# Fine-tuning of a diode laser wavelength with a liquid crystal intracavity element

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**Abstract.** A novel and simple approach for fine-tuning a laser wavelength is proposed and demonstrated. The key element is a planarly aligned nematic liquid crystal (NLC) cell inserted between the grating and end mirror of an external-cavity semiconductor laser (ECL). Varying the voltage driving the NLC cell, causes its extraordinary index of refraction to change due to field-induced reorientation of the LC director. This is equivalent to tuning the laser cavity length. As a result, the laser wavelength can be continuously tuned. With a 35.5-$\mu$m-thick NLC cell, the output frequency of the present laser can be continuously tuned over 4 GHz. The root mean square driving voltage required is 1.5 V or less. The tuning range is in good agreement with the theoretical predictions. 
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Subject terms: external-cavity diode laser; nematic liquid crystal; frequency tuning.

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## 1 Introduction

Tunable semiconductor lasers are compact and versatile sources that have a wide range of applications in optical communication, high-resolution optical spectroscopy, and precision metrology.[1] These lasers often employ an external cavity configuration. Littrow[2] and Littman[3] type external-cavity configurations are the dominant cavity designs. The wavelength of these external-cavity semiconductor lasers (ECLs) can be tuned mechanically by controlling the movement of the optical feedback element, e.g., the grating or end mirror.[4–7] Wavelength fine-tuning by inserting a single glass plate in an ECL was recently reported.[8] By tilting the 2-mm-thick intracavity glass plate in a tunable 633-nm ECL that changes the optical path, a continuous tuning range of 1.8 GHz was obtained. The introduction of the intracavity glass plate makes fine-tuning of the cavity length more convenient than in traditional cases. However, this approach still requires mechanical movement of a relatively bulky component. It is desirable to be able to tune the laser frequency electronically by varying the driving voltage applied to the tuning element only. Intracavity electro-optical $LiNbO_3$ crystals[9,10] or acousto-optic modulators[11] have been used for electronic wavelength tuning. One such approach utilized the electro-optic properties of liquid crystals.[12–19] Several types of liquid crystal elements have been successfully developed as intracavity tuning elements in external-cavity semiconductor or fiber lasers. These elements can be categorized as birefringent filters,[12–14] Fabry-Pérot étalons,[15,16] or spatial light modulators.[17–19] Liquid crystal tuning elements require driving voltages as low as several volts. This is typically much lower than the voltages required for other bulk electro-optic or acousto-optic tuning devices. In this paper, a novel and simple liquid-crystal-based approach for fine-tuning of the laser wavelength is proposed and demonstrated. The key element is a planarly aligned nematic liquid crystal (NLC) cell inserted between the diffraction grating and feedback mirror of an ECL. It is based on the principle of fine-tuning of the laser cavity length by electrically controlled birefringence of the NLC cell. Experimental methods and operation principles of the laser are described in Sec. 2 of the paper. Section 3 summarizes results and discussions. Experimental results are found in good agreement with theoretical predictions.

## 2 Experimental Methods and Operation Principles

A schematic of the laser configuration is shown in Fig. 1. It is basically an ECL of the classic Littman design. The gain medium is a laser diode (Sacher, model 780-40) with one facet antireflection (AR) coated ($R<1\times10^{-4}$) to suppress self-lasing and the other facet coated as a high-reflector. The temperature of the laser diode is stabilized at 20.0 $\pm 0.005$°C. The output from the AR-coated facet of the laser diode (LD) is collimated by an objective lens (numerical aperture, NA=0.5) for optical coupling to the diffraction grating (Optometrics, 1200 lines/mm, blazing wavelength $\sim$750 nm) at grazing incidence. The zeroth-order reflected beam from the grating is the output of the laser. The first-order reflection from the grating is retroreflected back into the diode by an end mirror. The longitudinal mode spacing for this external cavity of 15-cm length is about 1 GHz. A 30-cm-long cavity was also investigated. For tuning the laser frequency without moving any me-

