High-power diode laser spectrally narrowed with prism-etalon feedback

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A simple method for reducing the linewidth of a diode laser while maintaining high output power is described. It is based on a dispersive prism and a thin etalon for retroreflective feedback. The etalon creates two weak external cavities which provide spectral selectivity that is periodic with a period equal to the etalon's free spectral range. The method was applied to a multimode blue laser diode which in the absence of feedback features a linewidth of several nanometers. The spectral properties of the laser were investigated for different etalon thicknesses and operating currents, and tested in the presence of temperature fluctuations. With a SF11 equilateral uncoated prism near Brewster's angle and a 0.3 mm-thick uncoated fused silica etalon, the linewidth was reduced 20-fold to 70 pm (3.6 cm^{-1}) with an output power of 3 W at a current of 2.15 A. The largest diode current probed was 2.75 A which resulted in a linewidth of 100 pm (5.1 cm^{-1}) and output power of 4 W. In contrast to the use of, e.g., a volume Bragg grating, a high degree of flexibility is afforded as the same prism-etalon pair can be used across the visible and near infrared.

I. INTRODUCTION

Laser diode gain chips uniquely feature spectral output characteristics that can be conveniently tailored by feedback.[1] Typically, a frequency-selective element is positioned at the output of the laser diode after a collimation lens. The element effectively forces the laser to operate at a narrowed range of frequencies and the center frequency can be tuned via mechanical and/or electrical adjustments. The reduction in laser linewidth can be dramatic, narrowing the linewidth of several nm of the bare laser diode to a linewidth of order MHz ($\sim 10^{-6}$ nm) or below.[2–4] Over the years, this capability has enabled substantial advances in tunable laser spectroscopy, holography, Raman spectroscopy, metrology, etc.

However, a limitation in laser output power arises for such lasers due to their single-mode nature. Structures based on larger, multimode, wave-guided diodes can also be spectrally stabilized,[5,6] but when operated at high power (> 1 W) reducing the linewidth to below 0.1 nm can be expensive, requiring specialized components such as a volume Bragg grating[7–10] or tapered amplifiers.[11] Yet, numerous applications such as Raman gas spectroscopy could benefit from high (multi-watt) power, low cost and spectrally narrowed ($\sim cm^{-1}$ wide) diode laser light, particularly in the blue because the Raman scattering cross section grows with the fourth power of frequency.

The present work describes an approach to achieving spectrally narrowed (few cm^{-1} wide) laser light at an output power of over 3 W. Its working principle is based on the combination of a dispersive prism and a thin feedback etalon. The method is applied to an off-the-shelf consumer blue laser diode. It can likely be improved with minor modifications to achieve an output power of over 5 W with a linewidth of several cm^{-1}.

II. ANALYSIS AND RESULTS

The most common feedback optic in external cavity diode lasers are diffraction gratings.[12] Diffraction gratings are among the most dispersive elements and can also have high diffraction efficiency. However, commercial off-the-shelf gratings are not designed for high intensity operation and will suffer damage easily. Although it is possible to partially circumvent this limitation by beam expansion, the power loss incurred by grating feedback, even in Littrow configuration,[13] can easily be of order 30-50%.

Prisms have also been used in external cavity diode lasers,[14,15] and can tolerate high optical power because their dispersion relies on bulk material properties. Some high-density glasses such as Schott SF10 or SF11, feature dispersion with Abbe numbers as low as 28 and 26, respectively. Prisms are also generally much less lossy than diffraction gratings and for this reason have been traditionally employed as intracavity spectral selection elements in gas or dye lasers. Interface Fresnel losses can be dramatically suppressed by operating near Brewster's angle and can be further reduced, if desired, by applying a suitable anti-reflective coating. Propagation losses inside the prism are material-dependent and in the blue spectral range SF11 is among the most transmissive high-dispersion glasses available off-the-shelf. At longer

