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Commercial grating-tuned single-mode extended-cavity semiconductor lasers (ECLDs) can be tuned over 100 nm near 1.55 μm. This continuous tuning with no mode hopping requires delicate factory adjustments and high mechanical stability so that the wavelength precision is kept as high as possible and the mismatch between the lasing wavelength and the wavelength of minimum loss remains as small as possible. The addition of a photorefractive crystal inside the cavity creates an adaptive spectral filter that decreases the loss of the lasing mode and thus enhances its stability. For what is to our knowledge the first time, we demonstrate the extension of the available wavelength-mismatch range without mode hopping by the addition of a CdTe photorefractive crystal inside the cavity of a single-mode grating-tuned ECLD.   © 2001 Optical Society of America

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1.55-μm wavelength-tunable single-mode extended-cavity laser diodes (ECLDs) are widely used for testing optical communication networks and components. An ECLD is a semiconductor amplifier that is strongly coupled to an external cavity through its antireflection-coated facet.[1–7] Tunable single-mode emission is obtained by means of sending the light back from the external cavity into the semiconductor chip by use of a Littrow-[3,5,6,8] or a Littman-mounted grating.[9] The minimum-loss wavelength corresponds to the wavelength that is retroreflected by the grating and is thus optimally backcoupled into the semiconductor amplifier. For other wavelengths, the return beam is shifted from the best backcoupling position. Consequently, the loss increases with the detuning. The oscillating-mode wavelength is thus selected inside a small wavelength window.

Current commercial devices can be continuously tuned over more than 100 nm, but this requires delicate factory adjustments and high stability of the external cavity. Indeed, one must keep the wavelength mismatch, $\delta\lambda$, between the lasing wavelength and the wavelength of the minimum backcoupling loss within a restricted range of values to prevent mode hopping.

Here, we demonstrate that the insertion of a photorefractive crystal into the laser cavity increases the laser's spectral stability and thus its operating range. Up to now, this technique, known as intracavity dynamic holography, was used to force multimode lasers to oscillate on a single longitudinal mode.[10–13] In these previous experiments, the hologram, which was written by the oscillating mode in the photorefractive crystal, acted as an adaptive spectral filter that, in turn, reduced the number of oscillating modes. For a correctly designed system, the mutual adaptation of the filter to the modal structure led to single-mode operation after an adaptation time that depended on the photorefractive time constant.

We demonstrate in the following that intracavity dynamic holography can also increase the stability of a single-mode grating-tuned ECLD. The self-adaptive photorefractive filter permanently adjusts itself to the oscillating mode. The cavity is thus more tolerant to any misalignment that may result from thermal or mechanical instabilities.

The optical configuration of the laser is shown in Fig. 1. A multiple-quantum-well InGaAsP laser diode is optically coupled to an external cavity through its antireflection-coated facet. The antireflection coating is good enough to avoid bistability,[4,7] and the ECLD is operated in the single-mode regime at a wavelength of ~1.55 μm. The opposite facet serves as the
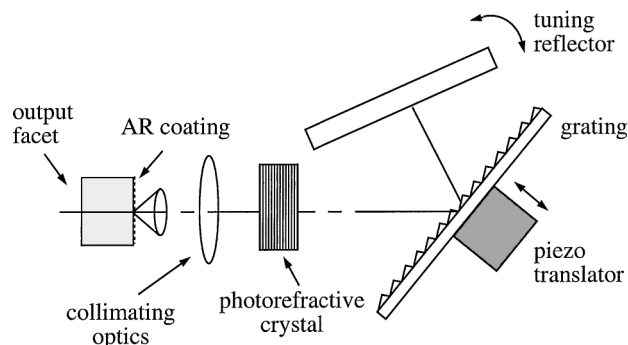

Fig. 1. Grating-tuned extended-cavity laser comprising an antireflection- (AR-) coated laser, a collimating optical system, a CdTe photorefractive crystal, and a Littman-mounted grating.