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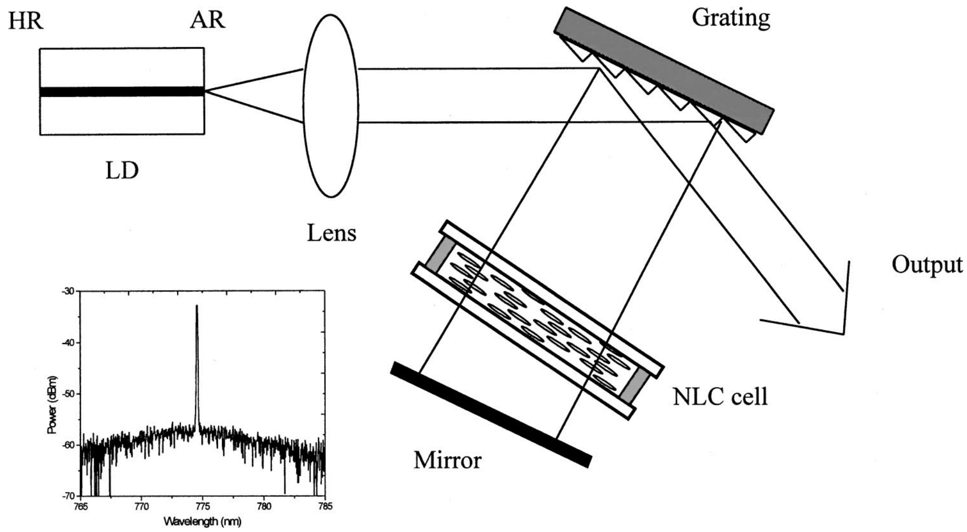


**Fig. 1** Schematic of the ECL with a planar liquid crystal cell: LD; laser diode; HR; high reflector; AR; antireflection coating; NLC, and nematic liquid crystal. The inset shows a typical laser output spectrum.

chanical part, an NLC cell was introduced between the grating and the mirror. The cell is tilted at an angle with respect to the laser axis. This helps to reduce the unwanted reflected light from either surface of the cell windows, which are not AR coated.

The NLC cell is constructed by sandwiching a 35.5-$\mu$m-thick layer of $4'$-$n$-pentyl-4-cyanobiphenyl (5CB) between two glass plates coated with indium tin oxide on the inner surfaces as electrodes. After assembly, the two glass plates are parallel within half a wavelength in the visible (i.e., less than 300 nm), as determined by an interference experiment. We chose 5CB as the LC material because its physical properties are well known and it is commercially available. We also experimented with another readily available liquid crystal (E7; Merck) with good success. 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. The transmission of the NLC cell as a function of the driving voltage is characterized before it is introduced in the ECL system. In the characterization measurement, the NLC cell is inserted between two crossed polarizers. The first polarizer is oriented to be parallel to the polarization of the incident laser beam, which is also at an angle of 45 deg to the rubbing direction of the planar NLC cell. The transmission intensity $I$ of this setup can be expressed as

$$I = I_0 \sin^2 \frac{\Delta\Phi}{2}, \tag{1}$$

where $\Delta\Phi = \Delta nkd$ is the phase retardation; $\Delta n$ is the difference in refractive indices for extraordinary and ordinary waves and is a function of the driving voltage; $d$ is the layer thickness of NLC cell; and $k = 2\pi/\lambda$, where $\lambda$ is the wavelength of the light. The transmission maxima and minima occur when $\Delta nd$ is a half-integral multiple and an integral multiple of wavelength, respectively. Figure 2 is a plot of the transmission of the NLC cell used in the ECL as a function of the driving voltage. The probing laser wavelength is 772 nm. Each cycle in Fig. 2 corresponds to a phase retardation of $2\pi$. There are eight cycles. Thus a phase retardation of $\Delta\Phi = 15\pi$ is possible by tuning the root mean square (rms) driving voltage from 0.55 to 10.0 V.