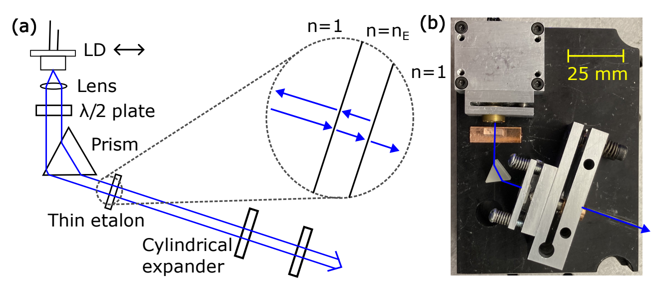

FIG. 1. (a) Schematic of prism-etalon external cavity diode laser. A multimode laser diode (Nichia NUBM44) oriented with the fast axis in the plane of the drawing, as indicated, generates blue light with a bandwidth of several nanometers when operated at a diode current of ∼1-3 A. After collimation by an aspheric lens, a half-wave plate makes the light p-polarized when incident on the prism at near Brewster's angle. Two reflections from the thin etalon create frequency-dependent feedback, spectrally narrowing the light put out. (b) Photograph of prism-etalon external cavity diode laser implemented with flexure adjusters.

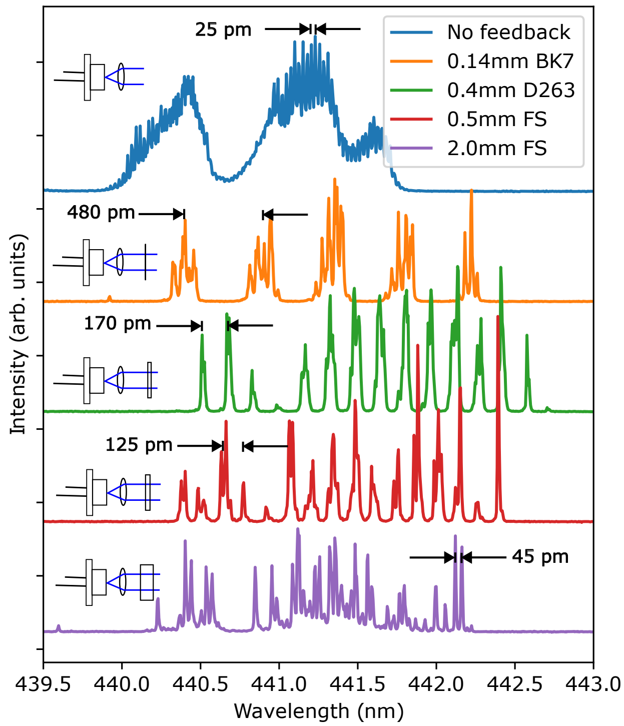

FIG. 2. Effect of etalon feedback on laser diode spectrum without prism. The diode is operated at a current of 2.5A. With feedback, the output power is greater than 4 W. Etalons of different thickness, as indicated, were made of borosilicate glass (BK7, D263), and fused silica (FS).

wavelengths, prisms find use for example as intracavity dispersion compensating elements in ultra-fast lasers, with total losses below 1%.

Since prism angular dispersion is significantly lower than grating dispersion can be, a secondary spectral selection is needed to reduce the multimode laser linewidth below 1 nm if a prism is employed instead of a diffraction grating. Secondary spectral selectivity can be provided by an etalon of thickness L_E which simultaneously serves as a feedback element if positioned after the prism, as shown in Fig. 1.

The effect of the etalon is to return light to the laser diode from two parallel surfaces separated by a distance L_E. This creates two weak external cavities with the laser diode gain chip back-facet. For a low-power single-spatial-mode laser diode *without* prism, such a feedback etalon is known to result in tunable single-longitudinal mode operation.[16] Etalon feedback on the multimode laser diode in Fig. 1 *without* a prism creates spectrally-periodic transmission through the external cavity and thus laser operation at spectrally-equidistant bands (Fig. 2). The spectral periodicity is equal to the etalon's free spectral range, in Hz,

$$\mathrm{FSR} = \frac{c}{2n_E L_E} \tag{1}$$

where c is the speed of light in vacuum and $n_E = 1.5$ is the etalon's index of refraction. Accordingly, as seen in Fig. 2, different etalon thicknesses of 0.14, 0.4, 0.5, and 2 mm yield a laser output spectrum with peaks separated by 480, 170, 125, and 45 pm, respectively, in agreement with the expected separations of 470, 160, 130, 33 pm, respectively.

