Coherent beam combination of broad-area laser diode array using off-axis external cavity with double feedback

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In this letter, we demonstrate coherent beam combination of laser diode array using the external Talbot cavity with double feedback. The double feedback elements consist of grating and high-reflection plane mirror. Compared with single high-reflection plane mirror feedback, the external Talbot cavity with double feedback reduce the number of interference strips in the far-field pattern and narrow spectral line-width of the laser diode array. The results indicate that the application of the external Talbot cavity with double feedback produces a clear far-field interference pattern. In addition, line-width is reduced to 0.15 nm full-width at half-maximum (FWHM).

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High-power broad-area laser diode arrays (LDAs) are of great interest due to their high efficiency, long lifetime, and small size[1−6]. Because of its large emitter aperture dimension along the slow axis, each broad-area laser diode in the array has many spatial modes. As a result, the beam quality of LDAs is very poor in the slow axis. Various means to improve the beam quality of LDAs have been studied[3−5]. However, these previous methods have not been able to improve the spatial coherence of LDAs. Many applications of LDA, such as in nonlinear frequency generation, directed energy, and space communication, require coherent beams[7]. External Talbot cavity is often used to achieve coherent beam combination[7−9]. However, broad-area laser diode has tens of spatial modes, so that it is very difficult to achieve coherent beam combination from broad-area LDA. In Refs. [9,10], in-phase output laser beams with narrow line-width were obtained from a broad-area LDA through quarter-Talbot cavity. The optical efficiency of this setup was very low because of the limited number of phase-locked emitters. Liu *et al.*[7] designed a V-shape external Talbot cavity that is capable of coherent beam combination of a broad-area LDA. Liu *et al.*[10] also designed a closed-V-shape external Talbot cavity with double feedback gratings that demonstrated excellent ability to select wavelength. Using the cavity, they was able to reduce the spectral line-width to 0.07 nm. In this study, we demonstrated a double-feedback off-axis external Talbot cavity. The two feedback elements consisted of plane mirror and blazed grating, respectively. The designed external cavity was simple in construction and required fewer optical elements.

Figure 1 is a schematic diagram of the experimental setup. The LDA used in the experiment was comprised of 49 broad-area laser diodes with a nominal wavelength of 808 nm. The pitch between emitters was 200 μm and the emitting area measured was 1×80 (μm). A collimator (FAC) was used to collimate diverging beams along the fast axis (y-axis).

Due to the wide emitting dimension along the slow axis, each broad-area laser diode in the array has many spatial modes in the slow axis. Each spatial mode has a two-lobe profile in the far field with different angular positions[1−4,11−13]. In order to reduce the number of spatial modes, we designed the setup with an off-axis configuration with two feedback branches forming two laser resonant cavities. The upper resonant cavity consisted of the front facet/rear facet of the laser diode and the high-reflection plane mirror M. The lower resonant cavity comprised the front facet, rear-facet, folding mirror beam spreader (BS), and blazed grating G. Folding mirror BS was a plane mirror that reflects 90% of light to grating G. The transmitted light that struck charged-coupled derice (CCD) was used as the diagnostic beam. In the upper resonant cavity, a confocal system consisting of lens L1 and L2 imaged the diode array onto the back focal plane of lens L2. With the high-reflection plane mirror M positioned at half Talbot plane, the upper resonant cavity became a Talbot cavity. Thus, a cavity round-trip corresponded to the laser's oscillation between the image plane of the 49 emitters and the high-reflection plane mirror M. The round trip laser cavity length was equal to a Talbot distance ($2d^2/\lambda$), where d was the array image pitch and λ was the laser wavelength. Thus the near field of the array (image of LDA array) can be imaged back onto the array itself, so the feedback light was effectively coupled with the LDA. In addition, the light from each emitter was diffracted into

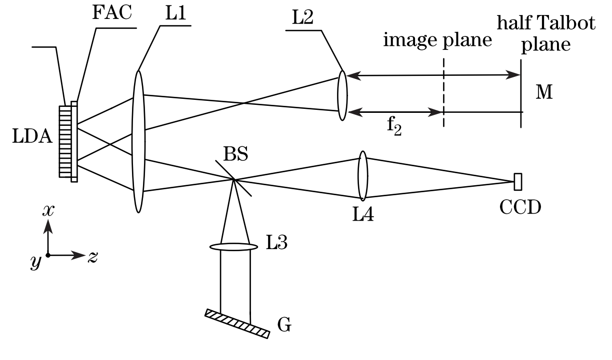


Fig. 1. Experimental setup.

the adjacent emitter, resulting in mutual coupling among emitters. The self-image of the laser array can then be calculated as follows[14]. The near field distribution of the laser array with 49 emitters can be expressed as[11]

$$E(x) = \left[\frac{1}{\sqrt{x_0}}\sin\left(\frac{m\pi x}{2x_0}+\frac{m\pi}{2}\right).rec\left(\frac{x}{x_0}\right)\right]\sum_{n=-24}^{24}\delta(x-nd), \tag{1}$$

where x_0 is the half width of the emitting area of each element (image of emitter) along the slow axis and m represents the order of spatial modes. We can obtain the spectrum of the near field by taking a Fourier transformation of Eq. (1) as follows

$$F(\xi) = F_0(\xi).\left(\frac{1}{d}\right)\sum_{n=-24}^{24}\delta\left(\xi-\frac{n}{d}\right), \tag{2}$$

where ξ is spatial frequency along the slow axis. Then, the free-space transfer function is[14]

$$H(\xi) = \exp(\mathrm{j}kz)\exp(-\mathrm{j}\pi\lambda z\xi^2). \tag{3}$$

Hence, the spectrum of the laser field at the z distance can be calculated as

$$G(\xi) = F(\xi)H(\xi) = \left(\frac{1}{d}\right)F_0(\xi)\sum_{n=-24}^{24}\delta\left(\xi-\frac{n}{d}\right) \cdot\exp(\mathrm{j}kz)\exp\left[-\mathrm{j}\pi\lambda z\left(\frac{n}{d}\right)^2\right]. \tag{4}$$

