, and R. Martinsen, Proc. SPIE **10514**, 105140P (2018).
5. S. Breitkopf, T. Eidam, A. Klenke, L. von Grafenstein, H. Carstens, S. Holzberger, E. Fill, T. Schreiber, F. Krausz, A. Tünnermann, I. Pupeza, and J. Limpert, Light: Sci. Appl. **3**, e211 (2014).
6. M. Fan, Z. Wang, H. Wu, W. Sun, and L. Zhang, IEEE Photon. Technol. Lett. **27**, 319 (2015).
7. J. Limpert, F. Stutzki, F. Jansen, H.-J. Otto, T. Eidam, C. Jauregui, and A. Tünnermann, Light: Sci. Appl. **1**, e8 (2012).
8. X. Liu, C. Holly, C. L. Jiang, Y. Xiong, S. McDougall, and Konstantin, in *IEEE High Power Diode Lasers and Systems Conference (HPD)* (2017), p. 33.
9. J. Zhang, H. Peng, X. Fu, Y. Liu, L. Qin, G. Miao, and L. Wang, Opt. Express **21**, 3627 (2013).
10. D. Vijayakumar, O. B. Jensen, R. Ostendorf, T. Westphalen, and B. Thestrup, Opt. Express **18**, 893 (2010).
11. A. Müller, D. Vijayakumar, O. B. Jensen, K.-H. Hasler, B. Sumpf, G. Erbert, P. E. Andersen, and P. M. Petersen, Opt. Express **19**, 1228 (2011).
12. O. B. Jensen, A. Klehr, F. Dittmar, B. Sumpf, G. Erbert, P. E. Andersen, and P. M. Petersen, Proc. SPIE **6456**, 64560A (2007).
13. R. K. Huang, B. Chann, L. J. Missaggia, C. T. Harris, Z.-L. Liau, A. K. Goyal, J. P. Donnelly, T.-Y. Fan, A. Sanchez-Rubio, and G. W. Turner, in *Conference on Lasers and Electro-Optics OSA* (2006), paper CFG2.
14. O. B. Jensen, B. Thestrup, P. E. Andersen, and P. M. Petersen, Appl. Phys. B **83**, 225 (2006).
15. D. Vijayakumar, O. B. Jensen, and B. Thestrup, Opt. Express **17**, 5684 (2009).
16. A. Jechow, V. Raab, and R. Menzel, Appl. Opt. **45**, 3545 (2006).
17. A. M. Jones and J. T. Gopinath, Opt. Express **21**, 17912 (2013).
18. Y. Champagne, S. Mailhot, and N. McCarthy, IEEE J. Quantum Electron. **31**, 795 (1995).
19. V. Svetikov, C. Peroz, I. Ivonin, S. Dhuey, S. Cabrini, S. Babin, A. Goltsov, and V. Yankov, J. Opt. Soc. Am. B **30**, 610 (2013).
20. L. J. Wang, C. Z. Tong, S. C. Tian, S. L. Shu, G. G. Zeng, J. M. Rong, H. Wu, E. B. Xing, Y. Q. Ning, and L. J. Wang, IEEE J. Sel. Top. Quantum Electron. **21**, 343 (2015).
21. L. Yang, Z. Wu, Z. Zhong, and B. Zhang, Opt. Commun. **384**, 30 (2017).