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High-brightness diode lasers obtained via off-axis spectral beam combining with selective feedback

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Abstract: We proposed a modified off-axis spectral beam combining method, based on the concept of selective feedback. A high reflectivity mirror with a fixed width was used to select and couple back the optical modes in the external cavity. The emission power exceeding 20 W with M^2 factors of 2.7 × 4.4 in the fast and slow axes was demonstrated. The beam quality of the system was improved by a factor of three to four compared with that of a single emitter, and a high brightness of 190 MW cm^{-2} str^{-1} was achieved.

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1. Introduction

High-power, high-brightness diode lasers are widely employed for many applications, such as cutting artificial materials [1], the pumping of solid state and fiber lasers [2,3], and security and defense, owing to their small physical size and high efficiency. Diode laser sources are typically coupled into a fiber for easy use via beam shaping and combining technologies. Spectral beam combining (SBC) [4–8] is an efficient way to realize power scaling and keep the beam quality close to that of a single emitter. However, the beam quality of a diode laser obtained by SBC is limited by the poor beam quality of the slow axis, owing to the inherent disadvantage of the broad waveguide. Efforts including optimizing the beam quality of a single emitter and off-axis SBC have been made towards improving the beam quality of SBC.

Off-axis SBC has yielded a beam quality of broad-area laser (BAL) diodes in excess of that of the single element, as reported by several groups [9–12]. A mini-bar with five elements was combined by off-axis SBC [9] using a gold-coated mirror and a spatial filter (SF), and a value of M^2_{slow} ≈2.4 was realized with an emission power of 0.56 W. The power was increased to 9 W with M^2_{slow} = 6.4 using the same method, and a calculated brightness of 79 MW cm^{-2} str^{-1} was reported [10]. The other approach to off-axis SBC involves using two gratings to form a V-shaped resonator, where the feedback is provided by a high reflectivity (HR) mirror. This method has yielded an output power in excess of 10 W with $M^2_{slow} < 14$ and $M^2_{fast} < 3$ [11, 12]. In these investigations, although a beam quality exceeding that of a single emitter was realized, the output power was low at most to the order of 10 W. In addition, off-axis cavities exhibit reduced electrical-to-optical efficiencies, owing to the asymmetric setup in which one lobe serves for feedback and there is a geometrical mismatch between the gain and mode profiles [13]. All the optical modes that transmit to the HR mirror, including high-order lateral modes, were entirely fed back to emitters. Not all the reflected modes contribute to the improvement of the beam quality. The entire reflection increases the feedback intensity, and hence reduces the efficiency.

Herein, we present a modified off-axis SBC method based on the concept of selective feedback. An HR mirror with a fixed width is employed to select and couple back the optical modes in the external cavity. The concept of selective feedback is discussed, and the light–

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current–voltage (L–I–V) characteristic is analyzed. The M^2 factors after combining are measured, and the current-dependent brightness is obtained.

2. Principle and experimental setup

A schematic of the off-axis SBC based on the concept of selective feedback is presented in Fig. 1(a). A diode laser array was employed in this setup. Collimation of the fast axis was performed by a beam-transformation system (BTS), which consists of a fast axis collimation lens (FAC) and a diagonal lens array for rotating the beams by 90°. In contrast, the slow axis was collimated by a single cylindrical lens. A Fourier transform lens (FTL) was used to overlap the collimated beams of the array elements on the Fourier plane, where the reflection grating (RG) was placed. This transformed the beam from the center element of the laser array into the RG with an incident angle of α. After the beam passed through the grating, a beam-expanding system (BES) was employed to expand the beam in the slow axis. Figure 1(b) presents a schematic of the BES and the selective-feedback parts. A stripe mirror (SM) coated with an HR dielectric film was placed between the BES and the SF to feed back the optical field. The purpose of using the BES was to select the optical modes more easily. An output coupler (OC) with a low reflectivity was used to obtain a stable operation of external cavity. Regarding the SF, both sides had a sharped edge, which was used to prevent the high-order lateral modes from hitting the OC and consequently being fed back. As a result, the beam quality in the slow-axis direction was further improved, and the diode laser source could achieve a stable and high-power output.

