Narrow-wavelength-spread spectral combining laser with a reflector for a double pass with a single grating

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We proposed a novel wavelength-spread compression technique for spectral beam combining of a diode laser array. A reflector, which is parallel to the grating, is introduced to achieve a double pass with a single grating. This facilitated the reduction of the wavelength spread by half and doubled the number of combined elements in the gain range of the diode laser. We achieved a power of 26.1 W under continuous wave operation using a 19 element single bar with a wavelength spread of 6.3 nm, which is nearly half of the original wavelength spread of 14.2 nm, demonstrating the double-compressed spectrum capability of this structure. The spectral beam combining efficiency was 63.7%. The grating efficiency and reflector reflectance were both over 95%; hence, the efficiency loss of the double-pass grating with a reflector is acceptable. In contrast to double-grating methods, the proposed method introduces a reflector that efficiently uses the single grating and shows significant potential for a more efficient spectral beam combining of diode laser arrays.

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High-power diode lasers significantly contribute to the rapid development of various fields, including optical pumping of solid-state lasers, materials processing, and national defense, owing to their superior efficiency, low price, small size, stability, and reliability[1]. The output power of diode lasers has been significantly enhanced with the progress in semiconductor materials. For example, an output power of approximately 1 kW (continuous wave, CW) has been achieved from a single 1 cm, 940 nm diode laser bar operated at 900 A and at a heat-sink temperature of 20°C[2]. However, diode lasers are limited by their low beam quality and low brightness. The improvement of their output power, while maintaining beam quality, is of key importance. Spectral beam combining (SBC) has been demonstrated as one of the most efficient approaches to achieve high beam quality and brightness for the development of high-efficiency diode lasers[3]; several demonstrations of SBC at different wavelengths have been reported. In 2000, Daneu *et al.*, for the first time, to the best of our knowledge, experimentally demonstrated the feasibility of SBC. They achieved beam combining of an 11 element diode laser array with a wavelength spread of 21.9 nm and CW output power of 1.8 W[4]. Chann *et al.* demonstrated near-diffraction-limited SBC of a slab-coupled optical waveguide laser diode array with a wavelength spread of 36 nm, and the beam quality $M^2 < 1.35$ in both directions, yielding a peak output power of 35 W[5]. Zhang *et al.* used a −1st-order transmission grating instead of a first-order reflective grating as the dispersion element. A spectrum span of 24.1 nm and CW output power of 50.8 W were achieved[6]. Zhu *et al.* introduced a beam transformation system (BTS) in the conventional SBC structure, which yielded a CW output power of 58.8 W and wavelength spread of 12.7 nm[7].

SBC can achieve high output power and beam quality by broadening the wavelength range. Theoretically, more emitters correspond to a broader wavelength range. The number of combined emitters is limited, as the gain bandwidth of diode lasers is usually tens of nanometers. Furthermore, the diffraction efficiency of a grating used in the SBC changes with the wavelength, and the range of high efficiency is limited. For example, a fused-silica polarization-independent transmission grating can provide a diffraction efficiency larger than 92% in a bandwidth of 100 nm[8]. Both factors limit the diode laser power in SBC. An ultra-high brightness with a narrow wavelength spread is necessary in various applications, including laser pumping and nonlinear frequency conversion. If the wavelength spread of each emitter is reduced, then we can obtain a narrow-wavelength high-power diode laser and add more emitters in the limited range for a higher laser power. The methods to obtain a narrow wavelength spread can be categorized into three types. The first type involves the use of a large-focal-length transform lens in the SBC; however, this lowers the stability of the system. The second method focuses on decreasing the interval between adjacent emitters in the diode laser array and using an optical imaging system[9], which shows a disadvantageous increase of the crosstalk between adjacent emitters and feedback reduction. The third method improves the diffraction ability by increasing the line density of the grating. Nevertheless, the line density of the grating cannot increase infinitely, owing to the limitation that the grating period cannot be smaller than half of the diode laser's wavelength in the SBC; in addition, the feasibility of industry manufacturing of high-line-density gratings is relatively low, owing to the high cost.

