行政院國家科學委員會補助專題研究計畫
■成果報告 □期中進度報告

新穎元件架構實驗型高密度波長多工通訊網路系統整合研究 -子計畫二：DWDM 用多波長雷射之研究(3/3)
Multi-wavelength lasers for DWDM applications

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中 華 民 國 93 年 9 月 30 日

一、中文摘要：

本計畫之主要目的是實現供密集波長多工光纖通訊系統採用的波長可調且能快速切換的多波長雷射（λ= 1.55μm）。雷射（以半導體雷射二極體或摻鉺光纖為增益介質）的設計是基於一種特殊的外腔結構。共振腔中的主要元件組是光柵與透鏡及其所構成的折疊式望遠鏡式 4-f 成像系統及在此成像系統的焦平面位置的可程式控制的液晶畫素反射鏡。我們實現了波長可快速切換，相鄰頻道頻率間隔滿足DWDM 之ITU 頻道間隔之多波長半導體雷射。此一設計亦被發展為其他 DWDM 用的主動元件，如電控濾光器及多工器。未來，並可指定此雷射輸出某一 ITU 頻道，乃至於將雷射頻率與銫原子鐘之類的頻率標準鎖定。整個雷射系統並可以微光機電技術製成一緊緻之系統。

本計畫之另一重要成果為提出一新型之可調波長雷射結構。我們在 Littman 結構外腔式半導體雷射系統的腔內置入一平行配向絲狀液晶相位板，利用其對於不同偏壓液晶分子旋轉角度變化產生不同的相位變化，造成雷射系統腔長的改變，因而達到微調雷射輸出波長的目的。我們並將此方法應用於雷射中心波長為 1556 nm 望遠鏡式折疊式外腔半導體雷射系統，在腔長 60 cm 的腔內置入厚度為 52.3 μm 的液晶相位板，改變加在液晶相位板上的電壓，得到可調雷射輸出波長 1.89 GHz，使得系統除了原先利用液晶像素反射鏡可選擇切換輸出波長的功能外，亦擴增波長微調的範圍。此雷射系統完全以電控的方式達成，未來對於指定中心波長及頻道間隔的調整將更容易。

關鍵詞：密集波長多工，多波長，外腔式半導體雷射，絲狀液晶，液晶相位板，液晶像素反射鏡，微光機電系統

Abstract

The goal of the present project is the realization of compact lasers (λ= 1.55μm) capable of generating coherent multiple-wavelength output. Such laser sources are essential for DWDM optical communication systems. The laser (with semiconductor or Er-doped fiber as the gain media, for example) is based on a proprietary external-cavity design with a liquid-crystal-based programmable mask at the imaging plane of a 4-f telescopic grating-lens system. Rapidly switchable, programmable generation of multiple wavelengths in semiconductor or fiber lasers is expected. It is also possible to select the lasing wavelengths according to the DWDM ITU grid. In the final stage of this project, the laser can be locked to absolute wavelength standards that can be chain-linked to the Cesium atomic clock. These designs can also potentially be miniaturized in the future with micro-fabrication technology.

In another development, a planar nematic liquid crystal (NLC) cell is incorporated in the Littman-type external-cavity as the wavelength-tuning device for a semiconductor laser diode. In this laser cavity, the NLC cell acts as a variable phase plate. Varying the voltage driving the NLC cell, one can tune the laser wavelength by changing the effective optical path length, which in turn changes the resonance frequency of the external-cavity modes. We have also successfully applied this method to a folded telescopic-type ECDL for fine-tuning the wavelength. An intracavity 52.3-μm-thick NLC cell is incorporated in the liquid-crystal-pixel-mirror based external-cavity. A 1.89 GHz range of tuning at λ=1556 nm is achieved by changing the voltages biasing the NLC cell. The laser system can be totally electronically controlled. It is expected to be much more convenient for selecting the central wavelength according to the ITU grid. Additional functionalities include adjusting the channel spacing and fine-tuning of the laser wavelength.

Keywords: DWDM, multiple wavelength, external-cavity semiconductor laser, nematic liquid crystal, liquid crystal phase plate, liquid crystal pixel mirror

I. Introduction

In this report, we summarize recent progress in our work on liquid-crystal-based tunable semiconductor lasers and related devices for dense-wavelength-division-multiplexing (DWDM) optical communication systems. Wavelength tuning of semiconductor lasers is usually achieved by changing the temperature or driving current of lasers. Different tuning mechanisms of external-cavity diode lasers (ECDL's) have been reported. The output wavelength of ECDL can be tuned either mechanically[3-6] or electronically.[7-8] One such approach, utilizing the electro-optic properties of liquid crystals, enables low-voltage electrical tuning. Several types of liquid crystal elements have been successfully developed as intracavity tuning elements in ECDL systems. These elements can be categorized as birefringent filters,[9-10] Fabry-Perot etalons[11-12] or a spatial light modulator.[13] In Sec. II, performance of a digitally tunable external cavity laser (ECL) with a liquid crystal pixel mirror (LCPM) is outlined. Other applications of the basic liquid crystal device include tunable optical demultiplexer and a tunable filter/demultiplexer. These are summarized in sec. III and IV. Finally, we also report a simple and novel configuration of a tunable laser diode, which is capable of continuous mode-hop-free tuning using a liquid crystal intra-cavity tuning element. A planarly aligned nematic liquid crystal (NLC) cell was inserted in the cavity of an ECDL. Varying the voltage driving the NLC cell, one can tune the laser wavelength by changing the effective optical path length, which in turn changes the resonance frequency of the external-cavity modes. The idea was also applied to the folded telescopic grazing-incidence grating-loaded external cavity incorporating a liquid crystal pixel mirror (LCPM).[14]

II. TUNABLE EXTERNAL CAVITY LASER DIODE WITH A LCPM

The basic laser configuration is shown in Fig. 1. An AR-coated laser diode (LD) from OptoSpeed was used as the gain element. Light emitted from the AR-coated (R ≈ 0.1%, estimated) front facet of the LD is collimated and incident on a grating (1100 lines/mm and working in the 1st order) at an angle of 75°. Diffracted light from the grating collected by a lens and focused on the LCPM. Spectrally selective optical feedback is provided by the retroreflected light from the LCPM. The primary laser output is the zeroth-order reflection of the grating (~ 60% of the incident light from the diode chip).

