

Increasing the output of a Littman-type laser by use of an intracavity Faraday rotator

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We present a method of external-cavity diode-laser grating stabilization that combines the high output power of the Littrow design with the fixed output pointing of the Littman–Metcalf design. Our new approach utilizes a Faraday-effect optical isolator inside the external cavity. Experimental testing and a model that describes the tuning range and optimal tuning parameters of the laser are described. Preliminary testing of this design has resulted in a short-term linewidth of 360 kHz and a side-mode suppression of 37 dB. The laser tunes mode hop free over 7 GHz, and we predict that much larger tuning ranges are possible. © 2004 Optical Society of America

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1. Introduction

Inexpensive single-mode laser diodes are readily available at a variety of wavelengths from the red to the near infrared. They require no maintenance, consume little electrical power, require almost no cooling, can have high amplitude and pointing stability, and can be easily modulated at high frequencies (see Ref. 1 and references therein). By use of optical feedback techniques and stable current and temperature controllers,^{1–3} laser diodes can be made to operate at a single frequency with a narrow linewidth, making them suitable for applications such as precision spectroscopy and laser cooling. Stabilized diode systems can often replace considerably more expensive systems requiring significant infrastructure and regular maintenance.

The two commonly used diode stabilization schemes, the Littrow⁴ and Littman–Metcalf^{5,6} (Littman) designs, each have their advantages. The simpler of the two designs is the Littrow scheme. In this arrangement a reflection grating is placed in front of a collimated diode at an angle such that the first-order diffraction peak at a particular wavelength is directed back into the diode. Mode competition then favors this wavelength. The zeroth-

order grating reflection is used as the output coupler to extract light from the cavity. Light diffracts off of the grating only once per round trip through the cavity in this configuration. As discussed below, this can result in higher output powers than is possible with the Littman design. This can be of great importance owing to the low power typical of single-mode diode-laser systems relative to what is possible with other technologies. Although it is possible to amplify a weak laser beam or use a weak stabilized beam to injection lock a free-running diode, this adds cost and complexity.

The main drawback of the Littrow design is that rotating the grating to tune the laser causes the pointing of the zeroth-order output beam to change. This is not the case in the Littman design. In a Littman laser the grating is placed in front of the diode at an angle closer to grazing incidence, such that the diffracted light does not return to the laser diode. Instead, the diffracted beam is directed to a mirror. Depending on the angle of the mirror, a particular wavelength will be precisely retroreflected back to the grating such that it returns to the diode after diffracting a second time. Like the Littrow design, the zeroth-order beam from the grating is used to couple light out of the cavity. The laser can be tuned with the mirror while keeping the grating fixed such that the output beam pointing does not change as the laser is tuned.

Because the angle between the incident beam and the grating is not fixed to the Littrow angle, it is possible to adjust the cavity of a Littman laser to accommodate grating angles closer to or further from grazing incidence, allowing the diffraction efficiency

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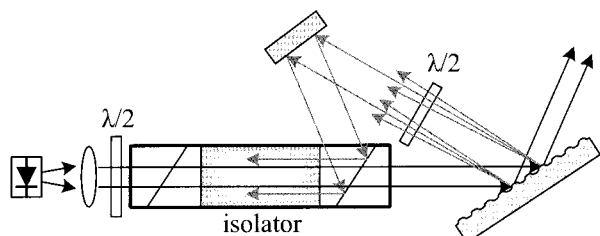


Fig. 1. Schematic of the grating stabilization scheme. The laser is first collimated, and then the polarization is rotated with a $\lambda/2$ plate such that all the light passes through the Faraday-effect isolator. On exiting the isolator, the light strikes a diffraction grating. The zeroth-order specular reflection is used as the output coupler for the laser. The first-order diffracted light passes through a $\lambda/2$ plate that rotates the polarization by 90 deg and is then reflected by a mirror into one of the rejection ports of the isolator. The frequency of light that is coupled back into the laser is determined by the angle of the grating and the position of the mirror.

