External-cavity diode laser using a grazing-incidence diffraction grating

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An external cavity has been developed for use with commercial diode lasers. It uses a diffraction grating at grazing incidence for wavelength selection and output coupling. This configuration allows a GaAlAs diode laser to be tuned conveniently anywhere in a range greater than 20 nm. Also, the linewidth is reduced by a factor of more than 1000 from 40 MHz to less than 10 kHz. The new laser system should be useful for high-resolution spectroscopy, laser cooling of atoms, time standards, and coherent optical communications.

For some applications, such as spectroscopy and laser cooling of atoms, a tunable single-frequency laser is required that is versatile and inexpensive. It needs to have a narrow linewidth but only modest power. A solitary diode laser largely satisfies this need. It can be tuned over a limited range by changing the temperature or current of the diode. However, the tuning range may have gaps in it, and the linewidth is large for a cw laser. Further, a solitary diode laser is sensitive to optical feedback. However, if an external cavity is coupled to the diode laser, the linewidth is narrowed and the frequency tuning of the diode laser is improved.

A diode laser has been weakly coupled to an external cavity that consists of a simple external mirror, and an étalon has been added to control the mode selection. More recently a laser diode has been optically locked to an external high-finesse cavity. This produced a greatly narrowed linewidth of only 20 kHz. The wavelength of the diode laser was stabilized by the cavity, and a commercial diode could be used. However, this approach is somewhat complex. Also, since it is restricted to the weak-feedback regime, the wavelength is limited to tuning ranges near the axial-mode resonances of the laser diode. Therefore there may still be gaps in the tuning range.

The diode laser has also been strongly coupled to an external cavity that has a frequency-selective element. An external cavity with a grating in Littrow mount produced a linewidth of 10 kHz. This linewidth was later considerably narrowed to as low as 300 Hz by appropriate detuning of the feedback phase of the external cavity from resonance with the field reflected from the antireflection-coated facet of the diode laser. However, these techniques require a diode laser to have specially prepared antireflection coatings on the facets. For simplicity, it is highly desirable to use commercial diode lasers. Configurations with diffraction gratings in Littrow mount have been used with commercial diode lasers. However, in these types of cavity the laser beam will rotate and translate when the frequency is changed by moving the grating.

We describe here a new external cavity that is used with a commercial GaAlAs diode laser. It is simple and versatile and is made of standard optical components. A diffraction grating at grazing incidence serves for wavelength selection and output coupling. The laser is single frequency, has a narrow linewidth, and is continuously tunable over a wide range. The laser beam has good directional stability when it is tuned. The laser cavity is shown in Fig. 1. It is a three-mirror cavity that consists of a high-reflection-coated rear facet of the diode laser, the lasing medium of the diode, the antireflection-coated front facet of the diode laser, the window of the diode-laser case, a collimating lens, a diffraction grating at grazing incidence, and an external mirror. The zeroth-order reflection from the grating is the output of the laser. The first-order reflection from the grating is reflected back into the laser by the external mirror. One end of the laser cavity is the rear facet of the diode laser, and the other end is the external mirror. The frequency is tuned by moving the external mirror. This arrangement is similar to the Littman configuration for pulsed lasers. However, it differs in that here a lens is added to collimate the beam, the gain medium is in a waveguide, and the laser is cw.

Fig. 1. Schematic diagram of the laser. PZT, piezoelectric ceramic.
The coarse tuning of the cavity is determined by the grating equation,\textsuperscript{15}

$$\lambda_L = \frac{d}{m} (\sin \alpha + \sin \beta),$$

(1)

where $\lambda_L$ is the wavelength of the laser, $d$ is the grating spacing, and $m$ is the diffraction order. $\alpha$ and $\beta$ are the angles shown in Fig. 1. For grazing incidence, $\sin \alpha \approx 1$. The single-pass dispersion of the grating is intrinsically twice as great as cavities that use a grating in Littrow mount. The single-pass linewidth (FWHM) of the cavity due to the grating is

$$\Delta \lambda_G = \frac{dw_1}{mf} \cos \alpha,$$

(2)

where $w_1$ is the beam waist at the diode and $f$ is the focal length of the collimating lens. Cavities that use a diffraction grating in Littrow mount typically have a larger grating passband because fewer lines of the diffraction grating are covered by the laser beam. The increased dispersion of the grazing-incidence diffraction grating improves selection of axial cavity modes and biasing of external cavity modes to diode-laser cavity modes, which is useful for some linewidth-reduction techniques.\textsuperscript{5} The linewidth of the laser is given by the modified Schawlow-Townes formula.\textsuperscript{5,7}

