CHAPTER 5

FINE-TUNING OF AN ECDL WITH AN INTRACAVITY LIQUID CRYSTAL ELEMENT

In this chapter, the experimental results for fine-tuning of the laser wavelength with an intracavity liquid crystal element are demonstrated. The key element is a planar-aligned nematic liquid crystal (NLC) cell. We insert the NLC cell into the external laser cavity of an external-cavity diode laser (ECDL). Varying the voltage driving the NLC cell, its extraordinary index of refraction would 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 tuned. Mode-hop-free tuning is ensured by synchronous regulation of the bias current of the laser diode.

This chapter is divided into two sections. The results of fine-tuning of an ECDL by the intracavity NLC cell and the mode-hop-free synchronous tuning are demonstrated in Sec. 5.1. In Sec. 5.2, we discuss some properties of the NLC cell in the laser cavity such as the hysterisis, response time, switching characteristic etc.

5.1 Mode-hop-free wavelength fine-tuning

The NLC cell used in the experiment is driven by an ac square wave at 1 kHz and operated at the environmental temperature of 25 °C. The cell thickness is 35.5 μm. The transmission of the NLC cell as a function of the driving voltage is characterized before it is introduced in the ECDL system. The measurement setup is shown in Fig. 5.1. In the characterization measurement, the NLC cell is mounted with its axes at an angle of 45° to the input linearly p-polarized laser beam. The light passes through the cell then is analyzed by an analyzer. The axis of the analyzer is adjusted to be orthogonal to the polarization direction of the input laser beam. The power meter measures final transmittance. The transmission intensity I of this setup can be derived from *Eq.* (4.14) and expressed as *Eq.* (5.1).

$$I = I_0 \sin^2 \frac{\Delta\Phi}{2} \qquad (5.1)$$

Figure 5.2 is a plot of the transmission of the NLC cell as a function of the driving voltage. The probing laser wavelength is 772 nm. Each cycle in Fig. 5.2 corresponds to a phase retardation of 2π. 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 V to 10.0 V.

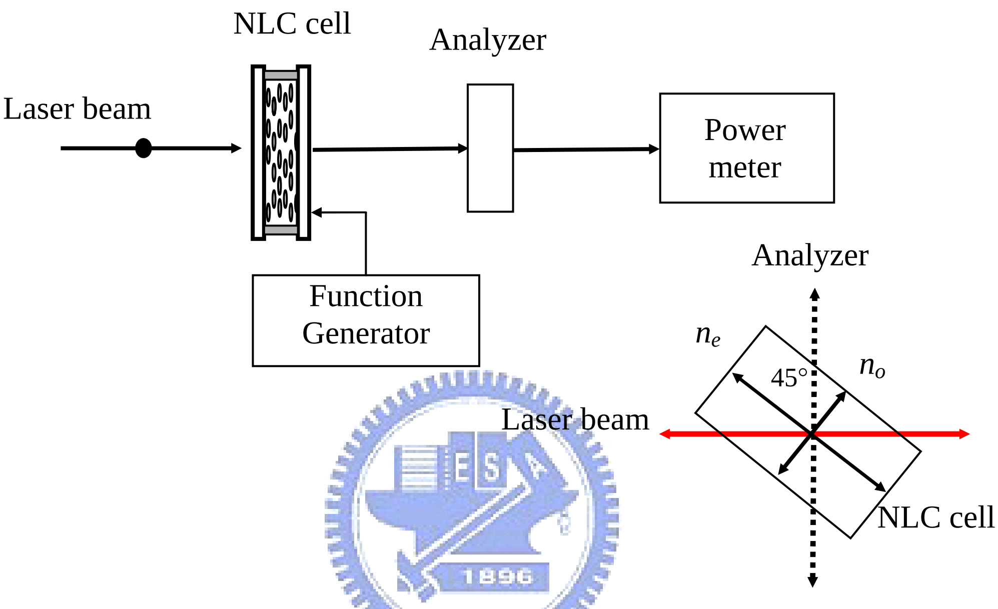


Fig. 5.1 Experimental setup for characterization of the NLC cell

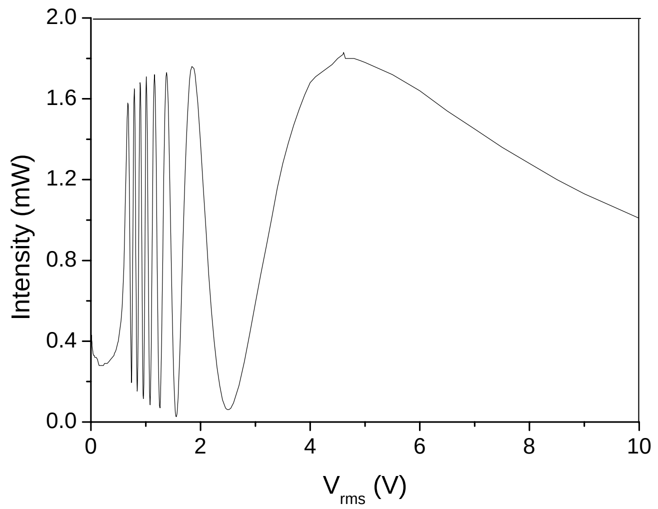


Fig. 5.2 Transmission of the NLC cell is plotted as a function of the rms driving voltage

In Fig. 5.3, we plot the theoretical prediction of the phase-change-induced optical length variation derived from Fig. 5.2 and *Eq.* (4.17). The laser cavity length is 10 cm. The solid circles correspond to the driving voltages of the LC cell at transmission maxima and minima of Fig. 5.2. The curve is for guiding of the eye only. It is obvious that a linear and continuous frequency variation of several GHz can be obtained by changing the driving voltage of the NLC cell over several volts in the linear portion of the curve.