of the grating to be tuned to produce the minimum necessary feedback, thereby optimizing the intensity of the output beam. Another advantage of the Littman design is that the user can scan it mode-hop free over the entire diode gain curve by simply pivoting the tuning mirror about a fixed axis.^{7,8}

The disadvantage of the Littman design is its inherently lower power. In the Littman scheme a single round trip through the cavity involves diffracting twice off of the grating. This has the fortunate side effect of increased side-mode suppression. But the double diffraction means that the grating efficiency needs to be larger in order for sufficient light to be coupled back to the diode. This results in less light being coupled out in the zeroth order of the first grating pass. The missing power is coupled out in the zeroth-order beam of the second grating pass in a secondary output beam that does not remain fixed as the laser is tuned. As such, commercial Littman-configuration lasers typically produce just over half of the power of comparable Littrow-configuration devices.⁹

We have devised and tested an external-cavity grating stabilization scheme that combines the single-diffraction power advantage of the Littrow configuration with the frequency-independent output pointing and freedom of grating alignment of the Littman scheme. Like the Littman design, in our scheme a mirror, rather than the grating, is used to tune the laser, keeping the output beam pointing fixed. But rather than reflecting the light back at the grating, in this new scheme the mirror directs the light into a rejection port of an intracavity Faraday-effect optical isolator such that the light is directly coupled back into the laser diode without striking the grating a second time. This design is similar to injection-locking schemes in which the master laser couples to the slave laser through the rejection port of an isolator.¹⁰ In this case, however, the laser is injection locked to itself. The design is illustrated in Fig. 1.

We should point out that our technique is not the only way to improve output power while keeping beam pointing fixed. For example, various multiarm grazing-incidence cavities developed to increase the mode selectivity¹¹ or lower the threshold¹² of Littman-type dye lasers could be used to increase the output of a Littman diode laser. Other previously demonstrated techniques include the employment of a mirror moving in conjunction with the grating to correct the beam pointing of a Littrow laser at the cost of a small parallel displacement of the beam.¹³ Our technique has the advantage that it requires only one moving element and creates no output beam displacement. And, unlike the multiarm cavities in which extra boundary conditions must be met to avoid mode hopping, this new scheme uses a simpler single loop cavity.

We should also note that, owing to the size of the isolator, there are practical limits on how small the external cavity can be in our design, possibly causing longitudinal modes to be stacked closer together than would be desirable. Nevertheless, despite the slightly larger-than-average cavity length in our setup, we have not had difficulty keeping the laser running in a single longitudinal mode. This limit could be mitigated with a miniature isolator at the expense of higher isolator losses.

2. Experiment

For our first test of this new stabilization scheme we utilized a 657-nm CircuLaser diode from Blue Sky Research¹⁴ collimated with an aspheric lens to a Gaussian beam waist radius of 0.5 mm. This diode, originally purchased for a different purpose, was not an optimum choice for this study because it lacked an antireflection coating on its front facet. Despite the greater susceptibility of an uncoated diode to mode hopping,¹⁵ we have achieved excellent results with this laser. Using a Fabry-Perot spectrum analyzer, we have verified a mode-hop-free tuning range of 7 GHz. Theoretical calculations presented in the last half of this paper suggest that much larger tuning ranges are possible.

In our current implementation the diode laser is placed 5.7 cm from the end of an 11.8-cm-long isolator. Prior to entering the isolator, the laser is collimated with a 1-mm focal-length aspheric lens and passed through a half-wave plate to align the polarization of the beam with the input polarizer of the isolator. A holographic grating is placed 2.8 cm from the isolator's output polarizer. The tuning mirror is mounted to a three-axis piezoelectric kinematic mount. Course tuning of the laser is done with threaded actuators on the mount, and fine-tuning is done with the piezos. The piezos are scanned such that the voltages on each side of the mount differ only by a proportionality constant, resulting in both rotation and translation of the mirror and effectively causing the mirror to pivot about an axis offset from its center.