output coupling mirror. The external cavity consists of a collimating lens and a Littman-mounted grating.[9] The photorefractive crystal is inserted between the collimating lens and the grating. We have chosen a vanadium-doped CdTe crystal for its high photorefractive sensitivity near 1.55 μm.[14] This sample was grown by J. C. Launay at the Institut de Chimie de la Matière Condensée de Bordeaux, France. The sample is 4 mm thick, and the [001] faces are polished and antireflection coated at 1.55 μm. The beam propagates along the (001) direction, whereas the other faces were [110] and [1$\bar{1}$0]. The polarization of the lasing wave is along the (110) direction. In this counterpropagating configuration, we have measured a photorefractive two-wave-mixing gain of $\Gamma \simeq 0.3$ cm^{-1} and an optical absorption of $\alpha \simeq 2.3$ cm^{-1}. The compound cavity length is ~30 mm. Without the CdTe crystal, this length corresponds to a longitudinal-mode spacing of $\Delta \simeq 40$ pm. Insertion of the crystal, whose refractive index is $n \simeq 2.8$, reduces this spacing to $\Delta \simeq 30$ pm.

A piezo translator translates the grating without changing its orientation: The cavity length can thus be changed without modification of the wavelength of minimum backcoupling loss, allowing us to scan the value of the mismatch $\delta\lambda$ between the wavelength of the lasing mode and the minimum loss wavelength. The measurement setup consists of a wavemeter with a resolution of ± 1 part in 10^6, a 10-GHz free-spectral-range scanning Fabry–Perot (FP) interferometer, and a powermeter.

Before giving any experimental results, we describe the mode stabilization induced by the self-adapted photorefractive filter. The lasing mode writes a hologram inside the crystal that reproduces the standing-wave pattern. Since the photorefractive effect builds up by pure diffusion of the charge carriers, the phase shift between the standing-wave pattern and the induced Bragg grating of the refractive index equals $\pi/2$.[15] We have chosen the orientation of the crystal so that the amount of the main-mode wave that is reflected by the Littman-mounted grating and that diffracted back by the hologram interfere constructively. Since the Littman-mounted grating efficiency is moderate, the lasing-mode intensity, which is backcoupled into the semiconductor chip, is increased when the photorefractive grating is written. In this way, the lasing-mode loss decreases. Conversely, the interference is not necessarily constructive for the other nonlasing modes: The photorefractive crystal associated with the Littman-mounted grating can be considered a FP filter whose maximal reflectivity is automatically adjusted to the lasing-mode wavelength.[11] Because the crystal is set near the middle of the optical length of the cavity, the free spectral range of the self-adapted FP corresponds to two mode spacings. Therefore, the differential loss between the oscillating mode, denoted mode 0 in the following, and the two closest side modes, -1 and $+1$, is increased.

Conversely, the differential loss between mode 0 and side modes -2 and $+2$, which are located near the self-adapted FP peaks, is slightly lowered by the reduction of Δ that is induced by the increase of the cavity's optical length. Because of the limited Bragg-

selectivity bandwidth of the dynamic hologram, the already high losses of the other modes are not significantly modified by the photorefractive hologram. The filtering properties of such a photorefractive filter are easily computed.[12] Using the parameters of our laser and those of the photorefractive crystal, in Fig. 2 we plot the differential loss with respect to the lasing mode as a function of the detuning from the lasing-mode wavelength with and without the photorefractive crystal. In Fig. 2(a), we assume that the cavity is perfectly aligned ($\delta\lambda = 0$); in Fig. 2(b), one can see that the losses induced by a mismatch $\delta\lambda$ that is equal to Δ are fully compensated for by the operation of the photorefractive crystal.

