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Polarization full feedback external cavity of open loop spectral beam combining based on multi-single emitters laser diode

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In this paper, a spectral beam combining (SBC) structure of multi-single emitters laser diode based on a polarization full feedback (PFF) external cavity is proposed and demonstrated. The maximum combining efficiency is 75.6%, which leads to an output power of 38.48 W, a degree of polarization (DOP) of 99.42%, and electro-optical conversion efficiency of 35.63% under continuous wave operation at a current of 8 A. Compared to the conventional SBC, the output power, the combining efficiency, the electro-optical conversion efficiency, and the DOP of the PFF-SBC structure present improvements of 5.73 W, 11.26 percentage points, 5.3 percentage points, and 7.26 percentage points, respectively. The results show that this SBC method can achieve a high efficiency and linearly polarized laser output of SBC, thereby making the subsequent polarization beam-combining efficiency approach the limit.

Keywords: diode laser; spectral beam combining; high efficiency; degree of polarization; external cavity feedback.

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1. Introduction

The spectral beam combining (SBC) structure has been proven to be one of the most effective and convenient methods for achieving high-power and high-quality laser output[1,2]. Under the influence of optical dispersion elements and external cavity feedback, SBC technology can achieve wavelength locking and linear superposition of output power of all laser diode (LD) emitters (theoretically equal to the total power of single emitters), while also ensuring high beam quality of the output beam (theoretically the same as a single emitter), thereby achieving an increase in laser brightness[3]. In 2000, the Lincoln Laboratory first demonstrated that SBC technology can improve the power and beam quality of semiconductor lasers[4]. It is worth noting that achieving efficient SBC also requires LD emitters with a high degree of polarization [DOP, defined by the absolute value of $(P_{TM} - P_{TE})/(P_{TM} + P_{TE})$, in which, P_{TM} is the power of transverse magnetic (TM) mode oscillating vertically to the epitaxial layers, and P_{TE} is the power of transverse electric (TE) mode oscillating parallel to the epitaxial layers] and high diffraction efficiency gratings. However, currently, due to the design of LD epitaxial growth and the influence of external stress during packaging, the DOP of LDs can only reach less than 90% under high current conditions[5]. At the same time, polarization-independent gratings are difficult to achieve in commercial use under high diffraction efficiency, and there are only relevant reports in the laboratory[6–8]. In SBC technology, polarization-dependent gratings are commonly used, with diffraction efficiency greater than 96% for the S polarization state and less than 20% for the P polarization state[9,10]. What is more, SBC is designed to achieve high power and beam quality; therefore, it needs to work under high currents[11]. However, as the current increases to the maximum, the DOP of LD decreases, leading to increased losses during grating diffraction and the reduction of combining efficiency. It also affects the stability of the system due to the presence of P-polarized beams that have not been diffracted. Even if there is partial diffraction of the P-polarized beam, it will still cause power loss when using polarization beam combining in the future. To achieve high combining power, Zhang *et al.* achieved high-efficiency SBC through polarization multiplexing, but the output beam is still of low DOP, which is not conducive to subsequent polarization beam combining[12].

In this paper, to solve these problems and obtain high power and high DOP of SBC, we propose an SBC structure of multi-single emitters LD based on polarization full feedback (PFF) external cavity of open loop SBC. Separating the wavelength locking with beam-combining output, 30% of the laser beam, which is the P polarization state, is used for external cavity full feedback for wavelength locking, and the other 70%, which is the S polarization state, is used for open loop SBC output. This structure can reduce the polarization loss of the grating, improve the output power, and obtain a high DOP beam output. To our knowledge, it is the first report to use LD emitters of low DOP to achieve high combining efficiency and high DOP of output beam through a PFF-SBC structure.

2. Experimental Setup

The experimental setup of PFF-SBC is shown in Fig. 1(a). The emission wavelength of each LD emitter is around 971 nm, and the gain spectral bandwidth exceeds 10 nm, which means that stable wavelength locking can be achieved at least between 961 and 981 nm through the external cavity, providing necessary conditions for SBC. Considering stable wavelength locking and improved feedback efficiency of the external cavity[5], the front facet of the emitter has an antireflection coating with a reflectivity smaller than 0.5%, and the rear facet has a high-reflection coating with a reflectivity larger than 99%.

