Tunable external-cavity diode laser at 650 nm based on a transmission diffraction grating

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A tunable external-cavity diode laser (ECDL) based on a transmission diffraction grating in a Littrow mount has been developed and characterized. A single-transverse-mode diode laser at 650 nm is used in an external-cavity configuration in which the transmission grating is used as a dispersive element to select the single longitudinal mode. The transmission diffraction grating is made with electron-beam lithography. A tunable true single-mode cw output power of >20 mW is obtained from the ECDL. The total wavelength tuning range is 12 nm, and the mode-hop-free continuous tunability is >20 GHz. © 2002 Optical Society of America

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1. Introduction

The applications of tunable-diode laser spectroscopy have developed rapidly during the past few years.¹⁻³ Spectroscopic applications of relatively new diode laser types, such as vertical cavity surface-emitting lasers⁴⁻⁶ and quantum cascade lasers.⁷⁻⁹ have also remarkably increased the interest in tunable-diode laser spectroscopy. Vertical cavity surface-emitting lasers and distributed-feedback-type lasers operate in single longitudinal mode, but these lasers are available only at a limited number of wavelength bands. Fabry-Perot-type diode lasers cover a large wavelength range, but because of their multimode emission characteristics they are not suitable for high-resolution applications, and external optical feedback, e.g. a grating, is needed for narrowband (<1-MHz) single-longitudinal-mode operation. The wavelength tuning characteristics of a Fabry-Perottype diode laser are remarkably improved by the presence of an external cavity, and the sensitivity to optical feedback is decreased.

Many external-cavity diode lasers (ECDLs) are based on reflective diffraction gratings in the Littrow

mount.^{10–14} This design has a drawback in applications for which the beam direction must not change when the wavelength is tuned, e.g., when the output beam is coupled into further external cavities as in enhanced second-harmonic generation. A few methods to prevent changes in the output beam's direction in a Littrow mount have been developed. In one of these methods an intracavity beam splitter is used as an output coupler.^{1,15} Another one employs an additional plane mirror to compensate for variation in beam direction.¹⁶ However, all these methods require more optical and mechanical components than the ECDL described in this paper. For an intracavity beam splitter, the required optical quality is also very high.

In ECDLs based on the reflective gratings in a Littman–Metcalf mount^{17,18} the directional variation of the beam is removed, but the design requires more components and the requirements for mechanical precision and thermal stability stricter. Merimaa *et al.*¹⁹ combined the mechanical simplicity and the directional stability of the beam by using a novel transmission diffraction grating. Electron-beam lithography, which has become commercially available, has made possible the manufacture of transmission gratings with a diffraction of 15–20% back to the laser and with ~75% transmission to the output order with only minor losses into other diffraction orders. The transmission grating yields compact ECDL designs.

The objective of the present study has been to design and construct a compact high-power ECDL to be used in frequency-doubled high-resolution spectroscopy. The convenience of testing various compo-

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Fig. 1. Schematic drawing of the ECDL. AR, antireflection.

nents of an ECDL system and the general-purpose use with different diode lasers were emphasized in the system design at the expense of the maximum compactness and the optimal rigidity of the system. The new ECDL system is based mainly on commercially available components and drivers.

2. Apparatus

A schematic drawing of the ECDL is shown in Fig. 1. The diode laser is a GaInP–AlGaInP ridge waveguide single-transverse-mode laser operating at 650 nm. Stable multimode cw output power of >30 mW has been achieved from this laser type at 20 °C and of as much as 60 mW at 15 °C.²⁰ The diode laser typically has a threshold current of 38 mA, and it operates longitudinally multimode, typically with ~10 lasing modes.

The design of the ECDL is shown in Fig. 2. In the external-cavity configuration the output facet of the diode laser is antireflection coated; it has a residual power reflectance of $\sim 2 \times 10^{-4}$. This low residual reflectance permits a large mode-hop-free tuning range. The laser chip is mounted upon a submount,



Fig. 2. Sectional view of the ECDL assembly: 1, XY translator; 2, kinematic mirror mount; 3, Z translator; 4, thermoelectric cooler; 5, transmission grating; 6, carbon fiber rods; 7, laser diode; 8, collimating lens; 9, piezoelectric transducer; 10, half-wave plate; 11, air-cooled heat sink.

which lies on a custom-made copper block that is used as a heat sink. The copper heat sink is temperature stabilized with a thermoelectric cooler. The diode laser's temperature and the current are controlled with a commercial diode laser driver (Profile ITC 510). The operating temperature of the diode laser is typically stabilized at 20.0 °C. The laser beam is collimated with an aspheric lens (f = 8.0 mm; N.A., 0.5). The polarization direction of the diode laser is turned with a zero-order half-wave plate for optimum performance of the grating. Both the collimating lens and the wave plate are antireflection (AR) coated. The output beam has an elliptical profile (8 mm \times 1.5 mm), which can be further modified by standard beam-shaping techniques.