Using our calculations, we found that the optimum pivot point for our configuration is approxi-

mately 17 cm from the center of the mirror [see Eq. (11) in Section 3]. This relatively large length means that the mirror must be translated a considerable distance per degree of rotation about its center to achieve the optimum tuning range. As a result, scanning a laser frequency over 7 GHz required the piezos to be scanned over their entire voltage range. We could possibly accomplish scans longer than 7 GHz by changing the dimensions of our cavity to move the optimum pivot point closer to the mirror or by using actuators with a greater range of motion.

The spectral properties of our laser are typical of what would be expected for a Littrow configuration. Using Fabry–Perot spectrum analyzers, we have measured a short-term linewidth of 360 kHz and a side-mode suppression of 37 dB. Owing to losses in the optical isolator, the output power is somewhat less than in a comparable Littrow laser. These losses are not a serious disadvantage because most installations of grating-stabilized lasers require the use of an isolator to prevent unwanted feedback. The loss due to an isolator in the low-finesse external cavity of a typical grating-stabilized laser is comparable with the loss caused by an isolator external to the cavity. The intracavity isolator in our design provides the same immunity to reflections as an external isolator.

3. Mode-Hop-Free Tuning Theory

To keep the laser from jumping between longitudinal modes as the frequency is scanned, the length of the cavity must increase in proportion to the wavelength of light injected back into the diode. If λ_0 represents the wavelength of light coupled back into the diode and S_0 represents the round-trip optical path length of the cavity before the laser is tuned, then mode-hop-free tuning is achieved when

$$\frac{\Delta S}{S_0} = \frac{\Delta \lambda}{\lambda_0}, \quad (1)$$

where ΔS and $\Delta \lambda$ represent the shift in the cavity length and the injected wavelength from their nominal values. This condition ensures that, as the wavelength of the laser is tuned, the round-trip length of the cavity is always a fixed integer times the wavelength of the laser:

$$S = m\lambda. \quad (2)$$

Owing to the low finesse of typical grating cavities, grating-stabilized lasers can operate in a single mode even when m is not precisely an integer. But if m increases or decreases by more than 0.5, the losses in the current mode become greater than the losses in an adjacent mode, and, with near certainty, the laser will hop to the next mode.

Using the simplest model of our laser, in which it is assumed that the light fed back to the laser exactly retraces the path of the outgoing beam, it would appear that it is impossible to scan our laser

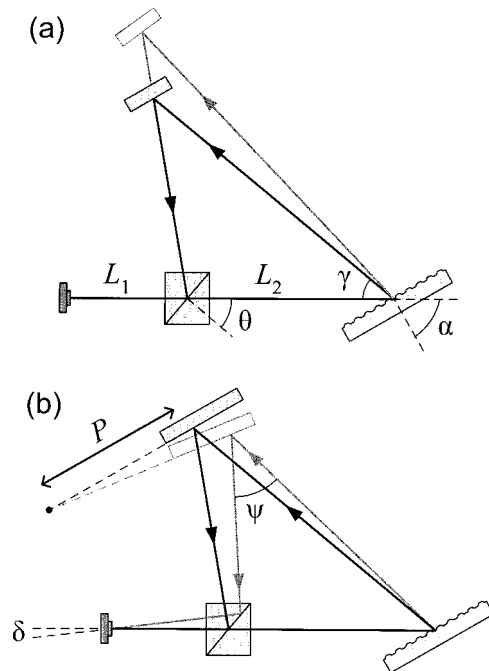


Fig. 2. Tuning the laser. (a) The four parameters L_1 , L_2 , θ , and α , which, along with the nominal laser wavelength and the grating line spacing, define the cavity. The angle γ is determined from Eq. (3). (b) Shortening the cavity at higher γ can be done by letting the beam return to the laser diode at a small angle δ relative to the outgoing beam.

in a way that satisfies Eq. (1). In Fig. 2(a) it can be seen that, by rotating and translating the upper mirror, it is possible to increase the angle between the beam incident on the grating and the diffracted beam (this angle is denoted as γ in the figure). When this is done, the length of the external cavity increases while the wavelength of light diffracted with increasing γ decreases, causing the feedback wavelength and the cavity length to scan in opposite directions. Using this model, we would predict that our laser should only be able to scan approximately 100 MHz before it became favorable to hop to another mode. The fact that we have been able to scan much further without mode hops indicates that this model is incomplete.

