Single-longitudinal-mode semiconductor laser with digital and mode-hop-free fine-tuning mechanisms

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Abstract: We report a novel external cavity laser diode (λ = 1.5 μm). An intra-cavity liquid crystal pixel mirror allows digitally tuning of the laser wavelength to more than 40 wavelength channels of 100 GHz spacing according to the International Telecommunication Union (ITU) grid. Laser wavelength can further be fine-tuned by varying the driving voltages applied to an intra-cavity planar nematic liquid crystal phase plate. With a cell 52.3 μm in thickness, the output frequency can be continuously tuned over 1.89 GHz. The root-mean-square voltage required for driving the phase plate was from 1.00 to 4.56 volts.

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References

1. H. Hatateyama, K. Kudo, Y. Yokoyama, K. Naniwae and T. Sasaki, “Wavelength-selectable microarray light source for wide-band DWDM applications,” IEEE J. Select. Topics Quantum. Electron. **8**, 1341-1348 (2002)
2. R. O’Dowd, S. O’Duill, G. Mulvihill, N. O’Gorman, and Y. Yu, “Frequency plan and wavelength switching limits for widely tunable semiconductor transmitters,” IEEE J. Select. Topics Quantum Electron. **7**, 259-269 (2001).
3. C. -K. Chan, K. L. Sherman, and M. Zirngibl, “A fast 100-channel wavelength-tunable transmitter for optical packet switching,” IEEE Photon. Technol. Lett. **13**, 729-731 (2001).
4. M. Kauer, M. Girault, J. Leuthold, J. Honthaas, O. Pellegri, C. Goullancourt, and M. Zringibl, “16-channel digitally tunable external-cavity laser with nanosecond switching time,” IEEE Photon. Technol. Lett. **15**, 371-373 (2003).
5. X. M. Zhang, A. Q. Liu, D. Y. Tang and C. Lu, "Discrete wavelength tunable laser using microelectromechanical systems technology, " Appl. Phys. Lett. **84**, 329-331 (2004).
6. N. J. C. Libatique, li Wang, and R. K. Jain, “Single-longitudinal-mode tunable WDM-channel-selectable fiber laser,” Opt. Express **10**, 1503-1507 (2002).
7. C. –L. Pan, S-H Tsai, R-P Pan,C-R Sheu , and S. C. Wang, "Tunable semiconductor laser with liquid crystal pixel mirror in grating-loaded external cavity, " Electron. Lett. **35**, 1472-1473 (1999).
8. R. –P. Pan, H.-C. Tung, C. –R. Sheu, M. –J. Huang and C. –L. Pan , “Wavelength Tunable Semiconductor Laser with a Liquid Crystal Pixel Mirror,” in *Liquid Crystal Materials, Devices VIII Applications*, L. C. Chien, Editors, Proceedings of SPIE, **4658**, 91-100 (2002).

#5670 - $15.00 US Received 5 November 2004; revised 4 December 2004; accepted 9 December 2004