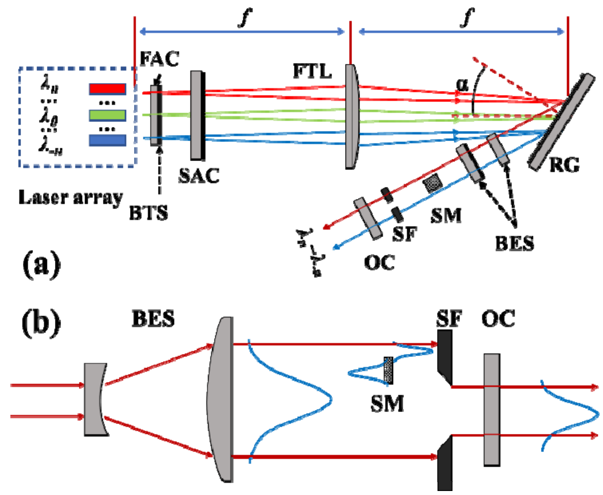

Fig. 1. (a) Schematic of the off-axis SBC with selective feedback from the top view and (b) optical path diagram after the grating. FAC: fast-axis collimation lens, BTS: beam-transformation system, SAC: slow-axis collimation lens, FTL: Fourier transform lens, RG: reflection grating, BES: beam-expanding system, SM: stripe mirror, SF: spatial filter, OC: output coupler.

Figure 2 presents details regarding the concept of selective feedback. For the BAL array, in the absence of any built-in index difference in the in-plane direction the gain induces a lower refractive index in the active region, and the BAL array performs gain guidance [14]. In this situation, the BAL is weakly perturbed by the gain, and the far-field predominantly consists of two main lobes according to the Huygens–Fresnel diffraction integral [15]. One of these lobes can be selectively reflected back, forming an external cavity [16]. Here, selective feedback was applied in the beam, combined with the focused geometry using the FTL and grating. The reflected light is coupled back into the array, is amplified, and forms a sharp single-lobed far-field output, as illustrated in Fig. 2(b). In the traditional off-axis SBC [9–12], a D-shaped HR mirror is used to supply feedback by overlapping with the beam from the upper side. The HR mirror is larger than the beam, and all the overlapped light is fed back indiscriminately. In contrast, the HR mirror providing selective feedback has a fixed width, and is adjusted to an optimum position in the beam in order to more accurately select and amplify the special groups of lateral modes in the external cavity.

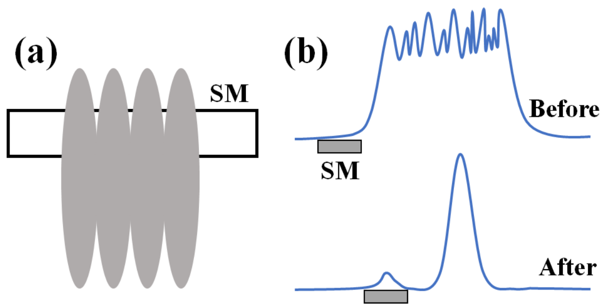

Fig. 2. (a) Schematic of the selective feedback and (b) partial reflection by the HR mirror before and after combining. SM: stripe mirror.