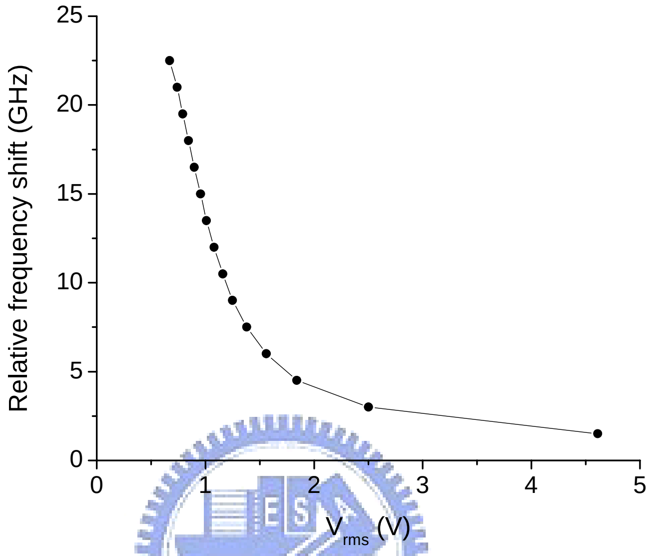


Fig. 5.3 Theoretical prediction of the relative frequency shift of the ECDL, 10 cm in length, as the voltage driving the NLC cell (5CB, 35.5 μm thick) is changed

5.1.1 Tuning by the NLC cell

A schematic of the laser configuration is shown as Fig. 4.10. It is basically an ECDL of the classic Littman-Metcalf design. The gain-medium is a laser diode (LD) with one facet anti-reflection (AR) coated to suppress self-lasing and the other facet coated as a high-reflector (HR). The temperature of the laser diode is stabilized at 20.0±0.005 °C. The output from the AR-coated facet of the LD is collimated by an objective lens (numerical aperture, N.A. = 0.5) for optical coupling to the diffraction grating (Optometrics, 1200 lines/mm, blazing wavelength ~ 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. For tuning the laser frequency without moving any mechanical part, a NLC cell is 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.

(1) Characteristics of the LD

A commercially AR-coated ($R<1\times10^{-4}$) LD (Sacher, model 780-40) with a nominal wavelength λ = 780 nm is used as the gain medium. The LI curves of the bare diode and diode in the Littman configuration are shown in Fig. 5.4. The threshold current is decreased from 53 mA to 31 mA when optical feedback is employed.

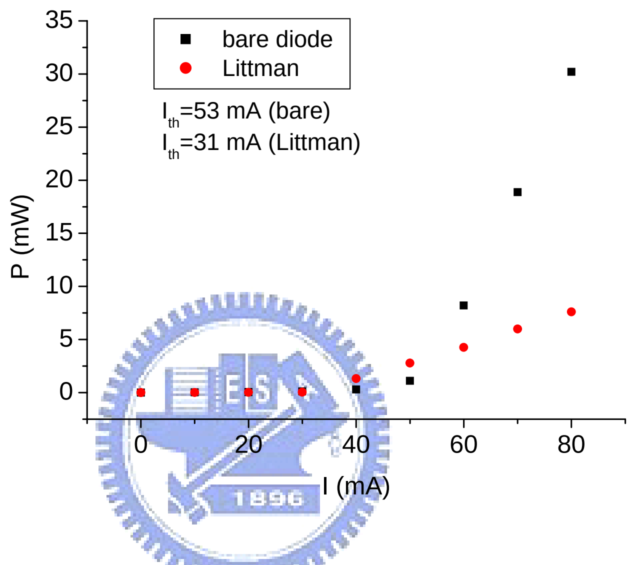


Fig. 5.4 L-I curves of the bare diode and the ECDL in Littman configuration

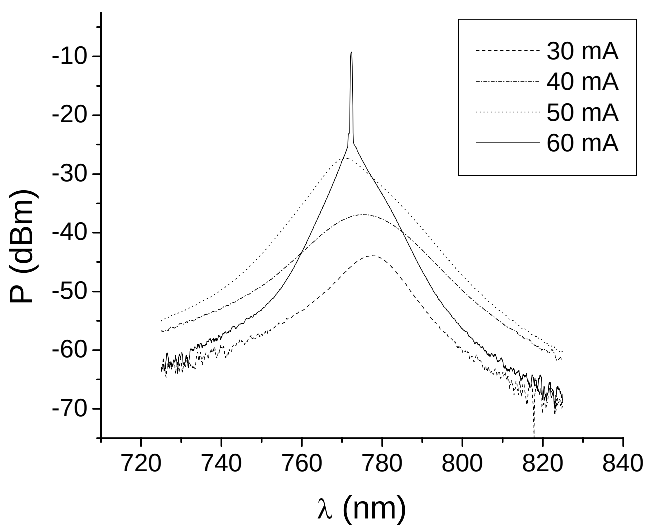


Fig. 5.5 Spontaneous emission spectra of the bare LD as a function of driving current

