CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 A summary of the present work

An ECDL with an intracavity liquid crystal element has been developed. 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 developed laser system. A planar-aligned nematic liquid crystal (NLC) cell can be used as a simple yet effective wavelength-fine-tuning device in an ECDL. The NLC cell behaves no apparent hysterisis, good tuning repeatability, and the response time is several tens milliseconds. With a cell of 35.5 μm in thickness, the output frequency of the present laser can be continuously tuned over 4.42 GHz for a 15-cm-long ECDL by changing the root-mean-square (rms) voltage applied to the liquid crystal cell from 0.9 volt to 1.23 volts. The tuning range is in good agreement with theoretical predictions of 4.30 GHz. Mode-hop-free wavelength tuning can be achieved by tuning the biasing voltage of the NLC cell and the injection current of the laser diode (LD) simultaneously. A continuous mode-hop-free tuning range of 19.2 GHz for a 10-cm-long ECDL is demonstrated. The LD current was changed by 6.08 mA when the driving voltage of the NLC cell varied from 0.64 V to 7.06 V. The mode-hop-free tuning results are in good agreement with theoretical predictions of 19.5 GHz and the results of 19.2 GHz measured by using an unbalanced Michelson interferometer with a fixed optical path difference. The introduction of this intracavity NLC cell makes it more convenient to realize fine-tuning of the laser frequency. The construction of the NLC cell is simple compared with the liquid-crystal Fabry-Perot étalon as the tunable filter. It needs not to be dielectric coated on the inner surfaces of glass plates of the NLC cell. With a thicker NLC cell or LC material with higher birefringence, broader continuous tuning range should be possible. The developed ECDL system is compact and easy to construct. It requires no mechanical moving part and no critical alignment. The driving voltage is relatively low (several volts).

The developed ECDL was used to observe the sub-Doppler resonances of the Rb D_2-line ($5S_{1/2}$ - $5P_{3/2}$, 780.245 nm). Scanning the applied voltage of the NLC cell scans laser frequency. The scan range is 200 mV with a scan speed of 30 mHz. The hyperfine structures of the 85B and 87B were demonstrated. The offset frequency between these two groups is about 1.14 GHz. The experiment results demonstrate that this ECDL system can operate in a single-mode and can be used for spectroscopic applications. Limited by the response time of liquid crystal 5CB, the scanning speed was slow in order to achieve better resolution. This can be improved by using the LC of faster response time, e.g. LC with lower viscosity.

The output wavelength of the developed ECDL was locked to an étalon (a 3-mm-thick BK7 glass plate with finesse of 30) by feedback control of the NLC cell. Relative wavelength stabilities were expressed by the square root of Allan variance. The results were compared with those of a commercial ECDL stabilized to the same étalon by feedback control of the PZT. For the developed ECDL, relative wavelength stabilities of 2.46×10^{-8} (sampling time 20 s) were achieved. The stabilities are of the same order of magnitude of the commercial product, which were 1.49×10^{-8} for sampling time of 60 s. The wavelength stabilities are mainly limited by the temperature coefficient of the étalon, $\alpha+n_T$. To achieve better results, the étalon should be temperature controlled. Furthermore, the stability can be improved by an additional fast servo loop applied for feedback control of the injection current of the LD.

The NLC cell can be applied for fine-tuning of a digitally channel-selectable laser (LCPM based ECDL) for which the cavity length is 60 cm and the cavity mode spacing is 0.25 GHz at λ=775 nm. The LCPM allows digitally tuning of the laser wavelength. Continuous tuning of 140 MHz of one selected channel was achieved by tuning the rms driving voltage of the LCPM from 2.8 V to 6.36 V. The laser wavelength can further be tuned by varying the driving voltages applied to the NLC phase plate. With an NLC cell 35.5 μm in thickness, the output frequency of the present laser can be continuously tuned over 1.75 GHz from V_{rms}=0.9 V to 2.26 V. The mode-hop-free tuning range is limited by the requirement of dedicated adjustment of the LD current. The method has been implemented in a DWDM laser system for selecting the central wavelength according to the ITU grid, and for adjusting the channel spacing.