9. J. Struckmeier, A. Euteneuer, B. Smarsly, M. Breede, M. Born, and M. Hofmann, "Electronically tunable external-cavity laser diode," Opt. Lett. **24**, 1573-1574 (1999).
10. M. Breede, et al., "Fourier-transform external cavity lasers," Opt. Commun. **207**, 261-271 (2002).
11. Yu-Ping Lan, Chao-Yuan Chen, Ru-Pin Pan and Ci-Ling Pan, "Fine tuning of a diode laser wavelength with a liquid crystal intracavity element, " Opt. Eng. **43**, 234-238 (2004).
12. Yu-Ping Lan, Ru-Pin Pan and Ci-Ling Pan, "Mode-hop-free fine-tuning of an external-cavity diode laser wavelength with an intracavity liquid crystal cell, " Opt. Lett. **29**, 510-512 (2004).
13. M. -J. Huang, et al., "Multimode optical demultiplexer for DWDM with liquid crystal enabled functionalities," IEEE Photon. Technol. Lett., **16**, 2254-2256 (2004).
14. S. Brugioni, S. Faetti Pan and R. Meucci, "Mid-infrared refractive indices of the nematic mixture," Liquid Crystals **30**, 927-930 (2003).
15. Shin-Tson. Wu, "Birefringence dispersions of liquid crystals, " Phys. Rev. A **33**, 1270-1274 (1986).
16. A. Godard, S. G. Pauliat, G. Roosen, P. Graindorge, and P. Martin, “Side-mode gain in grating-tuned extended-cavity semiconductor lasers: investigation of stable single-mode operation conditions,” IEEE J. Quantum Electron. **38**, 390-401 (2002).
17. A. Godard, S. G. Pauliat, G. Roosen, and E. Ducloux, “Modal competition via four-wave mixing in single-mode extended-cavity semiconductor lasers,” IEEE J. Quantum Electron. **40**, 970-981 (2004).

1. Introduction

The benefits of wavelength tunable/selectable lasers in DWDM (dense wavelength division multiplexed) optical communication systems are widely recognized [1], e.g., reduction of transmitter inventory and cost-effective standbys in the event of failed channels. Although conventional external-cavity diode lasers (ECDL) have a wide, continuously tuning range, applications such as channel reconfiguration and assignments require the laser wavelength to be digitally (discretely) tuned to match the ITU grid. Such digitally tunable lasers include integrated micro-array DFB-LDs [1], designs that integrated a gain section and one or multiple tunable grating sections (distributed Bragg reflector (DBR), sampled grating DBRs (SG-DBRs)) [2], devices incorporating grating-assisted co-directional coupler with sampled reflectors (GCSR) [3]; or integrating an amplifier array with a passive dispersive element such as an arrayed waveguide grating (AWG) or bulk diffraction grating [4]. A microelectromechanical systems (MEMS) discrete wavelength tunable laser was enabled by making use of a short external cavity and weak feedback [5]. Libatique *et al.* [6] reported a single-longitudinal-mode tunable WDM-channel-selectable fiber laser using a tunable fiber Bragg grating, saturable absorption filter and an intracavity etalon. Alternatively, our group and others have demonstrated digital tuning of wavelength using liquid crystal spatial light modulators (pixel mirrors) at the focal plane of a folded grating-lens cavity in 4-f configuration [7-10]. In the above designs, however, the laser output could still deviate from the expected wavelength, e.g. the ITU grid, due to environmental fluctuations or mechanical disturbances. For DWDM applications, the required accuracy of the central wavelength of the given channel is $\pm$ 5% of the channel spacing. Thus a wavelength fine-tuning mechanism built in the laser is desirable. Conventionally, this can be achieved through temperature control of the LD or mechanical control of the cavity length. Recently, we demonstrate a simple approach for mode-hop-free continuous wavelength fine-tuning of an ECDL using a liquid crystal phase plate in a Littman-type ECDL [11,12].

In this paper, we report a single-longitudinal-mode digitally WDM-channel-selectable tunable ECDL for which the wavelength can be finely tuned using liquid crystal technology. A planarly aligned nematic liquid crystal (NLC) phase plate is incorporated in our previous design of liquid-crystal-pixel-mirror (LCPM) based ECDL [7,8]. Output wavelength can be digitally tuned to the desired channels by switching on and off the desired pixel of the LCPM. Varying the driving voltages of the NLC phase plate, one can fine-tune the output wavelength by changing the effective optical path length, which in turn changes the resonance frequency of the external-cavity modes. We achieved digital tuning over 40 channels. The central wavelength of each channel is designed according to ITU grid, with 100 GHz channel spacing. Further, a 1.89 GHz range of continuous mode-hop-free wavelength tuning for a

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given channel is achieved by changing the voltages applied to the 52.3-μm-thick intracavity NLC phase plate.

