## Continuously tunable external-cavity diode laser with a double-grating arrangement

## D. Wandt, M. Laschek, A. Tünnermann, and H. Welling

Laser Zentrum Hannover e.V., Hollerithallee 8, Hannover, Germany D-30419

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A new external-cavity diode laser system based on an extended version of the Littman configuration is investigated. In our laser system the tuning mirror is replaced with a second grating mounted at the Littrow angle. This double-grating design provides a smaller passive bandwidth than the grating-mirror configuration, which is used to compensate for the large angle-of-incidence-dependent losses of the grazing-incidence grating. This results in a broader continuous tuning range with an improved mode stability. Because two laser diodes, emitting at 820 and 775 nm, respectively, are used, the external-cavity laser is continuously tunable without mode hops across 35 nm at 820 nm and 27 nm at 775 nm. Such a laser was used to measure the absorption lines of the oxygen A band around 762 nm. The complete *R*- and *P*-rotational branches of the  $b \, {}^{1}\Sigma_{g}{}^{-}(\nu'=0) \leftarrow X \, {}^{3}\Sigma_{g}{}^{-}(\nu'=0)$  transition were recorded in a single-wavelength scan. © 1997 Optical Society of America

Broadly tunable external-cavity diode lasers with emission wavelengths in the visible and the near-infrared spectral regions are compact and reliable light sources that are increasingly used in a variety of applications, including high-resolution spectroscopy, gas sensing, and metrology. Commonly such a laser system consists of an antireflection-coated laser diode located inside an external grating cavity and therefore serving as an active material with a broad gain spectrum. The strong wavelength-selective feedback of the grating in combination with the enlarged resonator length forces the laser diode to operate in a single longitudinal mode with a small linewidth. In addition, these lasers are continuously tunable across the gain spectrum of the diode by use of suitable resonator configurations. This was demonstrated recently by application of Littrow and Littman configurations: With Littrow arrangements, wavelength tuning without mode hops of 15 nm around 1.26  $\mu$ m, of 25 nm around 1.55  $\mu$ m, and even 82 nm around 1.54  $\mu$ m were obtained.<sup>1-3</sup> However, owing to the poor cavity dispersion of Littrow resonators, generally prism beam expanders or additional wavelength-selective elements such as étalons have to be used to achieve good mode stability.4 The Littman-Metcalf configuration consists of a grating mounted in grazing incidence and an external tuning mirror.<sup>5,6</sup> In this configuration the grating itself acts as a beam expander, and no additional wavelength-selective elements are needed to obtain stable single-frequency operation. However, the grating losses increase at greater angles of incidence, resulting in a higher laser threshold and therefore in a reduced tuning range. External-cavity diode lasers with a grating mounted at an angle of incidence of 85° show a typical continuous tuning range of 15–20 nm at 770 nm and of 20–25 nm at 803 nm.<sup>7,8</sup> Unlike those systems, a tuning range without mode hops of more than 40 nm at 825 nm has been obtained by use of a grating with an angle of incidence of 75°.<sup>9</sup> However, owing to the larger spectral bandwidth, small fluctuations of temperature or density or acoustical vibrations

might reduce the performance of the laser system, especially the mode stability.

In this Letter we report what we believe to be the first realization of an external-cavity diode laser based on an extended version of the Littman-Metcalf configuration. The laser system has an improved mode stability combined with a broad, continuous tuning range.

In contrast with the previously described externalcavity diode lasers, a Littrow grating is used in our new laser system, thus replacing the tuning mirror. This double-grating arrangement was first investigated theoretically by Littman<sup>10</sup> and experimentally by Shoshan and Oppenheim<sup>11</sup> in terms of the development of narrow-band pulsed dye lasers. Following their treatment, the passive bandwidth (in inverse seconds) of the combination of a grazing-incidence grating and a Littrow grating is

$$\delta \nu_{\rm dg} = \frac{2c}{\pi w \lambda \left( 2 \frac{m_1}{d_1 \cos \beta_1} + \frac{m_2}{d_2 \cos \beta_2} \right) \frac{\cos \beta_1}{\cos \alpha_1}}, \quad (1)$$