The mechanical design of the ECDL is based mainly on commercial optomechanical components. An XY translator is connected with four custom-made carbon fiber rods to a kinematic mirror mount. Carbon fiber was selected as the material for the cavity rods because of its low thermal expansion (expansion coefficient, $\sim 0.3 \times 10^{-6}$ 1/K). Although glassceramic materials with even lower thermal expansion coefficients are available, the carbon fiber was selected because it is more rigid than glass-ceramics and because carbon fiber rods are moderately easy to machine. The kinematic mirror mount is the mounting base for the transmission grating. The XY translator has differential micrometer adjusters for accurate transverse placement of the diode laser. The four carbon fiber rods support a Z translator, which allows for accurate positioning of the collimating lens with micrometer adjusters. During the operation of the ECDL we noted that correct positioning of the collimating lens was critical to efficient laser operation, so a micrometer adjuster really helps one to optimize the lens position. With the selected components the minimum ECDL cavity length is 20 mm, which corresponds to a longitudinal cavity-mode spacing of \sim 7.5 GHz. The coarse cavity length can be changed easily because all the components slide along the cavity rods after the locking screws are loosened. The optomechanical components used in the present ECDL were selected primarily to facilitate modification of the ECDL for various parameter and component tests. For specific applications, much more compact designs with smaller cavity lengths can be made with custom-made components. The external cavity is based on a transmission-type Littrow mount. The transmission grating is mounted upon an aluminum holder, which is supported at a 45° angle by three symmetrically located piezoelectric transducers (PZTs). The PZTs are located on the output facet side of the grating, making it possible to reduce the cavity length. The lowvoltage PZTs are controlled with a commercial threechannel piezo driver (Thorlabs MDT690). The ECDL is attached from the *XY* translator to an optical table, and the whole system is protected against dust and temperature variations by a polycarbonate box.

In a Littrow mount a grating has to reflect the -1st



Fig. 3. Notation for grating design parameters.

diffraction order. Therefore the required grating period is $d = \lambda/2 \sin \theta_{\text{in}}$. If the incident angle is $\theta_{\text{in}} = 45^{\circ}$ and $\lambda = 650$ nm, then the grating period is d =460 nm. The feasible feedback for the ECDL is 15– 20%, which is attainable with a transmission grating coated with a material of higher refractive index.¹⁹ Quartz, with $n_1 = 1.46$, was used as the grating material, and titanium dioxide (TiO₂), with $n_2 = 2.2$, was used for the coating. Because of the small period. the grating has to be designed by use of rigorous diffraction theory.²¹ The fill factor of the grating, f =c/d = 0.5, was fixed, so the free optimization parameters are grating depth h_1 and thickness of the coating layer h_2 ; see Fig. 3 for the notation. When a TE-polarized incident beam is assumed, the optimization gives $h_1 = 71$ nm and $h_2 = 140$ nm. These values offer 18.6% efficiency for the reflected -1storder and 74.7% transmittance. The losses to the 0th reflected order and to the -1st transmitted order are 2.8% and 3.9%, respectively. The coated grating is highly insensitive to parameter variations¹⁹; for example, over the ± 20 -nm tuning range the reflection of the -1st diffraction order remains above 18.1% and the 0th order transmission is above 73.3%.

The grating is fabricated by electron-beam lithography onto a 3-mm-thick quartz substrate of 1" (2.54cm) diameter and is then coated by vacuum evaporation. In vacuum evaporation some material is also deposited on the sidewalls of the grating, but that layer is so thin that the amount of additional material does not significantly influence the performance of the grating.¹⁹ Then the second facet of the grating is AR coated with a single standard magnesium fluoride (MgF₂) layer to improve the tuning properties by reducing the etalon effect that is due to the second facet.