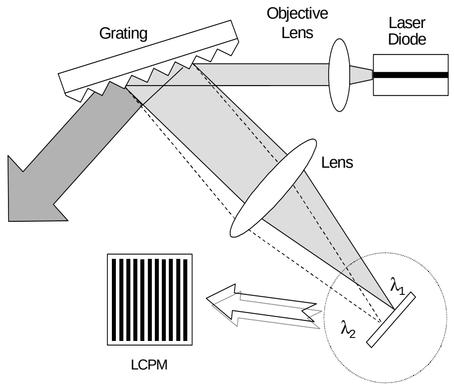
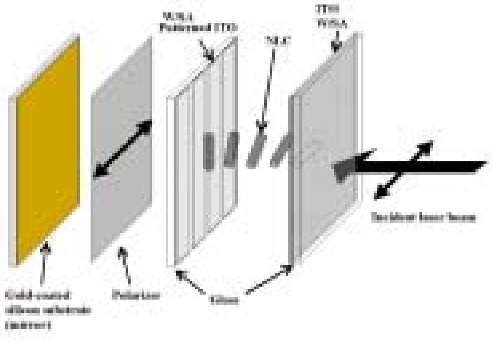


Fig. 1 A schematic of the electronically tunable laser with a folded telescopic grating-loaded external cavity and Liquid Crystal Pixel Mirror (LCPM).

A schematic of the LCPM is shown in Fig. 2. It is constructed as a reflection-type, normally black twisted nematic liquid crystal cell (TNLC) as described in our previous work.[2] The contrast ratio and on state reflectivity of the homemade LCPM were about 7:1 and 67% respectively. The threshold switching voltage of the LCPM was less than 5 V V_{pp} (peak – to – peak) at 1 kHz. Complete switching from off- to on-state is achieved at about 10V_{pp}.



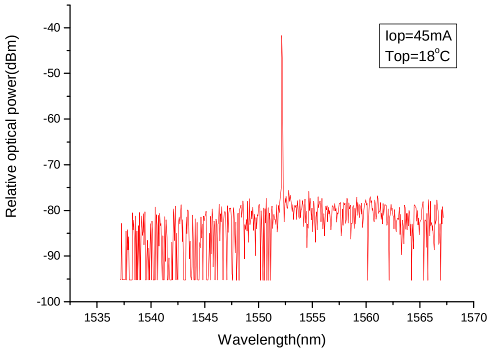


Fig. 3 Single-wavelength operation of the 1550 nm laser

Fig. 2(a)

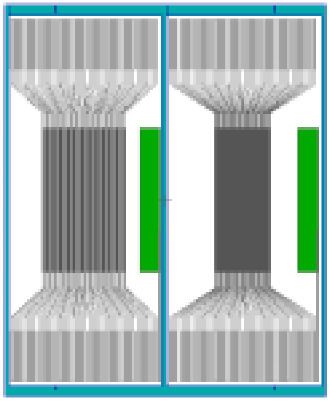


Fig. 2(b)

Fig. 2 (a) Construction of the LCPM: ITO: Indium Tin Oxide electrode; NLC: nematic liquid crystal; SA: surface alignment layer. (b) Mask for making the ITO pattern. For the mask on the left, the center-to-center spacing of the pixels is 125µm, while the width of each pixel is 100µm. The corresponding magnitudes on the right are 83.3µm and 79.3µm respectively. Flexible flab cables were use for ease of making the contacts.

The laser was electronically tuned by switching on the individual pixels. For pixels with center-to-center separation of Δx, the wavelength separation, Δλ, is determined by

$$\Delta\lambda=\Lambda cos\theta_r\Delta x/f, \quad (1)$$

where Λ is the grating period; θ_r is the first-order diffraction angle; f is the focal length of the lens. The laser generates output with multiple wavelengths when more than two of the pixels are switched on.

The output spectrum of the laser biased at I = 45 mA (I_{th} = 39 mA) at λ=1552 nm is shown in Fig. 3.

The SMSR at this wavelength is better than 35 dB. At the same current, the single wavelength tunable range of the laser was from 1526.2 nm to 1575.6 nm. The laser wavelength was tuned discretely by biasing different pixels of LCPM.

In Fig. 4(a), we plot the lasing wavelength against the relative position of the pixel. It is in good agreement with the theoretical prediction according to equation (1). Figure 4(b) demonstrates the SMSR corresponding to each wavelength. The result shows that the SMSR of the laser was better than 30 dB throughout this range. Generation of laser output in accordance to the ITU grid (100 GHz or 0.8 nm/channel) is shown in Fig. 4(c).

