行政院國家科學委員會專題研究計畫　期中進度報告

子計畫二：DWDM 用多波長雷射之研究(2/3)

計畫類別：整合型計畫
計畫編號：NSC91-2215-E-009-029-
執行期間：91 年 08 月 01 日至 92 年 07 月 31 日
執行單位：國立交通大學光電工程研究所

計畫主持人：潘犀靈

報告類型：精簡報告

處理方式：本計畫可公開查詢

中　華　民　國 92 年 5 月 21 日

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(1/3)

Multi-wavelength lasers for DWDM applications

計畫類別：□ 個別型計畫　　■ 整合型計畫
計畫編號：NSC 91－2215－E－009－029
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計畫主持人：潘犀靈　教授
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計畫參與人員：　藍玉屏 石宗盛

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執行單位：國立交通大學光電工程研究所

中 華 民 國 91 年 05 月 21 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（ $\lambda = 1.55\,\mu$m）。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。我們預期可實現波長可快速切換，相鄰頻道頻率間隔滿足 DWDM 之 ITU 頻道間隔之多波長半導體或光纖雷射。此一設計亦可能發展為其他 DWDM 用的主動元件，如電控濾光器。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。

本年度之另一進展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 ($\lambda = 1.55\,\mu$m) 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

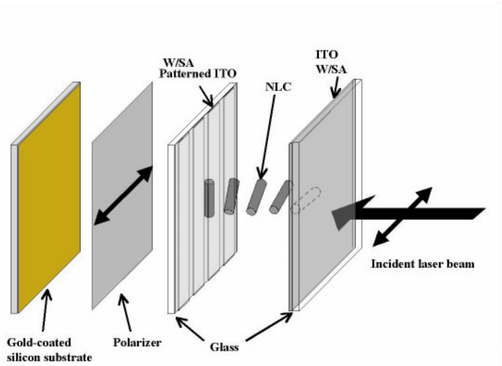
technology.

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).

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}.

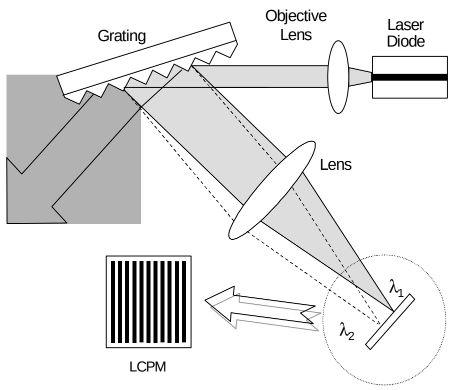


Fig. 1 A schematic of the electronically tunable laser with a folded telescopic grating-loaded external cavity and Liquid Crystal Pixel Mirror (LCPM).

Fig. 2(a)

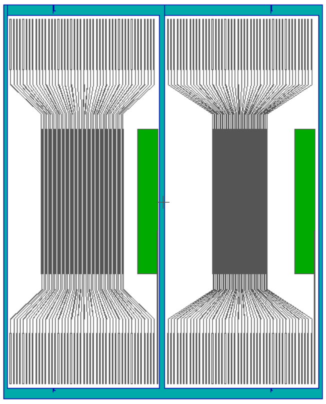


Fig. 2(b)

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, $\Delta\lambda$, is determined by

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

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 ~~single wavelength lasing~~the laser biased at I = 45 mA (I_{th} = 39 mA) at λ=1552 nm is shown in Fig. 3.

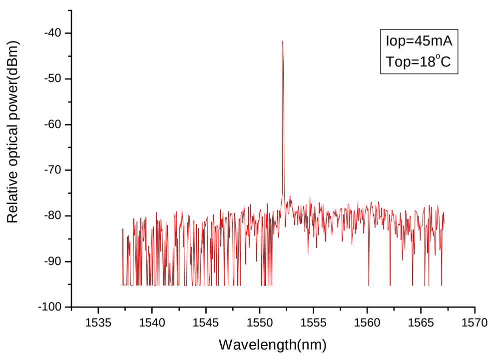


Fig. 3 Single-wavelength operation of the 1550 nm laser

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).