The spontaneously emission spectrum with a center wavelength at ~775 nm at different driving current of 30 mA, 40 mA, 50mA, and 60mA are demonstrated in Fig. 5.5. Self-lasing happens at the current above 50 mA. A typical lasing spectrum of the ECDL with an intracavity NLC cell monitored by a scanning Fabry-Perot (SFP, Melles Griot model 13SAE025) with a resolution of 1.5 MHz is shown in the Fig. 5.6. The free spectrum range (FSR) of the SFP is 300 MHz. The laser linewidth is estimated to be ~3.5 MHz. The lasing wavelength can be coarse tuned by rotating the feedback mirror. The side-mode suppression ratio is better than 30 dB throughout the tuning range of 19.1 nm from 767.7 nm to 786.8 nm of the laser. The spectra monitored by an optical spectrum analyzer (OSA, ANDO model AQ6317B) is shown in Fig. 5.7.

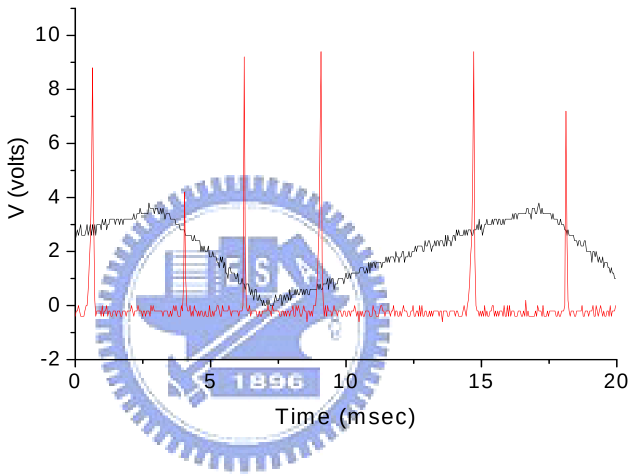


Fig. 5.6 Typical lasing spectrum of the ECDL as monitored by a SFP. The ramp voltage for driving the SFP is also shown

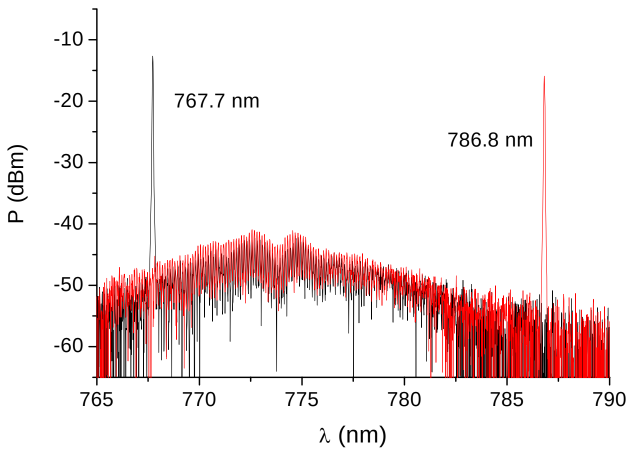


Fig. 5.7 Output wavelength of the ECDL can be tuned from 767.7 nm to 786.8 nm

(2) Wavelength fine-tuning

In the fine-tuning experiment, the laser frequency is monitored by using a wavelength meter (Burleigh WA-1500) with a resolution of 0.0001 nm, and also monitored by a SFP with a FSR of 2 GHz (Melles Griot model 13SAE005). Measurements are carried out at room temperature (~25 °C) for two cavity lengths. Wavelength fine-tuning is accomplished by changing the voltage driving the NLC cell in the linear operation region, i.e., from 0.9 V to 1.3 V. Examples of frequency shifts of the laser output as monitored by the SFP are shown in Fig. 5.8. Four sets of data are shown for the driving voltage increased successively by a step of 0.01 V. The frequency shift is evident.

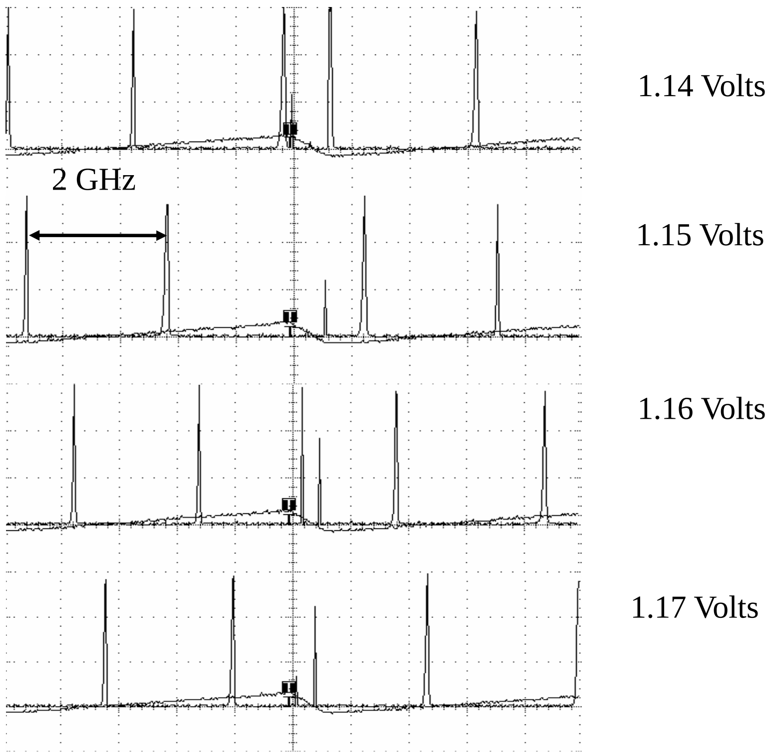


Fig. 5.8 Output frequency shift of the 15-cm ECDL for several driving voltages of the NLC cell