Recently, Zhou *et al.* proposed a non-parallel double-grating structure to narrow the whole spectral span of combined beams in the SBC technique. Two transmission gratings were employed in order to enhance the diffraction ability; the CW output power was 30.9 W with a wavelength spread of 7 nm, which corresponded to half of the spectral span in a conventional SBC system[10]. Compared with the non-parallel double grating, we propose a single transmission grating with a reflector to improve its diffraction ability; the reflector is parallel to the grating. The transmission grating is fully used, owing to the double diffraction, and the wavelength spread is narrowed down to 50%. The incident angle on the grating is limited to several degrees around the Littrow angle to obtain a high efficiency. After the first diffraction at the grating, the divergence angle of adjacent beams decreases to half of the initial value. Then, the beams are reflected by the reflector and pass through the grating again. The beam spot has the minimum size on the grating, achieved by adjusting the positions of the grating and reflector; adjacent beams become parallel after the second diffraction. Furthermore, this enables an easier method for adjusting the optical path, as the output and input planes are on opposite sides of the transmission grating, and the angle between the incident and diffracted beams is approximately 90°.

In this study, a single transmission grating and reflector are used for SBC, which demonstrated a completely new way of double-increased spectral differential by a two-times pass of a single transmission grating with a reflector. The experimental results are given in the following. At the pumping current of 60 A, a CW output power of 26.1 W and wavelength spread of 6.3 nm are achieved. The beam quality M^2 is 2.0 in the horizontal and 10.5 in the vertical directions, while the SBC efficiency is 63.7%.

Figure 1 shows a schematic of the improved SBC, similar to the conventional SBC setup. The cavity consists of a 940 nm commercial diode laser array with 19 emitters; anti-reflection (AR) coating is applied on the front facet of the array. The pitch of each emitter is 500 μm, while that of the active layer is 100 μm. The threshold current and output power specifications of a single diode laser are 8 A and 3 W, respectively. In addition, the divergence angles at 95% power along the fast and slow axes are 46° and 9°, respectively. The divergent beams along the vertical direction are collimated using a fast-axis collimator (FAC), which decreases the divergence angle along the fast axis below 8 mrad. A BTS as a beam shaping system (essentially, a 45° inclined micro cylindrical lens array) is employed to rotate the beams by 90°, i.e., the fast and slow axes are interchanged. Both FAC and BTS are mounted on a bottom tab. After passing the BTS, the beams in the vertical direction are collimated using a second plano-convex lens, called a slow-axis collimator (SAC), with an effective focal length of 60 mm, which ensures that the residual divergence angle is the same as that in the horizontal direction. The cylindrical transform lens with a focal length of 300 mm is placed one focal length away from the diode laser and employed to image the beams onto the transmission grating. The transmission grating with a line density of 1500 mm^{-1} is set with the grooves perpendicular to the slow axis under the Littrow angle and placed less than one focal length away from the transform lens. Moreover, the diffraction efficiency of the −1st-order is over 94% at 940 nm for both transverse-electric (TE) polarized and transverse-magnetic (TM) polarized waves[11]. The transform lens makes all of the beams partially overlapped on the grating. In addition, in order to compress the whole wavelength spread and ensure that all beams could pass through the single grating twice, a gold-coated reflector with an average reflectance of 96% in the range of 700–2000 nm is introduced. The diffracted beams are incident on a flat output coupler with a reflectivity of 20%, which completes the external cavity. Only the output beams with propagation directions perpendicular to the output coupler can contribute to the feedback and oscillations to form laser beams.

In this study, the front facet of the diode laser array is AR-coated to eliminate the impact of inner-cavity feedback; therefore, the laser resonator is formed by high-reflector coating on the rear facet of the diode laser array and output coupler. Each element of the array corresponds to a different incident angle on the grating.

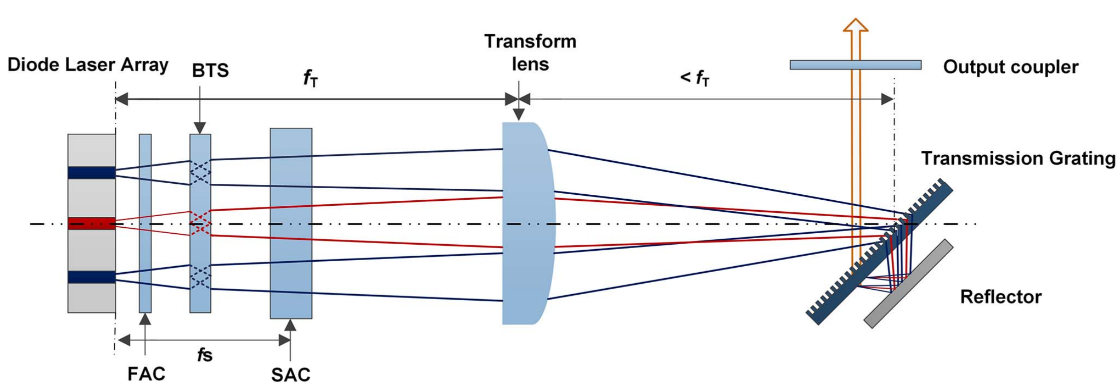

Fig. 1. Schematic of the SBC system with a double-pass transmission grating and reflector.