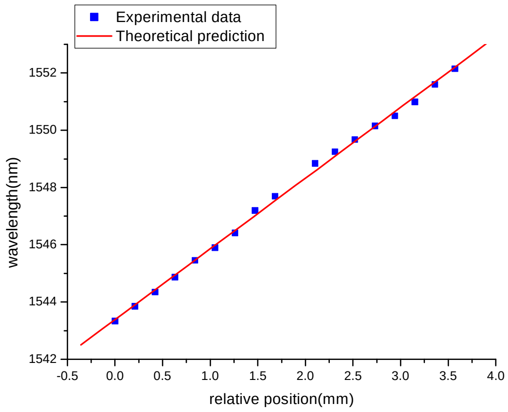


Fig. 4(a) Lasing wavelength vs. relative pixel position. The solid curve is the theoretical prediction according to Eq. (1).

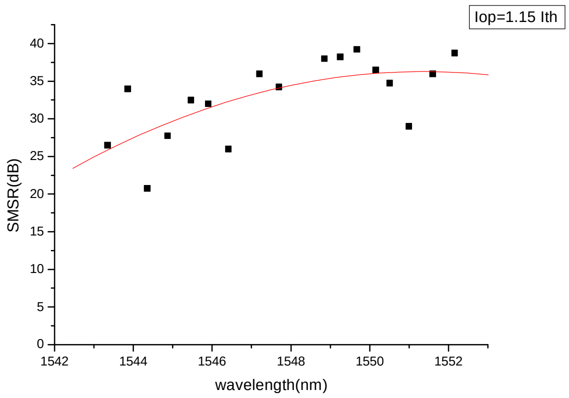


Fig. 4(b) Side mode suppression ratio of the laser output corresponding to each wavelength. The black squares are experimental points.

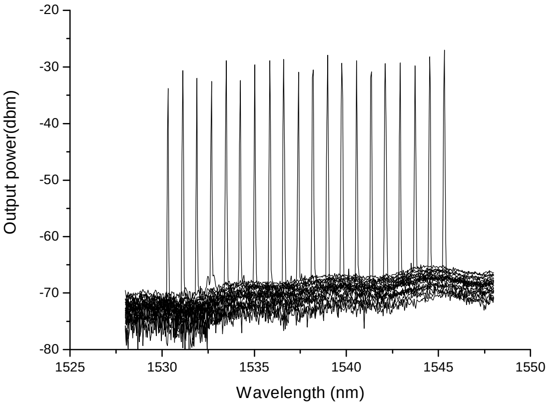


Fig. 4(c) Generation of tunable laser output in accordance to the ITU grid (100 GHz or ~ 0.8 nm)

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

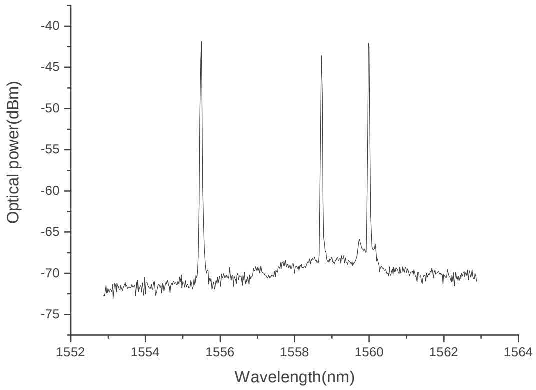


Fig. 5 Tunable triple-wavelength operation with wavelength separations of 3.22 nm to1.28 nm.

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

$$D_x = \frac{d^{a}}{dx} = a \cos \bar{\ }_{r} \bullet \frac{1}{f}$$

where a is the groove spacing of the grating , ¯$_r$ 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.