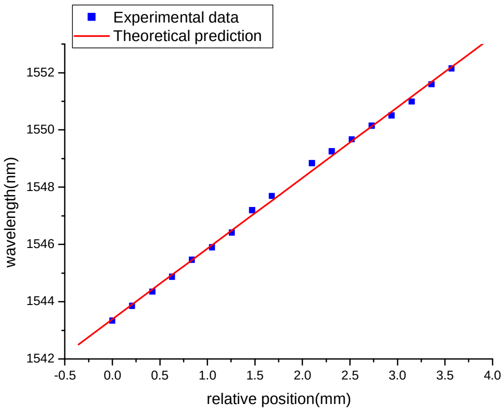


Fig. 4(a) Lasing wavelength vs. relative pixel position. The solid curve is the theoretical prediction according to Eq. (1).

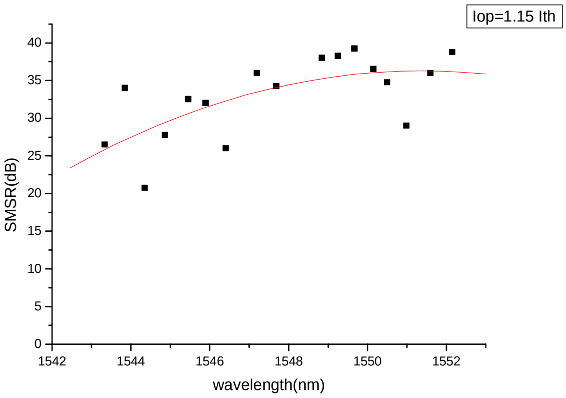


Fig. 4(b) Side mode suppression ratio of the laser output corresponding to each wavelength. The black squares are experimental points.

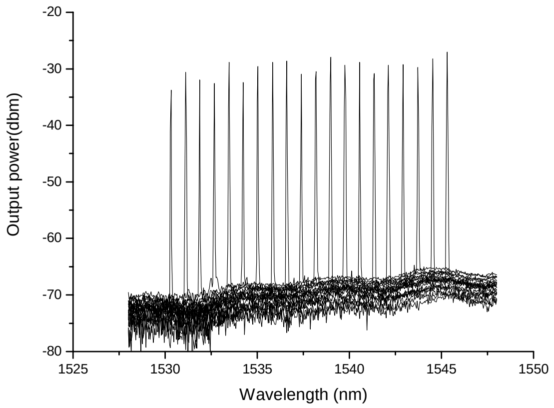


Fig. 4(c) Generation of tunable laser output in accordance to the ITU grid (100 GHz or ~ 0.8 nm)

Multi-wavelength operation of the laser is also possible, as illustrated in Fig. 5.

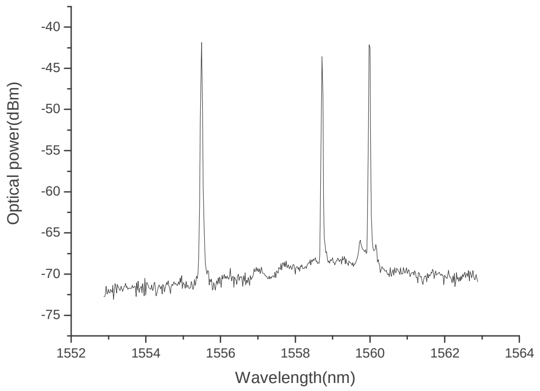


Fig. 5 Tunable triple-wavelength operation with wavelength separations of 3.22 nm to1.28 nm.

II. LIQUID-CRYSTAL-BASED TUNABLE OPTICALDEMULTIPLEXERS FOR WDM (λ = 1550 nm)

The experimental setup is illustrated in Fig 6. In this device, multi-wavelengths signal are amplified by an erbium-doped fiber amplifier (EDFA). The single mode fiber output from the EDFA is collimated by a lens, then incident on the grating after passing through a half-wave plate. The first-order light diffracted by the grating is directed to an AR-coated imaging lens and focused on to the liquid crystal spatial light modulator (LC_SLM) and a fiber array. The relation between the wavelength and the focal plane of imaging lens is expressed as

$$D_x = \frac{d\lambda}{dx} = a \cos \theta_r \bullet \frac{1}{f}$$

where a is the groove spacing of the grating , θ_r is the diffracted angle of the first order diffracted light, f is the focal length of the imaging lens. The LC_SLM, which operates in the normally-black mode, consists of a twisted nematic (TN)-LC cell and a polarizer. The polarizer is attached behind the TN-LC cell. The pixel pitch and width of the LC-SLM are 83.3 μm and 79.3 μm, respectively. The core pitch of the fiber array is 250 μm with 62.5 μm core diameter of each fiber. Each pixel of the LC_SLM and each fiber element of the fiber array have one by one correspondence. Selecting the appropriate LC_SLM pixels allows light of the desired wavelength to transmit into the fiber array. The channels are designed according to ITU grid with channel spacing of 100 GHz.