where c is the velocity of light, w is the beam radius,  $d_1$ and  $d_2$  are the groove spacings of the grazing-incidence grating and the Littrow grating, respectively, and  $m_1$ and  $m_2$  are the corresponding diffraction orders.  $\alpha_1$  is the angle of incidence,  $\beta_1$  is the diffraction angle of the first grating,  $\beta_2$  is the Littrow angle of the second grating, and  $\lambda$  is the laser wavelength. Equation (1) simplifies for the grating-mirror combination ( $m_2 = 0$ ) to

$$\delta \nu_{\rm sg} = \frac{cd_1}{\pi m_1 w \lambda} \cos \alpha_1. \tag{2}$$

By comparing Eqs. (1) and (2), one finds that the double-grating configuration permits a bandwidth that is a factor of  $1 + d_1 \cos \beta_1/2d_2 \cos \beta_2$  smaller than that of the grating-mirror cavity ( $m_1 = m_2 = 1$ ). At a fixed groove spacing of the grazing-incidence grating, this reduction is strongly dependent on the groove spacing of the Littrow grating. Using a Littrow grating with a grating period of 1200 mm<sup>-1</sup> and a typical

angle of incidence of 80° at a wavelength of 770 nm, we find that the bandwidth is reduced by a factor of 1.3. However, by using the same parameters but a grating with twice the above-mentioned grating period, one can achieve a reduction factor of 2.6. Therefore the angle of incidence  $\alpha_1$  can be reduced for operation with a given bandwidth. This reduces cavity losses, and hence the tuning range increases. In addition, the double-grating arrangement permits synchronization of the cavity mode scan and the feedback wavelength scan by means of a simple mechanical construction, and therefore wavelength tuning without mode hops, as shown in Ref. 12. Finally, the dependence of the wavelength on the rotation angle of the tuning element is smaller in the case of the double-grating design than in the grating-mirror configuration. Hence, the laser can be tuned with high-frequency resolution.

The schematic of our external-cavity diode laser is shown in Fig. 1. It consists mainly of a semiconductor laser, a collimating lens, and two diffraction gratings. For our experiments, we used two different laser diodes operating at wavelengths of 820 and 775 nm (Hitachi HL8312 and HL7806), respectively. The front facet of each laser diode is antireflection coated and has a residual reflection of the order of  $10^{-4}$ .<sup>13</sup> The rear face of each diode serves as a resonator end mirror. The emission of each laser diode is collimated by an antireflection-coated aspheric lens with a focal length of 4.5 mm and a numerical aperture of 0.55. Both the laser diodes and the lens are built in a collimator housing, which allows fine adjustment of the collimation and the position of the laser diodes perpendicular to the optical axis. The temperature of this module is actively stabilized by a thermistor and a Peltier module in a feedback system with a stability of the order of 1 mK. A gold-coated grating with an inverse groove spacing of 1800/mm is mounted at an angle of incidence of 81°. The specular reflection of this grating serves as an output beam, whereas the first-order diffracted beam is coupled back to the laser diode by means of a highly efficient gold-coated 1200/mm Littrow grating. This double-grating configuration has a bandwidth of 6.2 GHz, in contrast with the single-grating bandwidth of 8.3 GHz. The resonator length is approximately 5.5 cm, corresponding to a longitudinal mode spacing of 2.8 GHz. Continuous wavelength tuning is accomplished by a pure rotation of the Littrow grating around a special pivot point. Therefore the grating is mounted at the end of an arm, which is fixed at a dc-motor-driven precision rotation stage. The ideal pivot point given in Ref. 12 is computed for a resonator without dispersive elements inside. It is located at the intersection of the surface planes of the Littrow grating, the grazing-incidence grating and the laser diode. Owing to the correction of the dispersion of the diode chip and the collimator, this pivot point is slightly shifted from the ideal position and has been adjusted in our system by means of an x-y translation stage.