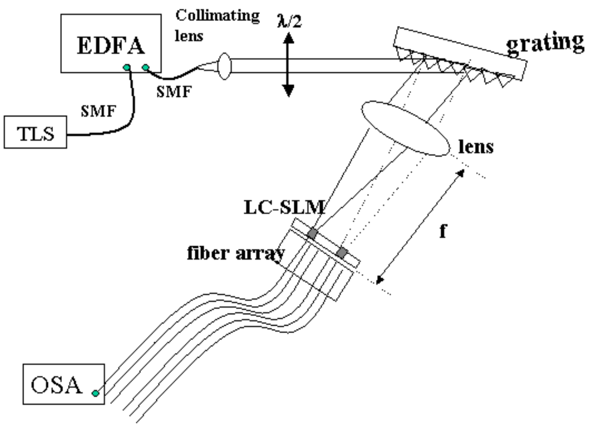


Fig. 6 Experimental setup of a liquid-crystal-based tunable optical demultiplexer: EDFA: Erbium-doped fiber amplifer, SMF: single mode fiber, TLS: tunable laser system, LC-SLM: liquid crystal spatial light modulator, OSA: Optical Spectrum Analyzer.

Typical demultiplexing results are shown in Fig. 7. There are totally twelve channels. The crosstalk between adjacent channels is less than –30 dB. The center wavelengths of all channels are designed according to the ITU grids with channel spacing of 100 GHz. The average 1dB, 3dB, and 30dB passbands of the demultiplexer are 0.06 nm, 0.11 nm, and 1.09 nm, respectively. The extinction ratio ranges from 5.4 dB to 22.1dB with the average of 10.7 dB. The fluctuation is probably due to the non-uniform thickness of the LC_SLM. The rise and fall time of switching on and off one channel is less than 1.6 ms and 88 ms respectively.

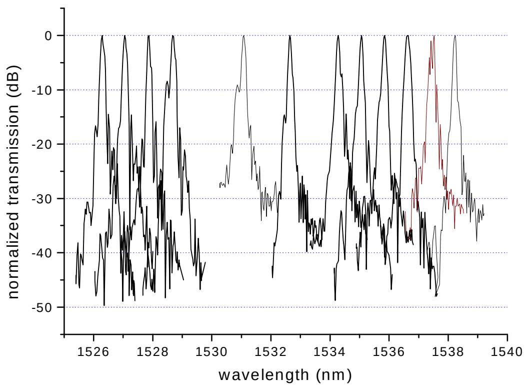


Fig. 7 Preliminary results of the tunable optical demultiplexer. The channels are designed according to ITU grid with channel spacing of 100 GHz.

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

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

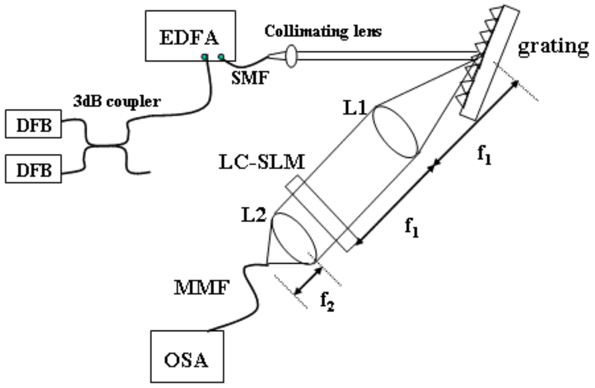


Fig. 8 Experimental setup of a liquid-crystal-based tunable optical filter/equalizer: EDFA: Erbium-doped fiber amplifer, SMF: single mode fiber, DFB: Distributed Feedback Lasers,, LC-SLM: liquid crystal spatial light modulator, L1 and L2: lenses, MMF: multi-mode fiber, OSA: Optical Spectrum Analyzer.

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. The power difference before (dotted line) and after (solid line) voltage adjustment decreased from 17.9 dB to 0.3 dB.