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 ECL cavities are also determined quantitatively and shown in Fig. 5.9. 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 longitudinal mode spacing for this external cavity of 15-cm length is about 1 GHz. The laser mode jumps one axial mode spacing (~ 1 GHz) at V_{rms} = 1.24 V. A 30-cm-long cavity has also been investigated. 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.* (4.17) for the two cavity lengths, respectively. The theoretical predictions are also plotted in Fig. 5.9 as solid and dashed curves for l=15 and 30 cm in that order.

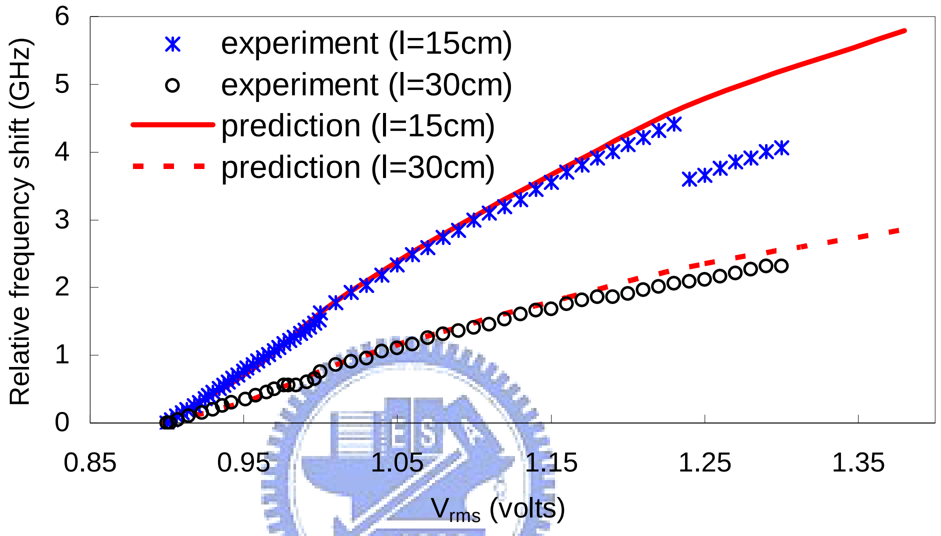


Fig. 5.9 Laser frequency shift with two different cavity lengths as the driving voltage of the NLC cell is changed

The slight discrepancies between the experimental and theoretical tuning ranges are within the accuracy of the wavelength meter, which was calibrated to be 3×10^{-7}.

5.1.2 Synchronous tuning

The maximum birefringence $(\Delta n)_{max} = n_e\text{-}n_o$ is 0.17 for 5CB at wavelength of 780 nm. The cell thickness is 35.5 μm. The maximum frequency shifts possible with the present NLC cell are 18.4 GHz and 9.2 GHz for 15-cm and 30-cm cavities. In principle, a continuous frequency shift of more than 20 GHz (10-cm cavity) can be obtained by varying the operation voltage of the present NLC cell under the assumption of mode-hop-free operation of the ECDL. Such large frequency shifts cannot 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.

Continuous wavelength tuning is accomplished by changing the voltage driving the NLC cell and the bias current of the LD synchronously. According to *Eq.* (4.22), the proportionality constant β should be known. For our laser, the average value of β is 6.5 nm/A over a range of ± 3 mA around 50 mA. The experimental result is shown in Fig. 5.10. The proportionality constants β are 6.8 nm/A and 6.3 nm/A for increasing and decreasing the current. The parameters of λ and *l* are 775 nm and 10 cm, respectively.

