Investigation on liquid crystal based tuning elements for tunable diode laser

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ABSTRACT

Investigation on Liquid Crystal Based Tuning Elements for Tunable Diode Laser

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ABSTRACT

Tunable lasers have a lot of applications ranging from light sources for fiber optic telecommunication systems to broadband sensors. One popular approach to the design of tunable laser is the external cavity laser (ECL). The review of the current tunable ECLs suggests that it is desired to have electronically tunable ECLs that are simple in configuration, easy in fabrication and assembly. Also, employing liquid crystals (LCs) as tuning elements for the tunable ECL permits low voltage tuning of the lasing wavelength. In this context, investigation into LC based tuning elements with novel concepts for tunable ECL applications has good relevance and significance.

This thesis focuses on the research and development of three novel configurations of tunable ECL using LC tuning elements. These include LC deflector as the tuning element, LC deflector with the ITU etalon as the tuning elements and liquid crystal Fabry-Perot interferometer (LC-FPI) and fine tuner as the tuning elements. A novel tunable ECL is proposed and demonstrated by combining a LC deflector in a prism configuration with a diffraction grating as the tunable filter. The tuning mechanism is based on the wavelength-dependent angular sensitivity combined with the angular deflection from the LC deflector. The tunable ECL shows a tuning range of 12nm and sidemode suppression ratio (SMSR) of 30dB.

In order to tune the lasing wavelengths to match the ITU grids, a WDM-selectable tunable ECL based on the LC deflector is proposed. An etalon is inserted into the external cavity to act as a frequency-periodic transmission filter referenced to the

ITU 100GHz. By changing the applied voltage to the LC deflector, the wavelength can be tuned to the desired ITU channels. The experimental results show that the lasing wavelength can be tuned to 19 wavelength channels of 100GHz spacing and the SMSR of each channel is about 35dB. The device only requires one parameter, applied voltage to the LC deflector, to tune the wavelength matching to the ITU grid.

Finally, an innovative tunable ECL is proposed with fine tuning capability using LC tuning elements. The tuning elements include a LC-FPI and a fine tuner. The LC-FPI creates multiple-beam interference inside the laser cavity and exhibits a transmission peak to determine the lasing wavelength. It fulfills the mode-hopping tuning. Here the fine tuner slightly modifies the cavity length to get the continuous tuning between the adjacent longitudinal modes. The tunable ECL shows a coarse wavelength tuning range of 40nm and an average SMSR of about 25dB.

The proposed electronically tunable ECLs using LC tuning elements are found to have the added advantages of compactness in structure, low power consumption, easiness in fabrication. They have the potential to be used in the area of optical communication and biomedical sensing.

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LIST OF SYMBOLS

Symbol	Meaning
a	The pitch of the grating.
c	The velocity of light.
C	The external feedback strength.
d_e	The distance between the etalon plates.
F_R	The reflection finesse of the LC-FPI.
F_S	The surface-defect finesse of the LC-FPI.
K_{11}, K_{22}, K_{33}	The splay, twist and bend constants of the LC respectively.
l	The distance between the two substrates of the LC-FPI.
l_f	The distance between the two substrates of the fine tuner.
n_o	The ordinary refractive index of the LC.
n_e	The extraordinary refractive index of the LC.
n_{eff}	The effective refractive index of the LC cell.
Δn	The birefringence of the LC.
n_t	The cavity refractive index of the etalon.
r_{eff}	The effective reflectance of the extended cavity.
V_{DEF}	The applied voltage to the LC deflector.
V_{FPI}	The applied voltage to the LC-FPI.
V_{FT}	The applied voltage to the fine tuner.
α	The prism angle of the LC deflector.
β	The absorption coefficient of the LC.
$\epsilon_{ }$	The principle dielectric permittivity parallel to the director.
$\epsilon_{\perp}$	The principle dielectric permittivity perpendicular to the director.
$\Delta\epsilon$	The dielectric anisotropy.
τ_r	The response time of the homogeneous nematic LC cell.

LIST OF SYMBOLS

ξ	The coupling coefficient to the external cavity.
g, γ	The gain and loss of the laser cavity.
θ_d	The deflection angle of the LC deflector.
θ_e	The incident angle to the etalon.
θ_i	The incident angle to the grating.
θ_l	The incident angle to the LC-FPI.
θ_v	Divergence angle of the output beam from the gain chip.
φ_m	The diffracted angle of the mth order.
$\Delta\lambda_{FSR}$	The free spectral range.
$\Delta\lambda_{FWHM}$	The full wave at half maximum bandwidth.

LIST OF ABBREVIATIONS

Abbreviation	Explanation
AO	Acousto-optic
AOTF	Acousto-optic tunable filter
AR	Antireflection
ASE	Amplified spontaneous emission
BIR	Bit rate
DI	Deionized
DWDM	Dense wavelength division multiplexing
ECL	External cavity laser
FP	Fabry-Perot
FSR	Free spectral range
FWHM	Full width at half maximum
GCSR	Grating assisted coupler and sampled reflector
GRIN	Graded index
HR	High reflection
IR	Infrared
ITU	International Telecommunication Union
ITO	Indium-tin-oxide
LC	Liquid crystal
LC-FPI	Liquid crystal Fabry-Perot interferometer
LCPM	Liquid crystal pixel mirror
MEMS	Microelectromechanical system
NA	Numerical aperture
NLC	Nematic liquid crystal
OSA	Optical spectrum analyzer
SG-DBR	Sampled grating distributed reflector
SMSR	Sidemode suppression ratio
TEC	Temperature controller

CHAPTER ONE

INTRODUCTION

1.1 Background

Tunable lasers have found a lot of applications in recent years, ranging from telecommunication systems, such as dense wavelength division multiplexing (DWDM) to sensing and metrology [1]. As far as DWDM systems are concerned, they are one of the most efficient means of increasing the transmission capability of telecommunication networks [2]. The system employs a discrete set of distinct optical wavelength channels with fixed channel positions and spacing set by the International Telecommunication Union (ITU). Currently, the standard is 100GHz (0.8nm) and 50GHz (0.4nm) channel spacing, and next generation 25GHz (0.2nm) system is under development. High bandwidth information is transmitted over individual optical channels at very high bit rate (BIR), or several lower bit rate data streams may be electronically multiplexed in a single optical channel using various means. The benefits of tunable lasers in DWDM are widely recognized, they can improve the efficiency of a variety of functions, including protection and restoration, bandwidth on demand, optical cross connects, wavelength routing, and next generation metro networking [3].

Besides the applications in optical network, tunable lasers also play an important role in sensing and metrology field [4-6]. For example, due to the presence of a large number of strong absorption peaks of various important trace gases in the infrared

band, tunable lasers can be effective for sensing of hazardous gases and industrial process control of trace impurities.

Among the various technologies of tunable lasers, the tunable external cavity laser (ECL) offers good promise due to its advantage of simple configuration, wide tuning range and high delivery power. Tunable ECLs use a gain medium in an external cavity architecture with wavelength tunability provided by an intracavity tunable filter. Most tunable ECL designs have moving parts such as motor-driven rotatable mirrors, prisms, and reflection gratings [7-9]. However, tunable ECLs with mechanically movable parts normally have difficulty in achieving good reliability. Highly sensitive alignment is involved in the packaging of these types of devices. Non-mechanical filters such as acousto-optic (AO) tunable filter [10-12] and electro-optic (EO) filter have also been used in tunable ECLs [13-15]. But these filters require high driving voltages and the power consumption is typically large. Therefore, it is desired to have an electronically driven tunable ECL with no mechanically moving parts to achieve high reliability, and with low driving voltage to minimize power consumption.

Utilizing liquid crystals (LCs) as tuning elements of tunable ECL permits low voltage electrical tuning of the laser wavelength. The LC based ECLs have the advantages of high system compactness, low power consumption and low cost. Hence, the main objectives of this research work are summarized below.

1.2 Objective

The main objectives of this research work include:

- Theoretical formulation, design and development of three tuning mechanisms for the proposed LC based tunable ECLs.
- One of the proposed tunable ECLs is aimed at application in optical communication. The proposed ECL must not only match the International Telecommunication Union (ITU) standard channels but also have low driving voltage of less than 20V with a simple enough configuration for the ease of fabrication combined with reasonable tuning speed.
- Another proposed tunable ECL is aiming at potential application in the area of sensing and metrology. The proposed ECL aims to have a wide tuning range with continuous tuning, tuning speed not more than 200ms and low driving voltage of not more than 15V.

1.3 Scope

For the liquid crystals, the refractive index along the optical axis will be changed with applied voltage. Based on this property, LC based tuning elements can be designed. For the LC based tunable ECL, through controlling the driving voltage to LC elements, the lasing wavelength can be tuned. In order to achieve the desired objective, the proposed research has the following scope of work:

- To carry out a literature review on the basics of tunable filters, conventional design of tunable ECLs by highlighting their limitations and advantages.

