Frequency-narrowed external-cavity broad-area-diode for rubidium laser pumping

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Using an external cavity with holographic grating, we demonstrate the spectral narrowing of a high power broad-area-diode with a single emitter. The spectral bandwidth of less than 15 GHz is obtained with output power exceeding 10 W and external cavity efficiency exceeding 60%. Absorption of 98% of the laser radiation by a 25-mm rubidium vapor cell filled with 600-torr ethane at a temperature of 368 K is acquired, which demonstrates the availability of this pump source for efficient rubidium laser pumping.

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Broad area laser diodes (BALs) have been widely used in recent years for their compactness, high efficiency, long usage time, and relatively low cost. BALs, along with laser diode arrays (LDAs), are often used for experiments which require relatively high output powers but allow for multimode operation, such as spin-exchange optical pumping[1] and alkali vapor laser pumping[2−5]. In such applications, a pumping spectral bandwidth less than 0.1 nm is required to match the atomic absorption while the typical spectral bandwidth for BALs is 1–3 nm. Several approaches utilizing different kinds of external cavities with wavelength-sensitive elements have been developed[6−8] to narrow down the spectral bandwidth. Babcock *et al.* succeeded in narrowing the LDA's spectral bandwidth to 64 GHz with 45-W output power and to 47 GHz with 12-W output power[6]. Talbot *et al.* obtained 66 GHz with 25-W output power[7]. However, the spectral bandwidths of these experiments remain significantly broader than the atomic absorption bandwidth of about 10 GHz. For the case of LDA, the spectral narrowing is limited by the smile. By using a LDA with the small size of smile, Zhdanov *et al.* obtained 11 GHz with 10-W output for efficient cesium laser pumping[9]. In this letter, we present the results of our experiments on a single-emitter BAL spectral narrowing to less than 15 GHz with a 10-W output power which is sufficient for rubidium laser pumping.

The external cavity used with the BAL is in the Littman-Metcalf configuration as shown in Fig. 1. The laser was a 20-W multimode diode laser (CS-780-020W-95 U, Axcel Photonics, USA) with emitter dimensions of 1×1000 (μm) and a cavity length of 3 mm mounted onto a CS-block kept at $17\,^\circ$C. The output beam had a far-field divergence of 35° full-width at half-maximum (FWHM) along the fast axis and 10° along the slow axis. To avoid parasitic lasing from the BAL's output facet, it was coated with anti-reflection (AR) of less than 0.5% reflectance. With this AR coating, the laser had a nominal bandwidth of 2-nm FWHM centered at approximately 780 nm at a maximum current of 26 A. We performed fast axis collimation (FAC) using a micro-optic cylindrical lens with $f=0.7$ mm attached directly to the diode

laser block. Slow axis collimation (SAC) was done by a $f=50$ mm plano-convex AR coated lens. By collimation, the beam size could be kept approximately 22 (slow axis)$\times 1.5$ (fast axis)(mm^2) with 95% of the power involved along the external cavity. We used a half-wave plate to optimize the feedback between the BAL and the grating. A 2400 grooves/mm holographic diffraction grating (GH50-24 V, Thorlabs, USA) was used as the frequency selective element with grazing incidence of approximately 90° and the first-order diffraction angle of 60°. The grating was mounted on a rotatable stage to make the grating grooves exactly parallel to the slow axis of the BAL. The feedback mirror was used for precise frequency tuning, reflecting the first-order diffracted beam from the grating back to the diode. The distance between the diode emitter and the grating was $L_1=23$ cm, while the distance between the grating and the feedback mirror was $L_2=6$ cm, which resulted in a total external cavity length of 29 cm.

We measured the spectrum using an optical spectrum analyzer (86142B, Agilent, USA) with a multimode fiber. The spectral resolution was 0.06 nm (30 GHz). For lack of a Fabry-Perot interferometer, we used a rubidium absorption cell as a spectrum filter to estimate spectral bandwidth and purity. The cell was filled with metallic rubidium and buffer gas of ethane at 600 torr measured at room temperature. This resulted in an absorption transition on the order of 12 GHz (FWHM). The cell length was 25 mm and the temperature of the cell body was kept at $95\,^\circ$C.
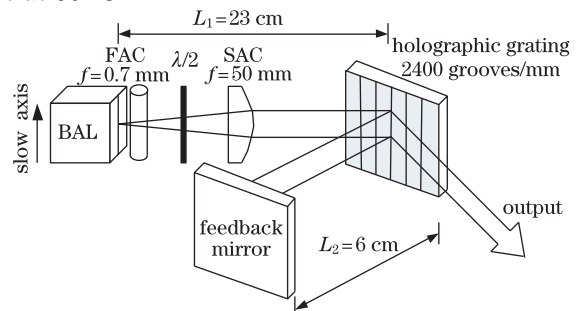