In our current model, the returning beam is allowed to be at a slight angle δ relative to the beam exiting the diode [see Fig. 2(b)]. Because the collimated laser beam has a finite width, the beam contains a spread of wave vectors. By measuring the Gaussian radius w_0 of the collimated beam, we can calculate the $1/e^2$ full angular divergence of the beam: $\phi = 2\lambda/\pi w_0$. In our model we assume that a beam returning with a δ that is considerably less than $\phi/2$ will couple back to the diode nearly as well as a beam going straight back with $\delta = 0$.

With this revised model we were able to calculate a theoretical tuning range for the laser. We did this by first using simple trigonometry to find the round-trip path length of the cavity. The optical path length from the laser diode to the rejection-

port polarizing beam splitter of the isolator (labeled as L_1 in Fig. 2), and the optical path length from the beam splitter to the grating (labeled L_2 in Fig. 2) were assumed to be known quantities. In addition, the angles between the incident beam and the normal vectors of the beam splitter and grating (labeled θ and α , respectively), the spacing between lines on the grating d , and the nominal ($\delta = 0$) wavelength of the laser λ_0 were assumed to be known. These six quantities define the configuration of a particular laser.

The calculated path length S is a function of the known parameters as well as the feedback angle δ and the angle between the incident and the diffracted beams at the grating γ . By use of the grating equation and assuming that the first diffraction order from the grating is the one fed back to the diode, the angle γ can be solved in terms of the wavelength of the laser:

$$\gamma = \alpha - \arcsin[\lambda/d - \sin(\alpha)]. \quad (3)$$

Substituting this relation for γ in our expression for S resulted in an equation for the round-trip path length that is only a function of known quantities, the angle δ , and the wavelength $\lambda = \lambda_0 + \Delta\lambda$.

Next, we substituted our expression for S into Eq. (1) to generate an equation that relates the wavelength shift $\Delta\lambda$ to δ under the condition that the mirror is moved and rotated in a manner that satisfies the criterion for mode-hop-free tuning. This somewhat complicated equation can be solved numerically to find $\Delta\lambda$ for a given δ . To generate an analytical solution, we first linearized this equation in δ and were then able to solve the resulting first-order equation for $\Delta\lambda$. Then, because the tuning range of a diode laser is more often discussed in terms of frequency than wavelength, we converted this into an equation for the frequency detuning Δf with the first-order relationship $\Delta f = \Delta\lambda c/\lambda_0^2$. Finally, we calculated the tuning range of the laser by assuming that allowed values of δ ranged from $-\phi/2$ to $\phi/2$.

The final result of this calculation is an equation for detuning that is just the maximum allowed range of δ times a constant:

$$\Delta f = Q\delta. \quad (4)$$

The tuning range of the laser can then be approximated by our taking the difference between Δf calculated at $\delta = \phi/2$ and at $\delta = -\phi/2$, which gives a tuning range of Q times the full-angle Gaussian divergence ϕ . The proportionality constant Q is given by the following expression:

$$Q = \frac{c(L_1A + L_2B)}{\lambda_0(S_0 + L_2\lambda_0C/d)}. \quad (5)$$

Here c is the speed of light and λ_0 is the nominal wavelength of the laser. The unitless parameters A , B , and C are given by

$$A \equiv \frac{1 + \cos \psi_0}{\sin \psi_0}, \quad (6)$$

$$B \equiv \frac{\sin \gamma_0}{1 - \cos \psi_0}, \quad (7)$$

$$C \equiv \frac{\sin 2\theta}{\cos(\alpha - \gamma_0)(1 - \cos \psi_0)}, \quad (8)$$

where γ_0 is the angle between the incident and the diffracted beams at the grating when $\delta = 0$. This angle can be measured physically for a particular laser or can be calculated from Eq. (3) with the wavelength $\lambda = \lambda_0$. The angle $\psi_0 = 2\theta - \gamma_0$ is the angle between the incident and the reflected beams at the tuning mirror [see Fig. 2(b)] when $\delta = 0$.