- To propose configurations and tuning mechanisms of tunable ECLs based on LC elements. Three novel configurations are proposed. I) LC deflector as the tuning element; II) LC deflector with the ITU etalon as the tuning element; III) LC-FPI and a fine tuner as the tuning elements.
- To design and carry out the theoretical analysis of LC based elements including LC deflector, LC-FPI and fine tuner.
- To design the fabrication process for each LC element.
- To fabricate the tuning elements based on the theoretical analysis results and test the performance of the elements such as insertion loss and response time.
- To implement the LC based tunable ECLs and align the systems to get lasing. Record the performance of the system using the optical spectrum analyzer. Compare the experimental results to the theoretical analysis.
- To carry out calibration of the proposed tunable ECL systems.

1.4 Organization of the Thesis

Chapter 2 gives an overview of the basics and classification of the tunable ECLs followed by various tuning elements for ECL. It is followed by the existing designs of tunable ECLs including single mode tunable ECL with diffraction grating, WDM-selectable tunable ECL and continuously tunable ECL. Their limitations are also discussed.

Chapter 3 explains the basics of liquid crystal followed by nematic LC (NLC) molecule structure. It is followed by electro-optic properties of NLC. This chapter also describes operational mechanism of the NLC cell.

Chapter 4 presents the design, fabrication and test details of the proposed LC deflector. The design and theoretical analysis of a tunable ECL using the LC deflector combined with a diffraction grating is described. It is followed by the experimental setup and performance of the tunable ECL. The comparison between the simulated results and experimental results of the tunable ECL is also discussed. Based on this tunable ECL, a WDM-channel selectable tunable ECL is presented by adding an ITU etalon into the external cavity. The experimental results are discussed and analyzed.

The theoretical analysis and design of LC tuning elements including a LC-FPI and a fine tuner are given in chapter 5. The comparison between the simulated results and test results of the LC-FPI and fine tuner is discussed. It is followed by the fabrication and test results of the tuning elements. A tunable ECL with fine tuner is proposed using the LC elements. It is followed by the experimental setup and the performance of the laser system.

Chapter 6 gives the conclusions of the findings of this research work followed by the recommendations for future work.

CHAPTER TWO

TUNABLE EXTERNAL CAVITY LASERS : AN OVERVIEW

This chapter gives an overview of the basics of tunable external cavity lasers. A detailed review about classification of tunable ECLs, the feedback model, the principle of wavelength selection, and various types of tuning elements will be discussed. This chapter will also discuss the existing tunable ECL designs.

2.1 Introduction

Semiconductor Fabry-Perot diode lasers are compact and easy to use, but they have a number of limitations. Solitary laser diodes are often multimode and exhibit large linewidths, which is due to short photon cavity lifetime and strong coupling between the phase and amplitude of the intracavity optical field. Lasers diodes can be tuned by varying their temperature or current, but this provides limited range and cannot exploit the broad gain bandwidth.

Figure 2.1 Generic tunable external cavity laser

A Tunable external cavity laser (ECL) (Figure 2.1) comprises an optical gain medium (a laser diode with antireflection coatings on one or both facets), optics for coupling the output of the gain medium waveguide to the free space mode of the external cavity, one or more wavelength selective filters, and one or more mirrors for defining an external feedback path. The external cavity may also contain additional components such as polarization optics, beam splitters, prism etc [16].

Tunable ECLs retain the compactness and ease of use of solitary cavity diode lasers and provide a number of performance enhancement. A properly designed ECL can obtain single external cavity longitudinal mode operation and phase continuous tuning can also be achieved. Compared to a solitary diode laser the linewidth of ECLs is greatly reduced due to longer photon lifetime of an external cavity. The tuning range can cover the bandwidth of the gain medium by using an external filter.

Compared with other types of tunable lasers such as the Fabry-Perot diode lasers [17], tunable ECLs are compact, are easily pumped by direct injection of current, having high wallplug efficiency, are air-cooled and have long lifetimes [16].

2.2 Classification of External Cavity Lasers

There are three classes of external cavities: the extended cavity, the double-ended cavity and the ring cavity [16]. Each of them is briefly described as follow.

Figure 2.2 Classes of external cavities for diode lasers. (a) Extended-cavity laser. (b) Double-ended external-cavity laser. (c) Ring external-cavity laser. [16]

2.2.1 Extended-Cavity Lasers

The extended-cavity laser as shown in Figure 2.2a consists of a gain chip with antireflection (AR) coating on one facet and high reflection coating on the other facet [18-20]. The output from the AR facet is optically coupled to an external optical system that includes a retroreflecting end mirror. The extended cavity is the most common configuration for the reasons listed as following: (1) it requires only one AR coating operation. (2) An extended cavity can be constructed using commercial diode laser packages where only the output from one facet is accessible. (3) The extended cavity laser is relatively easy to align because the sub-threshold emission from the gain chip is enough to act as a reference beam. (4) Excellent optical performance can be obtained if an excellent AR coating is applied. However, it is reported that even with a high quality coating, the effects of the residual diode cavity resonance are still observable and sometimes cause non-ideal performance [18-20].

2.2.2 Double-ended External Cavity Laser

Figure 2.2b shows the scheme of the double-ended external cavity laser. It contains a gain chip with AR coatings on both facets [21]. Each external cavity section retroreflects into its respective facet. One of the extended-cavity may contain all the tunable filters, while the other might only contain the coupling optics and a reflector. In an alternative design, both the extended-cavity sections may contain wavelength-selective elements. The advantage of double-ended external cavity configuration is increased suppression of diode cavity resonance by AR coating on both facets. The disadvantages are an increase in the optical components, difficulty for alignment, and additional coupling loss due to the second extended-cavity section.

2.2.3 Ring External Cavity Lasers

A ring-cavity (Figure 2.2c) laser contains a gain chip with reflection suppression on both facets and an external feedback that cross couples the outputs of the two facets [22-24]. It is the most difficult type of external cavity to align. It has the same advantage as the double-ended external cavity, which is the increased solitary suppression. It can be made unidirectional by inserting an optical isolator into the cavity.

2.3 Feedback Model of External Cavity Laser

The basic model of the Fabry-Perot laser with external cavity is based on the three-mirror model as shown in Figure 2.3 [25, 26]. F_1 and F_2 denote the mirrors of the Fabry-Perot laser, and F_3 is an external mirror that forms an external cavity to the

Fabry-Perot laser. r_1 and r_2 are real numbers representing the amplitude reflectance of F_1 and F_2 respectively, while r_3 denotes the effective amplitude reflectance of the external mirror F_3 . Being the effective amplitude reflectance, r_3 takes into account the coupling losses due to the mirror misalignment and the dispersion of the laser beam. n is the effective refractive index of the laser cavity, d and L are the lengths of the laser cavity and the external cavity, respectively.

Figure 2.3 Extended feedback model for the tunable external cavity laser

The effective reflectance of the extended cavity r_{eff} , including multiple reflections from the inside facet, is given by[16]

$$\begin{aligned}
 r_{eff} &= \frac{r_2 + r_3 \exp(j2\pi\tau_L\nu)}{1 + r_2 r_3 \exp(j2\pi\tau_L\nu)} \\
 &= r_2 \cdot f(\nu, L) \\
 &= r_2 \cdot r_L(\nu, L) \exp[j\phi_L(\nu, L)]
 \end{aligned} \tag{2.1}$$

where ν is the frequency of the FP laser given by $\nu = c/\lambda$, c is the light velocity in vacuum, and λ is the laser output wavelength. τ_L is round-trip delay of the external cavity given by $\tau_L = 2L/c$. $f(\nu, L)$ is a complex function varying with ν and L . $r_L(\nu, L)$ and $\phi_L(\nu, L)$ are the notations representing the amplitude and phase of $f(\nu, L)$.

Assuming $r_2 r_3 \ll 1$, the multiple reflections in the external cavity may be neglected.

Then r_L and ϕ_L are given by [27]

$$r_L = \sqrt{1 + \xi^2 + 2\xi \cos(2\pi\tau_L\nu)} \quad (2.2)$$

$$\phi_L = \arcsin[\xi \sin(2\pi\tau_L\nu) / r_L], \quad (2.3)$$

where ξ is the coupling coefficient to the external cavity given by $\xi = r_3(1 - r_2^2) / r_2$.

Both $r_L(\nu, L)$ and $\phi_L(\nu, L)$ have a period of $1/\tau_L$.

For an initial electrical field E_0 inside the laser cavity, after traveling a round trip through the laser cavity and the external cavity, it will become

$$E_1 = E_0 r_1 r_{eff} \exp[j2\pi\tau_d\nu + (g - \gamma)d], \quad (2.4)$$

where E_1 is the amplitude field, $\tau_d = 2nd/c$ is the round-trip delay of the laser cavity, and g and γ represent the gain and loss of the laser cavity respectively.