2. Laser configuration and operation principles

A schematic of the ECDL is shown in Fig. 1. The LCPM (see inset of Fig. 1) is based on the design of a normally off-state twisted nematic liquid crystal cell (TNLC) bonded to a polarizer and an Au-coated silicon substrate as the back mirror. The TNLC cell is constructed with a 6-μm-thick NLC (E7 manufactured by Merck) layer sandwiched between indium-tin-oxide (ITO) glass plates. One of the ITO electrodes is patterned. The pattern consists of fifty 100 μm × 2 cm stripes with 5-μm spacing. The NLC phase plate (also shown as an inset of Fig. 1) was constructed by sandwiching a 52.3-μm-thick layer of NLC (E7) layer between two glass plates coated with ITO on the inner surfaces. The outer surfaces of glass plates are anti-reflection (AR) coated to prevent the unwanted feedback light. Planar alignment of the nematic phase (parallel to polarization direction of the laser beam) was achieved by rubbing polyimide films coated on the inner sides of substrates. In the laser cavity, the NLC phase plate is oriented so that the laser polarization direction is along its rubbing direction. The output from the AR-coated front facet of a laser diode (Optospeed RSOA077, λ = 1.5 μm) is collimated by an objective lens (NA=0.47) and directed onto a grazing-incidence diffraction grating (1100 lines/mm) at an angle of 80°. Spectrally selective optical feedback is provided by the retro-reflected first-order-diffracted light from the grating, which is collected by an imaging lens (f = 25.7 cm) and focused on the LCPM. The zeroth-order reflection beam from the grating is the useful output. The cavity length is 65 cm.

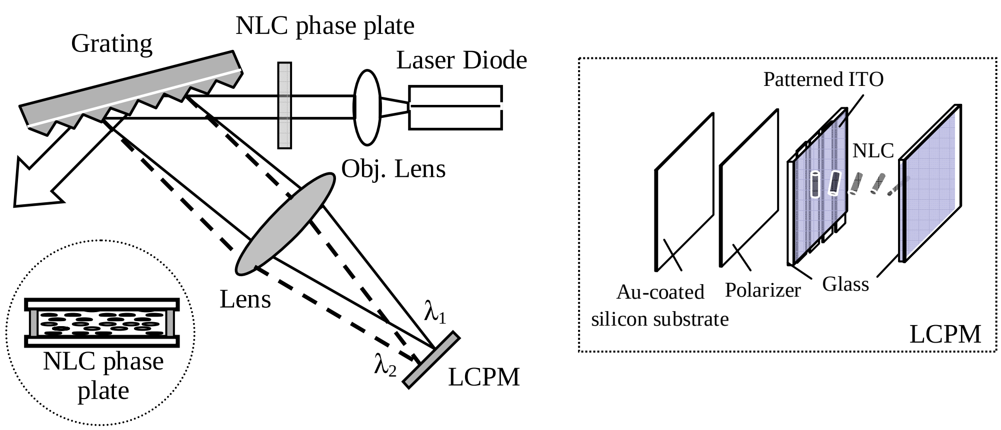

Fig. 1. Schematic diagram of the ECDL digitally tuned with the LCPM (see inset) and fine-tuned with an intracavity NLC phase plate (see inset).

The laser wavelength is digitally tuned and switched by biasing the individual pixels of the LCPM, with wavelength steps Δλ determined by the center-to-center separation of the adjacent pixel Δx:

$$\Delta\lambda = \Lambda \cos\theta_r \; \Delta x / f_{lens}\,, \tag{1}$$

where Λ is the grating period, θ_r is the first-order diffraction angle, and f_{lens} is the focal length of the lens. For the present laser Δλ/Δx = 2.397 nm/mm. The laser wavelength is fine-tuned by varying the voltage driving NLC phase plate, upon which the extraordinary index of

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refraction would change due to field-induced reorientation of the LC director. This results in an additional intracavity phase difference, $\Delta\Phi$, which corresponds to an optical path difference $\Delta l=\Delta\Phi/k$. This is equivalent to vary the laser cavity length. The relative frequency shift of the laser output is then given by

$$\frac{\Delta l}{l} = -\frac{\Delta f}{f}, \tag{2}$$

where $\Delta l = \Delta nd$ is the change in optical path through the NLC phase plate, l is the cavity length, Δf is the induced relative frequency shift, and f is the laser frequency.