The addition of an external cavity to a solitary diode laser reduces the linewidth primarily because the cavity length is greatly increased, which reduces the passive cavity linewidth and the relative influence of fluctuations in the index of refraction of the gain medium.\textsuperscript{5}

The external-cavity laser was constructed with a commercial GaAlAs diode laser (Sharp LTO24MD) that lased at a wavelength of 780 nm at room temperature. The output facet had an antireflection coating that had a reflectivity estimated to be between 2% and 10%. The other facet had a high-reflection coating of approximately 97% reflectivity. The solitary diode laser had a free-running linewidth of roughly 40 MHz and an axial mode spacing of 0.31 nm. The temperature of the diode laser was held constant by a thermoelectric cooler and a controller unit. The temperature was typically 19°C. The diode current was supplied by a precision current source. The diode current was typically 90 mA. The output of the diode laser was collimated by an antireflection-coated, bi-aspheric plastic lens that had a numerical aperture of 0.45 and a focal length of 4.5 mm. An 1800-line/mm holographic diffraction grating (American Holographic, catalog no. 135.1800) was used in grazing incidence. The diffraction angle $\alpha$ was measured to be approximately 85°. The diffraction efficiency into the first order was measured to be 40%. Thus, neglecting coupling losses, 15% of the power was returned to the diode-laser amplifier. The internal cavity modes of the diode laser were therefore strongly coupled to the external cavity. The junction plane of the diode laser was oriented to be perpendicular to the grooves of the diffraction grating to optimize the efficiency of the grating. For the parameters of this cavity, Eq. (2) gives the passband of the diffraction grating to be $\Delta \lambda_G = 0.03$ nm or $\Delta \lambda_G = 14$ GHz. The external mirror was coated for >99% reflection in the near infrared and was translated by a piezoelectric ceramic. The average length of the laser cavity was roughly 12 cm. This corresponds to an axial mode spacing of 1.2 GHz. The components of the laser were rigidly mounted on an aluminum plate. The laser was enclosed in a clear Lucite box to reduce air currents and stabilize the temperature of the laser cavity. This box was surrounded by another box made of polystyrene foam board to insulate the laser cavity and reduce temperature drift. The laser and associated optics were on a optical table that was pneumatically floated on four legs to provide vibration isolation. A charge-coupled-device television camera allowed us to observe the laser radiation for cavity alignment and beam adjustments.

The coarse wavelength of the diode laser was measured with a 0.5-m spectrometer. The spectrometer had a self-scanned linear photodiode array of 512 elements for real-time recording. The tuning range of the laser is shown in Fig. 2. For this figure the frequency was changed by rotating the external mirror while leaving the diode temperature and current constant. The laser could be tuned within 20 nm about its doped wavelength. If the temperature of the diode laser were changed it is expected that the tuning range would increase to 30 nm. To observe the wavelength with higher resolution, we used a scanning confocal interferometer that had a free spectral range of 8 GHz and a finesse of 200. The laser could be continuously tuned 6 GHz by translating the external mirror with the piezoelectric transducer. When the laser frequency was scanned, the diode current or temperature did not have to be changed but instead was held constant. For additional diagnostics, we could observe the resonance fluorescence from an atomic rubidium vapor cell. In general, to tune the laser to a particular wavelength, the external cavity was first misaligned and the diode current was adjusted to locate the wavelength of

\begin{figure}
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\includegraphics[width=0.5\textwidth]{tuning_curve.png}
\caption{Tuning curve of the laser. The point under the curve is the power of the laser when the external cavity is misaligned and the diode lases from its front facet.}
\end{figure}
these measurements. It was observed qualitatively that the diode current, optical feedback, and residual index technical noise such as mechanical vibrations, noise in the fast P-I-N diode. The signal from the photodiode was then amplified and sent to a spectrum analyzer. The beams from the two identical lasers were mixed in a external-cavity diode lasers were constructed. The grating and external mirror.

The laser beam has good directional stability since the direction of the beam is determined by the waveguide of the diode laser and the diffraction grating, which do not move when the frequency is tuned. Although the long-term frequency stability of this laser is less than that in Ref. 4, it can be improved by locking the laser to a passive external cavity. This laser should be useful for a number of applications, including high-resolution spectroscopy, the trapping and cooling of atoms, coherent optical communications, and frequency standards.

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References