To obtain a laser oscillation, the following amplitude and phase conditions must be satisfied:

$$r_1 r_2 \exp[(g - \gamma)d] r_L = 1 \quad (2.5)$$

$$\phi = \phi_L + 2\pi\tau_d\nu = 2\pi m, \quad (m=\text{integer}) \quad (2.6)$$

where ϕ denotes the round-trip phase of the laser beam after traveling through the laser cavity and external cavity.

Equation (2.5) and (2.6) show the influence of the external cavity on the Fabry-Perot laser oscillation. In case of no external cavity, that is $r_L = 1$ and $\phi_L = 0$, the laser

oscillation is fully determined by the gain profile and longitudinal modes. The presence of the external cavity changes the gain condition and the positions of the longitudinal modes [28]. The wavelength selection of the tunable ECL will be discussed in the following section.

2.4 Principle of Wavelength Selection of ECLs

The principle of wavelength selection in an ECL can be explained with a sketch of the round-trip gain and loss terms as shown in Figure 2.4. There is a sizeable coupling loss (about 5 to 15 dB round trip) between the guided wave in the active region and the free-space beam in the external cavity. Interference between the reflections from the gain medium facets creates an additional intracavity loss that is modulated at the period of the gain medium mode spacing [16].

Figure 2.4 The principle of wavelength selection in an external cavity laser [16].

When the gain medium is pumped sufficiently, oscillation will occur at the external cavity that gets the lowest net cavity loss. Ideally, the loss ripple due to the facet reflections of the gain chip is weak and the bandwidth of the filter is narrow compared to the period of the ripple. In this case the oscillation will occur at the external cavity mode that is closest to the minimum loss of the wavelength selective filter. Usually the external cavity modes are fixed, that is, they do not shift as the filter is tuned. Hence, when the minimum loss wavelength of the filter is varied, the laser oscillation will hop to the next external cavity mode.

2.5 Tunable Filters

The ideal filter for an ECL has a bandwidth that is less than the longitudinal mode spacing of the cavity and 0 dB insertion loss at its peak. However, no real filter is ideal. There are a number of different types of wavelength selective elements that can be used to tune the external cavity lasers. In the following section, the principle of operation and key distinguishing characteristics of these tunable filters will be discussed.

2.5.1 Diffraction Gratings

2.5.1.1 Types of Gratings

Diffraction gratings are the most common type of filter used in ECLs. A diffraction grating consists of a large number of regularly spaced grooves on a substrate. The distance between adjacent grooves is called the pitch. If the underlying substrate is reflective, then it is a reflection grating (Figure 2.5a). If the substrate is transmissive, then it is said to be a transmission grating (Figure 2.5b) [29].

Figure 2.5 Types of plane diffraction gratings. (a) Reflection grating; (b) Transmission grating [29].

2.5.1.2 Grating Concept

When an optical beam is incident on a grating, each groove generates a diffracted wavelet. For each wavelength component in the incident beam, the constructive interference of the diffracted components from each groove occurs at a set of discrete directions called the diffraction orders of the grating.

The diffraction pattern from a grating is governed by the grating equation [29]:

$$a(\sin \theta_i + \sin \varphi_m) = m\lambda \quad (2.7)$$

where a is the pitch, θ_i is the incident angle, φ_m is the diffracted angle of the m th order, and m is the order of the diffraction. The diffracted light is dispersed

according to its spectral content, with different wavelengths appearing at different angles.

2.5.1.3 Two Common Configurations

The functions of the diffraction gratings in external cavity lasers are the filter and external mirror. In extended cavities, the light from the grating must be retroreflected back to the gain chip. Two common mounting geometries for diffraction gratings in extended cavity lasers are the Littrow configuration and the Littman configuration as shown respectively in Fig2.6 (a) and (b) [30].

Figure 2.6 Diffraction grating mountings (a) Littrow, (b) Littman [30]

1. Littrow configuration

In the Littrow configuration (Figure 2.6a), the angles of incidence and diffraction are equal: $\theta_i = \phi_1$. The zeroth-order diffraction is the output. The grating equation becomes

$$\lambda = 2a \sin \theta_i . \quad (2.8)$$

The angular dispersion is given by

$$D_{Littrow} = \frac{d\phi_1}{d\lambda} = \frac{2 \tan \theta_i}{\lambda} . \quad (2.9)$$

In this configuration, the wavelength can be tuned by rotating the grating. The littrow mounting has simple configuration, high output power, but the output laser beam direction will be changed.

2. Littman Mounting

In the Littman mounting (Figure 2.6b), the zeroth-order reflection from the grating is the output and the first-order reflection from the grating is reflected back by the external mirror. Hence, the intracavity beam makes two passes at the grating. The diffracted light from the second pass is a retroreflection of the incident light from the first pass. The angular dispersion of the Littman configuration is expressed as:

$$D_{Littman} = 2 \frac{d\phi_1}{d\lambda} = \frac{4 \tan \theta_i}{\lambda} = 2D_{Littrow} . \quad (2.10)$$

The dispersion of the Littman configuration is twice that of the Littrow configuration for the same angle of incidence. The wavelength tuning can be obtained by moving the external mirror and the output laser beam has good directional stability, but the Littman configuration is difficult to align.

2.5.2 Distributed Bragg Reflector

Periodic modulation of the refractive index along the length of an optical waveguide results in a structure known as a distributed Bragg reflector [31]. The reflection is maximized at a wavelength for which the period of the modulation is equal to $\lambda/2$. If the modulation period can be changed, then the reflected wavelength can be tuned.

2.5.3 Fabry-Perot Etalon

Figure 2.7 The configuration of the Fabry-Perot etalon.

2.5.3.1 Principle of operation

The configuration of the Fabry-Perot etalon is shown in Figure 2.7. The filtering effect of the Fabry-Perot (FP) etalon utilizes the interference fringes produced in the transmitted light after multiple reflections between two highly reflective mirrors [32]. The periodic transmission peaks of the Fabry-Perot etalon are given by

$$2nd \cos \theta = m\lambda, \quad (2.11)$$

where d is the mirror spacing, n is the refractive index of the cavity between the mirrors, θ is the incident angle, and m is an integer.

2.5.3.2 Free Spectral Range

For a typical air-spaced or solid etalon, the mirror spacing is equal to a few millimeters. The free spectral range, $\Delta\lambda_{FSR}$ that is the wavelength spacing between the transmission peaks is given by

$$\Delta\lambda_{FSR} = \lambda_m - \lambda_{m+1} = \frac{2d \cos \theta}{m(m+1)} \approx \frac{\lambda^2}{2nd} . \quad (2.12)$$

2.5.3.3 Finesse

The finesse F is the spacing between the orders relative to the width of a single mode. It is defined as

$$F = \frac{\Delta\lambda_{FSR}}{\Delta\lambda_{FWHM}} , \quad (2.13)$$

where $\Delta\lambda_{FSR}$ is the free spectral range of the etalon, $\Delta\lambda_{FWHM}$ is the full width at half maximum(FWHM) bandwidth.

Tuning can be obtained by angular rotation of the etalon or PZT based tuning of the etalon spacing.

Figure 2.8 The configuration of Interference filter.

2.5.4 Interference Filter

A bandpass interference filter is a multilayer thin film device as shown in Figure 2.8. Although thin silver or aluminum coatings have been used for such filters, absorption-free multi-layer dielectrics are more suitable for infrared bandpass filters [33].

The interference filter is tuned by angular rotation. For small angles, the transmission peaks is given by

$$\lambda = \lambda_{\max} \sqrt{1 - \left(\frac{n_m}{n_s} \right)^2 \sin^2 \theta}, \quad (2.14)$$

where θ is the angle of incidence, n_m is the refractive index of the external medium, and n_s is the effective refractive index of the spacer.

2.5.5 Birefringent Filter

The birefringent filter, or Lyot filter, is based on the interference of incident polarized light after transmission through a birefringent material [34, 35]. In the simplified form, such a device consists of a birefringent crystal of length d between two polarizers. Linearly polarized light incident on the crystal is transformed into an elliptical state of polarization because of the optical path difference between the extraordinary and ordinary axes, which is given by

$$\phi = k(n_o - n_e)d = (2\pi / \lambda)\Delta n \cdot d \quad (2.15)$$

where k is the propagation constant, n_o is the ordinary refractive index, n_e is the extraordinary refractive index, and Δn is the birefringence. In general, the transmission T is a function of the phase retardation,

$$T = T_0 \cos^2(\pi\Delta n \cdot d / \lambda) , \quad (2.16)$$

where T_0 is the maximum transmission. The free spectral range $\Delta\nu_{FSR}$ is expressed by

$$\Delta\nu_{FSR} = c / (n_o - n_e)d . \quad (2.17)$$

The wavelength selectivity can be expressed by

$$R = \frac{\lambda}{\Delta\lambda} = \frac{4\Delta n \cdot d}{\lambda} . \quad (2.18)$$

The wavelength selectivity for this simple filter is not very high. In most bulk-optic filtering applications, more complicated higher order filters comprise of a series of birefringent plates separated by polarizers. If N elementary Lyot filters are placed in series, the thickness L_K of the K^{th} filter is given by $L_K = 2^{K-1}L_1$, then the Finesse of the filter is $F = 2^N$ [33].