As shown in Fig. 1(a), a Kepler beam expansion system is used for the fast axis direction, which includes two cylindrical lenses, CL1 and CL3, with focal lengths of 75 and 150 mm, respectively,

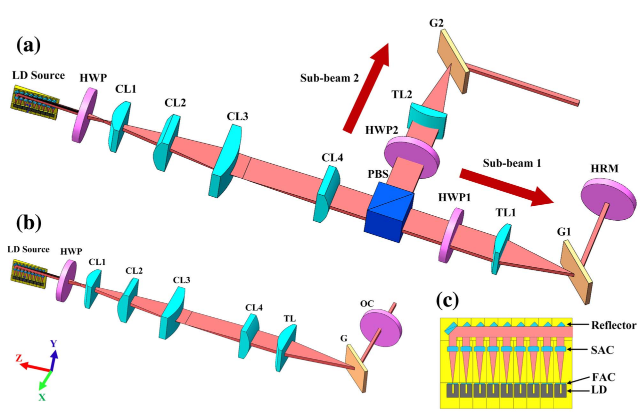

Fig. 1. Schematic diagram of (a) the PFF-SBC, (b) the conventional SBC, and (c) the LD source module. LD, laser diode; FAC, fast axis collimator; SAC, slow axis collimator; HWP, half-wave plate; CL1–CL4, cylindrical lenses; PBS, polarization beam splitter; TL, transform lens; G, transmission grating; HRM, high-reflectivity mirror; OC, output coupler.

to increase the distance between the emitters and the beam waist, thereby reducing spectral cross talk after wavelength locking[13]. The 4*F* optical system composed of two cylindrical lenses, CL2 and CL4, with focal lengths of 150 mm, is used in the slow axis direction to reduce the influence of long optical paths on the size of the slow axis spot. The distance between the front focus of CL2 and the rear focus of CL4 is 4 times the focal length *F*, which we call 4*F*, so this structure is defined as a 4*F* optical system. Next, a polarization beam splitter (PBS) is placed after CL4 to adjust the power ratio of the transmitted P-polarization state of PBS named sub-beam 1 to the reflected S-polarization state named sub-beam 2 to 30:70 by the half-wave plate (HWP) behind the LD source module. This is because the DOP of each LD is not completely consistent. We need to use a certain amount of feedback to ensure that all LD emitters can achieve stable wavelength locking. For sub-beam 1, place another HWP (HWP1) behind the PBS to convert the beam polarization direction to match the highest diffraction efficiency of the grating (G1). As for the G1 with 1851 lines/mm and a Littrow angle of 64.6°, the diffraction efficiency of the S polarization state in the 965–980 nm band reaches more than 94%. A cylindrical lens with a focal length of 300 mm is used as the transform lens (TL1) to focus the beam onto the transmission grating (G1). The output coupler (OC) feeds all sub-beam 1 back to the emitters through a high-reflectivity mirror (HRM), forming a polarization full feedback external cavity structure. Therefore, the external cavity is composed of HRM and LD rear facets. For sub-beam 2, the HWP-2 is the same function as HWP-1. After external cavity feedback of sub-beam 1 and wavelength selection of the grating, each LD emitter is stably locked at a specific wavelength. After being output through the reflection end of the PBS, an open loop SBC is achieved through a transform lens (TL2) and a grating (G2) with the same parameters as in the sub-beam 1. The distance between TL1 and TL2 from the PBS is equal to ensure that the incident angle of the same emitter on G1 and G2 is consistent. Therefore, compared to the conventional SBC structure, this experimental structure can ensure that the incident beams on the gratings are linearly polarized, thereby reducing the diffraction loss of the grating and improving the combining efficiency.

The experimental setup of the conventional SBC is shown in Fig. 1(b), which is similar to the structure reported in Ref. [14]. The conventional SBC is composed of the LD source module, HWP, CL1–CL4, TL, grating, and OC with a reflectivity of 30%. The parameters of the LD source module and all optical elements are the same as for the PFF-SBC.

Figure 1(c) shows the schematic diagram of the LD source module. The module is composed of nine single emitters and their corresponding fast axis collimators (FACs), slow axis collimators (SACs), and reflectors. The strip width of every single emitter is 90 μm, and its cavity length is 4 mm. The focal length of FAC is 0.3 mm and that of SAC is 13.8 mm. The step difference defined by the difference between adjacent chips in the SBC direction is 0.37 mm. The beam from each emitter is collimated by the FAC and the SAC and arranged along the fast axis through the reflectors.

3. Experimental Results and Discussion

When the cooling water temperature is 15°C, the power of sub-beam 1 and its ratio to the power of the free-running named sub-beam 1 ratio vary with the continuous wave current, as shown in Fig. 2. The free-running mode is such that no optical elements are placed after the LD source module, and the power, electro-optical efficiency, and DOP are directly tested. When the injection current is 8 A, the maximum output power in free-running mode is 50.9 W. The maximum output power of sub-beam 1 is 16.27 W. As the current gradually increases, the sub-beam 1 ratio is about 30%, indicating that the external cavity feedbacks are the same in the PFF-SBC and the conventional SBC structure.

