Linewidths below 100 kHz with external cavity diode lasers

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The linewidth of external cavity diode lasers (ECDLs) is an increasingly important characteristic for experiments in coherent optical communications and atomic physics. The Schawlow–Townes and time-averaged linewidths depend on free parameters of the design, such as cavity length, power, and grating characteristics. We show that the linewidth is also sensitive to the focus, set by the distance between the laser and the collimating lens, due to the effect on the external cavity backcoupling efficiency. By considering these factors, a simple ECDL can readily achieve linewidths below 100 kHz. © 2009 Optical Society of America

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1. Introduction

The highly controllable emission properties of external cavity diode lasers (ECDLs) make them an ideal lasing source for many experiments in coherent optical communications [1] and optical and atomic physics [2–7]. ECDLs use frequency selective feedback to achieve both narrow linewidth and tunability, typically with diffractive gratings in either the Littrow [8–10] or the Littman–Metcalf configurations [11,12]. There is extensive literature on ECDL design, including early articles and reviews [4,13–15], with attention to many different figures of merit including the linewidth [3,5], passive stability [8], tunability [3,16], simplicity of construction [9,17], or compactness [8,9,17].

Linewidth is an increasingly important performance metric, both the underlying Schawlow–Townes width and the effective time-averaged width broadened by technical noise. Applications in atomic clocks, atomic coherence processes such as electromagnetically induced transparency, and new developments in coherent detection for ultrafast fiber-optic communications [1] require passive laser linewidths well below 1 MHz. Several studies have introduced the important parameters and contributions [2,18,19], noting that the inherent linewidth depends on feedback from the external cavity. Experimental investigations have addressed the effect of cavity length [2,20], power [21,22], grating parameters [23], and detuning of the external cavity mode relative to the grating angle [24,25].

We show that the focus of the collimating lens affects the efficiency of feedback from the external cavity, and therefore the laser linewidth. Small and otherwise not obvious changes to the lens focus can have quite a significant effect on the linewidth but are apparent only if the technical noise is small, comparable to the intrinsic cavity linewidth. We demonstrate these effects using a simple ECDL design [17] constructed from a commercial kinematic mount, two piezoelectric actuators, and a mirror to fix the output beam direction. With attention to the linewidth-determining factors, including the focus, the time-averaged linewidth can be reduced to less than 100 kHz.

2. External Cavity Diode Laser

We consider a generic grating–feedback system, in particular the Littrow configuration shown

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schematically in Fig. 1. The discussion is also applicable to Littman–Metcalf lasers, and to ECDLs with other forms of feedback such as transmissive gratings and filters [26–29]. We used a simple laser based on a previously published design; see Fig. 2 [9,17]. We further simplified the construction by replacing the complex fold-mirror mount with a simple rotatable mounting block screwed directly to the kinematic mount, as shown.

The laser was constructed from a standard kinematic mount with a laser diode and aspheric collimating lens ($f = 4.5\,\mathrm{mm}$, 0.55 NA) mounted in a collimating tube fixed to the base of the kinematic mount [30]. A gold-coated 1800 grooves/mm holographic diffraction grating, with a p-mode diffraction efficiency of 25%, was attached at 45° to the tilting face of the mount. A plane mirror was fixed on the mount opposite the grating to reflect the output beam and maintain a constant output beam direction [17]. A piezoelectric stack actuator on the horizontal axis of the grating pivot arm was used to vary the frequency by 40 GHz over the 100 V range of the stack. A 1 mm thick piezoelectric disk behind the grating could be used for fast feedback control of the cavity length to stabilize the laser frequency.

The laser assembly was attached to an aluminum baseplate temperature-stabilized by a thermoelectric cooler (TEC), with a thermistor sensor and negative feedback PID temperature controller. The output power for p-plane polarization was typically 50 mW at 780 nm using a 70 mW diode. The wavelength could be tuned discontinuously over a 10 nm range by rotation of the grating alone and over a wider range with suitable temperature adjustment. The laser is relatively vibration insensitive because external disturbances tend to be common mode, such that the diode and grating vibrate together, with a comparatively slight effect on their separation.

3. Linewidth

For a bare semiconductor laser diode, the linewidth results from a combination of contributions such as laser gain and cavity losses, technical noise, and drifts. It is generally assumed that the intrinsic linewidth of an ECDL is small, 10 kHz or less, but effectively much broader over normal measurement times due to technical noise, e.g., a few megahertz over 1 s.