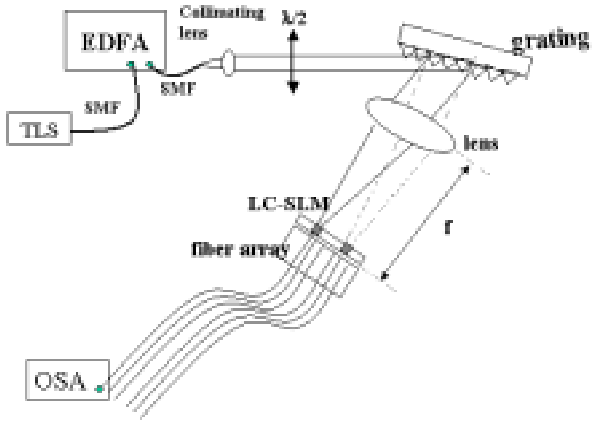
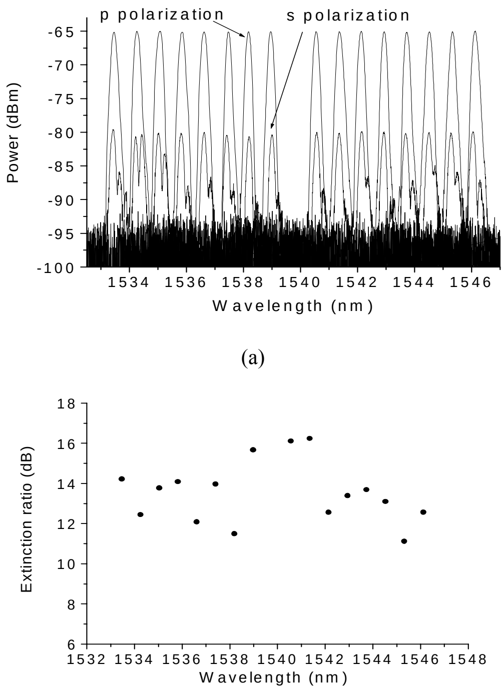


Fig. 6 Experimental setup of a liquid-crystal-based tunable optical demultiplexer: EDFA: Erbium-doped fiber amplifer, SMF: single mode fiber, TLS: tunable laser system, LC-SLM: liquid crystal spatial light modulator, OSA: Optical Spectrum Analyzer.

The output spectra for demultiplexing 16-channel 100-GHz-spaced signals into a 62.5-μm multimode-fiber array for both s and p polarizations are shown in Fig. 3. Adjacent channel crosstalk is less than –30 dB. The average 1 dB and 3 dB passbands of the DEMUX are 12.5 GHz and 22.5 GHz, respectively. A maximum extinction ratio of 16.2 dB is achieved. Different channels can be switched with rise and fall times of ~10 ms and ~70 ms, respectively. The outputs of the channels are equalized to –65 dBm. The variation between different channels reduced from ~ 10 dB to less than 0.5 dB.



(a)

(b)

Fig. 7. (a) Power-equalized output of the 16 channels of the LC-DEMUX, (b) Extinction ratios of the individual channels versus wavelengths (p-polarized).

III. LIQUID-CRYSTAL-BASED TUNABLE FILTER/EQUALIZER FOR WDM (λ = 1550 NM)

The structure of this device is shown in Fig. 8.

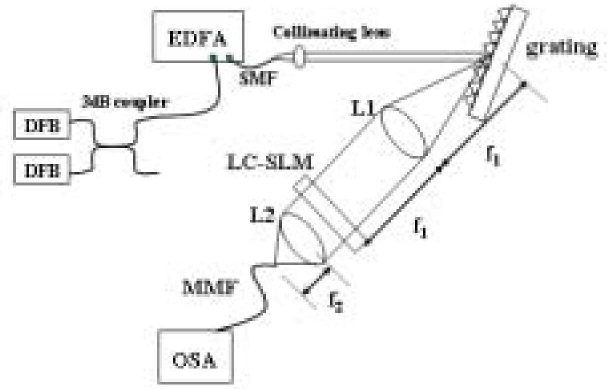


Fig. 8 Experimental setup of a liquid-crystal-based tunable optical filter/equalizer: EDFA: Erbium-doped fiber amplifer, SMF: single mode fiber, DFB: Distributed Feedback Lasers,, LC-SLM: liquid crystal spatial light modulator, L1 and L2: lenses, MMF: multi-mode fiber, OSA: Optical Spectrum Analyzer.

In this experiment, the wavelengths, 1542.5 nm and 1545.38 nm, of the two DFB lasers are adjusted to the ITU grids, and selected by the device by biasing desired pixels. The LC-based filter also function as an electrically controlled optical attenuator: The transmitted power of each wavelength will change as the voltage applied to each corresponding pixel will change. The power equalization function is illustrated in Fig. 9. We were able to reduce the power difference before (dotted line) and after (solid line) voltage adjustment from 17.9 dB to 0.3 dB.

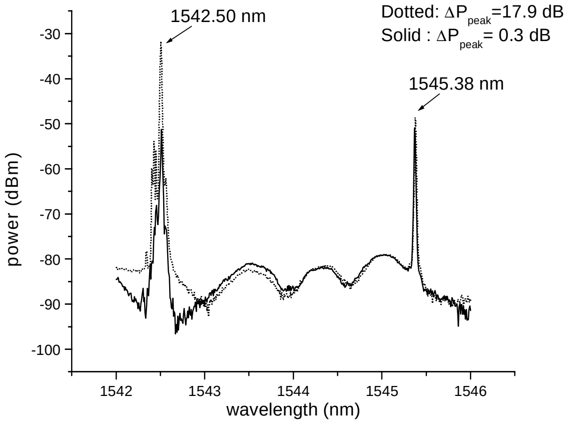


Fig. 9 Power equalization of two wavelengths by the LC-based filter. Dotted line: before equalization, Solid lime: after equalization

IV. A NOVEL TUNABLE DIODE LASER WITH LIQUID CRYSTAL INTRACAVITY TUNING ELEMENT

A novel and simple approach for tuning of the laser wavelength is proposed and demonstrated. The schematic of the laser configuration is shown in Fig. 10.