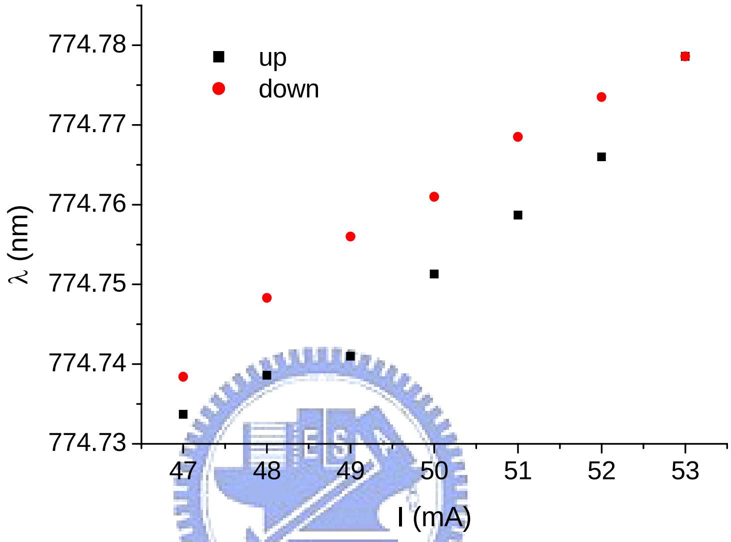


Fig. 5.10 The change in laser wavelength as a function of the LD driving current

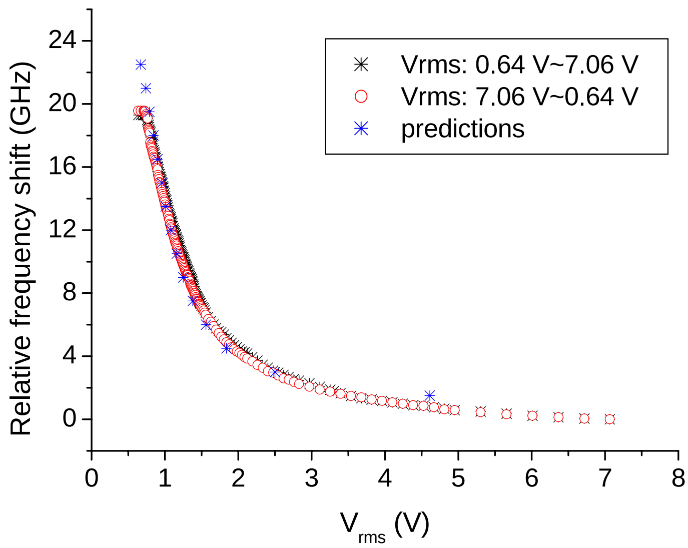


Fig. 5.11 Mode-hop-free tuning of the ECDL by varying the driving voltage of the NLC cell

The mode-hop-free tuning results of the laser are demonstrated in Fig. 5.11. Frequency shifts are observed by monitoring the output spectrum of the ECDL using a SFP with FSR of 2 GHz. The FSR of the FPI is calibrated by using a commercial tunable laser for which the wavelength is known. The FSR is found to be 2.06 GHz instead of 2 GHz. Taking this into account, the mode-hop-free ranges are 19.5 GHz and 19.2 GHz for up and down ramp of the driving voltage between 0.64 volt and 7.06 volts (Vrms), respectively. It is in good agreement with the theoretical predictions of 19.5 GHz according to Fig. 5.3. The variations of the LD drive current necessary for achieving mode-hop-free tuning of the lasing wavelength are shown as a function of the driving voltage of NLC cell (Fig. 5.12). We found that the current should be changed by 6.08 mA when the driving voltage of the NLC cell varied from 0.64 volt to 7.06 volts, and by 6.83 mA during the down ramp from 7.06 volts to 0.64 volt. The slight difference is due to the proportionality constants β, which are different for increasing and decreasing the current, respectively.

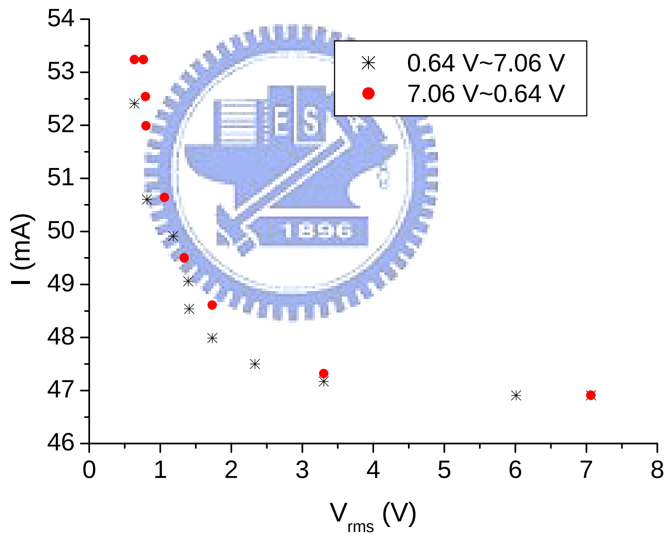


Fig. 5.12 Variations of LD drive current as a function of the driving voltage of the NLC cell for achieving mode-hop-free tuning

The continuous wavelength tuning range of the ECDL is also measured by using an unbalanced Michelson interferometer (Fig. 5.13) with a fixed optical path difference of 16 cm. We tune the laser wavelength instead of moving one of the end mirrors of the interferometer. The output interference intensity is detected by a photo detector. The longitudinal mode spectra are simultaneously monitored by a FPI. In Fig. 5.14, we show the interference fringes from the unbalanced Michelson interferometer as the laser frequency is tuned by changing the driving voltage to the NLC cell. As one can see from the trace, there are 21 fringes while the voltage is ramped from 0.64 volt to 7.06 volts. The mode-hop-free tuning range for the ECDL is thus 19.2 GHz.