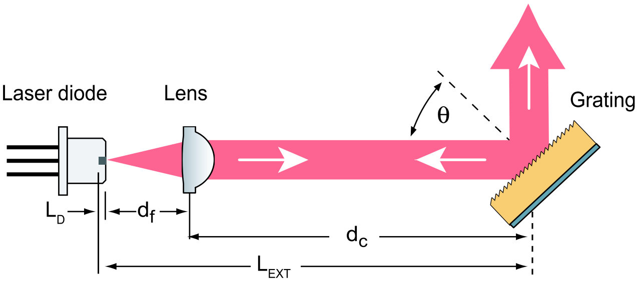

Fig. 1. (Color online) Schematic of a Littrow configuration ECDL showing the laser diode, collimating lens, diffraction grating, and output beam. θ is the Littrow angle, L_D is the diode cavity length, L_{ext} is the external cavity length, d_f is the distance from the diode to the lens, and d_c is the distance between the lens and the grating. A single longitudinal cavity mode is selected by dispersive feedback from the grating.

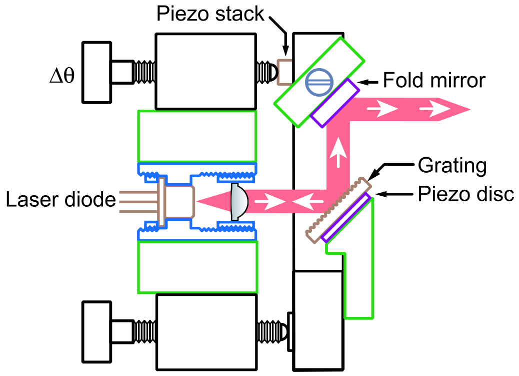

Fig. 2. (Color online) Littrow configured ECDL with a fixed output beam direction, adapted with permission from C. J. Hawthorn, K. P. Weber, and R. E. Scholten, Rev. Sci. Instrum. **72**, 4477 (2001). © 2001 American Institute of Physics.

The theoretical limit to laser linewidth $\Delta\nu$ is the Schawlow–Townes width [18], modified to include the linewidth enhancement factor $(1 + \alpha^2)$ that is due to coupling between intensity and phase noise in semiconductor diode lasers [2,19]:

$$\Delta\nu = \frac{\pi h\nu_m (\Delta\nu_c)^2 (1 + \alpha^2)}{P_m} n_{\mathrm{sp}}, \tag{1}$$

where $h\nu_m$ is the photon energy in mode m, $\Delta\nu_c$ is the cavity bandwidth, n_{sp} is the number of spontaneous photons in the mode, P_m is the power in the mode, and $\alpha = \Delta n'/\Delta n''$ is the ratio of the real and imaginary parts of the refractive index, where typically $\alpha \sim$ 4–8 [2,19]. Above threshold, $n_{\mathrm{sp}} \to 1$. The cavity bandwidth is given by [2]

$$\Delta\nu_c = \frac{c}{2\pi L_{\mathrm{eff}}} \left(\kappa_L L_D - \ln\sqrt{R_{\mathrm{eff}}}\right), \tag{2}$$

where κ_L is the internal diode transmission; we take $\kappa_L = 1$. The combined reflectivity of the cavity mirrors (or grating) is $R_{\mathrm{eff}} = R_1 R_2$ for the bare diode rear and front facets and $R_{\mathrm{eff}} = R_1 R_g$ for the ECDL.

For typical parameters see Table 1. We found that the bare diode linewidth is 5 MHz and the intrinsic ECDL linewidth is approximately 30 kHz, depending on the assumed effective feedback from the grating.

4. Technical and Current Noise

For an ECDL, external noise sources such as thermal and mechanical fluctuations broaden the time-averaged effective linewidth to the extent that changes to the intrinsic cavity-determined linewidth are difficult to observe. Feedback stabilization techniques [31–33] can be used to compensate such disturbances, but perturb measurement of the intrinsic cavity-determined linewidth. For our measurements of the intrinsic linewidth, only passive isolation and decoupling from the environment were used.