In the laser cavity, the NLC cell is oriented so that the laser polarization direction is along its rubbing direction. After insertion of the LC cell, the laser output power reduced by about 16%. Varying the voltage driving NLC cell, its extraordinary index of refraction would change due to field-induced reorientation of the LC director and results in an additional intracavity phase difference $\Delta\Phi$, which corresponds to an optical path difference $\Delta l = \Delta\Phi/k$. 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 optical path change through the

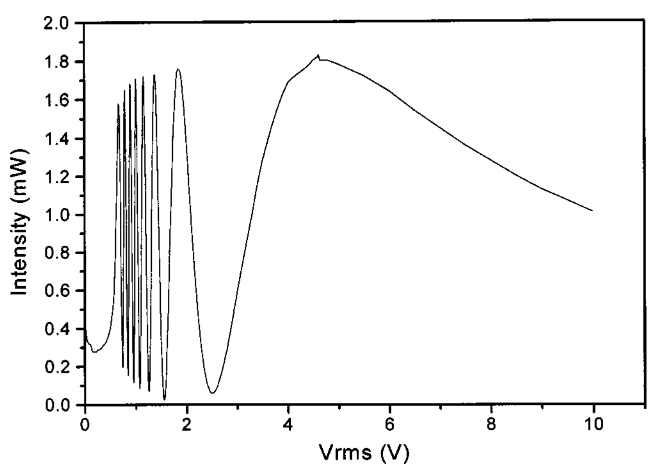


**Fig. 2** Transmission of the NLC cell between crossed polarizers at 772 nm plotted as a function of the driving voltage.

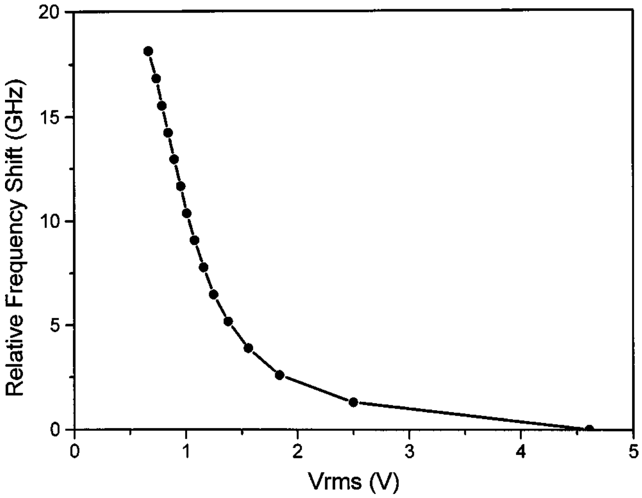


**Fig. 3** Theoretical prediction of the relative frequency shift of a 15-cm ECL as the voltage driving the NLC cell is changed.

NLC cell, $l$ is the cavity length, $\Delta f$ is the induced relative frequency shift, and $f$ is the laser frequency. The maximum tuning range of the LC cell is then

$$|(\Delta f)_{\max}| = f|n_e - n_o|(\mathrm{d}/l). \quad (3)$$

Figure 3 plots the theoretical prediction of the phase-change-induced optical length variation derived from Fig. 2 and Eq. (2). The solid circles correspond to the driving voltages of the LC cell at transmission maxima and minima of Fig. 2. The curve is intended only as a guide for the eye. It is obvious that a linear and continuous frequency variation of several gigahertz can be obtained by changing the driving voltage of the NLC cell over several volts in the linear portion of the curve.

## 3 Results and Discussion

A typical lasing spectrum of the ECL with an NLC cell is shown in the inset of Fig. 1. The laser linewidth is less than 0.015 nm (instrument-limited, as measured by an optical spectrum analyzer ANDO model AQ6317B). The side-mode suppression ratio is better than 30 dB throughout the tuning range of the laser ($\sim$19.1 nm). The output wavelength and the wavelength tuning range of the ECL were measured using a wavelength meter (Burleigh WA-1500) with a resolution of 0.0001 nm. In the fine-tuning experiment, the laser frequency was also monitored by a scanning Fabry-Pérot interferometer (SFP, Melles Griot model 13SAE005) with a free spectral range of 2 GHz. Measurements were carried out at room temperature ($\sim$25°C) for two cavity lengths. Fine wavelength tuning was accomplished by changing the voltage driving the NLC cell in the linear operation region of Fig. 3, i.e., from 0.9 to 1.3 V. Examples of frequency shifts of the laser output as monitored by the SFP are shown in Fig. 4. Four sets of data are shown for the driving voltage increased successively by a step of 0.01 V. The frequency shift is evident. Using the wavelength meter, the laser frequency shift as the applied voltage on NLC cell in the range of 0.9 to 1.3 V for 15- and 30-cm ECL cavities were also determined quantitatively