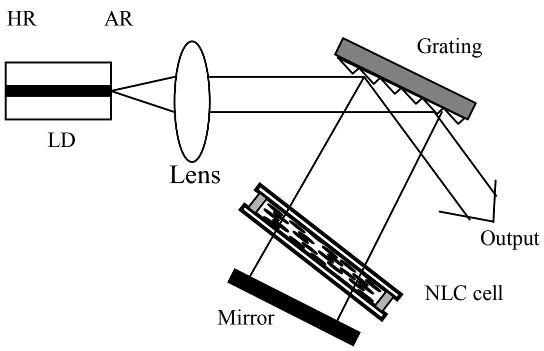


Fig. 10 A schematic of the laser configuration. LD: Laser Diode; HR: High Reflector; AR: Anti-reflection Coating; NLC: Nematic Liquid Crystal

The output from the anti-reflection (AR) coated front facet of a commercial laser diode is collimated with an objective lens and directed onto a diffraction grating with 1200 lines/mm. The first-order reflection from the grating was retroreflected back into the diode by a mirror completing the external cavity. The zeroth-order reflected beam from the grating was the useful output. The laser wavelength is 775 nm. An NLC cell was inserted between the grating and the end mirror of the cavity.

The NLC cell is constructed by sandwitching the 4'-n- pentyl-4- cyanobiphenyl (5CB) LC between two glass plates coated with Indium-Tin-Oxide as electrodes. The thickness of the cell is controlled by Mylar spacers. In the experimental result described in this section, we use a 35.5-µm-thick NLC cell. Planar alignment of the nematic phase is achieved by rubbing polyimide films coated on the inner sides of substrates. The NLC cell is driven by a square wave at 1 kHz.

In the laser cavity, the NLC cell is oriented so that the laser polarization direction is along its rubbing direction. Varying the voltage driving NLC cell, its extraordinary index of refraction would change due to field-induced reorientation of the LC director. This is equivalent to vary the laser cavity length. The relative frequency shift of the laser output is then given by

$$\frac{\Delta l}{l} = -\frac{\Delta f}{f}, \qquad (2)$$

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

By using the wavelength meter, the laser frequency shift as the applied voltage on NLC cell in the range of 0.9 V to 1.3 V for 15-cm and 30-cm ECDL cavities are also determined quantitatively and shown in Fig. 11.

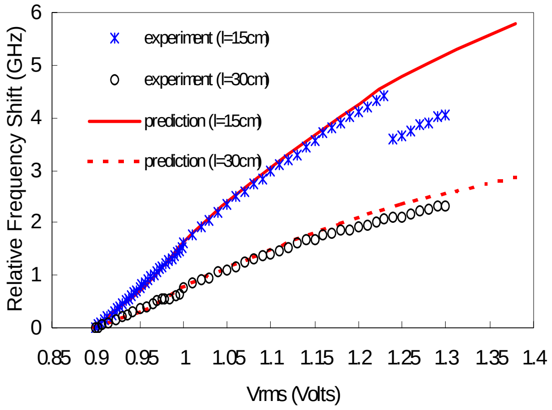


Fig.11: Laser frequency shift measured by a wavemeter. The theoretical curves are also shown.

For the 15-cm-long ECDL cavity, the mode-hop-free tuning range of the laser is 4.42 GHz (from 0.9 V to 1.23 V). The laser mode jumps one axial mode spacing (~ 1 GHz) at V_{rms} = 1.24 V. For the 30-cm-long cavity, the mode-hop-free tuning range is 2.77 GHz (0.9 V to 1.3 V). The tuning characteristics are in good agreement with the theoretical predictions of 4.30 GHz and 2.46 GHz according to Eq. (1) for the two cavity lengths, respectively.

We have also experimented with combining schemes in Sec. 2.2 with the intracavity liquid crystal phase plate. The output from the AR- coated front facet of a commercial laser diode is collimated with an objective lens and directed onto a diffraction grating (1100 *lines/mm*). A schematic of the laser configuration is shown in Fig. 13.

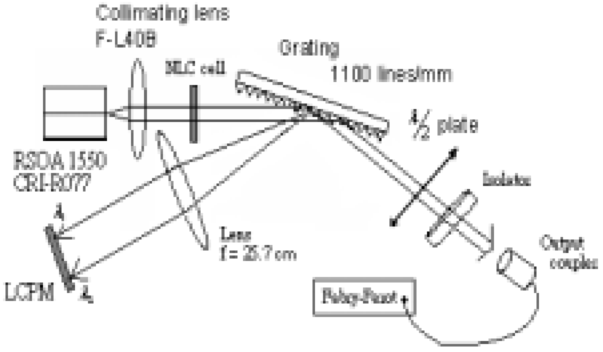


Fig.13: Schematic of the LCPM based ECDL with an intracavity nematic liquid crystal cell.

Briefly, 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 laser is electronically tunable by biasing the individual pixels. The zeroth-order reflection beam from the grating is the useful output. The cavity length is 60 cm. An intracavity 52.3-μm-thick NLC cell is used for electronically fine tuning the cavity resonance frequency. The basic operational principle is as the same as in the Littman-type ECDL system that we have described previously.

With the pixel mirrors, the laser wavelength can be tuned in step. We demonstrate different wavelength output by switching pixel of the LCPM on/off sequentially in figure 14. The channel spacing is 100 GHz. There are forty-four channels in this work.