3. Results and discussions

We measured the transmission of the TNLC cell used in the LCPM by varying the voltage across these elements separately. The maximum transmission of the TNLC cell used in the LCPM) is about 80 % when the root-mean-square (rms) driving voltage V_{rms} is larger than 3.5 V (Fig. 2(a)). A slight hysterisis is observed. The LCPM is operated at 7.06 V at 1kHz.

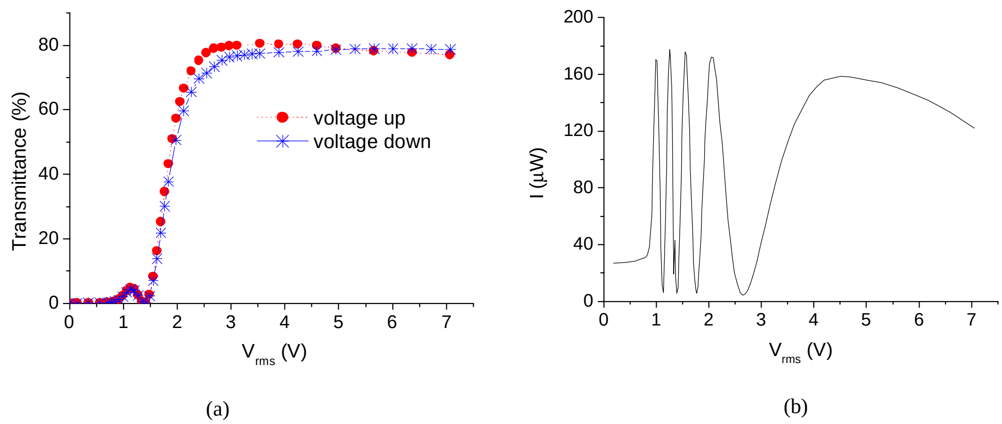

Fig. 2. The transmission intensity of the (a) TNLC cell in the LCPM and (b) NLC phase plate.

The optical path change of the NLC phase plate is determined by measuring the light intensity I transmitted through the phase plate with a pair of crossed polarizers, the first of which is oriented at 45 degrees with respect to the rubbing direction of the NLC phase plate. A plot of the transmission I versus the driving voltage of the NLC phase plate is shown in Fig. 2(b). Note that the transmission oscillates with maxima and minima occuring when Δnd is half-integral and integral multiple of the optical wavelength, respectively. Each cycle in Fig. 2(b) corresponds to a phase retardation of 2π. There are five cycles. Thus a phase retardation of $\Delta\Phi = 9\pi$ is possible by tuning the driving voltage from 0.88 V to 7.06 V.

The minimum channel spacing for the LCPM is 31.5 GHz. Thus the full tuning range is ~ 1.6 THz. Single-longitudinal-mode channel selectable laser operation has been demonstrated over 44 channels (100 GHz channel spacing) from 1531.12 to 1565.50 nm by digital tuning and mechanical movement of the LCPM. The spectra of twenty of these channels near the center of the gain bandwidth, tuned digitally by switching the pixels of the LCPM on and off sequentially, are shown in Fig. 3. The output power is ~0.4 mW. The maximum power variation between different channels is ~ 7.5 dB. Power equalization is possible by adjusting the driving voltages of each pixel. The variation can be less than 0.5 dB, as demonstrated in our recent work [13]. By using an optical spectrum analyzer with a spectral resolution of 0.01 nm, we have determined that the output central wavelength of the laser by turning on the