The output power of the PFF-SBC and that of the conventional SBC, varying as a function of the continuous wave current, are shown in Fig. 3. The output power was measured by a pyroelectric power meter (Ophir FL500A). When the injection current is 8 A, the maximal output power of the LD source module in the free-running mode is 50.9 W. For the PFF-SBC, the output power is 38.48 W, and the output power of the conventional SBC is equal to 32.75 W. When the current is less than 8 A, the slope efficiency of the free-running mode, the conventional SBC, and the PFF-SBC is 7.19, 4.55, and 5.4 W/A, respectively.

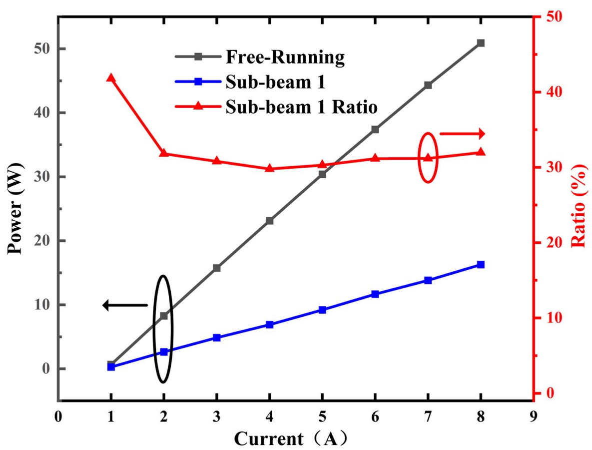

Fig. 2. Power and ratio versus the injection current of PFF-SBC.

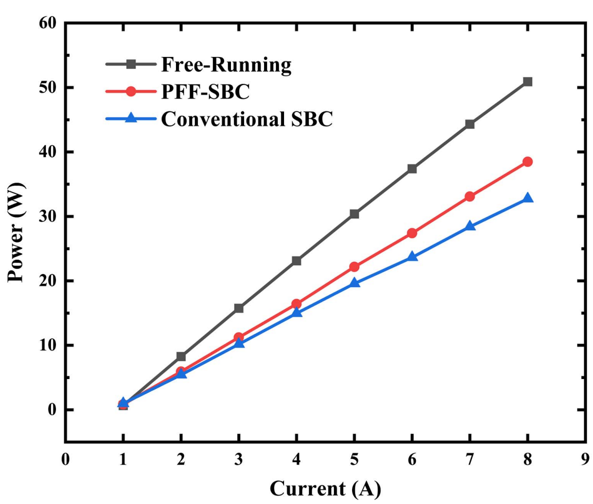

Fig. 3. Power versus the injection current for the free-running, PFF-SBC, and conventional SBC modes.

Figure 4(a) shows the electro-optical (E-O) conversion efficiency and voltage versus the injection current in the free-running mode, conventional SBC mode, and PFF-SBC mode. At a current of 8 A, the electro-optical conversion efficiency in the free-running mode is 47.13%. For the conventional SBC and PFF-SBC, the electro-optical conversion efficiency is 30.33% and 35.63%, respectively.

The combining efficiencies of conventional SBC and PFF-SBC are shown in Fig. 4(b). The definition of combining efficiency is the ratio of the output power of SBC to the output power of the free-running mode. When the current is 1 A, the combining efficiencies of both conventional SBC and PFF-SBC are greater than 100%.This is because the feedback of the external cavity makes the threshold current drop. According to Ref. [15], the higher feedback means the lower combining efficiency. As Fig. 2 shows, more than 40% of the beam is used for feedback in the PFF-SBC mode at the current of 1 A. So, the combining efficiency is lower than that in the conventional SBC mode, whose feedback is only 30%. At a current of 8 A, the combining efficiency of the PFF-SBC is 75.6%, while that of the conventional SBC is 64.34%. The reason why the output power and slope efficiency of the PFF-SBC are higher than that of the conventional SBC is that the DOP of LD emitters is less than 100%, leading to more diffraction loss of the grating caused by polarization in the conventional SBC, which is less in the PFF-SBC mode.