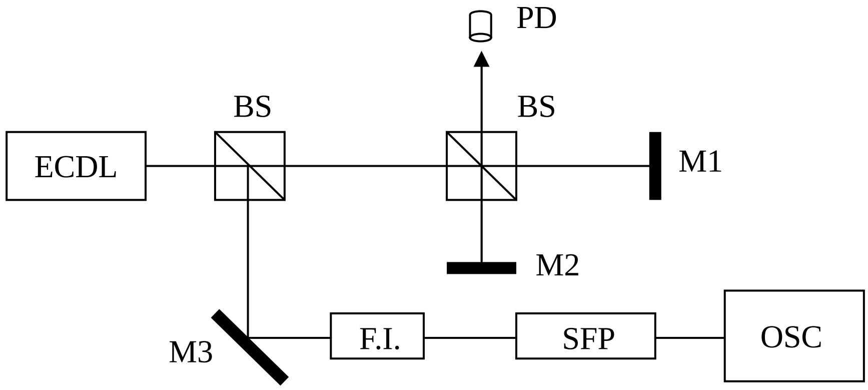


Fig. 5.13 Unbalanced Michelson interferometer. BS: Beam splitter; M: Mirror; PD: Photodiode; F.I.: Faraday Isolator; OSC: Oscilloscope.

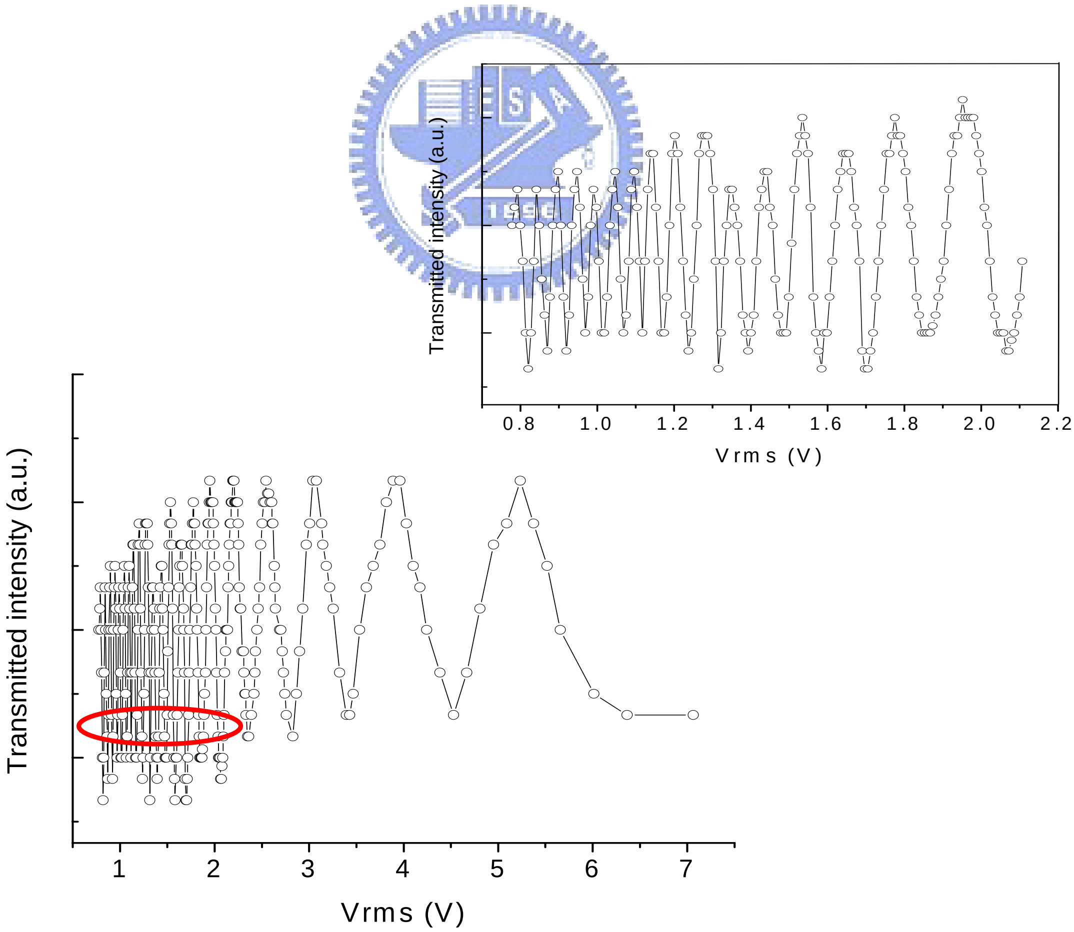


Fig. 5.14 Interference fringes of the unbalanced Michelson interferometer

During the experiment, the temperature of the NLC cell changes by about 0.2 °C for the period of 2 hours. According to the data published by S-T Wu [75], $\Delta n/\Delta T_{temp} = 2.42\times10^{-3}/°C$ for nematic 5CB at λ=775 nm. Thus the refractive index of the NLC cell changes by 0.484×10^{-3} during the experiment, which corresponds to a frequency error of 0.05 GHz. Further, for a 10-cm cavity, the error in the estimated cavity length is about 1 mm, or an uncertainty of 0.2 GHz in frequency. The combined error is then 0.25 GHz. The mode-hop-free tuning results are thus in good agreement with theoretical predictions.

5.2 Properties of the NLC cell in the laser cavity

Some properties of the NLC cell in the laser cavity and the proportionality constant β of the ECDL system are further investigated

5.2.1 Tilt angle of the NLC cell

In the experimental setup for characterizing its phase shifting property, the NLC cell is mounted perpendicular to the propagation direction of the laser beam. While in the ECDL, the cell is tilted at an angle with respect to the laser axis to prevent the unwanted feedback light. The tuning range affected by the cell mounted at different angle is investigated. According to the results demonstrated in Fig. 5.15, the cell mounted at an angle smaller than 30° in the ECDL is allowable.