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LCPM pixels is within ± 0.02 nm (± 2.5 GHz) of the ITU grid. In this work, the channel number is limited by the gain bandwidth of the laser diode (~ 30 nm) and the LCPM (50 pixels). Consider a lens focal length of 10 mm and a pixel size of 10 microns, a LCPM with 100 channels would be less than 1.5 mm in size. Such LCPM can be fabricated with Liquid Crystal on Silicon (LCOS) technology. Laser diodes with gain bandwidth of ~ 80 nm have been reported in the literature. Thus digital tuning over 100 channels with 100-GHz spacing should be possible without moving part in the present ECDL.

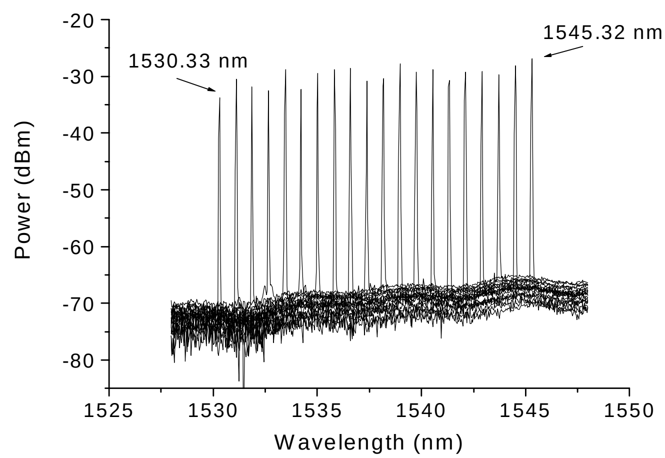

Fig. 3. Digitally step-tuned laser output spectrum for 20 ITU channels near the gain center.

Fine-tuning of the frequency for one channel by varying the applied voltages of the NLC phase plate is shown in Fig. 4. Frequency shifts of the laser output as monitored by a scanning Fabry-Perot interferometer (FPI, with Free Spectrum Range, FSR= 2 GHz) are shown in Fig. 4(a). Four sets of data are shown for the driving voltage increased successively from V_{rms}=1 V to 4.6 V. The tuning range is 1.89 GHz. During the experiment, the temperature of laser cavity changes by about 0.5 °C for the period of 1 hour. According to the data published by S. Brugioni et al. [14] and S-T. Wu [15], the temperature coefficient on LC refractive indices $\Delta n/\Delta T$ is estimated to be approximately equal to -2.0×10^{-3}/°C at λ=1550 nm. Thus the refractive index of the NLC cell changes by ~ -1×10^{-3} during the experiment. This corresponds to a frequency error of -0.02 GHz. Further, for a 65-cm cavity, the error in the estimated cavity length is about 5 mm, or an uncertainty of 0.02 GHz in frequency. The uncertainty in the frequency shift measurement by the FPI is estimated to be about 0.05 GHz. The combined error is then 0.05 GHz. The experimental results is thus in good agreement with the theoretical predications of 1.85 GHz according to Eq. (2). In the laboratory, the frequency typically drifted ~ 1 GHz during an hour. The fine-tuning range of 1.89 GHz is sufficient for correcting the shift. The fine-tuning range is limited by the cavity mode-hop effect. It can be improved by varying the driving voltage of the NLC cell and laser diode bias current simultaneously [12]. Broader continuous tuning range could be anticipated by employing a shorter external cavity and/or an NLC cell with greater optical thickness.