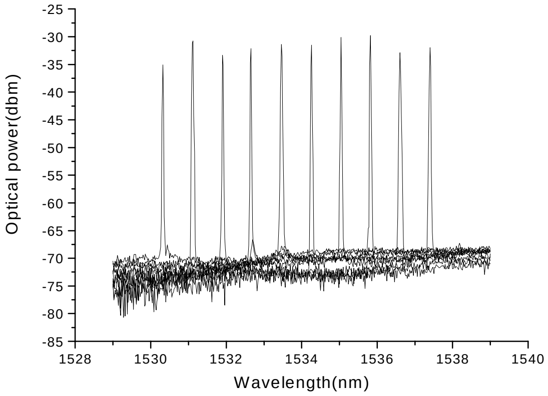


Fig. 14 Tuning the laser wavelength is steps of 100 GHz

The output wavelength can be continuously tuned by varying the applied voltages of the NLC cell. The frequency tuning range measured is 1.89 GHz as the driving voltage of the NLC cell is changed from 1 volt to 4.6 volts (Vrms). The result is in good agreement with the theoretical predications of 1.85 GHz. In figure 13, we demonstrate the tuning results. Frequency shift is observed by monitoring the output spectrum of a scanning FPI (FSR= 2 GHz).

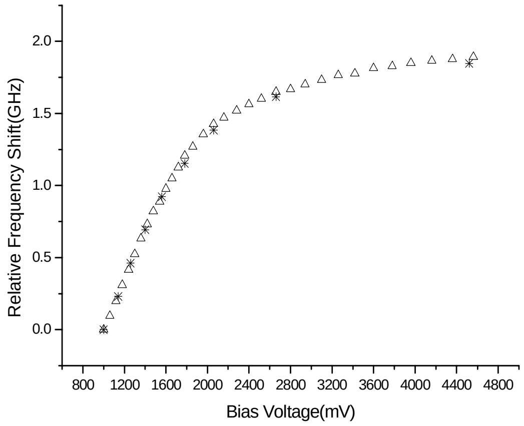


Fig. 14: Wavelength fine-tuning of the LCPM based ECDL system. Δ: Experimental results. □: Theoretical predictions.

V. CONCLUSIONS

In summary, we report several liquid-crystal-based tunable lasers and devices for DWDM optical communication systems. Single and multiple wavelength generation and tunable laser output in accordance to the ITU grid (100 GHz or 0.8 nm/channel) is demonstrated. The key element is a liquid crystal spatial light modulator in the reflection or transmission mode. It can also be used for wavelength demultiplexing, filtering and power equalization. A new laser configuration that allows mode-hop-free tuning of laser wavelength as opposed to digital tuning is also shown.

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14. Ci-Ling Pan, S-H Tsai, R-P Pan, C-R Sheu and S. C. Wang, Electron. Lett. **35**, 17 (1999).

VII. Research Output

7.1 Refereed Journal Papers

1. Yu-Pin Lan, Chao-Yuan Chen, Ru-Pin Pan, and Ci-Ling Pan, “Fine Tuning of a Diode Laser Wavelength by a Liquid Crystal Intracavity Element,” *Opt. Eng.*, Vol. 43, No. 1, pp. 234-238, January 2004.
2. Yu-Pin Lan, Ci-Ling Pan, and Ru-Pin Pan, “Mode-hop-free tuning of an external cavity diode laser with an intracavity liquid crystal cell,” *Optics Lett.*, Vol. 29, No. 5, pp. 510-512, March 1, 2004.
3. Ming-Jay Huang, Ru-Pin Pan, Chia-Rong Sheu, Yu-Ping Lan, Yi-Fan Lai and Ci-Ling Pan, “Multimode Optical Demultiplexer for DWDM with Liquid Crystal Enabled Functionalities,” *IEEE Photon. Technol. Lett.*, Vol. 40, No. 10, pp. 2254-2256, October 2004.

7.2 Refereed Proceeding Papers

1. R.-P. Pan, C.-R. Sheu, W.-L. Lu, M.-J. Huang, C.-L. Pan, “Wavelength tuning and multiple-wavelength generation using a reflection-type liquid crystal spatial light mudolator,” presented at the SPIE Annual Meeting, July 31 – August 1, 2001, San Diego, CA, USA. Paper published in *Spatial Light Modulators: Technology and Applications*, Uzi Efron, Editor, Proceedings of SPIE Vol. 4457, pp. 111-114 (2001).
2. R.-P. Pan, X.-X. Tung, J.-Y. Chen, M.-J. Huang, C.-L. Pan, “Liquid-crystal-based tunable optical filtering devices for DWDM,” presented at ITCOM 2002, Aug. 21 –24, 2001, Denver, Colorado, USA. Paper published in *Active and Passive Optical Components for WDM Communication*, Achyut K. Dutta, Abdul Ahad S. Awwal, Niloy K. Dutta, Katsunari Okamoto, Editors, Proceedings of SPIE Vol. 4532, pp. 244-248 (2001).
3. Ru-Pin Pan, Hsiu-Chi Tung, Chia-Rong Sheu, Ming-Jay Huang and Ci-Ling Pan , “Wavelength Tunable Semiconductor Laser with a Liquid Crystal Pixel Mirror,” **Invited paper**, presented at Photonics West 2002, Jan. 19-26, 2002, San Jose, California, **USA.** Paper published in *Liquid Crystal Materials, Devices VIII Applications*, L. C. Chien, Editors, Proceedings of SPIE Vol. 4658, pp. 91-100 (2002).
4. Ru-Pin Pan, Yu-Pin Lan, Chao-Yuan Chen, and Ci-Ling Pan, “Liquid Crystal Element For Fine Tuning Of Laser Wavelength,” presented at the 19th International Liquid Crystal Conference, June 30 –July 5, Edinburgh, UK. Paper entitled “A Novel Tunable Diode Laser with Liquid Crystal Intracavity Tuning Element,” *Mol. Cryst. Liq. Cryst.*, Vol. 413, pp. 499-506, 2004.
5. Ci-Ling Pan, Minjay Huang And Ru-Pin Pan,” Liquid-Crystal-Based Tunable Filter For WDM ($\lambda = 1550$ nm),” presented at the 19th International Liquid Crystal Conference, June 30 –July 5, Edinburgh, UK. *Mol. Cryst. Liq. Crystl.*, Vol. 413, pp. 561-568, 2004.