To demonstrate the relaxation of the tolerances experimentally, we performed measurements of the mode-hop-free wavelength-mismatch range, with and without a photorefractive crystal inside the cavity, according to the following procedure: Near threshold and at $\delta\lambda = 0$, the laser oscillated on mode 0. The cavity was lengthened by use of a piezo translator. The wavelength of mode 0 was thus increased with respect to its reference value until a mode hop occurred toward shorter wavelengths, at a given value of $\delta\lambda$. Then, we shortened the cavity to recover mode 0. This shortening was continued until mode hopping occurred toward longer wavelengths. Next, we again lengthened the cavity to return to mode 0. Afterward, the same procedure was carried out for each increasing value of the injection current.
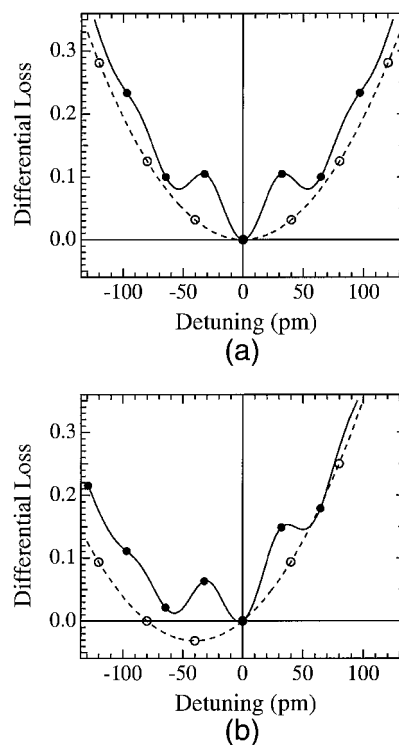

Fig. 2. Differential loss with respect to lasing mode at (a) $\delta\lambda = 0$ and (b) $\delta\lambda = \Delta$ as a function of detuning from the lasing-mode wavelength with (solid curve) and without (dashed curve) a photorefractive crystal inside the cavity. The filled and open circles correspond to the mode positions with and without the CdTe crystal inside the cavity, respectively.
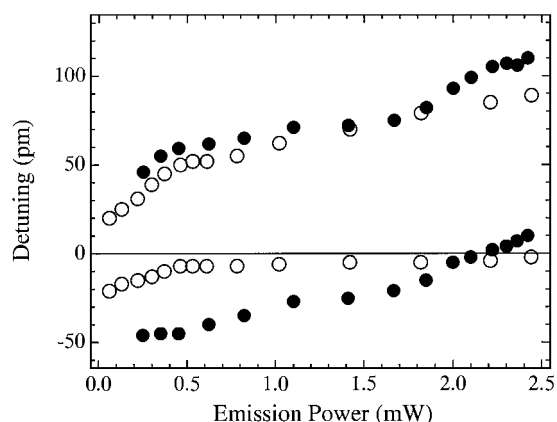
Fig. 3. Measured values of maximum mode-hop-free wavelength mismatches $\delta\lambda$ between the lasing wavelength and the wavelength of minimum backcoupling loss as a function of the emission power. The filled and open circles correspond to measurements with and without the CdTe crystal inside the cavity, respectively.

Inclusion of the crystal inside the cavity generates additional losses because of the crystal's absorption. Accordingly, the threshold value of the ECLD increased from 20 to 45 mA and the injection current needed to achieve 2.5 mW of output power increased from 55 to 130 mA. Hence, to compare the results with and without the crystal, in Fig. 3 we show measurements of the mode-hop-free wavelength-mismatch range in these two cases as a function of the maximum emission power, which can be obtained for a given value of the injection current when the piezo-translator voltage is changed.

Below 0.1 mW, the middle of the mode-hop-free wavelength-mismatch range coincides with the wavelength of minimum backcoupling loss and mode hopping occurs when the lasing-mode loss and one of the side mode's losses are equal. This condition corresponds to $\delta\lambda = \pm\Delta/2$ without the photofractive crystal, and, as expected, the range is extended when the crystal is placed inside the cavity. When the emitted power increases, the middle of the range shifts toward positive values of $\delta\lambda$, corresponding to longer wavelengths, and the short-wavelength-side boundary of the mode-hop-free wavelength-mismatch range eventually cuts the $\delta\lambda = 0$ line. We can fully interpret this wavelength shift by considering mode-coupling phenomena.[16–18] The shift is more important when the crystal is put inside the cavity, because doing so shortens the mode spacing and, consequently, increases the strength of the coupling. Nevertheless, despite the increase of the center-wavelength shift, the mode-hop-free wavelength-mismatch range is actually increased by the addition of the CdTe crystal.