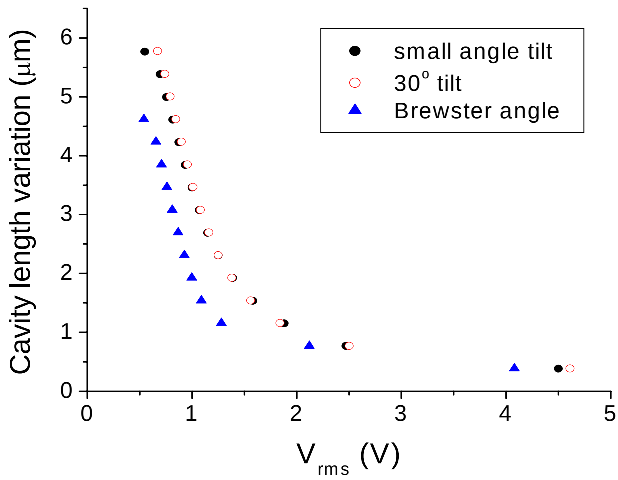
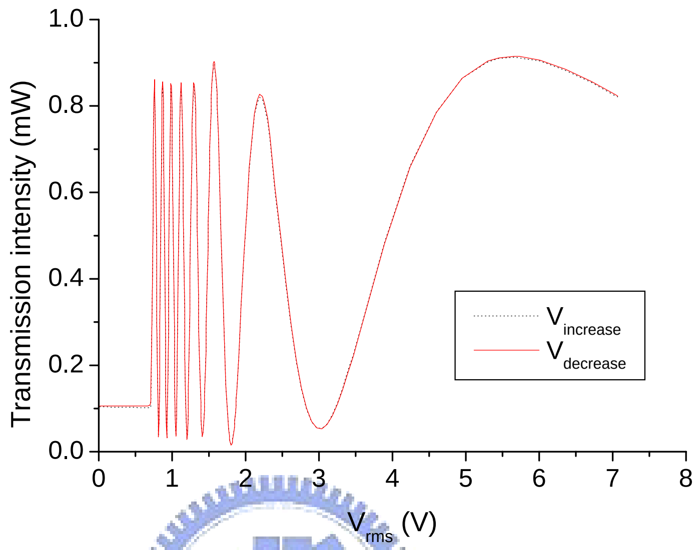


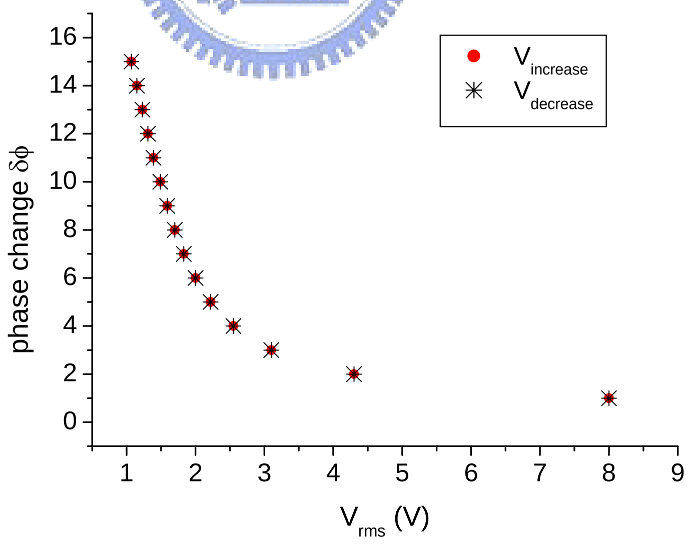
Fig. 5.15 The effect of tilt angle of the NLC cell on tuning of the laser cavity length by varying the driving voltage of the NLC cell

5.2.2 Hysterisis and tuning repeatability

Hysteresis is another issue in the NLC cell's operation in wavelength tuning experiment. We have proved experimentally that no apparent hysteresis is found. The experimental result is shown in Fig. 5.16 (a) and (b).



(a)



(b)

Fig. 5.16 Hysterisis effect of the NLC cell. (a) Transmission (b) phase change of the NLC cell for up and down ramp of the driving voltage between 0.64 volt and 7.06 volts, respectively.

In Fig. 5.17, the NLC cell is repeatedly switched between 0.92 V and 2.12 V ten times. The temperature varies 0.04 °C for a period of 10 minutes during the experiment, and the frequency drifts the same amount of 0.23 GHz for each applied voltage. The average frequency difference is 0.295 GHz with a standard deviation of 0.02 GHz. The frequency and temperature drift of the ECDL are also monitored. The LD is operated at the current of 50.02 mA, temperate of 20.01 °C, and the applied voltage of the NLC cell is 0.81 V. The frequency drifts 0.73 GHz and the temperature changes 0.07 °C for a period of 30 minutes (Fig. 5.18).

