Achieving single-lobed far-field patterns of broad area laser diode with external cavity feedback

Jianhong Ge (葛剑虹)[1], Jun Chen (陈 军)[1], Andreas Hermerschmidt[2], and H. J. Eichler[2]

[1] *The State Key Laboratory of Modern Optical Instrumentation, Zhejiang University, Hangzhou 310027*
[2] *Optisches Institut, Technische Universität Berlin, Straße des 17. Juni 135, 10623 Berlin, Germany*

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We demonstrate a technique for single transverse mode operation of high-power broad area laser diode (BAL). In the experiment, the HR mirror is used as an external cavity mirror and the grating is used as a wavelength selective component. By tiling the HR mirror and the grating, the number of transverse modes oscillating in the cavity can be limited and the spectral bandwidth of the laser diode can be reduced. A single-lobed near diffraction-limited laser beam with the beam divergence (FWHM) of 0.43°, the spectral line-width of 0.7 nm and the output power of 350 mW are obtained. With the feedback, the power density of the output laser beam is increased 6 times in comparison with the free running.
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In recent years high power semiconductor laser sources have become key elements in many applications such as solid-state laser pumping, optical measurement and free-space optical communications due to their small size and high efficiency. The most direct method to increase the optical output power is to increase the dimension of the lasing medium such as arraying the stripe and widening the stripe. However, these kinds of structure will cause strongly incoherent light emission at high power, inducing multi-transverse modes oscillation and no single-lobed diffraction-limited laser beam could be achieved[1]. Many techniques for increasing the spatial coherence of high power laser diodes have been studied. An external cavity such as the Talbot cavity has been used and the diffraction-limited output beams were obtained[2]. Injection locking techniques have been applied to increase the spatial coherence[3]. Unstable resonators have also been used to obtain diffraction-limited beams from large-active-area laser diodes[4]. While injection locking technique requires a master laser, feedback isolation optics and fine control of the temperatures of the master and slave lasers. It is also difficult to fabricate unstable resonator of laser diode because the techniques for etching curved mirror facets are not well developed.

In this paper, we introduce a simple external cavity structure which is easy to adjust, insensitive with the misalignment of optical component and also has good mode discrimination. With the setup, a single-lobed near diffraction-limited laser beam has been obtained.

The experimental scheme is shown in Fig. 1. The BAL used in experiment is a GaAsP/AlGaAs structure gain-guided broad area laser diode (from Ferdinand-Braun-Institute), with a 100-μm-wide emitting cross-section and AR coating at the front facet. It emits in a wider far-field angle and does not exhibit an intensity minimum at the center of the slow-axis pattern as shown in Fig. 2(a). The BAL has a threshold of 964 mA and a maximum output power of 2 W at 3.01 A. Cylindrical lens L_1 is used to collimate the laser beam at the direction of fast axis. At the plane of the slow axis, laser beam part 1 from the BAL is collimated through L_2 and focused on the HR mirror by L_3, which is placed at the image plane of the BAL. When the mirror is tilted with respect to the slow axis direction, only the beam which perpendicularly incident on the mirror can be reflected back to the BAL along the original path and gets amplified and forms the output beam with symmetric distribution. Through such a selectable amplification, only this mode can oscillate and extract most of the oscillation. Other parts of the beam will leak out after the round trips inside laser cavity. The transverse mode of feedback is selected through the combination of tilting the HR mirror and moving the prism. Laser beam part 2 from the BAL is reflected out by a 45° prism which is placed at the far field focal plane and focused by L_4, then incident at the grating which is also placed at the image plane, with its fringes parallel to the slow axis. At 808 nm approximately 62% of the intensity is reflected into the first order. The grating used here is a plane mirror at the slow axis as well as a wavelength selective component at the fast axis. Only the first diffraction order of the grating can be reflected back into the BAL.