7.3 Conference Papers

1. Ci-Ling Pan, Ru-Pin Pan, Wen-Li Lu, and Chia-Reng Sheu, "Electronically Tunable

Multiple Wavelength Semiconductor Laseer by Using a Liquid Crystal Pixel Mirror" presented at the 18th International Liquid Crystal Conference., Sendai International Center, Sendai, Japan, July 24 – 28, 2000, paper 25D-24-P, p. 297.

1. Ru-Pin Pan, Wen-Li Lu, Chia-Rong Sheu, and Ci-Ling Pan, "Electronically Tunable Single- and Multiple- Wavelength Broad-Area Semiconductor Laser," in 2000 IEEE/LEOS Annual Meeting Conference Proceedings, 13-16, November 2000, The Westin Rio Mar Beach, Puerto Rico, paper ThP 6, pp. 830-831.
2. Hsiu-Chi Tung (董修琦), Ming-Chieh Huang (黃銘杰), Wen-Li Lu (呂文禮), Ru-Pin Pan (趙如蘋), C. L. Pan (潘犀靈), "Progress in Tunable External-Cavity Semiconductor Laser Using Liquid Crystal Pixel Mirror," 2000 國際華人液晶研討會,18-19 December 2000, 台南成功大學, p. 102.
3. 牛崇翰, 林素圓, 王佳祥, 趙如蘋, 潘犀靈, "利用液晶像素反射鏡達成電控可調多波長輸出之主動鎖模半導體雷射系統", 論文集(I) 2001 年台灣光電科技研討會，Dec 13 – Dec 14, 2001, 台灣高雄，Paper TD2-5, pp 257-260.
4. 王佳祥, 林素圓, 牛崇翰, 趙如蘋, 潘犀靈, "鎖模半導體雷射注入放大之研究", 論文集(I) 2001 年台灣光電科技研討會，Dec 13 – Dec 14, 2001, 台灣高雄，Paper TD2-8, pp 268-271.
5. Yea-Ling Sheu (許雅伶), Yu-Ping Lan (藍玉屏), Andy G. Fu (傅永貴), Ru-Pin Chao Pan (趙如蘋), Ci-Ling Pan (潘犀靈), "可調單波長及多波長外腔半導體雷射（λ= 1550 nm）", 論文集(I) 2001 年台灣光電科技研討會, Dec 13 – Dec 14, 2001, 台灣高雄，Paper TC1-2, pp 195-197.
6. Jun-Yu Chen (陳俊宇), Ming-Jay Huang (黃銘杰), Hsiu-Chi Tung (董修琦), Ru-Pin Chao Pan (趙如蘋), Ci-Ling Pan (潘犀靈), "DWDM 用液晶式可調光解多工器", 論文集(II) 2001 年台灣光電科技研討會，Dec 13 – Dec 14, 2001, 台灣高雄，Paper FC1-7, pp 591-593.
7. Tsung-Sheng Shih (石宗盛), Ru-Pin Chao (趙如蘋), and Ci-Ling Pan (潘犀靈), "Tunable External Cavity Semiconductor Laser(λ=1.5 μ m) with a Liquid Crystal Pixel Mirror", 論文集 I, 2002 台灣光電科技研討會, Dec.12 - Dec.13, 2002, Taipei, Taiwan, paper TG1-5, pp.157-159.
8. Yu-Ping Lan (藍玉屏), Chao-Yuan Chen (陳昭遠), Ru-Pin Chao (趙如蘋), and Ci-Ling Pan (潘犀靈), "Mode-Hop-Free Tuning of an External-Cavity Tunable Diode Laser with an Intracavity Liquid Crystal Tuning Element", 論文集 I, 2002 台灣光電科技研討會, Dec.12 - Dec.13, 2002, Taipei, Taiwan, paper TG1-8, pp.166-168.
9. Ming-Chieh Huang (黃銘杰), Ru-Pin Chao (趙如蘋) and Ci-Ling Pan (潘犀靈), "Liquid-Crystal-Based Tunable Filter/Equalizer", 論文集 II, 2002 台灣光電科技研討會, Dec.12 - Dec.13, 2002, Taipei, Taiwan, paper FE2-2, pp.207-209.
10. Ming-Chieh Huang (黃銘杰), Ru-Pin Chao (趙如蘋) and Ci-Ling Pan (潘犀靈), "Liquid-Crystal-Based Tunable Optical Demultiplexers", 論文集 III, 2002 台灣光電科技研討會, Dec.12 - Dec.13, 2002, Taipei, Taiwan, poster PC-15, pp.275-277.
11. Ci-Ling Pan, Yu-Pin Lan and Ru-Pin Pan, "Mode-hop-free tuning of an external cavity diode laser with an intracavity liquid crystal cell," presented at the 10th International Topical Meeting on Optics of Liquid Crystals, Aussois (Modane), France, Sept. 13-19, 2003.
12. Yu-Ping Lan (藍玉屏), Tsung-Sheng Shih, Ru-Pin Pan and Ci-Ling Pan, " Electronically tuned multi-wavelength lasers", (*Optics and Photonics Taiwan*), Dec.25 - 26, 2003, Taipei, Taiwan, paper FE2-6, OPT03 Proc. Vol. II, pp.348-350.
13. Yu-Ping Lan (藍玉屏), Ci-Ling Pan and Ru-Pin Pan, "Mode-hop-free fine-tuning of an external cavity diode laser", paper MF-9, presented at Annual Meeting of Physical of Society, Feb. 9-11, 2004, Hsinchu, Taiwan,

in Conference Proceedings, 物理雙月刊, Vol. 26, No. 1, February 2004, pp.90.