The filter can be tuned by changing the birefringence through mechanical or electro-optic means. In the uniaxial crystal, the extraordinary refractive index n_e is tuned by rotating an angle between the optical axis and the wave vector. Electro-optic tuning can be obtained by using different functional dependencies of refractive indices n_o and n_e on an applied electric field. Electronically tuned birefringent filters can be realized using liquid crystal cells as the birefringent plates[36, 37]. The electro-optic effect can also be used, either in bulk crystals [38] or in birefringent lithium niobate waveguides [39].

2.5.6 Acousto-Optic Tunable Filter

The acousto-optic tunable filter (AOTF) operates on the principle of anisotropic Bragg diffraction in birefringent crystal [40]. The acoustic wave produces a moving refractive index grating (phase grating) in the crystal via the elasto-optic effect. The induced diffraction grating characterized by wavevector k , obeys the energy conservation and must satisfy the phase matching condition $k_d = k_i \pm k_a$, where k_i , k_d and k_a are the momentum vectors of the incident, diffracted and acoustic waves respectively.

If the material has a high photoelastic coefficient, it is possible to construct a tunable filter that is characterized by a wavelength selectivity of:

$$R = \frac{\lambda}{\Delta\lambda} \cong \frac{L}{\Lambda}, \quad (2.19)$$

where L is the acousto-optic interaction length, Λ is the wavelength of the acoustic wave.

The AOTF is functionally an RF-controlled narrow-band optical polarization converter. Changing the acoustic drive frequency shifts the band of optical wavelengths for which the optical polarization is flipped. An electronically controlled optical filtering operation can be achieved by separating diffracted light from the residual undiffracted zeroth-order component.

2.6 Survey of Tunable External Cavity Laser Design

Three types of tunable ECLs including single mode tunable ECL with diffraction grating, WDM-selectable tunable ECL and continuously tunable ECL are investigated in this thesis. In the following section, each type of tunable ECL will be discussed.

2.6.1 Single Mode Tunable ECL with Diffraction Grating

Among the various types of tunable laser diodes, external-cavity laser diodes (ECLs) with diffraction gratings are considered to be promising because the grating has the inherent potential to achieve the single-mode oscillation with a narrow spectral linewidth.

The grating-tuned extended-cavity laser is by far the most commonly reported type of ECL. The common design used is the Littrow configuration. Zorabedian and Trutna, made use of an intracavity lens to illuminate grating with narrow stripe beam for improving tolerance to angular misalignment as shown in Figure 2.9 [19]. A 1300nm Littrow grating extended cavity laser with a Gradient index (GRIN) rod lens collimator and intracavity silicon prism beam expanders was described by

Zorabedian as shown in Figure 2.10 [20]. A Littrow tunable ECL with a tapered-stripe gain chip that has a power of 1W output has been reported by Mehuys *et al* [9].

Figure 2.9 Alignment stabilization of a littrow-grating ECL using a cylindrical lens [19].

Figure 2.10 Littrow-grating extended-cavity laser with a GRIN rod lens collimator and intracavity silicon prism beam expanders [20].

Figure 2.11 Littman grating extended-cavity laser [41].

Figure 2.11 shows a Littman grating extended-cavity tunable ECL that has been developed by Harvey and Myatt [41]. By rotating the external mirror, authors could achieve a tuning range of about 20nm as reported. The tuning range was limited by the 3-dB width of the diode laser.

Figure 2.12 Grating-tuned double-ended extended cavity laser [21].

The double-ended external cavity lasers and ring external cavity lasers based on diffraction grating have also been demonstrated. A double-ended ECL based on an 830nm AlGaAs diode was described by Fleming and Mooradian as shown in Figure 2.12 [21]. The large diameter beam produced by the camera lenses made the laser very sensitive to acoustic and thermal disturbances. Peng and Su described a 1300nm free-space ring ECL comprising a $1000\mu\text{m}$ long tilted stripe amplifier, a 600 groove/mm grating and an optical isolator to force traveling-wave operation [22]. Over a 35nm range, quasi-single mode oscillation was obtained, but the SMSR was less than 20dB.

Figure 2.13 Schematic diagram of the MEMS laser with a fixed grating and a movable mirror [42].

The microelectromechanical system (MEMS) technology has been used to downscale a bulky tunable laser to a miniaturized device while improving the tuning speed and the mechanical reliability at lower fabrication cost. A MEMS tunable ECL based on the Littman configuration with a mirror mounted on an electrostatic rotary was described as shown in Figure 2.13 [42]. One advantage of this type of laser is that the gain chip can be designed mainly to provide high power, since all the

other functions are outside the laser. The results reported in ref [42] included 5mW power over a 40nm tuning range.

An external cavity laser based on a stripe waveguide semiconductor optical amplifier, a ball lens, and a blazed diffraction grating fabricated by vertical deep reactive ion etching of silicon was demonstrated [30]. Tuning of an external cavity laser over a 120nm spectral range was obtained with a maximum single-mode fiber-coupled power of 1 mW and SMSR of 30 dB.

For the mechanically grating-tuned ECL, the wavelength tuning is obtained by rotating the grating or the external mirror. They usually suffer from backlash and hysteresis and have difficulty in achieving good reliability. Other tuning filters such as the EO crystal and AO modulator have also been used for tunable ECL with diffraction grating.

Kouroggi *et al.* reported a tunable ECL with rapid tuning as shown in Figure 2.14 [43]. Two internal AO devices controlled the angle of incidence on a diffraction grating and the effective round-trip phase electronically. Single-mode operation and electric tuning over 2nm were confirmed.

Figure 2.14 Tunable ECL with two AO modulators and diffraction grating [43].

Figure 2.15 Electro-optically activated external-cavity diode laser [44].

A simple external-cavity laser was designed to provide high-speed, high phase coherence tuning over 3GHz by Boggs *et al.* as shown in Figure 2.15 [44]. By applying a 300V voltage to the electro-optic crystal, wavelength tuning can be obtained. Tuning rate as fast as 2.3GHz/ μ s is demonstrated.

Levin proposed a tunable external-cavity Littrow diode laser with an intracavity EO crystal as shown in Figure 2.16 [15]. The change in cavity length that is imposed by

the electro-optical crystal is inversely proportional to the crystal thickness. If the crystal thickness changes across the beam perpendicularly to the propagation direction, the difference in cavity elongation that is required for mode-hop-free tuning can be achieved. A mode-hop-free single-mode tuning range of 50GHz at 793nm with an output power of 60mW and tuning speeds of 1.5GHz/ μ s was demonstrated. The tuning rate was about 10GHz/kV. The power consumption of the tunable ECL is high.

Figure 2.16 The tunable ECL with an intracavity EO crystal [15].

The tuning range for the above tunable ECLs is very small: 6.2pm and 0.4nm for the EO crystal [15, 44], 2nm for the AO modulator [43]. This is due to the fact that for this type of tunable ECLs a large voltage is required which tends to limit the tuning range to be significantly less than the bandwidth of the gain chip.

Electro-optically tunable ECLs with wide tunable range have also been reported. A tunable ECL that simultaneously achieves rapid tuning rate and wide tuning range by electrical control has been proposed by Kwon et al [45]. The device contained a new type of integrated laser diode, collimating lens, and diffraction grating. The integrated laser diode consisted of a FP laser diode and a waveguide-type deflector,

which deflects beam passing through the waveguide. Maximum wavelength variation of 8.6nm and SMSR of more than 35dB were demonstrated.

A near-IR tunable laser that uses an integrated LiTaO₃ deflector in combination with a reflection grating as an electronically tunable filter has been demonstrated [14]. Applying a voltage to the deflector changed the incident angle onto the grating. The wavelength-dependent angular sensitivity, combined with the angular deflection from the EO deflector, acted as the wavelength tuning mechanism. A tuning efficiency of 5.3nm/kV and a total tuning range of 31.9nm were obtained.

Figure 2.17 Schematic diagram of the tunable ECL with a LCA [46].

An electronically tunable diode laser with a LC array has been described by Struckmeier *et al.* as shown in Figure 2.17 [46]. The tunability is achieved by insertion of a LC array as an electronically controlled aperture into the region of spatial separation of the spectral components. A tuning range of 10nm and dual-color operation were demonstrated with a 670nm laser diode.

The tunable ECLs discussed above are complex in configuration and are not easy to assemble.

Table 2.1 Single mode tunable ECL with diffraction grating-A brief review of previous research.