In the experimental setup, the commercial 976-nm diode laser array consisted of 19 elements, each around 100 µm wide and with a pitch spacing of 500 µm. The epitaxial structure of laser array is the super-large optical cavity (SLOC) structure. The gain medium is two InGaAs/GaAsP quantum wells (QWs) and embedded in the 3.0 µm and 1.2 µm-thick *n*- and *p*-type $Al_{0.1}Ga_{0.9}As$ layers. The top and bottom cladding layers are respectively *p*- and *n*-doped $Al_{0.15}Ga_{0.85}As$ and $Al_{0.2}Ga_{0.8}As$. The cavity length of the laser array was 1.5 mm. The laser array had a standard antireflection coating on the front facet with a reflectivity of 5%, and an HR coating on the back facet with a reflectivity of 95%. At a high injection current, the M^2 factor of a single emitter was approximately 14–16 along the slow axis, and near diffraction-limited in the fast axis. When a current of 55 A was applied to the laser array, the output power under free running conditions was approximately 48 W. The collimation of the fast axis was performed using a BTS, which consisted of an FAC with a focal length of 365 µm and a diagonal lens array for rotating the beams by 90°. The slow axis was collimated by a single cylindrical lens with a focal length of 22 mm. The FTL, with a focal length of 400 mm, transformed the beam from the center element of the laser array into the RG with an incident angle (α) of 55°. The RG consisted of 1,800 lines/mm, and its measured 1st-order diffraction efficiency was 87% at a wavelength of 976 nm. After a 4-fold BES, the beam width along the slow axis was approximately 10 mm. The HR SM was 3.3 mm wide, and the reflectivity of the OC was 4.6%.

3. Results and discussion

Figure 3 shows the L–I–V characteristics of the diode laser array combined with off-axis SBC with selective feedback. This was measured using an air-cooling system at a temperature of 25 °C. As can be observed, the output power at 55 A was 20.7 W and no thermal roll-over appeared. To our best knowledge, this is the highest emission power achieved by off-axis SBC. Higher injection-current led to an instable temperature controlling, so the data were measured below 55 A. The slope efficiency reached its maximum of 0.57 W/A, and then decreased. The maximum electrical-to-optical efficiency was approximately 27%, which is lower than that of conventional SBC [7].

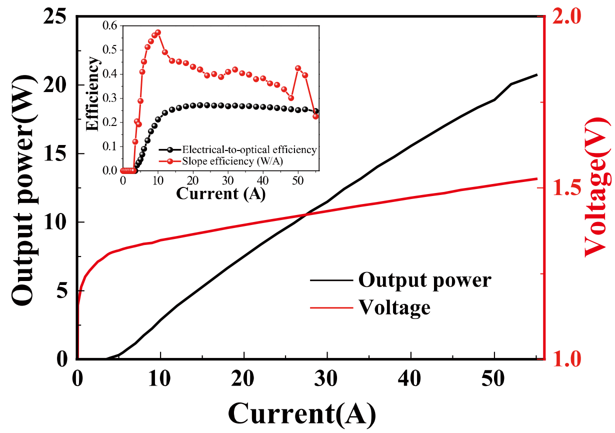

Fig. 3. L–I–V characteristics of the diode laser array combined with off-axis SBC with selective feedback. The inset graph shows the efficiency characteristics of off-axis SBC.

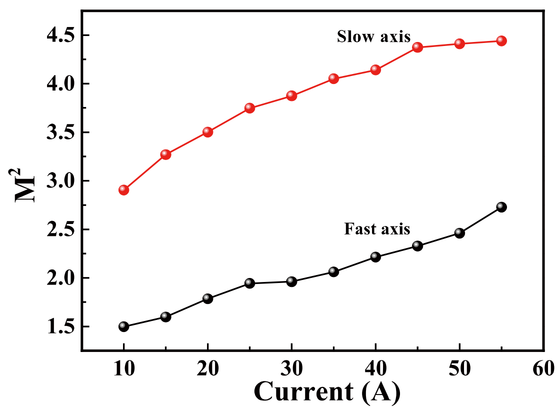

Fig. 4. M^2 factors in the fast and slow axes.

The beam quality of the combined laser array was measured by Ophir-spiricon M^2-200s-FW, and the beam profiles with the definition of $1/e^2$ value were measured at different injection currents. The obtained M^2 factors in the fast axis (M^2_{fast}) and slow axes (M^2_{slow}) are illustrated in Fig. 4 as a function of the injection current. It can be observed that both M^2 factors grow up with the increase of current. M^2_{slow} increases from 2.9 to 4.4, and M^2_{fast} increases from 1.5 to 2.7. Although the M^2_{fast} value of 2.7 was a little higher than that of a single emitter (<2), the M^2_{slow} value is considerably lower than that of a single emitter (M^2 ~14–16). This represents approximately a three- to four-fold improvement. This result is also significantly better than the previously reported value (M^2_{slow} ~6.4) achieved by traditional off-axis SBC [10] and standard SBC (M^2_{slow} ~10.9) [7]. The other important parameter for evaluating the performance of high power diode lasers is the brightness, which is defined as