In the top part of Fig. 2, the tuning curve of an optimized 820-nm laser system is shown. At an injec-

tion current of 90 mA and a temperature of 20 °C the laser is tunable without mode hops in the wavelength range from 805 to 840 nm in a single longitudinal mode. We examined this by observing the frequency scan of a scanning Fabry-Perot interferometer with a free spectral range of 10 GHz and a finesse of 180. In addition, the tuning curve was carefully investigated for abrupt power jumps, which are typical indications of mode hops. At the center of the tuning curve at 820 nm a maximum output power of 6 mW is achieved. The modulation of the output power is caused by the weak residual reflection of the front facet of the laser diode, forming a low-quality resonator. The free spectral range, i.e., the modulation period of the power tuning curve, therefore depends on the chip length of the laser diode and was estimated to be 130 GHz. Applying the system's maximum tuning speed, the whole tuning range is scanned within 4 s, which corresponds to an average wavelength scan rate of nearly 9 nm/s. In comparison with the rate of our single-grating laser system this scan rate is slightly reduced owing to the smaller dependence of the wavelength on the rotation angle of the Littrow grating, as mentioned above.

The dependence of the output power on the wavelength for our 775-nm external-cavity laser system is shown in the bottom part of Fig. 2. The laser is continuously tunable from 758 to 785 nm with an output power of 4.5 mW at the peak of the tuning curve at 775 nm. By using the same components in a single-grating Littman configuration but with an angle of incidence on the grating of 84°, we achieved a continuous tuning range of 20 nm. This value is  $\sim$ 7 nm smaller than that of the previously discussed double-grating laser system and comparable with the above-mentioned external-cavity diode lasers.<sup>7,8</sup> In our investigations the laser diode was operated at an injection current of 96 mA and a temperature of 20 °C. In the left part of the tuning curve around 762 nm several absorption lines of the spin-forbidden  $b^{-1}\Sigma_g^{+}(\nu'=0) \leftarrow X^{-3}\Sigma_g^{-}(\nu''=0)$  electronic transition of gaseous oxygen (A band) in ambient air appear.<sup>14</sup> Considering the separation of the laser system and the detector of only 3 m, the lines are well resolved in spite of the large power modulation.



Fig. 1. Schematic of the double-grating arrangement. AR, antireflection.



Fig. 2. Output power versus wavelength for the 820-nm laser system (top) and for the 775-nm external-cavity laser (bottom). Wavelength tuning is performed without any mode hop across the entire spectra. The expanded view of the 775-nm tuning curve shows several absorption lines of atmospheric oxygen.



Fig. 3. Absorption spectrum of the oxygen A band, measured in ambient air. Temperature 22 °C, pressure 1013 hPa, absorption length 40 m.

The sensing of oxygen was demonstrated by measurement of several absorption lines in a small wavelength interval by application of Fabry–Perot laser diodes.<sup>15</sup> More recently, distributed-feedback, vertical-cavity surface-emitting, and external-cavity diode lasers were used for this purpose.<sup>16,17</sup> However, only a limited range of the complete A band was detected, owing to the tuning limits of the used lasers. Therefore we measured the absorption spectrum of atmospheric oxygen in the whole wavelength range from 758 to 771 nm in a single scan. For this measurement the output of our laser system is split into

three beams: one beam is coupled into a wavemeter (Burleigh WA-4500) for a precise wavelength determination. A second beam is directed onto an Si photodiode located a small distance from the laser and is used as a reference signal to eliminate the modulation of the output power. The main portion of the output beam is coupled into a multipass reflection arrangement, permitting a total absorption path length of approximately 40 m. The output light of this Herriot cell is detected by a second Si photodiode. Both the reference signal and the absorption signal are registered and processed by a data-aquisition system. In Fig. 3, the result of our measurement is shown. All absorption lines of the R-rotational and the P-rotational branches of the A band with transition strengths larger than  $5\times 10^{-26}~cm^{-1}/(molecules~cm^{-2})$  were detected, which we verified using the HITRAN database.^{18}  $\,$  An improvement of the sensitivity, so that the absorption path length can be reduced, is possible when advanced spectroscopic techniques such as wavelength-modulation spectroscopy and harmonic detection are applied.

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