As can be seen in Fig. 2, varying the thickness of the etalon indeed creates lasing at spectral regions that are following the external cavity transmission modulation, albeit small due to the ≈4% single surface etalon power reflectivity. In the spectrum of the light emerging from the laser diode without any feedback (upper blue trace in Fig. 2), a periodic modulation is also seen. It is due to the cavity formed between the front and back facets of the laser diode gain chip itself. The periodic spectral features (the longitudinal cavity mode peaks) associated with the cavity formed by the gain chip back facet and each *individual* etalon surface is not visible on the spectral scale of Fig. 2.

When the prism is introduced, as in the configuration shown in Fig. 1, the spectral transmission of the etalon and that of the prism combine. For a given prism, the spectral selectivity occurs in association with its angular dispersion, i.e., the prism's transmission bandwidth is defined by the degree to which light is returned into the gain chip waveguide after reflection from the etalon and a second pass through the prism. To minimize the overall lasing bandwidth, the etalon thickness must be optimally chosen. If the etalon is too thick, then the prism's transmission bandwidth will encompass more than one etalon transmission peak. If the etalon is too thin, a single spectral peak will result but its bandwidth will be sizeable. The best results were obtained with an etalon thickness between 0.15 mm and 0.3 mm. Figure 3 shows the output spectrum of a prism-etalon feedback laser using a fused silica etalon of 0.3 mm thickness (LightMachinery), for five different laser diode currents. The corresponding output powers are indicated in the Fig. 3 legend box. Generally speaking, the linewidth is narrower at lower current. A linewidth of about 70 pm (≈3.6 cm^{-1}) was obtained at a current of 2.15 A. An output power of 3 W resulted for this diode current. It should be noted that this twenty-fold reduction in linewidth, compared to the bare diode linewidth is only realized when the diode is oriented as illustrated in Fig. 1, i.e., with the dispersion plane aligned with the diode fast axis. With the diode rotated by 90 degrees, such narrowing is not possible because of the multimodal nature of the diode waveguide along this direction (the slow axis).

Numerous parameters are involved in optimizing the performance of the laser in terms of stability and spectral linewidth and a wide range of operating currents and temperatures were tested. Below is a synopsis of the most critical considerations:

Cavity length—A shorter overall length of the arrangement shown in Fig. 1 is generally preferred, since the beam diverges along the direction defined by the diode's slow axis. This divergence is due to the multimodal nature of the laser operation along the slow axis. The cavity length realized in the setup depicted in Fig. 1(b) is approximately 40 mm. It can be further reduced with a more compact arrangement of components. The beam can also be corrected using a cylindrical beam expander—after or before the feedback etalon—as