Each beam corresponds to a different feedback and laser beam at a unique wavelength that varies monotonously along the array. Therefore, all emitter beams are spatially overlapped into a single output beam in both the near- and far-fields; the beam quality is equal to that of a single emitter. In order to obtain the highest diffraction efficiency, the diffraction angles of all emitter beams are equal to the Littrow angle of the grating. The diffraction equation of the grating is

$$d \cdot (\sin\theta_i + \sin\theta_d) = m\lambda_i, \tag{1}$$

where d is the grating period, θ_i and θ_d are the incident and diffraction angles, respectively, λ_i is the wavelength of the ith emitter, and $m = -1$. When $\lambda = 940$ nm, and $d = 1/1500$ mm, $\theta_{\text{littrow}} = \theta_d = \theta_0 = 44.8°$; therefore, Eq. (1) can be expressed as

$$d \cdot \cos\theta_i \mathrm{d}\theta_i = \mathrm{d}\lambda. \tag{2}$$

The whole wavelength-spread $\Delta\lambda$ is

$$\Delta\lambda = (d/f_T)\cos\theta_i\Delta x, \tag{3}$$

where Δx is the interval between the emitters of the array, and f_T is the focal length of the transform lens. Using the parameters employed in our experiment, the calculated whole wavelength spread of the diode laser array is 14.2 nm.

Figure 2 shows a schematic of the improved SBC with a double-pass single-grating setup. The theoretical analysis is similar to that for the conventional SBC. However, the distance between the transform lens and transmission grating is smaller than f_T. Therefore, after the beams pass through the grating for the first time, the differential equation can be simplified:

$$d\cos\theta_i\mathrm{d}\theta_i + d\cos\theta_d\mathrm{d}\theta_d = \mathrm{d}\lambda. \tag{4}$$

When all of the beams pass through the grating for the second time, they are under the same diffraction angle. Therefore, the differential equation becomes

$$d\cos\theta_{i2}\mathrm{d}\theta_{i2} = \mathrm{d}\lambda. \tag{5}$$

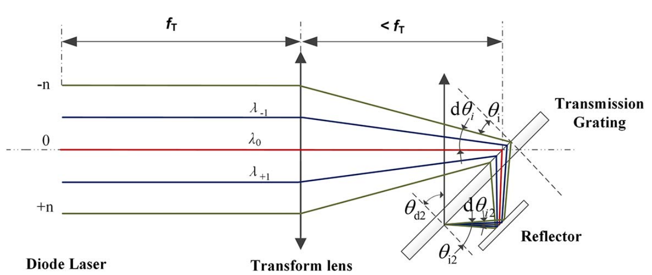

Fig. 2. Schematic of the proposed approach with a double-pass transmission grating and reflector.

Both incidence angles (first and second incidences) of the central beam on the grating are equal to the Littrow angle, hence, $\theta_i = \theta_{i2} = \theta_d = \theta_{\text{littrow}} = 44.8°$; according to the geometrical relationship, $\mathrm{d}\theta_d = -\mathrm{d}\theta_{i2}$, the wavelength spread is

$$\Delta\lambda = (d/2f_T)\cos\theta_i\Delta x. \tag{6}$$

The comparison between Eqs. (3) and (6) shows that the calculated wavelength spread is 7.1 nm, narrowed down to 50% of that in the conventional SBC, when the other experimental parameters are fixed. Therefore, the new approach, by adding a reflector to achieve double pass with a single grating, can double the number of emitters in the limited gain range and achieve a high-power diode laser. Using Eq. (6), we can show that the focal length of the transform lens f_T is inversely proportional to the wavelength-spread $\Delta\lambda$; therefore, the focal length of the transform lens could be two-times smaller, while maintaining the wavelength spread. Consequently, the length of the resonant cavity can be significantly reduced, which implies that the diode laser has a more compact structure, more stable mode, and smaller size.