First Author (Ref.)	Year	Wavelength (nm)	Configuration and Performance	Remarks
Fleming [21]	1981	830	Littrow configuration Double-ended extended cavity laser, Camera lenses (Figure 2.12)	Mechanical tuning
Zorabedian [19]	1990	1300	Littrow configuration; intracavity cylinder lens. (Figure 2.9)	Mechanical tuning
Harvey [41]	1991	780	Littman configuration, The output power is about 15mW. (Figure 2.11)	Mechanical tuning
Zorabedian [20]	1992	1300	Littrow configuration, GRIN rod lens collimator, intracavity silicon prism beam expander (Figure 2.10)	Mechanical tuning
Peng [22]	1992	1300	Littrow configuration; Ring external cavity laser; 45nm tuning range, 24mW free- space output power	Mechanical tuning
Mehuys [9]	1993	850	Littrow configuration; 1W air beam output	Mechanical tuning, Large output power
Boggs [44]	1998	790	Littrow configuration based on electro-optic crystal; 3GHz tuning range, 300V applied voltage (Figure 2.15)	Electro-optic tuning, small tuning range, large applied voltage
Struckmeier [46]	1999	670	Littman configuration, 10nm tuning range (Figure 2.17)	Electro-optic tuning, complex in configuration
Kouroggi [43]	2000	1500	Littrow configuration based on two internal Acousto-optic devices; 2nm tuning range, (Figure 2.14)	Acousto-optic tuning, small tuning range, high RF signal
Berger [42]	2001	1550	Littman configuration; 40nm tuning range, 5mW output power (Figure 2.13)	Mechanical tuning, MEMS Technology
Levin [15]	2002	793	Littrow configuration based on electro-optic crystal; 50GHz tuning range, 60mW output power, tuning rate is 10GHz/kV (Figure 2.16)	Electro-optic tuning, small tuning range, large applied voltage
Casson [14]	2002	1550	Littrow configuration, 31.9nm tuning range, tuning efficiency of 5.3nm/kV	Electro-optic tuning, large applied voltage
Lohmann [30]	2003	1550	Littrow configuration based on vertical etched silicon braze grating; 120nm tuning range, 1mW output power	Mechanical tuning, large tuning range
Kwon [45]	2004	1550	Littrow configuration based on electro-optic crystal, 8.6nm tuning range, 2mW output power	Electro-optic tuning, small tuning range

Table 2.1 summarizes some of the important works done so far in the field of tunable ECL with diffraction grating. It can be seen that an electronically tunable ECL that allows for accurate and reproductive wavelength tuning, low-cost fabrication, and wide tuning range is desirable. In this context, a tunable ECL that uses an electro-optical tuning mechanism based on a beam steering device combined with a reflection grating is proposed. The existing beam steering devices have been reviewed as the following.

A nonmechanical beam steering device is a key element for various optoelectronic system for optical interconnects [47], optical fiber communication [48], projection display [49], and optical data storage [50]. Among various technologies, a LC deflector is most promising due to its low driving voltage and low cost fabrication. The design and performance of a digital scanner based on ferroelectric liquid-crystal switchable wave plates and passive nematic liquid-crystal prisms are reported by McRuer *et al.* [51]. Beam steering devices with a LC phased array have been demonstrated by several groups [52-54]. Park *et al.* proposed a LC deflector with a photopolymer prism produced by ultraviolet exposure [55]. However, these LC based deflectors required complicated fabrication process or device operation. Hence, a novel LC deflector with a prism sharp capable of electronically controlled beam steering is proposed in this context. By combining this LC deflector with a diffraction grating, a novel electronically tunable ECL with diffraction grating is designed.

2.6.2 WDM-Channel-Selected Tunable External Cavity Laser

The benefits of tunable lasers in DWDM are widely recognized, such as reducing the required number of inventory lasers and inventory cost. In order to satisfy the requirement of the applications of channel reconfiguration and assignment in DWDM systems, the laser wavelengths of the tunable lasers need to be tuned to match the ITU grids. The current existing WDM-channel-selectable tunable lasers are reviewed below.

Tunable lasers for WDM system have been demonstrated based on grating assisted coupler and sampled reflector (GCSR) [56-58], and sampled grating distributed reflector (SG-DBR)[59]. However, these lasers need complex control of three or more currents.

Tunable ECLs have also been investigated for applications in WDM system. Full C and L band MEMS tunable external cavity laser based on a MEMS actuated adjustable lens was demonstrated by Anthon *et al.* [60]. However, it contains the mechanical parts that should be avoided.

Figure 2.18 Schematic diagram of WDM-selectable tunable ECL with AOTF [12].

A wide wavelength tunable ECL containing a semiconductor optical amplifier, a tunable acousto-optic filter and a Fabry-Perot etalon has been demonstrated by Takabayashi *et al.* as shown in Figure 2.18 [12]. By changing the RF frequency applied to the AOTF, a tuning range of 132nm and SMSR of 40dB can be obtained. It covered both the C-band and L-band in communication systems. However, the tunable ECL required RF signal and the power consumption is very large.

Figure 2.19 Schematic diagram of the tunable ECL with a LC tunable mirror [61].

De Merlier and coworkers proposed a compact full C-band external cavity wavelength tunable laser using a LC tunable mirror as shown in Figure 2.19 [61]. The device consisted of a chip containing a gain and a phase section and a free space region with a collimating lens, a fixed etalon and a liquid-crystal-based mirror. It only required two parameters to tune the wavelength over the whole C-band, namely the phase current and the voltage over the tunable mirror. A tuning range of 35nm and a SMSR of higher than 50dB were obtained. However, the lasing wavelengths of the tunable ECL were not tuned to match ITU grids.

Figure 2.20 16-channel digitally tunable external-cavity laser [62].

Figure 2.21 Schematic diagram of the tunable ECL digitally tuned with the LCPM and fine tuned with an intracavity NLC phase plate [63].

A 16 channel tunable ECL integrating a multi-strip laser diode chip with a diffraction grating was proposed by M. Kauer *et al.* as shown in Figure 2.20 [62]. The emission wavelength of the tunable ECL can be switched by selecting the desired laser diode on the chip. All the 16 channels are within 2.1GHz of the ITU grid. A tunable ECL with a intracavity LC pixel mirror (LCPM) and a planar nematic liquid crystal phase plate was presented by T. S. Shih *et al.* as shown in Figure 2.21 [63]. The LC pixel mirror allows digitally tuning of the laser wavelength to more than 40 wavelength

channels of 100GHz spacing according to ITU grids. By changing the applied voltage to NLC phase plate, 1.89GHz continuous wavelength tuning for a given channel can be achieved. It can be seen that the devices mentioned in reference [62] and [63] are quite complex, requiring assembly of several components.

Table 2.2 WDM-channel-selectable tunable ECL-A brief review of previous research.

First Author (ref.)	Year	Wavelength	Configuration and performance	Remarks
Kauer [62]	2003	16 ITU channels	Tunable ECL based on a multi-strip laser diode and grating; 0 dBm output power, SMSR of more than 50dB (Figure 2.20)	Tuning by Selecting the desired laser diode; complex in configuration
Anthon [60]	2004	C+L band	Tunable ECL based on a MEMS actuated adjustable lens, 10dBm output power,	Mechanical tuning; Large tuning range
Takabayashi [12]	2004	C+L band	Tunable ECL with AO filter and etalon, 132nm tuning range, 7dBm output power, SMSR of 40dB (Figure 2.18)	Acousto-optic tuning; large tuning range; Require RF signal
Shin [63]	2004	40 ITU channels	Tunable ECL with a LCPM and a LC phase plate; -30dBm output power, SMSR of more than 30dB (Figure 2.21)	Electro-optic tuning; Complex in configuration
De Merlier [61]	2005	C band	Tunable ECL using liquid crystal tunable mirror; 35nm tuning range, more than 15dBm output power, SMSR of higher than 50dB (Figure 2.19)	Electro-optic tuning, Lasing wavelengths do not match ITU grids

Table 2.2 summarizes some of the important works done so far in the field of WDM-channel-selectable tunable external cavity laser. From the review, a WDM-channel-selectable tunable ECL that simple in configuration, electro-optic tuning and easy in operation is desirable. In this context, a WDM-channel selectable tunable ECL with a LC deflector is proposed. The tunable ECL is simple in structure, has low power consumption and only requires one parameter, the applied voltage to the LC deflector, to tune the lasing wavelength matching ITU grids.

2.6.3 Continuously Tunable External Cavity Laser

Tunable lasers that can be tuned continuously are of great importance to many applications such as optical communication, bio-sensing, and environment monitoring. Among the various technologies, the tunable external cavity laser (ECL) is very promising for continuous wavelength tuning due to its advantage of simple configuration, wide tuning range, and high delivery power. The reported tunable ECLs with continuously wavelength have been investigated. Most of the continuously tunable ECLs are tuned by rotating the mirror, the diffraction grating or the wedge[8, 64, 65].

Figure 2.22 Schematic diagram of an ECL using MEMS grating [64].

A. Q. Liu *et al.* have reported a tunable ECL using a micromachined grating with continuous wavelength tuning, as shown in Figure 2.22 [64]. It had a tuning range of 30.3nm, a maximum power of 0.4dBm and a SMSR of 26dB.