3. Results

We characterized the ECDL's performance by measuring the optical output power, the relative intensity noise (RIN), the linewidth, and the tuning range. Typical L–I curves of the solitary diode laser before deposition of the output facet's AR coating and of the ECDL are shown in Fig. 4. The optical output power was measured with a calibrated optical powermeter (Ophir LaserStar). At 20 °C temperature a maximum single-mode cw output power greater than 21 mW at 85-mA laser diode current was measured from the ECDL. At each current value the grating was adjusted with the PZTs to maximize the output power. The solitary diode laser was taken from the same batch as those used in the ECDL. Its charac-



Fig. 4. cw optical output power of the diode laser before deposition of the AR coating, and of the ECDL. Two different diode laser chips were used in the ECDL: the chips 5 and 7 have residual reflectivities of 4×10^{-4} and 2×10^{-4} , respectively. The heat-sink temperature was stabilized at 20 °C.

teristics are expected to be representative of the ECDL emitters before deposition of the AR coating.

The RIN characterizes the intensity noise of a diode laser.²² RIN values are usually defined at high frequencies to be useful in telecom applications. In spectroscopic applications the low-frequency RIN values are more important, and therefore RIN values in the range from 10 Hz to 1 MHz were measured. RIN was measured with a photodiode, a preamplifier, and a fast-Fourier-transform spectrum analyzer (Hewlett-Packard HP4395A). The results of the RIN measurement are shown in Fig. 5. The RIN level that we achieved was below -150 dB at 7.5-mW optical power at frequencies higher than 200 kHz. The inset of Fig. 5 shows the dependence of the RIN on the optical output power at three frequencies: 10, 50, and 100 kHz. The measured power dependence fits the theoretical P^{-3} slope well.²³

Phase or frequency modulation noise in lasers is well known, and it sets the fundamental limit for the



Fig. 5. Relative intensity noise of the ECDL. The apparent discontinuity at 10 kHz is due to the fact that the whole spectrum was measured in two parts. Inset, RIN power dependence at three different frequencies. The line shows the theoretical P^{-3} slope.



Fig. 6. Averaged intensity spectra of the diode laser and the ECDL measured with a diffraction grating optical spectrum analyzer. The linewidths are limited by the instrument's resolution (0.05 nm).

ECDL linewidth. One can calculate the limiting value from the modified Schawlow–Townes formula,²⁴ taking into account the linewidth reduction of the external cavity under strong optical feedback.²⁵ In the present case the calculation gives a fundamental linewidth of $\Delta \nu \sim 65$ kHz. However, this value is scarcely achievable in practical measurements because of the presence of 1/f-type noise, which increases the practical linewidth at lower frequencies. Many sources, such as current noise of the laser diode driver, voltage noise of the piezo driver, temperature fluctuations caused by the nonideal temperature controller, and external disturbances such as thermal drifts and mechanical and acoustic vibrations,²⁶ contribute to the total 1/f noise.

Single-mode operation of the ECDL was first verified by use of three different spectrum analyzers. We verified the theoretical linewidth limit by measuring the power spectral density of the frequency noise, and finally we estimated the practical linewidth by measuring short-term linewidth in the time domain. Single-mode operation was first observed with a diffraction grating optical spectrum analyzer (Anritsu MS9710B). The spectrum of the diode laser before deposition of the AR coating, and the ECDL spectrum, are shown Fig. 6. The frequency spacing of the diode laser modes is ~80 GHz, corresponding to the 400-µm diode laser cavity length. Figure 7 shows the laser diode spectrum measured with a Fabry-Perot interferometer (FPI; TecOptics FPI-25; finesse, 25). The inset of Fig. 7 shows the ECDL output measured with a confocal FPI that has a better finesse (160) and 2-GHz free spectral range (TecOptics SA-2). An instrument-limited linewidth of 12 MHz was observed.

We verified the fundamental linewidth limit by measuring the power spectral density of the frequency noise, $S_{\rm FM}(f)$. In the measurement the ECDL line was locked to the approximately linear region of the side of the FPI transmission curve and the power spectral density of the amplified photo-



Fig. 7. Spectra of the solitary diode laser and the ECDL measured with a FPI. The ECDL spectrum is shown schematically on the same scale. Inset, ECDL spectrum measured with a higherresolution FPI. The instrument-limited linewidth is 12 MHz.

diode signal was measured with a fast-Fouriertransform spectrum analyzer. The linewidth was determined from the measured noise spectrum according to the equation²⁷

$$\Delta \nu = \pi S_{\rm FM}(f).$$

The measured power spectral density of the frequency noise is shown in Fig. 8. At frequencies greater than 100 kHz the value of the noise floor corresponds to a linewidth of 70 kHz. On the scale of Fig. 8 the contributing fraction from the intensity noise to the linewidth is more than an order of magnitude smaller than the total power spectral density shown over the whole frequency range; thus the intensity noise makes a minor contribution to the linewidth.