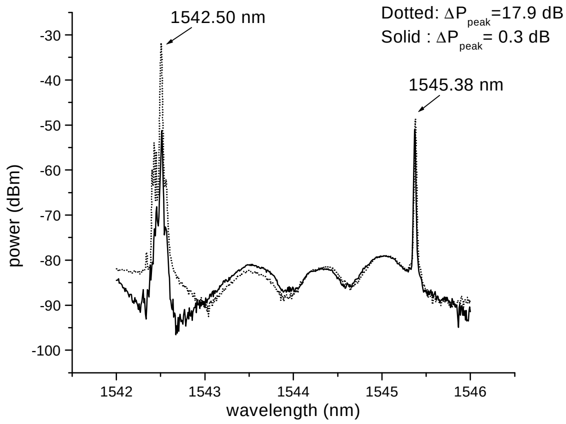


Fig. 9 Power equalization of two wavelengths by the LC-based filter. Dotted line: before equalization, Solid lime: after equalization

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. 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.

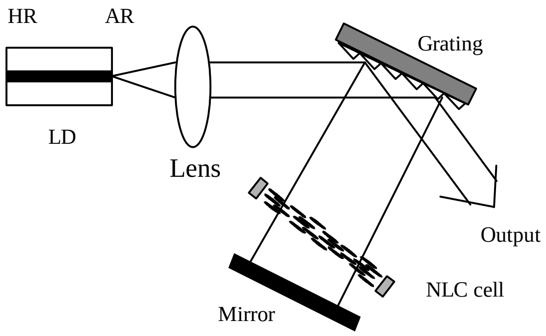


Fig. 10 A schematic of the laser configuration. LD: Laser Diode; HR: High Reflector; AR: Anti-reflection Coating; NLC: Nematic Liquid Crystal

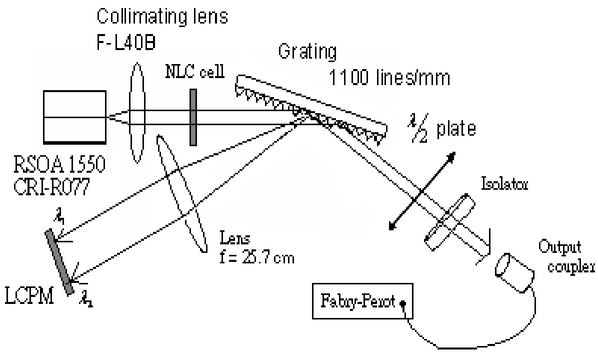
The NLC cell is constructed by sandwitching the 4'-n- pentyl-4- cyanobiphenyl (5CB) LC between two glass plates coated with Indium-Tin-Oxide as electrodes. The thickness of the cell is controlled by Mylar spacers. In the experimental result described in this section, we use a 35.5-μm-thick NLC cell. 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 $\Delta l = \Delta n d$ 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.



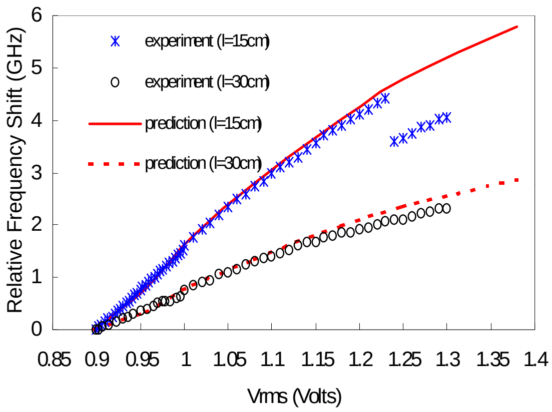


Fig.11: Laser frequency shift measured by a wavemeter. The theoretical curves are also shown.

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. II 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. 12. 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.

Fig.12: Schematic of the LCPM based ECDL with an intracavity nematic liquid crystal cell.

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 12. The channel spacing is 0.252 nm. There are forty-four channels in this work.

Fig. 12 Tuning the laser wavelength is steps

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).