Figure 2.23 Schematic of the wedge-controlled cavity configuration [8].

A tunable ECL that can be tuned continuously without mode hopping over a 120GHz range has been developed by Filimonov and Borysow as shown in Figure 2.23 [8]. The wavelength is tuned by rotating the wedge. Chao *et al.* demonstrated a 633nm tunable ECL which consists a gain chip, a collimating lens, a intracavity glass plate and a diffraction grating [65]. A coarse tuning range of 4nm is obtained by rotating the grating and continuous tuning over 1.8GHz is achieved by tilting the glass plate. However, for the mechanically tunable ECLs with continuous wavelength tuning, they usually have difficulty in achieving good reliability.

Figure 2.24 Diagram of the Littrow cavity with an electro-optic prism [66].

Non-mechanical filters such as acousto-optic tunable filter and electro-optic filters have also been used for continuously tunable ECLs. A continuously tunable ECL with two AO filters was reported by M. Kourogi et al [43]. A pair of AO tunable filters and an external grating was used as the wavelength-selective element. Single-mode operation and electric tuning over 2nm were confirmed. A long optical delay line was employed to offer continuous tuning over several gigahertzes. However, the tunable ECL need high frequency signal of more than 100MHz to be applied to the AO filter. L. Menager et al. proposed a mode-hop-free tunable ECL based on an electro-optic prism as shown in Figure 2.24 [66]. The electro-optic prism was used to synchronously tune the cavity length and the grating incident angle to obtain continuous tuning. Mode-hop-free frequency scans of 12 GHz for a 4-kV voltage variation could be achieved with high linearity and reproducibility. However, the above tunable ECLs require high driving voltage.

Figure 2.25 External cavity laser using an LC-FPI and an MQW semiconductor laser diode with a PC section [67].

The tunable ECLs based on LC elements have the advantage of compact design, low driving voltage of less than 20V and low cost.

A tunable ECL with liquid crystal Fabry-Perot Interferometer (LC-FPI) has been constructed by H.Tsuda *et al* as shown in Figure 2.25 [67]. The extended cavity contained a coupling lens, the LC-FPI and an external mirror. The lens focused the intracavity beam on the mirror 3cm from the diode. The FPI was placed near the rear focus to help improve the FPI performance. Nevertheless, the external feedback was estimated to be less than 1%. Due to the weak feedback, coordinated adjustment of the LC-FPI voltage and phase-control current was necessary to select arbitrary external-cavity modes. By changing the voltage from 0 to 20V and phase-control current of less than 1mA, tuning from 1522nm to 1563nm was obtained. But it cannot obtain continuous tuning.

Figure 2.26 A tunable ECL using nematic liquid crystal [68].

Continuously tunable ECLs based on LC elements have also been demonstrated by B. Wacogne *et al.* [68]. They developed a tunable ECL based on a tunable filter formed

by two liquid crystal cells and a birefringence plate as shown in Figure 2.26. The coarse tuning range was 6nm and continuous tuning over about 500MHz was demonstrated.

Figure 2.27 A tunable ECL with an intracavity liquid crystal cell [69].

A Littman-type external laser based on a planar nematic liquid crystal cell was demonstrated by Y. P. Lan *et al.* as shown in Figure 2.27 [69]. By varying the driving voltage of the NLC cell and laser diode bias current simultaneously, the single-mode oscillation and mode-hop-free tuning over 19.2GHz at 775nm were obtained. It can be seen that the above two continuous tunable ECLs have small tuning range.

Table 2.3 Continuously tunable external cavity laser- A brief review of previous research.

First Author (ref.)	Year	Wavelength (nm)	Configuration and Performance	Remarks
Tsuda [67]	1991	1550	Tunable ECL with LC-FPI; tuning range of 40nm. (Figure 2.25)	Electro-optic tuning, can not obtain continuous tuning
Wacogne [68]	1993	1500	Tunable ECL with two LC cells and a birefringence plate; coarse tuning of 6nm, continuous tuning over about 500MHz (Figure 2.26)	Electro-optic tuning, Small tuning range
Filimonov [8]	1995	746	Littrow configuration; tuning range of 120GHz. (Figure 2.23)	Mechanical tuning by rotating the prism; small tuning range
Kouroggi [43]	2000	1500	Continuous tuning over several gigahertz	Acousto-optic tuning; Require RF signal
Menager [66]	2000	800	Continuous tuning range of 12 GHz for a 4kV voltage variation; tuning rate of 1.7GHz/kV (Figure 2.14)	Electro-optic tuning, require high applied voltage
Chao [65]	2001	633	Littrow configuration; coarse tuning range of 4nm and continuous tuning over 1.8GHz;	Mechanical tuning by rotating the glass plate; small tuning range
Liu [64]	2004	1550	Littrow configuration based on micromachined grating; tuning range of 30.3nm, output power of 0.4 dBm and SMSR of 26dB to 12dB (Figure 2.22)	Mechanical tuning by rotating the grating
Lan [69]	2004	775	Tunable ECL with LC cell; Continuous tuning range of 19.2GHz (Figure 2.27)	Electro-optic tuning, Small tuning range

Table 2.3 summarizes some of the important works done so far in the field of continuously tunable external cavity laser. From the review of the current electronically tunable ECLs, it can be found that it is difficult to obtain continuous tuning over a large tuning range with a single tunable element. Hence, a tunable ECL based on a tuning mechanism combining coarse tuning and fine tuning is proposed. The LC-FPI is used to obtain mode-hopping tuning and the continuous tuning can be fulfilled by the fine tuner. The proposed electronically tunable ECL has wide tuning range, and is simple in structure for easy fabrication.

2.7 Summary

From the review of the existing tunable ECLs, it can be concluded that tunable ECLs with mechanically movable parts normally have difficulty in achieving good reliability and require highly sensitive alignment. As for tunable ECLs based on AO tunable filter and conventional EO filter, they require high driving voltages and the power consumption are large. Hence, in order to design a tunable ECL with simple configuration, and low driving voltage or low power consumption, liquid crystal must be used as the tuning element in the tunable ECLs.

Based on the review conducted as tabulated in Table 2.1, it can be found that the reported past researches has their own limitations in terms of structure and complexity. In this context, a tunable ECL based on a LC deflector and a reflection grating is proposed, which has the main advantage of simple in configuration for ease of fabrication and assembly.

From the review as shown in Tables 2.2, the limitation of the LC based WDM-Channel-selectable ECLs are complex in structure, requiring assembly of several components. In this context, a WDM-channel selectable tunable ECL with LC deflector is proposed, which has the advantage of simple in structure, easy to operate and matching to the ITU standard wavelengths.

As shown in Table 2.3, continuous tunable ECLs based on LC elements have small tuning ranges. Hence, a continuous tunable ECL based on a LC-FPI and a LC based fine tuner is proposed in this context, which has a wider tuning range and simple in structure, in comparison.

CHAPTER THREE

PROPERTY OF LIQUID CRYSTALS

Liquid crystals (LCs) have been widely used in the optical devices. It has been dominant in display because of its color change property. Besides that, LCs also have birefringence, which makes them attractive materials for nondisplay devices such as elements of optical data processing systems, LC shutters and LC light modulators [70]. Based on its optical birefringence property, LC is chosen to be the tuning elements for this project. It has the advantages of high compactness, low driving voltage and low power consumption. Furthermore, LC is compatible with infrared wavelength and its absorption coefficient is low at the infrared band [71].

3.1 Introduction

Liquid crystal behavior was first discovered in 1888 by Austrian Botanist Friedrich Reinitzer who described two distinct melting points of cholesteryl benzoate. He observed that the substance melted at 145.5°C to give a cloudy but still liquid phase and the material changed again into a clear, transparent liquid at 178.5°C [72].

Liquid crystals are fluids in which there are still certain degrees of molecular orders. As a result, there is an anisotropy in the mechanical, electrical, magnetic, and optical properties. The basis of electro-optical effects is the reorientation of the director under an external applied field. Anisotropy of the electrical properties of the

medium is the basis for reorientation, whereas the dynamics of the process also depend on the viscoelastic properties and the initial orientation of the director relative to the field. The optical properties of the medium are changed as a result of the reorientation of the director in all known eletro-optic effects.

Liquid crystalline phases are formed by molecules of a specific, anisometric shape. Typical molecules shapes are rod-like or rod-like molecular aggregates and disc-like. The molecules exhibit some positional and orientational order in a liquid crystalline phase. The simplest liquid crystal is the nematic phase, in which there is a high probability that the molecular axes of neighboring molecules point in a certain and same direction, though the molecules may diffuse throughout the sample [73]. That is, it exhibits intermediate strong long-range orientational order but weak positional order. Other common types of liquid crystals are the cholesteric phase, the various smectic phases, discotic liquid crystals, and lyotropic liquid crystals. The nematic liquid crystal is the only one whose refractive index can be continuously tuned [74]. Due to the simplicity and the above mentioned electro-optic properties of nematic liquid crystals, it is chosen to fabricate the tunable elements in this project.