The output power of the BAL with and without feedback of external cavity is shown in Fig. 3(a). When the drive current is lower than 1.5 A, the output power with

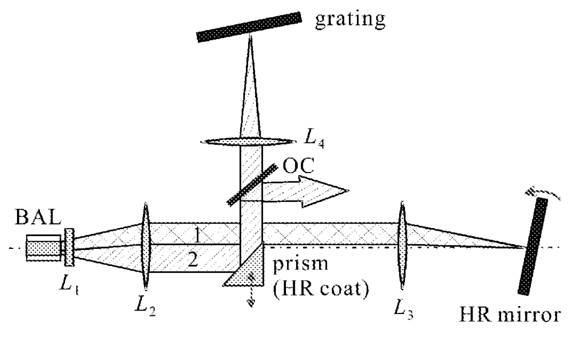

Fig. 1. Experimental setup at slow axis. L_1: fast axis collimating (FAC) lens, f_1 = 500 μm; L_2: cylindrical lens, f_2 = 100 mm; L_3, spherical lens, f_3 = 200 mm; L_4: cylindrical lens, f_4 = 200 mm; OC: output coupler, 60% reflectivity at 808 nm; grating: 400 lines/mm blaze angle of 10° (850 nm); HR mirror: flat mirror with surface high reflectivity coated at 808 nm.

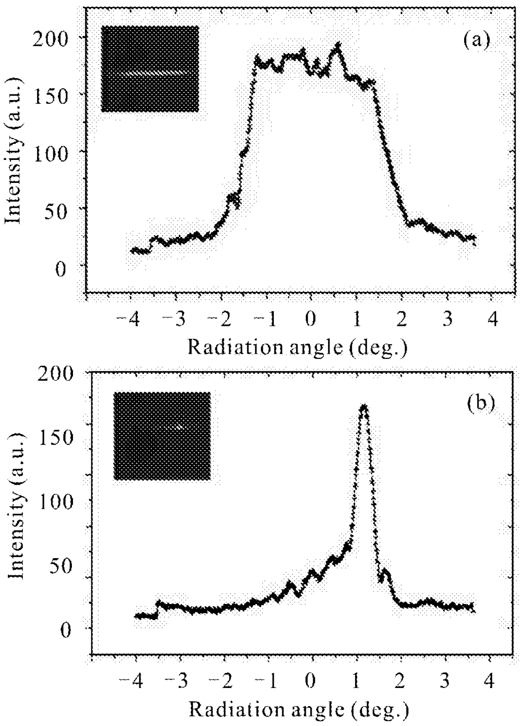

Fig. 2. Far field beam profile at $I = 1.5$ A. (a) Free running output; (b) output with feed back of the external cavity with the HR mirror and the grating.

feedback is higher than free running. When the drive current is increased to more than 1.5 A, the output powers with feedback and free running are almost the same. The influence of the feedback is very weak at high drive current because the laser emitting is relatively strong compared to the feedback.

The power of the lobe part and the total beam with feedback is shown in Fig. 3(b). The coupling efficiency takes the form $C = I_1/I_2$, where I_1 is the power of the lobe and I_2 is the power of the total beam. When the drive current is lower than 1.5 A, the coupling efficiency is approximately 70%. Consider the beam divergence, the power density increases 6 times compared with that of the free running case.

Threshold reduction is also observed in the experiment. With feedback, the threshold of BAL reduced from 964 to 800 mA. The results can be explained by[5]

$$G = 1/\tau_{\rm ph} - R_{\rm sp}/S_{\rm lm} - 2\alpha K_{\rm c}\sqrt{S_{\rm i}/(1+\alpha^2)S_{\rm lm}}, \quad (1)$$

where G is the gain of laser, $\tau_{\rm ph}$ is the photon number lifetime, $R_{\rm sp}$ is the spectral density, $S_{\rm lm}$ is the photon number in the locked mode, α is the line-width broadening factor, $K_{\rm c}$ is the coupling coefficient, and $S_{\rm i}$ is the photon number injected into the laser cavity. The first term on right-hand side is the cavity loss rate for the free running laser. The second term represents the influence of spontaneous emission. The last term represents the effect of external light injection on the threshold. We can find that its role is to reduce the threshold.

The output beam profile at far field at slow axis is shown in Fig. 2. When block the feedback from the grating, only let the feedback from HR mirror pass