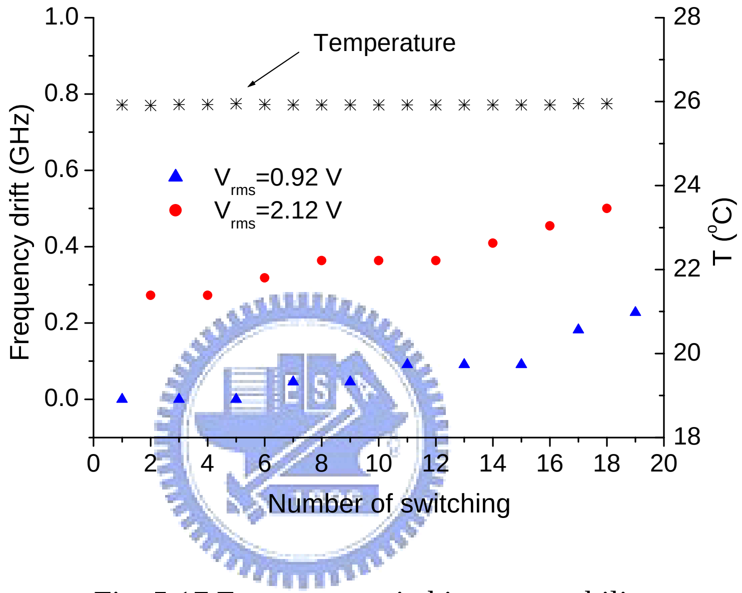


Fig. 5.17 Frequency switching repeatability

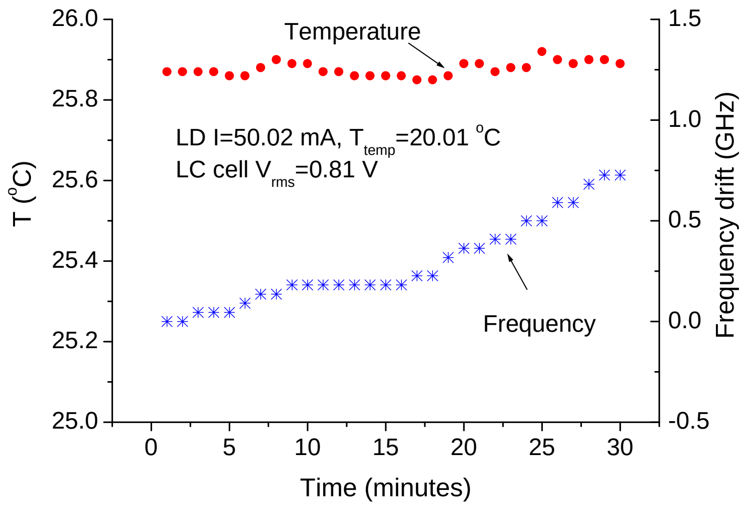


Fig. 5.18 Temperature and frequency drift

5.2.3 Response time

The transmittance of the cell is measured to be about 83.3 %. This is reasonable because of the 4 % reflectivity of surfaces of the glass plates. The cell response time is measured by driven the NLC cell by a 1 kHz sinusoidal wave with amplitude modulated. The amplitude is modulated by a square wave with frequency from 0.1 Hz to 1 Hz. The experimental setup is similar to Fig. 4.10 (in the laser cavity). Typical trigger (upper curve) and response signals (lower curve) are plotted in Fig. 5.19. The response time depends on the modulation width and driving voltages. The measurement results show the response of 5CB is about a few tens milliseconds either in or not in the laser cavity.

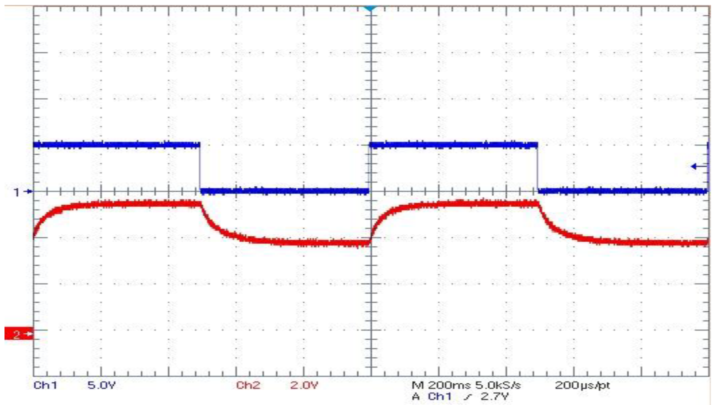


Fig. 5.19 Trigger (upper curve) and response (lower curve) signals

5.2.4 Proportional constant β of the laser

The output wavelength of the ECDL shows apparent hysterisis with bias current (Fig. 5.10). We found, however, that the amount of optical feedback of the ECDL in our experiment does affect the proportional constant β. The experimental results are listed in Table 5.1. The value of β varies from 0.11 to 6.8. In the experiment, the cavity length of the ECDL is 10 cm. We didn’t measure the amount of feedback but only slightly adjust the angle of the feedback mirror. Comparing with other ECDL, the constant β of a commercial ECDL (NewFocus model 6328-H) is 0.07 nm/A for increasing (forward) and 0.10 nm/A decreasing (backward) the bias current. The hysterisis exists though it is not obvious.

Table 5.1 Proportional constant β

	1	2	3	4
Forward (nm/A)	0.13	0.11	5.23	6.53
Backward (nm/A)	0.24	0.16	5.30	6.8

The output wavelengths versus bias current for single LD's without AR coated are measured. The proportionality constant β is 5.78 nm/A for increasing and decreasing the bias current of 657 nm LD. For 1550 nm LD, β are 7.92 nm/A and 7.87 nm/A respectively. The output wavelength of the LD chip itself does not show apparent hysterisis with bias current.