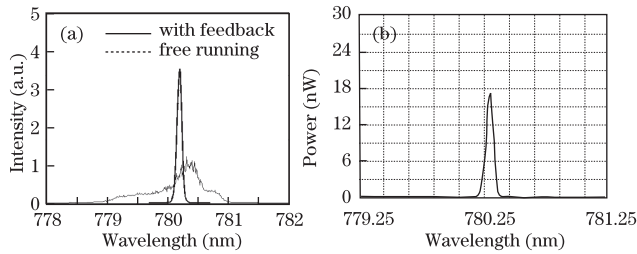Fig. 1. Experimental setup for a BAL with external cavity.

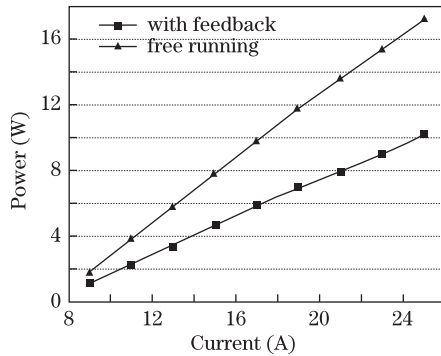Fig. 2. Measured spectra for the spectral narrowed and free-running BAL.

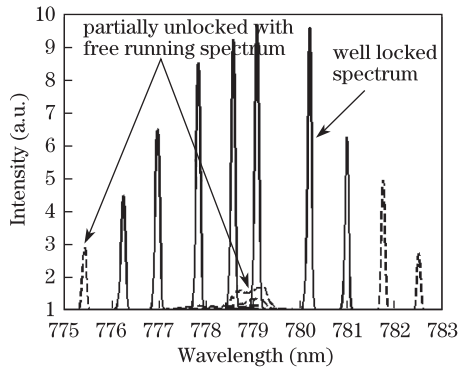Fig. 3. Output powers of spectral narrowed and free-running BAL versus driving current.

Fig. 4. Tuning range at driving current of $I=20$ A.

Figure 2(a) shows the spectra of free-running and line-narrowed BAL measured at 10-W output power from the external cavity. The spectrum of the free-running BAL has a maximum value at approximately 780.5 nm and a spectral bandwidth of 1.5 nm (FWHM). After integration of the BAL into the external cavity, the spectrum is narrowed down to less than 30 GHz (0.06 nm) (FWHM), which is the spectral resolution of the spectrometer (Fig. 2(b)). The side-mode suppression ratio is approximately 35 dB. Figure 3 shows the comparison between the power of line-narrowed laser output and the free-running case. The output power at current $I=25$ A exceeds 10 W with an external cavity efficiency of 60%. By changing the angle of the feedback mirror relative to the grating, the center wavelength of the line-narrowed spectrum can be tuned (Fig. 4). The solid line represents the well locked line-narrowed spectrum, and the dashed line represents the partially unlocked spectrum. This means that the locked spectrum and the free running spectrum appeared at the same time. The tuning range at $I=20$ A is approximately 5 nm. Moreover, the change of relative intensity

of the tuned spectral lines can be seen. Based on these, a relatively large output laser power and good locked effect can be obtained if the center wavelength of the locked spectral line is among the free running spectral range. Thus, to obtain good experimental results, the free running spectrum at driven current $I=25$ A is tuned to cover the required wavelength (780.25 nm) by adjusting the water temperature to 17 °C (Fig. 2(a)). The current shifting coefficient of the locked spectrum is 0.03 nm/A (Fig. 5), while the coefficient of the free running laser is 0.3 nm/A.