3.2 Nematic Liquid Crystal Molecule Structure

The schematic of a nematic liquid crystal (NLC) is shown in Figure 3.1. The most probable directional axis of the molecules is defined as the director of the NLC and is denoted $\mathbf{n}$. In order to describe the orientation order, an average orientational distribution function $f(\theta)$ is defined, where θ is the angle between the long axis of

the molecule and the director. The distribution function can be expanded in a series of Legendre polynomials, but retaining only the even powers because the director can be defined in either of the two opposite directions, n or $-n$ [75],

$$f(\theta) = S_0P_0(\cos \theta) + S_2P_2(\cos \theta) + \dots \tag{3.1}$$

where $P_n(\cos \theta)$ are the Legendre polynomials and S_n are the coefficients describing the orientational distribution function. The dominant parameter is S_2 and it can be used as an orientational order parameter when properly normalized.

Figure 3.1 schematic of a nematic liquid crystal.

As the temperature is increased, the order parameter decreases and becomes zero at the transition to the isotropic phase. The temperature of the phase transition T_c is called the “clearing point” and is higher than room temperature for most LCs. Since the order can be altered by changing the temperature, an isotropic phase can be transformed into the nematic liquid crystalline phase by decreasing the temperature to below the clearing point and vice versa.

Since the nematic liquid crystal molecule is typically a rod-like molecule that has long and short molecular axes, it will exhibit birefringence as its refractive indices parallel and perpendicular to the long axis are different. Through applying an external field the director can be reoriented. By combining this property with the birefringence, the NLC can be a very useful electro-optic material.

3.3 Electro-optical Properties of Nematic Liquid Crystal

A NLC is uniaxially symmetric. With the optical axis parallel to the axes of the molecules, the anisotropy of the refractive index is given by

$$\Delta n = n_e - n_o, \quad (3.2)$$

where n_e and n_o are the extraordinary and ordinary refractive indices. For all known NLCs, the anisotropy Δn is positive [76]. The dielectric anisotropy is expressed as

$$\Delta \varepsilon = \varepsilon_{\parallel} - \varepsilon_{\perp}, \quad (3.3)$$

where $\varepsilon_{\parallel}$ and $\varepsilon_{\perp}$ refer to the principle dielectric permittivity parallel and perpendicular to the director. In a nematic liquid crystal, the dielectric anisotropy can be positive or negative. $\Delta \varepsilon$ is the most critical in determining how a liquid crystal will response to an applied electric voltage. The director tends to align itself to the direction of the applied field if the anisotropy is positive ($\Delta \varepsilon > 0$), and perpendicular to it if the anisotropy is negative ($\Delta \varepsilon < 0$) [76].

A NLC cell is made by sandwiching a liquid crystal layer between two glass substrates with indium-tin-oxide (ITO) transparent electrodes. An alignment layer is used to align the LC molecules. Before the field is applied, the initial director

orientation is fixed by the boundary conditions on the surface of the liquid crystal cell and is supported by the elastic torque. This initial orientation is referred to as the “anchoring”. There are two general forms of anchoring for nematic liquid crystal molecules: homogeneous and homeotropic. In homogeneous alignment, the director is oriented parallel to the surface of the boundary, typically by surface topology. While in homeotropic alignment, the director is perpendicular to the surface and typically achieved by applying a monomolecular layer of surfactant onto the surface. In this project, homogenous alignment is applied to fabricate the tuning elements. Due to the interaction of the liquid crystal and the alignment layer, the director is not perfectly parallel to the glass surface. Typically the pretilt angles for the homogeneous alignment are $1^\circ - 10^\circ$ [77].

3.4 Electrically Controlled Birefringence NLC Cell

For a NLC with positive dielectric anisotropy, when the electric field is applied the director tends to be reoriented along the direction of the field. The action of the electric field on the liquid crystal layer results in the deformation of the initial director distribution and a subsequent variation of the LC cell optical properties. The process of electric field induced reorientation of the director in a NLC is known as the Frederiks transition. In the simplest model that ignores magnetic field and conductivity, the director reorients in a sufficiently slow-varying applied field under the action of the dielectric torque, which is proportional to the dielectric anisotropy.

Figure 3.2 shows a LC aligned homogeneously in a parallel plate capacitor configuration. In this configuration, a strong parallel alignment is produced along the surfaces by spin coating an anchoring chemical agent and then rubbing the surface. The elasticity of the LC, the applied electrical field, and the surface anchoring layers resulted in a symmetrical smooth rotation of the molecule directors inside the nematic film.

Figure 3.2 Effect of the applied electric field on nematic liquid crystal
(a) below threshold, (b) above threshold.

Frederik’s transition begins abruptly once the applied voltage reaches the Frederik’s transition threshold. The threshold voltage V_{th} is given by [78]

$$V_{th} = \pi \left(\frac{K_{11}}{\epsilon_0 \Delta \epsilon} \right)^{1/2}. \quad (3.4)$$

where K_{11} is the splay elastic constant, ϵ_0 is the free space dielectric permittivity and $\Delta \epsilon$ is the dielectric anisotropy. It can be noted from equation (3.4), V_{th} is more or less constant for a certain nematic LC. If the applied voltage is weak and below threshold, the liquid crystal molecules remain parallel to the surface. As the applied voltage is above the threshold, the LC molecules tend to align to the applied field. At saturation, all but those molecules anchored to the two surfaces will be completely aligned with the field. When the applied voltage is removed, the liquid crystal molecules will relax back to their original alignment due to the elastic restoring force.

When the driving voltage is applied, the LC molecule director distribution will be stable when its net free energy is minimized. The net free energy F_{net} is given by [79]

$$F_{net} = \frac{1}{2} \int_0^\infty \left\{ K_{11} (\nabla \cdot \mathbf{n})^2 + K_{22} [\mathbf{n} \cdot (\nabla \times \mathbf{n})]^2 + K_{33} [\mathbf{n} \times (\nabla \times \mathbf{n})]^2 - \mathbf{D} \cdot \mathbf{E} \right\} dV, \quad (3.5)$$

where K_{11} , K_{22} and K_{33} are the splay, twist and bend constants, $\mathbf{D}$ is the electric displacement, $\mathbf{E}$ is the electric field and the molecule vector direction is $\mathbf{n}(x, y, z)$.

In order to numerically model the LC electro-optic effect, three assumptions are made: (1) strong anchoring at both surfaces, that is the boundary condition is defined exclusively by the surface orientation angle; (2) no twist orientation is involved, which makes K_{22} term disappear in equation (3.5); (3) only considered one-

dimensional modeling, which implies $E_x = E_y = 0$. Based on these assumptions, equation (3.5) can be written as

$$F_{net} = \frac{1}{2} \int_0^L (K_{11} \cos^2 \theta + K_{33} \sin^2 \theta) \left(\frac{d\theta}{dz} \right)^2 dz - \frac{1}{2\epsilon_0} \int_0^L \frac{D_z^2}{\epsilon_{\perp} \cos^2 \theta + \epsilon_{\parallel} \sin^2 \theta} dz \quad (3.6)$$

Where ϵ_0 is the dielectric constant in free space, D_z is the electric displacement along the Z direction. The integral equation can be changed into a differential equation [53]:

$$\left(\frac{dz}{d\theta} \right)^2 = \frac{K_{11}(1 + K \sin^2 \theta)}{C - \frac{D_z^2}{\epsilon_0 \epsilon_{\perp} (1 + r \sin^2 \theta)}} \quad (3.7)$$

where $K = (K_{33} - K_{11}) / K_{11}$, $r = (\epsilon_{\parallel} - \epsilon_{\perp}) / \epsilon_{\perp}$, $C = D_z^2 / [\epsilon_0 \epsilon_{\perp} (1 + r \sin^2 \theta_m)]$, and θ_m is the largest orientation angle that is located in the middle of the whole thickness. Numerically solving equation (3.7) with the orientation angles at the two boundary layers, the molecule director distribution inside the whole cell at a given driving voltage is obtained.

Using the well-known formula for an anisotropic medium's index ellipse, the distribution of refractive index for extraordinary light inside the LC cell is given by [53]

$$n_e(\theta_z) = \frac{n_o n_e}{(n_o^2 \cos^2 \theta_z + n_e^2 \sin^2 \theta_z)^{1/2}}, \quad (3.8)$$

where θ_z is the orientation angle, n_e and n_o are the LC's extraordinary and ordinary refractive indices, respectively. The effective refractive index of the whole cell is given by

$$n_{eff} = \frac{1}{d} \int_0^d n_e(z) dz, \quad (3.9)$$

where d is the thickness of the cell.