The cell thickness or cell gap is one of the key parameters in the design and fabrication of liquid crystal displays (LCD). It affects the brightness, contrast ratio and response speed of the LCDs. The developed ECDL can be applied for measuring the gap of the LC cell placed in the laser cavity through tuning of the wavelength of the laser. The method is particularly suitable for measurement of LC cells of small phase retardation. Measurement errors of ±0.5 % and ±0.6 % for 9.6-μm and 4.25-μm planar-aligned cells with phase retardations of 1.63 μm and 0.20 μm respectively are demonstrated. The accuracy of cell gap measurements depend on the accuracy of the measurement of the cavity length, birefringence Δn, non-perpendicular between the input laser beam and the LC cell, drift of the laser frequency, and the resolution of the wavelength meter. According to the analysis, the accuracy of measurement is limited mainly by the resolution of the wavelength meter and the frequency drift of the ECDL. The frequency drift (measured to be 200 MHz/hr) of the developed ECDL is primarily caused by the thermal drift or mechanical instability of the laser cavity, and the thermal effect of the LC cell. Obviously, there is still a lot of room for improvement, e. g. constructing the ECDL to be more rigid and reducing the effect of temperature variation in the laboratory by isolating the laser system in a box, even employing a temperature-compensating mechanism for the external cavity. Frequency drift induced by the thermal effect of the LC cell can be alleviated by temperature control of the LC cell. Instead of the wavelength meter, the laser frequency can be measured by heterodyning the ECDL with a frequency-stabilized laser. The beating signal between the two lasers can be easily detected with a typical resolution of 100 kHz, which is about five hundred times better than that of the wavelength meter. Employing both approaches, the phase retardation due to the LC layer as small as 4×10^{-5} μm can be measured. This is far beyond the requirement of the manufacturing process of LCD panels at present.

7.2 Recommendations for further work

7.2.1 Channel-selectable laser with LC enabled functionalities

Fine-tuning of a digitally channel-selectable laser, especially for WDM laser applications, the present structure can be modified. In present design, the planar-aligned NLC cell and the LCPM are separate elements. They can be replaced by a sandwich-type LCPM [118], which is designed to be a double layer structure composed by a pixellated NLC plate and a LCPM. As shown in Fig. 7.1, the sandwich-type LCPM is composed by three glass plates to form a structure like a sandwich. The rubbing direction of back surface of glass plate 1 and surface A of glass plate 2 are parallel to each other, while the rubbing direction of surface B of glass plate 2 and the front surface of glass plate 3 are perpendicular to each other. Between glass plates are filled with nematic liquid crystals. Thus the NLC are planar-aligned in the first layer and are twisted in the second layer. ITO patterns are coated on surface A and B of glass plate 2 to form the pixels. The voltage of each layer and can be controlled independently, and the voltage of every pixel can be controlled individually. A polarizer and a high reflector, e.g. a gold reflected mirror are attached to the back surface of the glass plate 3. By using this sandwich-type LCPM in the laser cavity, the output wavelength is channel selectable by switching on the selected pixel of the second layer. And the channel wavelength can be continuously tuned by varying the voltages applied to the corresponding pixel of the first layer. The output power can be adjusted by controlling the applied voltage of the selected pixel of the second layer.