In spectroscopic measurements 1/f noise is present, and that is why the linewidth that includes the contribution from the 1/f noise is of great practical importance. We estimated this practical linewidth by measuring the short-term (2-s) linewidth of the ECDL in the time domain.²⁶ The laser line was



Fig. 8. Frequency noise spectral density of the ECDL. In this measurement the ECDL was driven from a battery to reduce 1/f noise.



Fig. 9. Short-term practical linewidth. Inset, the amplitude distribution of the data sample and a Gaussian fit.

locked to the side of the FPI transmission curve, and the photodiode signal was stored with an oscilloscope. The inset of Fig. 9 shows the amplitude distribution of the data sample. The main noise band (100 kHz) is narrower than the rms value of the frequency fluctuation (1.5 MHz), so a Gaussian shape was fitted to the amplitude distribution.²⁷ The Gaussian fit has a width (FWHM) of 4 MHz. In the present ECDL system all the power drivers and controllers were commercial, and the setup was not optimized for maximum passive stability. An open-air FPI was used as the frequency discriminator, which degraded the optical stability of the setup. With custom-made electronics, more-detailed component optimization and materials selection and an absorption cell as a frequency discriminator, a short-term (1-s) linewidth of the order of 100 kHz has been achieved.²⁶

The ECDL wavelength can be tuned coarsely by adjustment of the grating angle with adjustment screws of the kinematic mount. Fine mode-hop-free tuning is done with the three PZTs. A coarse tuning range of ± 6 nm about the center wavelength of 646 nm was measured at constant 20 °C heat-sink temperature. For the solitary diode laser a temperature tuning rate of the wavelength of $\sim 0.2 \text{ nm/°C}$ was measured, so the coarse tuning range can be further increased by simultaneous adjustment of the heatsink temperature. The grating holder is so designed that the three PZTs are symmetrically attached to the holder. Effectively, the design utilizes a virtual pivot point for grating tuning and achieves a condition in which the cavity resonance is maintained by simultaneous changes in cavity length and diffraction angle, a condition that is needed for continuous single-mode tuning.²⁸ The three tuning PZTs of the grating were controlled with a computer program and a 16-bit digital-to-analog card. The computercontrolled analog signals adjusted the PZTs in such a way that the optimum resonance condition was fulfilled during the wavelength tuning. With this control method we demonstrated a continuous modehop-free tuning range greater than 20 GHz at 650 nm with the piezo control only. Optimization of the software parameters should further increase the tuning range; however, in the present system the maximum extension of the PZTs starts to limit the tuning range. The fine-tuning range can be further increased by introduction of a simultaneous control of the laser diode current.³ We suggest that the improvement in the tuning range that we have described is due mainly to the high quality AR coating of the diode laser facet and to the introduction of the AR coating upon the second facet of the grating that was not used in the earlier experiments of Merimaa et al., in which an 18-GHz fine-tuning range was achieved when the current was adjusted simultaneously with the grating.¹⁹ At 1510 nm, a 50-GHz mode-hop-free tuning range with a piezo-controlled reflection grating ECDL has been demonstrated.²⁹

4. Conclusions

The new and relatively simple ECDL design presented here can easily be modified for commercial diode laser types and can be made even more compact, to microelectromechanical proportions. True single-mode output power at 650 nm is as great as 21 mW at room temperature. With high quality AR coatings of both the diode laser facet and the output facet of the grating the wavelength tuning was improved, and a good mode-hop-free tuning range greater than 20 GHz was obtained with the grating angle tuning only. Solitary diode lasers with highquality AR coatings have started to become commercially available, but the commercial availability of custom-made high-quality AR coatings for different diode laser materials is still limited. The computercontrolled tuning has great potential for further improvement of the tuning range with control parameter optimization and simultaneous diode laser current control. Adjusting the heat-sink temperature can further increase the coarse-tuning range. The measured performance parameters with commercially available drivers indicate the suitability of the new ECDL design for applications in which high spectral resolution and directionally stable tunable diode laser sources are needed. The use of diffractive optics in manufacturing transmission gratings offers many degrees of freedom that can be used to improve system performance, e.g., beam quality, in the future. However, manufacture of a transmission grating is currently relatively expensive because the electron-beam lithography process is expensive. But, with larger quantities or if replicas of the master grating were made, the grating price could be reduced.

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