When propagation distance is $\frac{2d^2}{\lambda}$ (the laser direct back array plane), the spectrum can be expressed as

$$\begin{aligned}G(\xi) &= \left(\frac{1}{d}\right)F_0(\xi)\sum_{n=-24}^{24}\delta\left(\xi-\frac{n}{d}\right)\exp(\mathrm{j}kz)\exp(-\mathrm{j}2\pi n^2)\\ &= \left(\frac{1}{d}\right)F_0(\xi)\sum_{n=-24}^{24}\delta\left(\xi-\frac{n}{d}\right)\exp\left(\mathrm{j}\frac{4\pi d^2}{\lambda^2}\right).\end{aligned} \tag{5}$$

Compared with Eq. (2) and Eq. (5), the distribution at Talbot distance is identical to the original near field of the laser, which corresponds to a self-image.

In the lower branch, L1 and L3 form a confocal lens pair. The grating, which is arranged in a Littrow mount, is positioned ~100 mm away from L3. The first-order diffraction from the grating provides feedback to the LDA in the lower branch. The zero-order reflection off the grating can be used as laser output. The far-field pattern can be imaged onto CCD by lens L4. The focal lengthes of lens L1, L2, and L3 are 100, 200, and 200 mm, respectively, with transmission as high as 99% at 808 nm. M is a high-reflection plane mirror with a reflectivity of 99% at 808 nm.

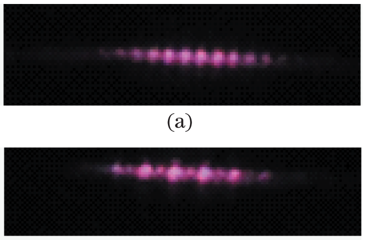
The off-axis external feedback can effectively reduce the number of spatial modes. Through the Talbot cavity, a few spatial modes can couple to self and the adjacent emitters. As a result, the LDA can generate interference strips in the far field.

At first, we operated the setup without the lower branch, thus forming a single feedback LDA. A set of clear interference strips was observed in the far-field after careful adjustment of high-reflection mirror M (Fig. 2(a)). Addition of feedback from the grating into the setup leads to the formation of a double feedback LDA. Figure 2(b) shows the far-field pattern of LDA with double feedback. Both Figs. 2(a) and (b) were measured with a driver current of 12 A. Compared with the far-field pattern of single feedback LDA, the number of interference strips in the far-field was significantly reduced by the application of double feedback.

Numerical simulation revealed that the number of interference scrips depends on the number of the spatial modes (Fig. 3). We simulated far-field interference strips uisng laser with 6 (Fig. 3 (a)) and 4 spatial modes (Fig. 3(b)). We found that the presence of less spatial modes leads to decreased number of interference strips. This shows that the external cavity with double feedback has more excellent mode-selection ability than that of single feedback.

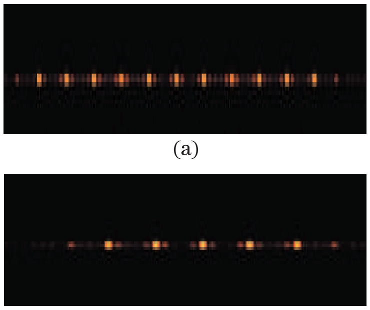
In addition, the grating plays a role in wavelength-selection, leading to narrowing of the line-width from 1.9 to 0.15 nm (FWHM). Figures 4(a) and (b) respent the spectra of free-running and double feedback LDA, respectively. A narrower line-width can be obtained by replacing the plane mirror with a blazed grating or a volume Bragg grating. However, this can result in weaker feedback because of the diffraction loss of grating, so that the threshold current can become elevated.

In conclusion, we apply the external cavity with double feedback in order to obtain coherent laser beams with a spectral line-width of 0.15 nm. The coherent beams generate clear and stable interference strips in the far field. Results of experimental and numerical simulations reveal that the external cavity with double feedback has more excellent mode-selection ability than that of single


(a)

(b)

Fig. 2. Far-field beam pattern. (a) Single feedback; (b) double feedback.


(a)

(b)

Fig. 3. Simulation of far-field beam pattern with different numbers of spatial modes. (a) 6 spatial modes; (b) 3 spatial modes.

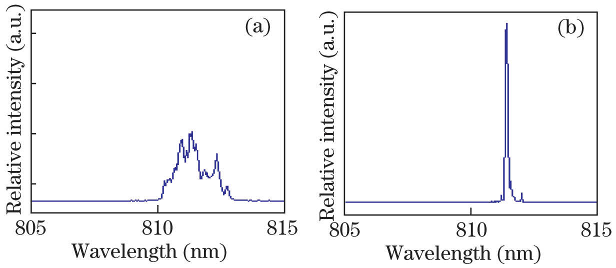


Fig. 4. Spectral profile of free-running LDA and double feedback LDA.

feedback. In addition, the cavity has simple structure with fewer optical elements.

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