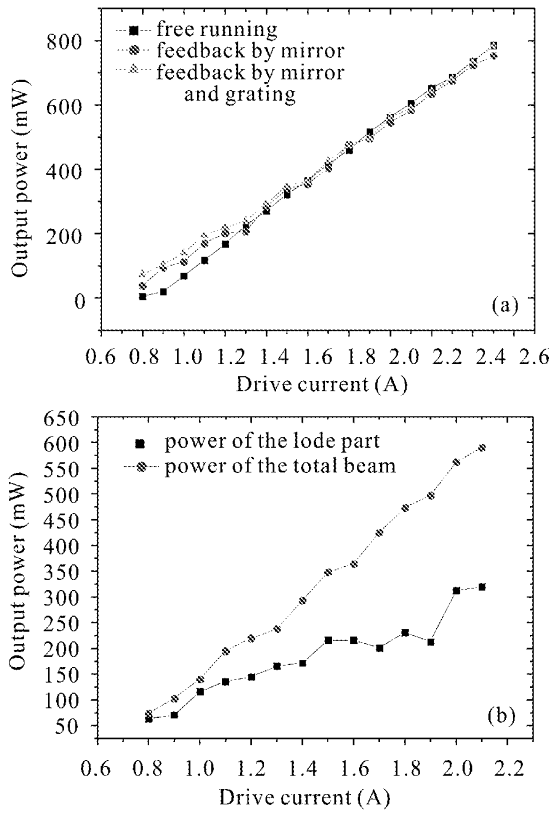

Fig. 3. (a) Output power of the laser beam with and without feedback of external cavity; (b) power of the lobe part and the total beam with feedback.

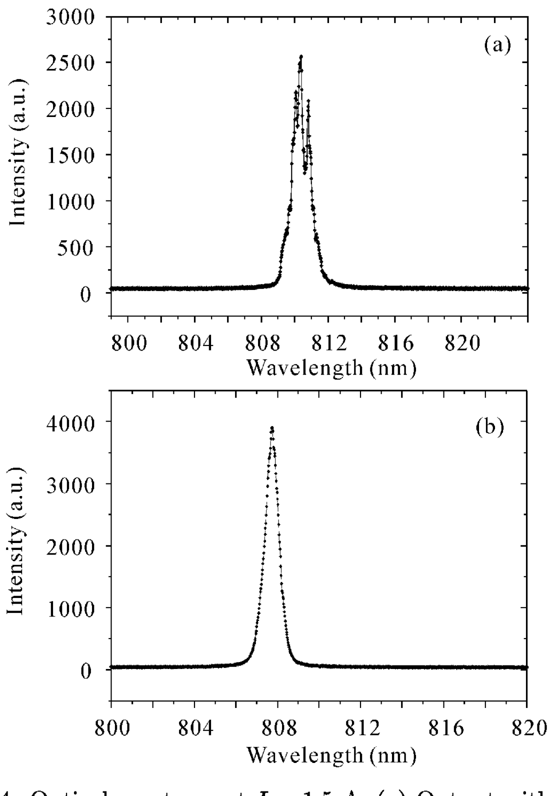

Fig. 4. Optical spectrum at $I = 1.5$ A. (a) Output with feed back of the HR mirror, FWHM = 1.50 nm; (b) output with feed back of the HR mirror and the grating, FWHM = 0.7 nm.

through, we can get an improved output beam with the beam divergence (FWHM) of 0.74° at a drive current $1.5 \times I_{\text{th}}$. With the feed back from both grating and HR mirror, we can narrow the beam divergence (FWHM) to 0.43°. If we quote the definition of diffraction limit $\theta_D = 0.886\lambda/D$[6], for the BAL diode used in the experiment, the diffraction limit is 0.41°. That corresponds to a beam quality of $M^2 = 1.1$ obtained at a drive current $1.5 \times I_{\text{th}}$ in the experiment. But the influence of the external cavity will decrease at higher drive current because the feedback is relatively week compared to stronger laser emission of the BAL.

With the feedback of the HR mirror, the spectral line-width of the BAL diode is 1.5 nm. While with the feedback from both HR mirror and the grating, the spectral line width can be narrowed from 1.5 to 0.7 nm as shown in Fig. 4. This can be explained by

$$\Delta\lambda = \frac{\lambda}{mN}, \tag{2}$$

where $\Delta\lambda$ is the spectral line-width, m is the refraction order, and N is the lines of the grating. After calculated, we can know that the spectral line-width of the BAL diode should be 0.63 nm theoretically.

A technique that uses a simple external cavity to enhance the spatial coherence of high power broad area laser diode has been demonstrated. For a drive current of $1.5 \times I_{\text{th}}$, a single-lobed near diffraction-limited laser beam has been obtained. When operating with the feedback of both a mirror and a grating, the beam profile and the spectral line width of the laser diode have been narrowed at the same time. With the AR coating on the front facet of laser diode, more efficient control and better results are achieved than the normal laser diode[7]. Threshold reduction by injection is also demonstrated in the experiment.

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