The ripple effect due to the diode facet AR-coating introduces spectral loss in the cavity, this can be compensated by changing the laser diode bias current. The corresponding frequency shift is nonetheless small for our laser diode chip, $\Delta\lambda/\Delta I$ = -0.16 pm/mA or 0.02 GHz/mA. The laser is operated at the current of 50 mA or 1.25 I_{th}. Changing the operating current from 50 mA to 60 mA, the laser frequency would change only by 0.2 GHz. The

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spectral bandwidth of the LCPM pixels of the grating-lens 4f configuration is ~ 0.046 nm or 5.75 GHz. This is much larger than that of the fine-tuning range using the NLC phase plate. Thus the spectral filtering properties by the LCPM remains unchanged during fine-tuning by the NLC phase plate. Following Godard and co-workers [16,17], the spectral detuning of the ECDL is a function of the emitted power or bias current. Our ECDL operates in the weak coupling regime, the spectral detuning was found to be 0.5 pm/mW or 0.07 GHz/mW. Thus the effect of emitted power on the fine-tuning performance of the laser is minimal.

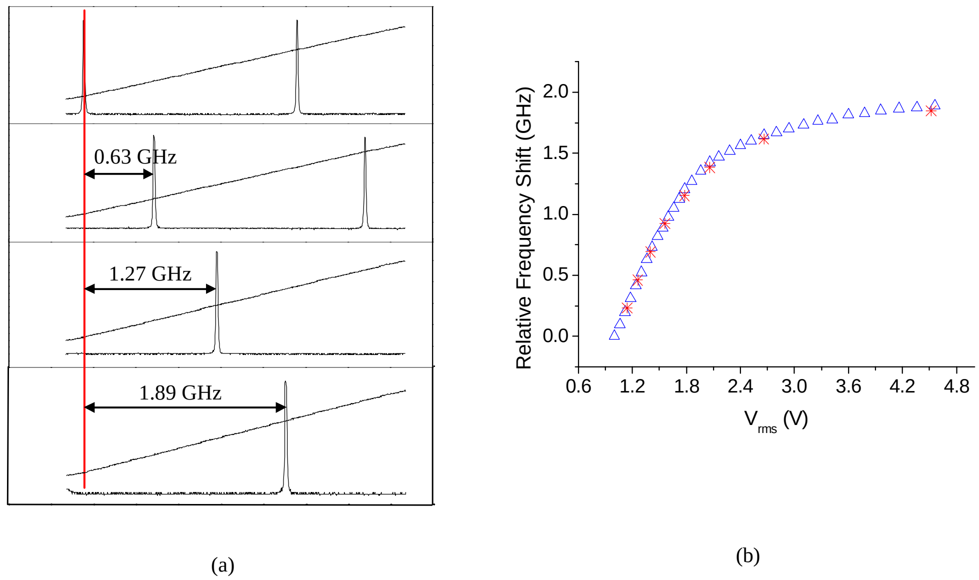

Fig. 4. Frequency fine-tuning of the ECDL. (a) Frequency shift observed by a scanning Fabry-Perot Interferometer (b) Measured and predicted fine-tuning range. Δ: measured frequency, *: predicted frequency

4. Conclusions

We report a novel external cavity laser diode (λ = 1.5 μm) with two liquid crystal (LC) tuning elements. A twisted nematic liquid crystal pixel mirror (LCPM) allows digitally tuning of the laser wavelength according to the International Telecommunication Union (ITU) grid. More than 40 wavelength channels of 100 GHz spacing are demonstrated. The side mode suppression ratio of each channel is better than 32.5 dB over 20 of the channels near the center of the gain curve. Laser wavelength can further be fine-tuned by varying the driving voltages applied to an intra-cavity planar nematic liquid crystal (NLC) phase plate. With an NLC cell 52.3 μm in thickness, the output frequency of the present laser can be continuously tuned over 1.89 GHz. The root-mean-square voltage required for driving the NLC phase plate was from 1.00 to 4.56 volts. The method is convenient for selecting the central wavelength according to the ITU grid, and for adjusting the channel spacing. This system requires no mechanical moving part and no critical alignment. The driving voltage is relatively low (few voltages). It has the potential to be used for DWDM optical communication applications.

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