Table 1. Parameters for Calculating $\Delta\nu$ for a 780 nm AlGaAs Diode that Operates in a Littrow Configured External Cavity [a]

Parameter	P Plane	S Plane	Short Focus
L_D, FSR	0.25 mm, 170 GHz		
n_D, α	3.6, 7		
L_{ext}, FSR	15 mm, 10 GHz		
R_1, R_2	0.85, 0.02		
P_m	40 mW		
z (m)	2	2	0.3
R_g'	0.040	0.135	0.0012
$\Delta\nu_{\text{th}}$ (kHz)	36	27	110
$\Delta\nu_{\text{L}}$ (kHz)	47	29	102
$\Delta\nu_{\text{G}}$ (kHz)	121	142	192

[a] The R_g' values take into account the backcoupling efficiency for a diode output with an external beam waist position at z; see Section 5. $\Delta\nu_{\text{th}}$ is calculated from Eqs. (1) and (2) using the cavity formed between the rear diode facet and the grating, and then convolved with the $\Delta f = 25$ kHz resolution of the measurement technique. $\Delta\nu_{\text{L}}$ and $\Delta\nu_{\text{G}}$ are the Lorentzian and Gaussian widths obtained by fitting the data in Fig. 4.

The diode is also sensitive to the injection current. Resistive heating causes thermal expansion of the diode, and the charge carrier density directly affects the index of refraction; both affect the optical path length, which then changes the longitudinal mode frequency. The combined resistive and carrier density sensitivity is around $-3\text{MHz}/\mu\text{A}$ at low frequencies [4,34].

To achieve 100 kHz linewidth, comparable to the intrinsic ECDL linewidth, the current noise must therefore be less than 30 nA (rms). Commercial drivers typically contribute current noise with rms amplitudes of the order of several microamps over a 100 kHz bandwidth, corresponding to linewidths of several megahertz from the current noise alone. Supplies based on batteries can provide some improvement, but electrochemical batteries are generally electrically noisy in comparison with a well-designed active feedback-regulated current supply [35,36]. We found that, with a low-noise supply [36] and simple acoustic isolation [37], the intrinsic and technical noise components of the linewidth could be adequately separated.

5. Gaussian Beam Backcoupling

Typically the collimation lens is adjusted to focus the beam waist at some finite distance outside the external cavity. The first-order diffracted beam does not then perfectly focus back to the emitting region of the laser diode. The backcoupled beam waist radius w can be calculated as follows using standard Gaussian beam propagation [38].

We begin with a Gaussian beam at the front exit facet of the diode, propagate to the lens, through the lens, then to the grating, and back. The emission region dimensions are related to the divergence angles specified by the diode manufacturer: $w_0 = \lambda/(\pi\theta_{\text{half}})$, where w_0 is the waist radius and θ_{half} is the divergence half-angle. By use of $ABCD$ matrices the propagated Gaussian beam parameter is given by

$$\frac{1}{q} = \frac{Cq_0 + D}{Aq_0 + B}, \tag{3}$$

where $q_0 = i\pi w_0^2/\lambda$ is the initial complex Gaussian beam parameter. Assuming the thin lens approximation, for our system we have

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & d_f \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix} \begin{bmatrix} 1 & 2d_c \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix} \begin{bmatrix} 1 & d_f \\ 0 & 1 \end{bmatrix}, \tag{4}$$

where $f = 4.5\text{mm}$ is the lens focal length, d_f is the distance from the diode to the lens, and d_c is the distance between the lens and the grating; see Fig. 1. The final beam waist diameter can be found from

$$w^2 = \frac{\lambda}{\pi} \frac{1}{\Im(1/q)}. \tag{5}$$

The collimation lens is usually adjusted to obtain an external beam waist at a large distance z from the cavity, typically several meters. The distance d_f can then be estimated for a given z by solution of the thin lens equation:

$$\frac{1}{f} = \frac{1}{d_f} + \frac{1}{z}. \tag{6}$$

Figure 3 shows the calculated backcoupling efficiency for each axis of an elliptical Gaussian beam in a 780 nm ECDL. The spot diameter at the laser diode decreases with increasing focus distance z and hence couples the diode and cavity more effectively. The efficiency at a given focus distance also increases if the focal length of the collimating lens