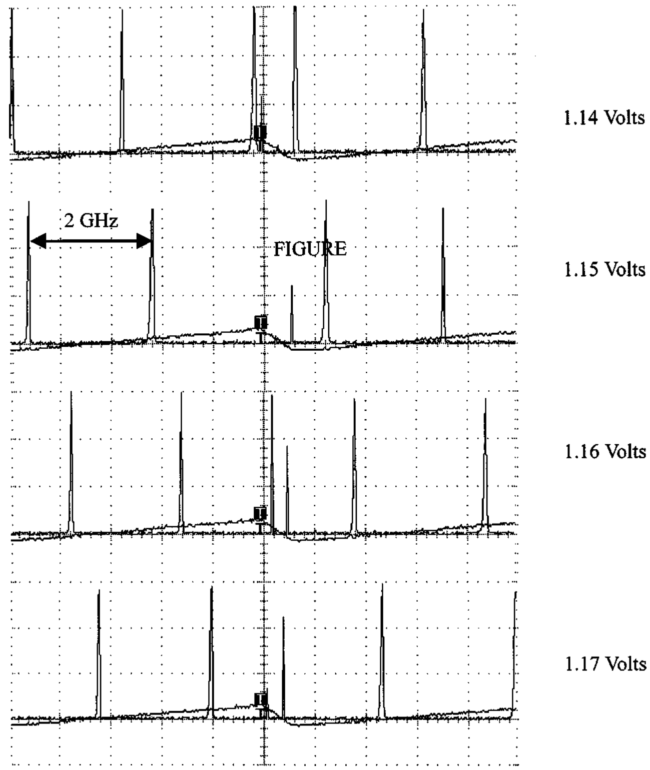


**Fig. 4** Single-mode operation and output frequency shift of the 15-cm ECL for several driving voltages of the NLC cell, as observed by an SFP with a free spectral range of 2 GHz.

and are shown in Fig. 5. For the 15-cm-long ECL cavity, the mode-hop-free tuning range of the laser is 4.42 GHz (from 0.9 to 1.23 V). The laser mode jumps one axial mode spacing ($\sim$1 GHz) at $V_{\mathrm{rms}} = 1.24$ V. For the 30-cm-long cavity, the mode-hop-free tuning range is 2.77 GHz (0.9 to 1.3 V). The tuning characteristics are in good agreement with the theoretical predictions of 4.30 and 2.46 GHz according to Eq. (2) for the two cavity lengths, respectively. The theoretical predictions according to Fig. 3 are also plotted in Fig. 5 as solid and dashed curves for $l = 15$ and 30 cm in that order. The slight discrepancies between the experimental and theoretical tuning ranges are within the ac-

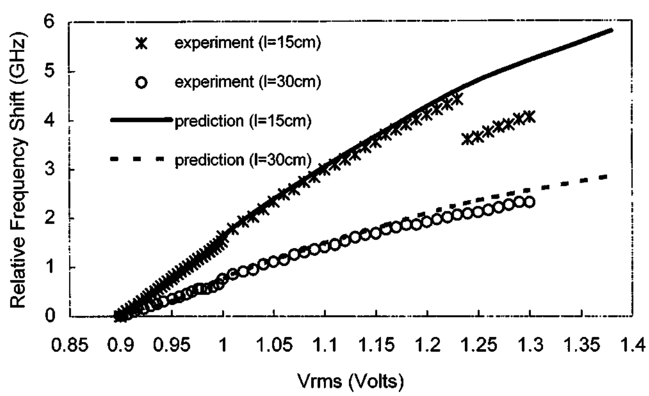


**Fig. 5** Laser frequency shift measured by a wavemeter as the driving voltage of the NLC cell is in the range of 0.9 to 1.3 V. Data for the two cavity lengths $l = 15$ cm and $l = 30$ cm are shown.