Figure 5 shows the measured results for the DOP versus the injection current in the free-running, PFF-SBC, and conventional SBC modes. At a current of 8 A, the DOP of the beam is 75.59%, 92.16%, and 99.42% in free-running, conventional SBC, and PFF-SBC modes, respectively. Compared to the free-running mode, the DOP of the beam in conventional SBC mode is increased by 16.57 percentage points due to the polarization-dependent grating. Compared to the conventional SBC, the DOP is further increased by 7.26 percentage points in the PFF-SBC mode. This is because the grating diffracts beams of different polarization directions, resulting in insufficient

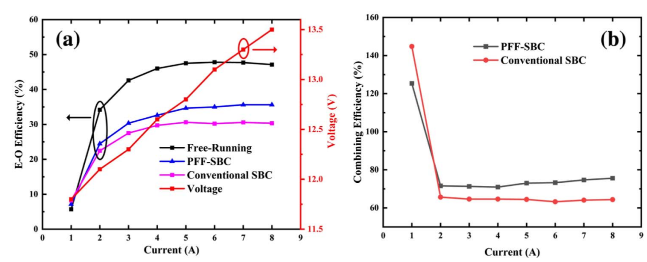

Fig. 4. E-O efficiency, voltage, and combining efficiency of free-running, PFF-SBC, and conventional SBC modes versus the injection current. (a) E-O efficiency and voltage; (b) combining efficiency.

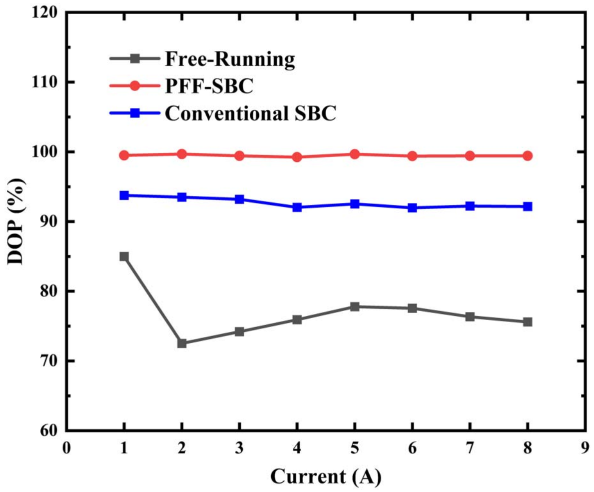

Fig. 5. Measured results for the DOP versus the injection current in the free-running, PFF-SBC, and conventional SBC modes.

output beam polarization in conventional SBC. However, the PBS in the PFF-SBC divides the beam into two linearly polarized beams with polarization directions perpendicular to each other, making the combined beam linearly polarized. Therefore, the efficiency of subsequent polarization beam combining can approach the limit.

Compared with the conventional SBC, the improvements in the output power, the electro-optical conversion efficiency, the combining efficiency, and the DOP of the PFF-SBC are shown in Figs. 6(a)–6(d). Because the PFF-SBC structure can reduce the diffraction loss of the grating caused by the insufficient DOP of LD emitters, its output power is improved by 5.73 W, the electro-optical conversion efficiency is improved by 5.3 percentage points, the combining efficiency is improved by 11.26 percentage points, and the DOP is improved by 7.26 percentage points. Moreover, the higher the injection current, the greater the improvements in these aspects above. Because SBC aims to improve the output power and beam quality, requiring LD to operate at high currents, PFF-SBC has more advantages than the conventional SBC.

Figure 7 shows the combined laser spectrum of the PFF-SBC at an injection current of 8 A. Due to high-quality feedback by HRM and the grating dispersion effect, the spectrum is clear, consisting of nine independent spectral peaks without any cross talk. The nine spectral peaks correspond to the nine emitters in the LD source module. The total spectral width is 4.6 nm, and the wavelength separation between adjacent spectral peaks is 0.58 nm. According to the theoretical calculation of SBC[9], the total spectral width of the PFF-SBC mode is 4.57 nm, and the wavelength separation between adjacent spectral peaks is

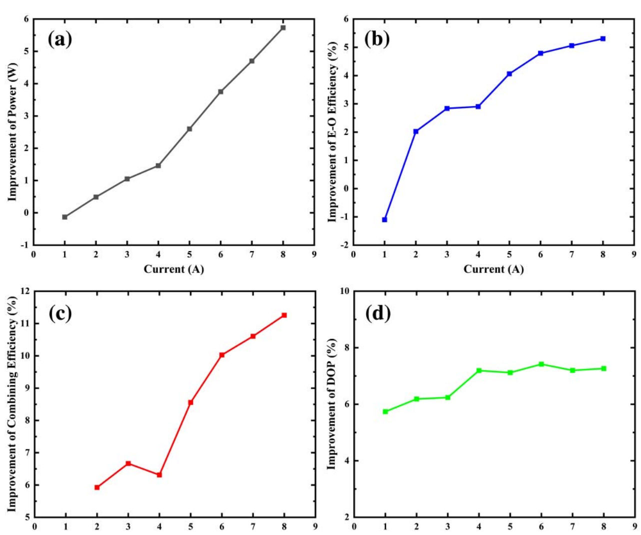

Fig. 6. Improvement in PFF-SBC relative to the conventional SBC. (a) Power, (b) E-O efficiency, (c) combining efficiency, and (d) DOP.