14. Y. F Lai (賴亦帆), M. J. Huang, Y. P. Lan, Ci-Ling Pan, C. R. Shen, and Ru-Pin Pan, “Opatical Demultiplexer for DWDM with Liquid Crystal Enabled functionality”, *ibid.,* paper PE-49, in Conference Proceedings, 物理雙月刊, Vol. 26, No. 1, February 2004, pp.242.
15. Ci-Ling Pan, “Tunable Lasers and Related Devices with Liquid Crystal Enabled Functionalities for DWDM Optical Communication,” **invited talk**, presented at the 2004 Wireless and Optical Communication Conference (WOOC’04), Taipei, Taiwan, March 8-10, 2004.

7.4 Patent Disclosures

1. “具數位及無跳模連續微調波長機制之多波長外腔雷射系統，” 中華民國專利申請中（Sept. 10, 2003）, No. 92124960.
2. “A multi-wavelength external-cavity laser with digital and mode-hop-free fine tuning mechanisms, ” U.S. Patent filed,（Nov. 16, 2003）, No. 10-738,893.
3. 潘犀靈, 趙如蘋, 黃銘杰, 藍玉屏, “具多種功能之電控液晶式可調光多工器及光解多工器,” 中華民國專利獲交大智才中心同意提出申請中。

7.5 Honors and Recognitions

1. Mr. Minjay Huang received the NSC Undergraduate Research Award, 2000.黃銘杰獲頒**國科會大專生專題研究獎**。
2. Miss X.-X. Tung received the Best Dissertation Award of the Optical Engineering Society of ROC, 2001.董修琦獲光學工程學會學生論文獎
3. Mr. Minjay Huang received Best Poster Paper Award at the Optics and Photonics Taiwan 2002(OPT’02) Conference, 2002.黃銘杰獲 OPT’02 台灣光電科技研討會壁報論文獎。
4. Processor Ru-Pin Chao Pan presented at invited Talk at SPIE Photonics West Conference, 2002. 趙如蘋教授在 SPIE Photonic West 會議作邀請演講。
5. Prof. Ci-Ling Pan received the Merit NSC Research Fellow Award in 2002. 潘犀靈教授獲國科會傑出特約研究員獎。
6. Professor Ci-Ling Pan was elected a Fellow of the Optical Society of America (OSA) in October 2003.潘犀靈教授榮膺美國光學學會會士。
7. Professor Ci-Ling Pan was elected a Fellow of the Society of Photographic and Instrumentation Engineers (SPIE), the International Society for Optical Engineering, in January 2004.潘犀靈教授榮膺國際光學工程學會會士。
8. Professor Ci-Ling Pan was honored as Communication and Photonics Chair Professor, the Far Eastern Y. Z. Hsu Science & Technology Memorial Foundatio, 2003. 潘犀靈教授榮膺第二屆有庠科技講座 (通訊光電類)
9. Professor Ci-Ling Pan presented an invited talk at Wireless and Optical Communication Conference, WOOC’04, March 8, 2004. 潘犀靈教授在 WOCC’04 會議作邀請演講。

可供推廣之研發成果資料表

■ 可申請專利　■ 可技術移轉　日期：93年9月30日

國科會補助計畫	計畫名稱：**DWDM 用多波長雷射之研究** 計畫主持人：潘犀靈 計畫編號：NSC 92-2215-E-009-010　學門領域：光電
技術/創作名稱	液晶式可調波長、增益平坦化、可加減頻道濾波器 Liquid-crystal-based tunable, gain-flattened, add/drop filter
發明人/創作人	潘犀靈、趙如蘋、黃銘杰、藍玉屏
技術說明	中文： 本發明為一具增益平坦化功能之波長可調帶通濾波器，其選擇之頻道可任意加減，而不同頻道之輸出功率可均一化。可調功能是利用一液晶元件。
	英文：This invention relates generally to gain flattening, ***wavelength*** tunable bandpass filters, and more particularly to gain flattening filters and tunable add/drop filters which do not create unwanted intensity modulation.
可利用之產業 及 可開發之產品	（波長多工）光纖通訊、光網路（optical network）系統中所需之波長可調帶通濾波器，兼具增益平坦化、頻道可加減功能。
技術特點	Optical bandpass filter with liquid-crystal-enabled multi-functionalities, e.g., tunable, switchble,gain-flattening, add/drop and interleaving.
推廣及運用的價值	Potential device for DWDM optical communication systems and networks.

※　1.每項研發成果請填寫一式二份，一份隨成果報告送繳本會，一份送　貴單位研發成果推廣單位（如技術移轉中心）。

※　**2.本項研發成果若尚未申請專利，請勿揭露可申請專利之主要內容。**

※　3.本表若不敷使用，請自行影印使用。