$$B = \frac{P}{\lambda^2 M^2_{fast} M^2_{slow}}, \tag{1}$$

where P represents the output power and λ is the center wavelength of the laser. The calculated brightness is plotted in Fig. 5 as a function of the current. As shown in Fig. 5, the brightness initially increases and reaches its maximum of 190 MW cm^{-2} str^{-1} at 50 A, which is about 2.4 times higher than that given in a previous report (~79 MW cm^{-2} str^{-1}) [10]. Subsequently, the brightness decreases. The attainment of the maximum brightness is owing to the M^2 factors increasing with the injection current.

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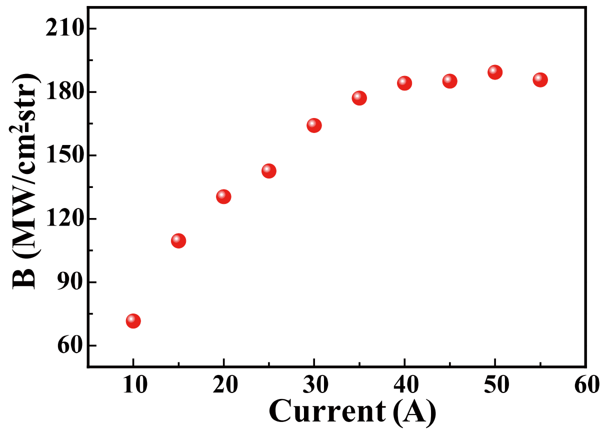

Fig. 5. Brightness with respect to the injection current.

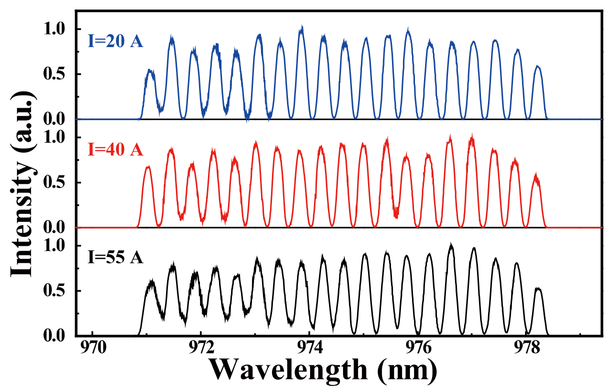

Fig. 6. Lasing spectra of off-axis SBC with selective feedback at different currents.

Selective feedback provides high-quality feedback without any crosstalk between the adjacent emitters [17] according to the measured lasing spectra shown in Fig. 6. The lasing spectra clearly exhibit 19 peaks corresponding to the 19 elements in the laser array, even at a high injection current of 50 A. The measured wavelength spread $\Delta\lambda$ was 7.16 nm, which agrees with the value of 7.17 nm calculated using the equation $\Delta\lambda = (\lambda_n\text{-}\lambda_{\text{-}n}) = (2n\beta\Lambda\cos\alpha)/f$ [7]. Here, $(2n + 1)$ is the number of emitter in laser array, β is the pitch spacing between 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, which is 55° in this work.

4. Conclusion

We have presented off-axis SBC for a diode laser array with a high beam quality, based on the concept of selective feedback. An HR mirror with a fixed width was adjusted to an optimum position to selectively couple the lateral modes back to the array. The efficiency and power were improved compared with traditional off-axis SBC. The beam quality was improved by a factor of between three and four compared with that of a single emitter. The combined power reached 20.7 W, and a brightness as high as 190 MW cm^{-2} str^{-1} was achieved.

The most prominent advantage of off-axis SBC is its high beam quality, exceeding that of a single emitter. The selective feedback mechanism is simple, but it noticeably improves the efficiency and power, despite the fact that the efficiency is still lower than that of conventional SBC. More efforts will be performed on enhancing the efficiency and output power in our future work.

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