Using an intracavity photorefractive filter relaxes the mechanical tolerancing of the tuning mirror's rotation-point position, which corresponds to synchronous cavity mode and feedback wavelength scanning, by the same factor by which the mode-hop-free wave-length-mismatch range is increased. We estimate that for 1 mW of output power the photorefractive-effect buildup time is ~2 ms. This buildup time corresponds to a maximum continuous tuning speed of 10 nm/s.

In conclusion, we have shown that the addition of a photorefractive crystal inside the cavity of a grating-tuned extended-cavity semiconductor laser prevents mode hopping by enhancing modal selectivity. Thus, the operating range of grating-tuned ECLDs could be extended. The CdTe sample used in this work was not optimized at $\lambda = 1.55$ μm and presented large absorption. The lower absorption ($\alpha \simeq 0.2$ cm^{-1}) of optimized CdTe samples should make the output-power reduction negligible, and their larger photorefractive gain ($\Gamma \simeq 0.6$ cm^{-1}) should further increase the mode selectively.

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References

1. R. Ludeke and E. P. Harris, Appl. Phys. Lett. **20,** 499–500 (1972).
2. R. Wyatt and W. J. Devlin, Electron. Lett. **19,** 110–112 (1983).
3. F. Favre and D. Le Guen, Electron. Lett. **27,** 183–184 (1991).
4. P. Zorabedian, IEEE J. Quantum Electron. **30,** 1542–1552 (1994).
5. M. de Labachelerie, H. Sasada, and G. Passedat, Appl. Opt. **32,** 269–274 (1993).
6. Erratum of Ref. 5, Appl. Opt. **33,** 3817–3819 (1994).
7. Y. Li, Y. Lu, J. Chen, D. Li, and X. Zhou, J. Opt. A **1,** 466–470 (1999).
8. T. W. Hänsch, Appl. Opt. **11,** 895–898 (1972).
9. K. Liu and M. G. Littman, Opt. Lett. **6,** 117–118 (1981).
10. J. M. Ramsey and W. B. Whitten, Opt. Lett. **12,** 915–917 (1987).
11. N. Huot, J. M. Jonathan, G. Pauliat, P. Georges, A. Brun, and G. Roosen, Appl. Phys. B **69,** 155–157 (1999).
12. L. Meilhac, N. Dubreuil, G. Pauliat, and G. Roosen, Opt. Mater. **18,** 37–40 (2001).
13. G. Delcourt, F. Seguineau, N. Dubreuil, and G. Roosen, in *Digest of Conference on Lasers and Electro-Optics (CLEO/Europe)* (Optical Society of America, Washington, D.C., 2000), postdealine paper CPD1.7.
14. Ph. Delaye, L. A. de Montmorillon, I. Biagio, J. C. Launay, and G. Roosen, Opt. Commun. **134,** 580–590 (1997).
15. M. P. Petrov, S. I. Stepanov, and A. V. Khomenko, *Photorefractive Crystals in Coherent Optical Systems*, Vol. 59 of Springer Series in Optical Sciences (Springer-Verlag, Berlin, 1991).
16. N. Ogasawara and R. Ito, Jpn. J. Appl. Phys. **27,** 607–614 (1988).
17. N. Ogasawara and R. Ito, Jpn. J. Appl. Phys. **27,** 615–626 (1988).
18. M. Yamada, J. Appl. Phys. **66,** 81–89 (1989).
19. A. Uskov, J. Mørk, and J. Mark, IEEE J. Quantum Electron. **30,** 1769–1781 (1994).