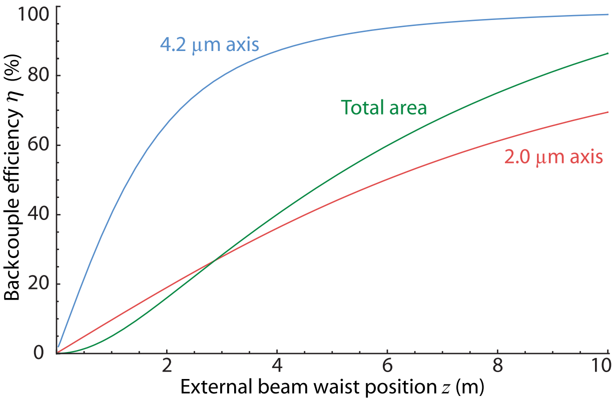

Fig. 3. (Color online) Calculated ratio of source size to backreflected spot size for the two axes of an elliptical Gaussian beam emitted from a 780 nm ECDL with $L_{\text{ext}} = 20$ mm. Also shown is the total backreflected efficiency for the effective area of the source. The source size is $4.2\,\mu\text{m} \times 2.0\,\mu\text{m}$, calculated from the divergence full angles specified by the diode manufacturer, 8° and 17°.

is reduced. The effect of the calculated backcoupling losses can be included as efficiency η in the grating reflectivity when calculating the linewidth from Eqs. (1) and (2): $R_g' = \eta R_g$ and so $R_{\mathrm{eff}} = \eta R_1 R_g$; see Table 1.

Examples of the measured linewidth are shown in Fig. 4, where the measured linewidth decreases with longer z, consistent with the calculated enhanced feedback. However, a small spot size at the laser diode demands more precise alignment and stability of the diode, diffraction grating, and collimating lens, such that the very small waist overlaps well with the very small diode waveguide cross section. A laser with perfectly collimated output is particularly sensitive to vibration and thermal creep. We typically collimate our ECDLs such that the beam waist is approximately 2 m from the collimating lens. An alternative approach uses a cat's-eye reflector, which is both insensitive to vibration and perfectly collimated for maximum optical feedback but is not compatible with grating feedback [39,40].

6. Grating Parameters

Grating efficiency affects the cavity feedback and hence linewidth [Eq. (2)], as shown by experiments in which a 20% decrease in linewidth was observed with a threefold increase in the first-order diffraction reflectivity [23]. The grating efficiency can also be varied by rotating the incident light polarization. ECDLs are usually operated in a p-plane configuration, with polarization parallel to the rulings on the grating. The first-order diffraction is then relatively weak to increase the useful directly reflected (nondiffracted) output power. Operating an ECDL instead in an s-plane configuration increases the grating efficiency and cavity feedback, reducing the linewidth at the expense of output power. We measured the effect and show that, if technical noise is small, the linewidth reduction can be substantial, as shown in Fig. 4. The time-averaged laser linewidth was reduced consistently by 15%, and the intrinsic Lorentzian component by more than 30%, for an increase in R_g from 25% to 85%.

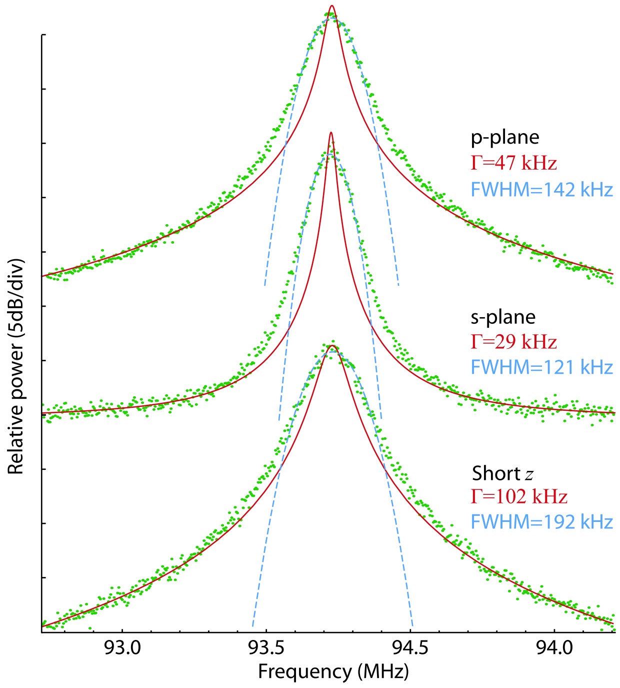

Fig. 4. (Color online) Free-running laser linewidth measurements of an ECDL operating in the p plane (top), s plane (middle), and p plane with a short focal distance z (bottom). Linewidths were measured using a self-heterodyne technique [41] with a 2 km length of multimode optical fiber giving a resolution limit of $\Delta f = 25\,\mathrm{kHz}$. Measurememts were taken on an rf spectrum analyzer with a resolution bandwidth of 3 kHz averaging 40 sweeps with a sweep time of 225 ms. Parameters for each ECDL configuration are listed in Table 1. The ECDL output power was approximately five times greater for the p plane than for the s plane. Lorentzian (Γ) fits excluded the central 1 MHz and Gaussian (FWHM) fits were to the central 1 MHz only.