The spectral distribution of the output beams after the SBC is shown in Fig. 3. There are 19 resonance peaks, which correspond to the 19 beams from the emitters. Each element is stabilized at a unique wavelength without

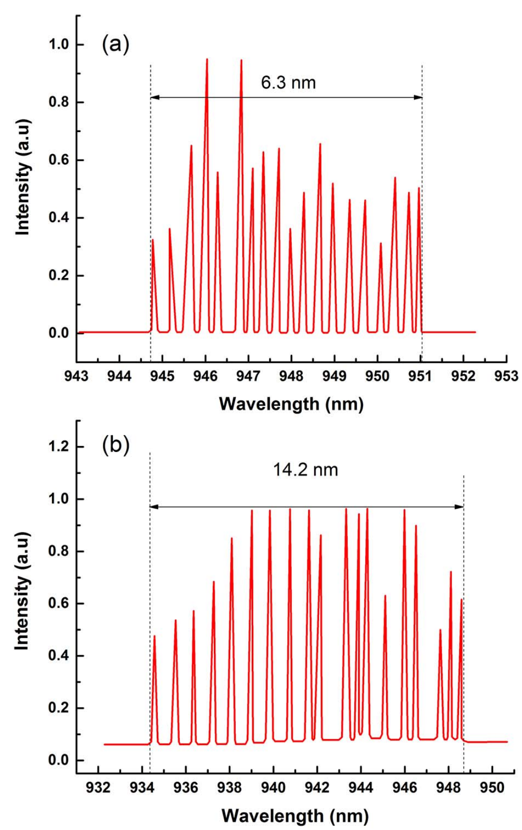

Fig. 3. (a) Spectral characteristic of the system with a single grating and double pass using a reflector. (b) Spectral characteristic of a conventional SBC laser.

influences from neighboring emitters. The wavelength spread of each emitter is reduced, and hence, the crosstalk is effectively prevented. The 'smile' effect in the vertical direction is changed to the spatial displacement in the horizontal direction by BTS. The spatial displacement in the horizontal direction influences the locked wavelength of each emitter. Hence, the center wavelength of each element is changed, which results in the wavelength spread of interval elements not being uniform. All peaks have almost the same intensities; therefore, the 'smile' and edge effects are reduced. Figure 3(a) shows spectral characteristics curves of the single grating with a reflector. The whole wavelength spread is 6.3 nm, which is slightly smaller than the theoretical value. This is most likely owing to the fact that the focal length of the transform lens for a longer wavelength is more than f_T of 300 mm. Figure 3(b) shows spectral characteristics of a conventional SBC laser. The spectral span is 14.2 nm, consistent with the calculated value. The comparison between Figs. 3(a) and 3(b) shows that the wavelength spread is reduced by half, which demonstrates the efficiency of the proposed method. The center wavelength of the output beam can be locked at different values by rotating the transmission grating of the SBC cavity.

Figure 4 shows the CW output power of the narrow-wavelength-spread SBC, its free-running mode power, and electro-optical conversion efficiency. The results show that the threshold current density from the initial value of 8 A decreases to 6 A, and that the SBC power can be larger than the free-running power when the operating current is around the threshold current. In our experiment, the front facet of the diode laser array is AR-coated with a reflectivity of 1%. When the diode laser array is running in the free modes, the feedback of the inner-cavity is weak and requires a higher current to form the laser's oscillations. However, in the external cavity, the output coupler with a reflectivity of 20% can provide a strong feedback, and the threshold current is smaller than that of the free modes. The maximum SBC CW output power is 26.1 W with an electrical-to-optical (E-O) efficiency of 22.9% at a pumping current of 60 A. In the free-running mode, the maximum output power is 41.5 W at the same current of 60 A. The beam combining efficiency is 63.7%, defined as the ratio between the SBC and free-running mode powers. The main cause of the low combining efficiency is the loss at the grating, because the theoretical diffraction efficiency of the −1st order is over 94%, but the actual diffraction efficiency is about 90% in experiment. Besides, the surface scattering and reflection of all optical components in the cavity also cause a power loss. On the other hand, the combining efficiency is related to the reflectivity of the output coupler. The reflectivity of the output coupler cannot be too high or too low, otherwise the beam combining efficiency will be lower. In our experiment, the reflectivity of the output coupler is as high as 20%, which will also lead to a power loss. Therefore, if the diffraction efficiency of the grating is over 99%, after a double pass through the grating, the efficiency would be still over 98%. So, the development of highly efficient gratings is of key importance for SBC. In previous studies, we designed and fabricated polarization-independent gratings using the simplified modal method[11–14]. The diffraction efficiency of the −1st order (Littrow angle) was larger than 97% for a bandwidth of tens of nanometers. The most important advantage is that the laser cavity's size can be reduced by half, and the number of combining elements can be doubled, while maintaining a fixed wavelength spread. Therefore, there is a trade-off between the high efficiency and laser cavity size. We chose the latter in order to achieve a smaller disturbance of the output laser beams and high stability of the laser modes. In addition, the combining efficiency can be increased if all of the optical components in the cavity are AR-coated, and the reflectance of the reflector is improved; meanwhile, the reflectivity of the output coupler is optimized.