By tuning the wavelength, the rubidium cell absorbs 98% of the 10-W laser emission at the wavelength of approximate 780.25 nm. This demonstrates the availability for rubidium laser pumping. A calculation was made to estimate the spectral bandwidth of the pump source with the following parameters: rubidium cell length $l=25$ mm, single cell window transmission $t=93\%$, operation temperature $T=95$ °C, and ethane pressure $P=600$ torr at 25 °C. Additionally, the pump center wavelength was set as equal to the peak absorption wavelength at approximate 780.25 nm, and the pump intensity was $I=30$ W/cm². The latter was considerably below the saturated pump intensity of $I=243$ W/cm²[10]. Based on the calculation result (Fig. 6), the maximum spectral bandwidth was estimated to be less than 15 GHz. In the calculation, we dealt with the rubidium absorption line shape, including the effects of hyperfine splitting, pressure broadening, and line center shifting[11]. And the absorption model was based on the rate equations[12] rather than on the simple Beer law. Another important factor for efficient alkali laser pumping is the wavelength stability of the pump source due to the temperature or
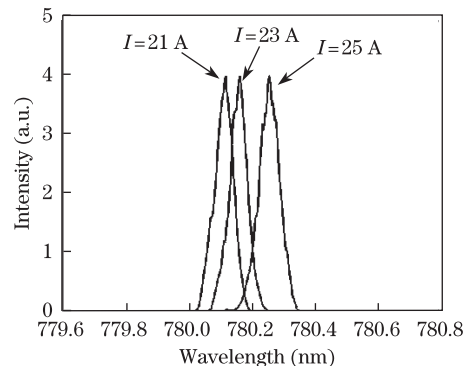

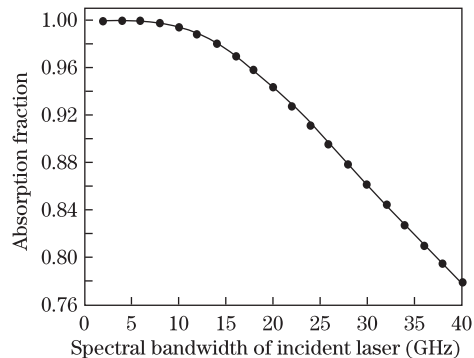Fig. 5. Current influence on center wavelength of locked spectrum.

Fig. 6. Comparative calculation between the pump absorption through rubidium vapor cell and the pump spectral bandwidth.

current shifting. In our experiment, the absorption fraction is very stable and no fluctuation is observed.

In the experiment, several system errors exist. The pump and absorption spectra may not reach the best overlap due to the low precise manual rotation tuning. The temperature measured is of the cell's outer surface, which may be a little higher than the temperature of the rubidium's vapor-liquid interface that determines the saturated vapor pressure. However, these factors provide no reasons for a broader spectral bandwidth. In contrast, if they are considered, the actual spectral bandwidth may be still narrower than the estimated value. An important factor that affects the line-narrowing effect is the parallelism between the slow axis and the grating lines. Different positions of the emitter can be seen as relatively individual sub-emitters because the BAL's emitter has a very large dimension (1000 μm) along the slow axis. Thus, although the BALD has a single emitter, the external cavity is actually composed of many sub external cavities along the slow axis. If the slow axis and the grating lines are not parallel, different sub-emitters may have different incident angles onto the grating. This will induce different center wavelengths among these sub external cavities, which will result in a different center wavelength for different position of the output laser beam along the slow axis and the serious broadening of the overall spectrum. By precise tuning of the parallelism, this negative effect can be eliminated. Another influencing factor is the astigmation of the optical system. In our experiment, the feedback of the edge of the beam along the slow axis into the emitter was not perfect due to the astigmation of the slow axis collimated lens. This resulted in a worse spectrum at the edge of the output beam. Thus, for an overall good line-narrowed effect, an astigmation-eliminated optical system is required.

On the other hand, as the pumping source of alkali vapor lasers, the spectral bandwidth should not be much narrower than the atom absorption linewidth. For alkali atoms, the absorption cross section is large even in the far wings of the absorption spectrum, and sufficient pump power absorption can be obtained even if the pump spectral bandwidth is a few multiples broader than the absorption linewidth. If the pump spectral bandwidth is much narrower, no obvious increase of the pump absorption will be obtained further. However, the resistance of pump wavelength shifting may be worse[12] and the laser efficiency will be dramatically affected by the pump wavelength shifting.

In conclusion, we demonstrate the efficient spectral narrowing of a single-emitter BAL using an external cavity with holographic grating. The spectral bandwidth is estimated to be less than 15 GHz with an output power exceeding 10 W and an efficiency exceeding 60%. The rubidium cell absorbs 98% of the incident power, which demonstrates the availability for efficient rubidium vapor laser pumping.

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