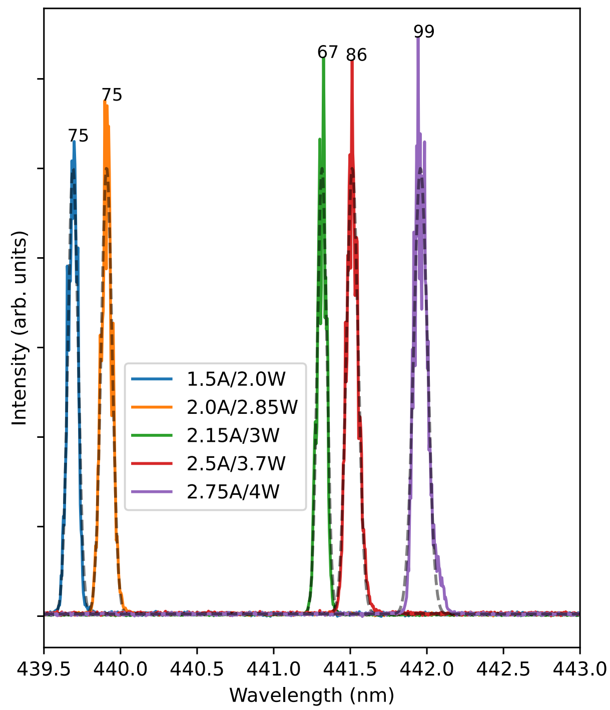

FIG. 3. Normalized output spectrum with both prism (equilateral SF11) and etalon (0.3 mm-thick fused silica) in place. The numbers above the peaks are the full width at half maximum (FWHM), in pm, obtained from gaussian fits (dashed lines). The legend indicates the associated diode currents in amperes (A) and output power in watts (W). For each operating current, the angle of the etalon was readjusted to achieve a spectrum with a single narrow peak.

indicated in the sketch of Fig. 1(a).

Collimation—The aspheric lens positioned in front of the diode serves to collimate the beam along the fast axis. Being single-mode along this direction the beam can be collimated precisely. Here a high numerical aperture aspheric lens was employed and mounted on a fine-adjustable flexure arm. Crucially, the optimal lens position differs for different diode operating currents, likely associated with a change in the lens' index of refraction.

Etalon reflectivity—The etalon reflectivity plays a key role in that higher reflectivity implies stronger feedback. However, it also leads to a reduced output power. A solid fused silica etalon with a single-surface reflectivity of around 4% offers a good compromise between feedback strength and output power.

Diode current—For the recording of spectra shown in Fig. 3, the etalon angle was readjusted for each operating current. This is in addition to the lens position adjustment, as described above. In general, unless these adjustments are made, more than one peak is observed in the spectrum when the current is changed. Because the diode gain redshifts with increasing current, the optimal center frequency of operation shifts accordingly to a longer (redder) wavelength as seen in Fig. 3. This highlights one major benefit of this approach compared to feedback with a volume Bragg grating which is fabricated for a fixed wavelength of operation. The threshold current was 0.3 A and the output power at threshold was 0.1 W. Thus the operation reported above is in a regime well above threshold.

Laser diode front facet reflectivity—For the particular laser diode investigated, the limited information available suggests that an anti-reflection coating is present on the front facet which reduces the front facet reflectivity to a few percent. While minimizing front facet reflectivity is crucial for achieving mode-hop-free tuning in single-mode external cavity diode lasers, it is less critical for spectral narrowing at any particular frequency, and even less so for a multimode external cavity diode laser. The method described here should thus work with any multimode laser diode.

Diode temperature—For the measurements in Fig. 3, no active temperature control was employed. The laser was set up on an aluminum plate that was mounted on an optical table. Thus, heat generated by the diode was dissipated primarily through the metal holders in a slow fashion, and the temperature of the mount was slowly rising. Nevertheless, the spectral output remained stable unless the temperature changed by at least a few degrees °C. Thus, coarse temperature stabilization is preferred for stable long-term operation.

Improvements could lead to a narrower linewidth and higher output power. In particular, the prism in the configuration is still creating losses of about 5% which weaken the feedback and could be eliminated with an optimized prism apex angle or anti-reflective coatings. Furthermore, a more dispersive prism or a combination of two prisms could be employed to reduce the prism filtering bandwidth. Finally, an etalon coated so that its reflectivity is greater than 4% could provide strengthened feedback and thus further spectral narrowing.

III. CONCLUSION

A simple and economical method was described to reduce the spectral linewidth of a diode laser by more than an order of magnitude without much sacrifice in output power. The key components of the method include a dispersive prism and an etalon that returns the light emitted by the diode at two surfaces to create spectral selectivity. While other means exist to achieve such result, notably by using a volume Bragg grating with fixed spectral properties, the simplicity and flexibility of the method presented here provides utility in applications where high power and high efficiency are important, for example in a portable Raman gas analyzer.

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