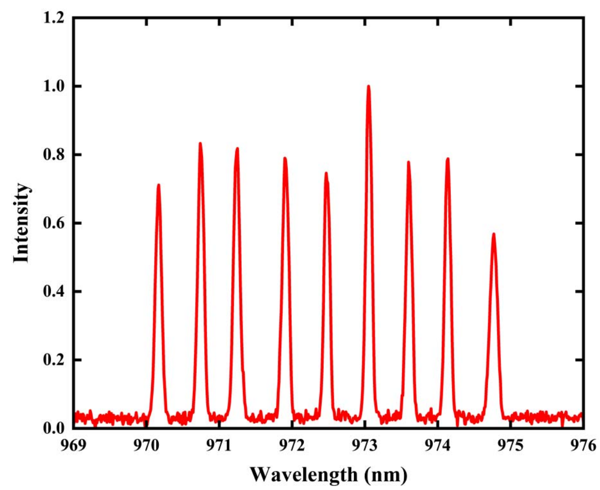

Fig. 7. Emission spectrum of the PFF-SBC at a current of 8 A.

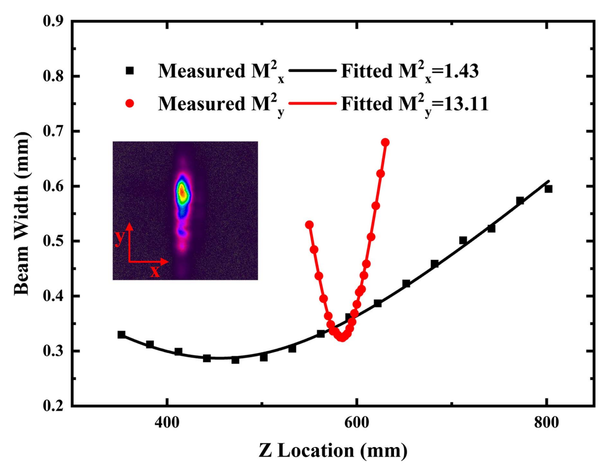

Fig. 8. Measured results for the beam quality of the PFF-SBC at an injection current of 8 A.

0.57 nm, indicating that the experimental results are consistent with theoretical calculations. The inhomogeneity of the spectral intensity and the nonuniformity of wavelength spacing are caused by the inconsistent directionality of the LD source module during spatial beam combining.

At a current of 8 A, the beam quality of the PFF-SBC was measured by the BSQ-SP920 (Ophir Spiricon) in the justification criterion at D4σ, which evaluates the beam intensity profile in the x and y directions, defining the beam width as 4 times the standard deviation (σ); the test results are shown in Fig. 8. The x axis is the fast axis, which is also the SBC direction, and the y axis is the slow axis. The M^2 value of the PFF-SBC beam is 1.43 in the SBC direction and 13.11 in the non-SBC direction. The beam quality is similar to that of a single emitter in the free-running mode. This result proves that all beams from the LD source module achieve a high quality of SBC to increase brightness.

4. Conclusion

In conclusion, we have demonstrated a structure of SBC that improves the electro-optical efficiency and the DOP of the SBC by polarization full feedback, which we call PFF-SBC. An HWP and a polarizing beam splitter are combined to separate wavelength locking with beam-combining output. This structure can reduce the diffraction loss of the grating, improve the output power and electro-optical conversion efficiency of SBC, and achieve high DOP laser output. At a pump current of 8 A, the output power, the electro-optical conversion efficiency, the combining efficiency, and the DOP of PFF-SBC are 38.48 W, 35.63%, 75.6%, and 99.42%, respectively. Compared with conventional SBC, the output power is improved by 5.73 W, the electro-optical conversion efficiency is improved by 5.3 percentage points, the combining efficiency is improved by 11.26 percentage points, and the DOP is improved by 7.26 percentage points. In addition, the higher the injection current, the greater the improvements in these aspects above. Therefore, the PFF-SBC provides an effective technology to achieve high power, high electro-optical conversion efficiency, and high DOP laser output for the SBC of LD emitters with insufficient DOP under high injected currents.

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