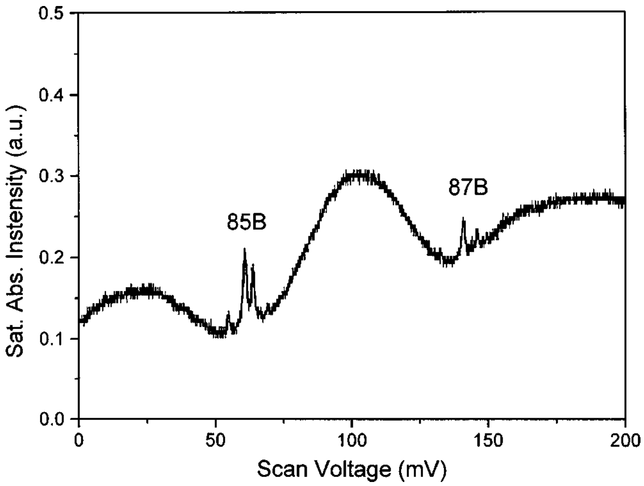


**Fig. 6** Sub-Doppler resonances of the Rb $D_2$-line ($5S_{1/2}$ to $5P_{3/2}$, 780 nm) in a mixture of isotopes $^{85}$Rb and $^{87}$Rb observed using the present ECL by scanning the driving voltage of the NLC cell.

curacy of the wavelength meter, which was calibrated to be $3\times10^{-7}$ by the National Measurement Laboratory of Taiwan. With $n_e$-$n_o=0.2$ for 5CB and $d=35.5\ \mu$m, the maximum frequency shift possible with the present LC cell are 18.4 and 9.2 GHz for the 15- and 30-cm cavities. Such large frequency shifts can not be realized in the present laser system due to the occurrence of mode hopping. Approaches such as synchronous scanning of the bias current of the laser diode could remedy this situation.[20]

We used this ECL system to observe the sub-Doppler resonances of the Rb $D_2$-line ($5S_{1/2}$ to $5P_{3/2}$, 780 nm) at room temperature ($\sim$25°C). A standard saturation absorption experimental setup was employed.[21] The rubidium cell is 25 mm long and 1 in. in diameter. It is made up of a mixture of isotopes $^{85}$Rb and $^{87}$Rb. We scanned the driving voltage of the NLC cell with a sinusoidal wave at 30 mHz. The observed spectrum is shown in Fig. 6. The hyperfine structure components of linear absorption profile for rubidium isotopes $^{85}$Rb ($F=3\rightarrow F'$) and $^{87}$Rb ($F=2\rightarrow F'$), designated as 85B and 87B, can be clearly seen. The voltage scan range of the NLC cell required is only 200 mV.

## 4 Conclusions

We demonstrated that a planar NLC cell can be used as the fine-tuning device in an ECL. With a 35.5-$\mu$m-thick cell, the output frequency of the present laser can be continuously tuned over 4.42 GHz for a 15-cm-long ECL by changing the rms voltage applied to the LC cell from 0.9 to 1.23 V. The tuning range is in good agreement with theoretical predictions. To demonstrate, we used this ECL system to observe the sub-Doppler resonances of the Rb $D_2$-line ($5S_{1/2}$ to $5P_{3/2}$, 780 nm). The experiment results demonstrate that this ECL system can operate in a single mode and can be used for spectroscopic applications. The system is superior because no mechanical moving part is required. The driving voltage is low ($<1.5$ V). No critical alignment is required. The introduction of this intracavity NLC cell makes it more convenient to realize fine-tuning of the laser frequency. With a thicker NLC cell or LC material with higher birefringence, a broader continuous tuning range should be possible. Coarse tuning over tens of nanometers can be realized with conventional techniques, e.g., mechanical tuning of the laser cavity length.

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