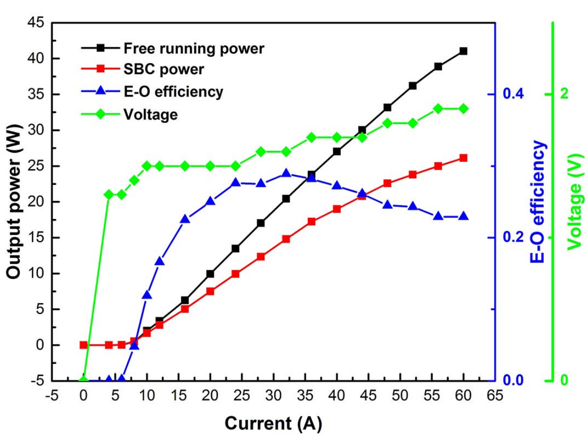

Fig. 4. CW output power and E-O efficiency.

Figure 5 shows the caustic of the output beam along the fast axis and the slow axis, respectively. The values of the beam width at different positions were measured throughout the experiment, and the solid lines represent the numerical fits of the experimental data. The combining beam is focused by a lens of 50 mm focal length. The beam quality M^2 in the vertical direction (slow axis) is 10.5, while that in the horizontal direction (fast axis) is 2.0. Therefore, the beam qualities in both directions are similar to those of an individual emitter. The output power increases with the pumping current; however, the beam quality slightly decreases, owing to the increase in the divergence angle of the emission from the diode laser array.

A large potential market exists for high-power, high-beam-quality, narrow-wavelength-spread diode lasers. Competitive cost and equivalent reliability are of key importance to make the diode lasers more desirable than the well-established solid-state lasers. However, their output power is limited by the gain bandwidth and grating efficiency; therefore, it is essential to develop methods to narrow the wavelength spread. In terms of system stability and crosstalk between adjacent emitters, utilizing a large-focal-length transform lens or optical imaging system is not an efficient approach. Another approach would

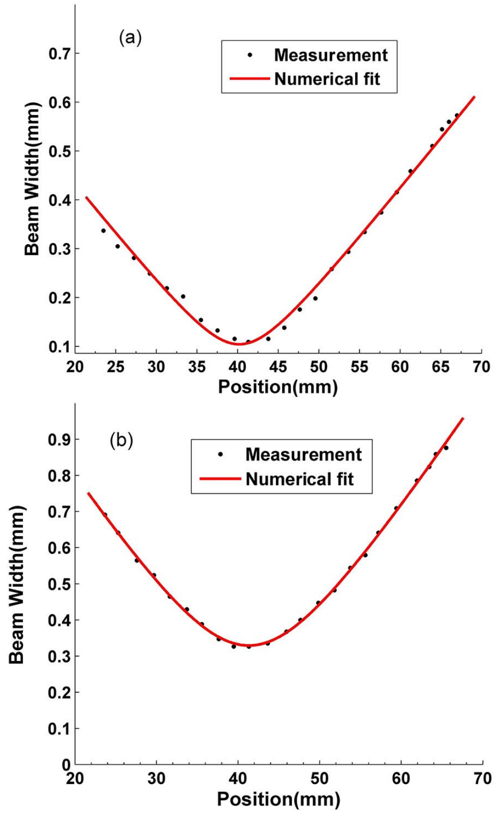

Fig. 5. Beam quality measurment of the diode laser array after SBC using numerical fits. (a) Fast axis. (b) Slow axis.

be to enhance the diffraction ability of the grating, for example, using a double-grating structure; however, the production cost would increase.

In this study, we proposed an efficient method for narrow-wavelength-spread SBC with a reflector to achieve a double pass using a single grating. The grating could be efficiently employed by double diffraction. Furthermore, the wavelength spread was only half that in the conventional method, assuming the other parameters were the same. The cavity length could be approximately decreased by half while maintaining a fixed wavelength spread.

We achieved a wavelength spread of 6.3 nm and CW output power of 26.1 W. The obtained E-O conversion efficiency of 22.9% at 60 A is relatively low, while the combining efficiency of approximately 63.7% at 60 A is acceptable. Most of the observed loss could be attributed to losses in the optical coatings and grating. Therefore, the E-O efficiency could be significantly increased with the performances of the optical components in the cavity. This implies a trade-off between the combining efficiency and compact structure of the diode laser.

If the grating and the reflector have a high efficiency of 98%–99%, the total loss of the grating and the reflector should be less than 3%–6%, which ought to be acceptable for most applications. Besides, if the optical damage threshold of the grating and the reflector are high enough, this structure can generate more output power of up to kilowatts if more powerful bars are used. Therefore, this novel technology has significant potential for industry applications.

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