7. Discussion

In principle, the linewidth can be reduced by increasing the feedback from the external cavity or by increasing the cavity length. A short cavity is desirable to maximize the mode-hop-free scan range [13], but this is gained at the expense of linewidth [Eq. (2)]. The linewidth scales with $1/L_{\mathrm{eff}}^2$ in comparison with the $1/L_{\mathrm{eff}}$ scaling of the free spectral range (FSR) so a small sacrifice in the FSR can be used to gain a substantial reduction in the linewidth.

With a short cavity (15 mm) and low efficiency p-plane polarization grating configuration, we achieved a linewidth of 140 kHz; see Fig. 4. The line shape shows that technical noise was still a large contribution, in particular the effects of external vibrations on the cavity length. The laser frequency sensitivity to cavity length variations is 25 MHz/nm for a 780 nm diode, and so the external cavity and in particular the grating mount must be rigid. Alternatively, servo control feedback with an acoustic bandwidth can dramatically reduce the effect of low-frequency vibration. To differentiate between current noise and acoustic disturbances, we actively

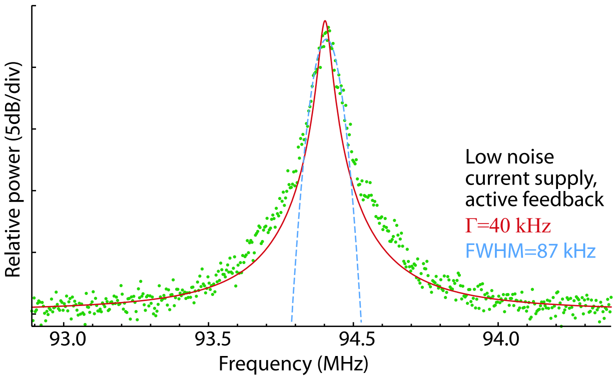

Fig. 5. (Color online) Self-heterodyne laser linewidth measurement with low-noise current supply [36], active frequency feedback [36], and $z = 2\,\mathrm{m}$ collimating focus distance. The inherent resolution bandwidth limit of the measurement technique is approximately 25 kHz.

stabilized the cavity length using a saturated absorption atomic reference [36], with feedback bandwidth of a few kilohertz; see Fig. 5. The linewidth was reduced to below 90 kHz, in comparison with the Schawlow–Townes limit of 40 kHz. The remaining technical noise, contributing 50 kHz to the linewidth, is consistent with an integrated current noise of 15 nA (rms).

8. Conclusion

The instantaneous intrinsic diode laser linewidth is given by Eq. (1). For many applications, such as laser cooling and trapping of alkali atoms, a sufficiently narrow linewidth (<300 kHz) is easily accomplished even with very short cavity lengths (15 mm). Often the effects of changing cavity length or grating efficiency are not clearly observed experimentally, because the linewidth is dominated by technical noise, particularly electrical current noise. Using a low-noise current source we were able to observe the effects of varying the feedback on the intrinsic laser linewidth.

Changing the polarization relative to the grating reduced the linewidth but also reduced the available output power from the laser. The external cavity feedback was shown to strongly depend on the focus of the laser collimation lens, and for a laser focused 2 m outside the cavity, the effective backcoupling efficiency was found to be less than 20% of the feedback efficiency typically quoted. These backcoupling losses increase the linewidth, without changing the output power. We found that the collimation should be adjusted to a long but not infinite focus distance to ensure good backcoupling efficiency while retaining stable feedback and linewidth of the order of 100 kHz.

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and a DL-7140-201 diode from Sanyo, Tokyo, Japan. Note: certain commercial equipment, instruments, and materials are identified in to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement nor does it imply that the materials or equipment are necessarily the best available for the purpose.

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