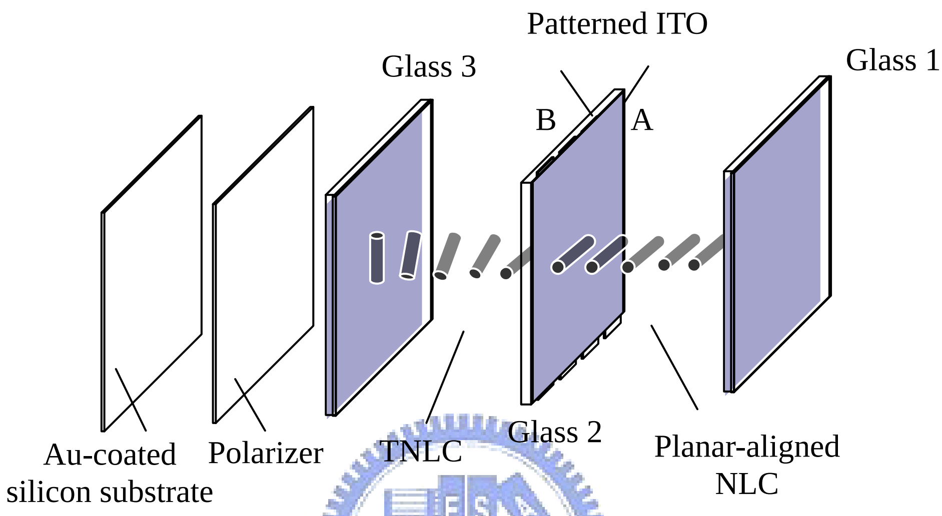

Fig. 7.1 A sandwich-type LCPM

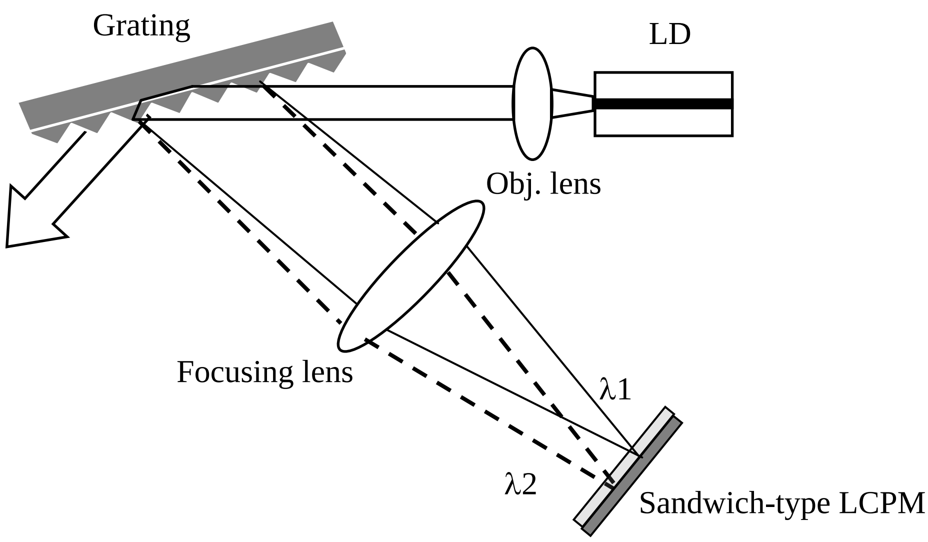

Fig. 7.2 Schematic of a channel selectable laser with LC enabled functionalities

7.2.2 Terahertz frequency standards

The LCPM based ECDL has a potential to be a good candidate for cw terahertz (THz) generation. The external-cavity arrangements have advantages of easily tuned for a wide range of the difference frequency and narrow linewidths [51, 54-63]. In chapter 6.2.2, the ECDL locked to the femtosecond (fs) combs by feedback control of the intracavity NLC cell was demonstrated. The concept can be applied to the LCPM based ECDL while dual-wavelengths are selected for output. The two output frequency can be measured by the fs-comb precisely. The laser system thus can be used as the THz frequency standards. By now, stable dual-wavelengths generation from our laser system hasn't been achieved yet. There are some problems need to be solved. For examples, it was found that equal intensities of the two wavelengths are unstable, and single-longitudinal-mode lasing was obtained for only one of the lasing wavelength. We have done some efforts to solve these problems. The experimental results are summarized in Appendix B.

7.2.3 Cell gap measurements

The wavelength tuning method can also be applied to measure the cell gap of the vertical aligned (VA) liquid crystal panels widely employed by the LCD industry for enlarging the viewing angle. The optical axis of the VA LC is in a direction perpendicular to the glass surfaces. Thus the type of variation in birefringence is similar to the planar-aligned LC cells. The present method has also been applied to measure the cell gap of the twisted nematic LC (TNLC) cell but failed. The output power of the ECDL was variable while varying the applied voltage of the TNLC cell. The wavelength meter does not response to the light of too low power (< 200 nW). We analyze the possible reason of power variations. According to the Jones calculations, the polarization state of the light is rotated and the output polarization state is an ellipsoid when a linearly polarized light passes through a TNLC cell. In the developed ECDL, the grating we use is polarization dependent. Thus the laser output power is low or even not lasing when the polarization is in the state of low diffraction efficiency. To employ a half-wave plate in the laser cavity or use a grating of polarization independent may solve this problem.

The uniformities of the cell gap are important parameters of LC panels too. Measurements of at least three to five points of different locations on the LC cell are required. For this purpose, the wavelength tuning method can be applied in the LCPM or stripe mirror based

ECDL structure. As shown in Fig. 7.3, different wavelengths correspond to different lateral positions.

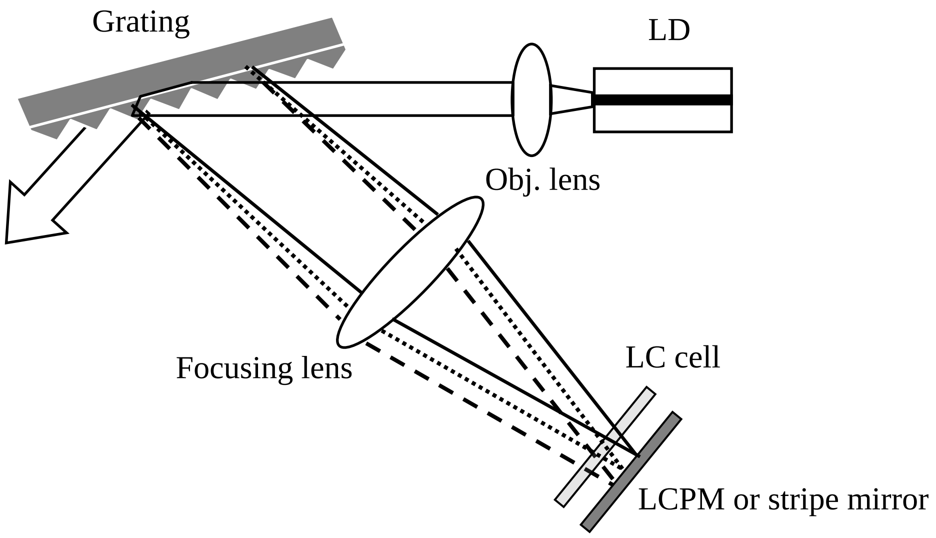

Fig. 7.3 Schematic for measurement of uniformity of LC cell gaps