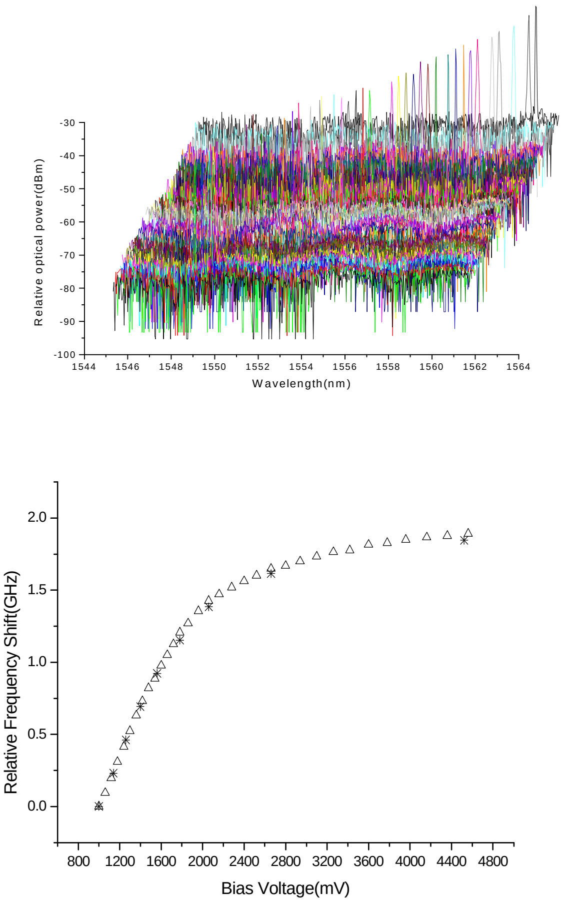


Fig. 13: Wavelength fine-tuning of the LCPM based ECDL system. Δ: Experimental results. □: Theoretical predictions.

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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VII. Research Output

Students	1. 博士生: 藍玉屏、陳昭遠 2. 碩士生: 黃銘杰、石宗盛
Student Graduated	黃銘杰, M.S., 2002
Refereed Journal Papers	1. Ci-Ling Pan , Minjay Huang And Ru-Pin Pan,” Liquid-Crystal-Based Tunable Filter For WDM (λ = 1550 nm),” accepted for publication in Mol. Cryst. Liq. Crystl., Nov., 2002. 2. Ru-Pin Pan, Yu-Pin Lan, Chao-Yuan Chen, and Ci-Ling Pan, “A Novel Tunable Diode Laser with Liquid Crystal Intracavity Tuning Element,” accepted for publication in *Mol. Cryst. Liq. Cryst.* May 6 2003. 3. 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,” submitted to *Opt. Eng.*, April 2003. 4. 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,” submitted to Optics Letters, May 21, 2003

Conference Papers	1. 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) 2. 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. 3. Ci-Ling Pan , Minjay Huang And Ru-Pin Pan,” Liquid-Crystal-Based Tunable Filter For Wdm (λ = 1550 nm),” presented at the 19th International Liquid Crystal Conference, June 30 –July 5, Edinburgh, UK 4. Tsung-Sheng Shih (石宗盛), Ru-Pin Chao (趙如蘋), and Ci-Ling Pan (潘犀靈), “Tunable External Cavity Semiconductor Laser(ë=1.5 μm) 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. 5. 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. 6. 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. 7. 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.

Patent Disclosures	1. An external cavity semiconductor laser with step-tuning and mode-hop-free fine-tuning functionality (submitted) 2. Liquid-Crystal-Based Tunable Filter/Equalizer (in preparation) 3. Liquid-Crystal-Based Tunable Optical Demultiplexers (in preparation)
Honors and Recognitions	1. 黃銘杰獲 **OPT'02 台灣光電科技研討會壁報論文獎**。 2. 趙如蘋在 **SPIE Photonic West 會議作邀請演講**。