The S_0 term in Eq. (5) is the round-trip optical path length of the cavity when $\delta = 0$, given by the relation

$$S_0 = 2L_1 + \left(1 + \frac{\sin 2\theta + \sin \gamma_0}{\sin \psi_0}\right)L_2. \quad (9)$$

With the parameters of the laser that we tested, the first-order model predicts a mode-hop-free tuning range of $\approx 4 \times 10^{11}$ Hz (or approximately 0.6 nm), well in excess of the measured range, implying that we have not realized the maximum possible tuning range for our configuration. This first-order tuning range estimate agrees with the predicted tuning range determined from a full numerical solution to better than 0.1%.

Unlike the Littman design, in this design simple pivoting of the mirror about a fixed axis does not result in ideal tuning. In many cases, however, this simple method is close enough to the ideal geometry to achieve the full tuning range predicted by Eq. (4). For example, a complete numerical model of our current laser configuration reveals that, if the correct pivot point is chosen, the integer m in Eq. (2) will change by only 0.08 over the entire tuning range predicted by Eq. (4). The precise location of this pivot point, however, is important. The numerical model of our laser shows that changing the pivot point by ± 1 mm reduces the expected scan range by more than an order of magnitude.

To calculate the ideal pivot lever arm P [see Fig. 2(b)] for a maximum mode-hop-free tuning range, we first used Eqs. (3) and (4) to find γ as a function of δ . This relation was reduced to lowest order in δ to produce the equation $\gamma = \gamma_0 + G\delta$, where G is given by

$$G = \frac{Q\lambda_0^2}{cd \cos(\alpha - \gamma_0)}. \quad (10)$$

We were then able to find the angle $\psi = 2\theta_0 - \gamma + \delta \approx 2\theta_0 - \gamma_0 + (1 - G)\delta$ in Fig. 2(b), as well as the location of the point in space where the beam reflects off of the

mirror, as a function of known quantities and δ . From this, and using the law of reflection, we were able to write an equation for the line that follows the surface of the mirror [indicated by the dashed lines near the top of Fig. 2(b)] as a function of δ in slope–intercept form. We then set both sides of the equation for a line at finite δ equal to the equation for the $\delta = 0$ line. After linearizing this relation, we solved for the point at which these two lines cross. The distance from this point to the place at which the beam strikes the mirror when $\delta = 0$ is given by the relation

$$P = \frac{2 \sin(\theta + \gamma_0/2)(L_1 D + L_2 E)}{(1 + G)\sin^2 \psi_0}, \quad (11)$$

where the unitless parameters D and E are given by

$$D \equiv \frac{\sin \psi_0}{\sin(2\theta + \gamma_0)} (\cos 2\theta + \cos \gamma_0), \quad (12)$$

$$E \equiv \frac{\cos 2\theta + \cos \gamma_0}{\sin(2\theta + \gamma_0)} (\sin \gamma_0 - G \sin 2\theta). \quad (13)$$

4. Conclusion

In conclusion, we have demonstrated a new scheme for external-cavity diode-laser stabilization that combines the higher output of the Littrow scheme with the stable output pointing of the Littman–Metcalf scheme. We have measured the spectral properties of a prototype laser and found them to be comparable with typical Littrow lasers. We have measured a mode-hop-free scan range of several gigahertz when tuning the laser by pivoting the mirror about a fixed axis, and we have developed a model that predicts that much larger tuning ranges are possible.

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