For a homogeneous nematic LC cell, the response time is given by [78]

$$\tau_r = \frac{\tau_0}{\left[\left(\frac{V}{V_{th}} \right)^2 - 1 \right]} \quad (3.10)$$

where V_{th} is the threshold voltage of the nematic LC. τ_0 is the relaxation time of the LC director and is expressed as

$$\tau_0 = \frac{\gamma_1 d^2}{\pi^2 K_{11}}, \quad (3.11)$$

where γ_1 is the rotational viscosity. It can be seen from the equation (3.10) that the response time has a square-law relation with the cell thickness d . Hence a smaller cell thickness will result in a shorter response time. For example, reducing the thickness by half results in four times faster response. On the other hand, by choosing low viscosity-to-elasticity ratio, short response time can also be obtained.

3.5 Summary

The basic characteristics of liquid crystal are studied in this chapter. LCs have one of the largest values of optical anisotropy available, approximately 0.2, which allows liquid crystal cells to be thin and compact. Furthermore, LC cells operate at low voltages of about 10V, have low power consumption and can be integrated into arrays of more than 10^5 cells. Based on the electro-optical properties of the LC, in this project the tuning elements including LC deflector, LC-FPI and fine tuner are designed. By using these tuning elements, three novel configurations of tunable ECL are investigated in this study, which are LC deflector as the tuning element, LC deflector with the ITU etalon as the tuning elements and LC-FPI and fine tuner as the tuning elements. The design, theoretical analysis, fabrication, implementation and calibration of the tunable ECLs will be presented in the following two chapters.

CHAPTER FOUR

TUNABLE EXTERNAL CAVITY LASER BASED ON LIQUID CRYSTAL DEFLECTOR

4.1 Introduction

The literature survey suggested the need for developing electronically tunable ECLs that are simple in configuration, easy in fabrication and assembly, low in power consumption. In this context, a transmission-type nonmechanical liquid crystal beam steering device is proposed to combine with the diffraction grating as the tunable filter. The LC deflector has a simple structure, low power consumption, easy operation and fabrication. The design and fabrication process of the LC deflector are discussed.

A tunable ECL based on a LC deflector combined with a reflection grating is proposed. The configuration and tuning mechanism of the tunable ECL are highlighted, followed by the experimental setup and the performance of the tunable laser will be presented.

For the applications in DWDM systems, the laser wavelengths need to be tuned to match the ITU grids. Based on the above tunable ECL system, a novel 19 channel 100GHz-spacing tunable laser is proposed. The detailed tuning mechanism and performance of the tunable ECL will also be discussed.

4.2 LC Deflector

A novel LC deflector with a prism shape capable of electronically controlled beam steering is proposed and discussed in this section.

4.2.1 Theoretical Design of the LC Deflector

Figure 4.1 shows the structure of the LC deflector. The two substrates form a prism configuration, which is filled with NLC material. The alignment layer and ITO transparent electrodes are deposited on the inner sides of two glass substrates. The rubbing direction of the alignment layers is parallel to the intended prism vertex to produce splay-free homogeneous alignment of the NLC. The outer sides of the substrates are antireflection coated for 1500-1600nm and the residual reflectivity is less than 0.15%.

Figure 4.1 Structure of the LC deflector.

The operational mechanism of the LC deflector basically uses the dielectric wedge prism to achieve a voltage-controlled steering angle. The schematic diagram of the device is shown in Figure 4.2. The input beam is decomposed into two orthogonal linearly polarized states in the x -direction and the y -direction. In the case when the LC molecules are aligned unidirectionally along the x -direction, the input beam polarized along the y -direction cannot experience any phase difference, whereas the input beam polarized along the x -direction can experience the refractive index change and be deflected in the xz plane.

Figure 4.2 the schematic diagram of the LC deflector with the coordinate system.

For numerical simulation, a one-dimensional model is considered for simplicity [80]. When the coordinate axes are set as shown in Figure 4.2 and the LC aligned along the x axis in both surfaces, the director of LC is expressed as follows

$$\vec{n} = (n_x, n_y, n_z) = (\cos \theta, 0, \sin \theta) , \quad (4.1)$$

where the θ is the tilt angle measured from the surface toward the z-axis. In order to determine the orientation of LC, the Ossen-Frank strain free energy was applied [70]:

$$F = \frac{1}{2} K_{11} (\nabla \cdot \vec{n})^2 + \frac{1}{2} K_{22} (\vec{n} \cdot \nabla \times \vec{n})^2 + \frac{1}{2} K_{33} (\vec{n} \times \nabla \times \vec{n})^2 - \frac{1}{2} \vec{E} \cdot \vec{\epsilon} \cdot \vec{E} , \quad (4.2)$$

where $\vec{n}$ is the unit direction vector of LC, K_{11}, K_{22}, K_{33} are the elastic constants, $\vec{E}$ is the electric field vector and $\vec{\epsilon}$ is the dielectric tensor, respectively. After the initial state is set in the cell, the director field of LC is deformed by the interaction between the electric field and dielectric anisotropy of the LC, which creates a deformation of the director. The deformation increases the elastic energy, which is minimized by the Euler-Lagrange equation as:

$$\gamma \frac{\partial n_i}{\partial t} = \frac{d}{dz} \left(\frac{\partial F}{\partial (dn_i / dz)} \right) - \frac{\partial F}{\partial n_i} , \quad i = x, y, z . \quad (4.3)$$

where $\gamma = \frac{\epsilon_{\parallel}}{\epsilon_{\perp}} - 1$. For the proposed LC deflector, no twist orientation is involved, which makes the K_{22} term in equation (4.2) disappear. The director profile can be calculated using the relaxation method. From the calculated director profiles $\theta(z)$, the effective refractive index of LC n_{LC} is given by

$$n_{LC} = \frac{n_o n_e}{d} \int_0^d (n_e^2 \sin^2 \theta(z) + n_o^2 \cos^2 \theta(z))^{-1/2} dz . \quad (4.4)$$

In the presence of an applied voltage V , the director profiles can be calculated as a function of the applied voltage and the resultant refractive index of the LC is varied. For the effective refractive index n_{LC} , when no voltage is applied, it is maximum, which is approximately equal to n_e . When the applied voltage reaches the saturated voltage, n_{LC} is minimum, which is approximately equal to n_o .

Figure 4.3 shows the operating principle of the LC deflector. For the input beam polarized along the y direction, when the voltage is applied, the direction of the output beam will not change. Whereas for the input beam polarized along the x direction, when no voltage is applied to the LC deflector, the input polarization is parallel to the optical axis, which is the molecular axis direction. Since the prism angle α is very small, the beam experiences the extraordinary refractive index n_e of the LC. When high enough voltage is applied, the LC molecules align to the z direction. The beam experiences the ordinary refractive index n_o . For the case when the applied voltage is between the threshold voltage and the saturated voltage of the LC, the LC molecules align themselves towards the z direction [81].

Figure 4.3 The operating principle of the LC deflector:
(a) with no voltage; (b) with high enough voltage.

Through applying Snell's law, the output angle θ_p is given by

$$\theta_p = \sin^{-1}(n_{LC} \sin \alpha) - \alpha. \quad (4.5)$$

Hence when no voltage is applied to the deflector, the output angle θ_{p0} is given as

$$\theta_{p0} = \sin^{-1}(n_e \sin \alpha) - \alpha. \quad (4.6)$$

When high enough voltage is applied, the output angle θ_{p1} is expressed as

$$\theta_{p1} = \sin^{-1}(n_o \sin \alpha) - \alpha. \quad (4.7)$$

As shown in Figure 4.3, the deflection angle θ_d is defined by

$$\theta_d = \theta_p - \theta_{p1} = \sin^{-1}(n_{LC} \sin \alpha) - \sin^{-1}(n_o \sin \alpha). \quad (4.8)$$

From equation (4.8), it can be seen that when no voltage is applied, the deflection angle is maximum and is given by

$$\theta_{d\max} \approx \theta_{p0} - \theta_{p1}. \quad (4.9)$$

As the applied voltage increases, the deflection angle is decreased. When the applied voltage is higher than the saturated limit, minimum steering of the beam occurs.

From the above analysis, it can be seen that a relatively large birefringence Δn and α will result in large deflection angle θ_d as shown in Figure 4.4. However, large α will result in long response time.

Figure 4.4 The deflection angle as a function of the change of the refractive index under various wedge angles.

4.2.2 Fabrication of LC Deflector

The LC deflector is fabricated in a class 1000 clean room. The fabricate process of the LC deflector is shown in Figure 4.5. The two substrates are BK7 glass and ITO (10-40nm thickness) is coated on one side of the substrates (ZC&R coating for optics, Inc.). The size of the substrate is $32mm \times 32mm \times 1.1mm$. The outer sides of the substrates are antireflection coated. The substrates are cleaned with standard glass cleaning process including ultrasonic clean with detergent, ultrasonic clean and spray with de-ionized (DI) water, and thermo-dry. The Sunever 130 (SE-130) alignment layer is spincoated onto the substrates with 4000rpm for 30s and baked at $200^\circ C$ for 1 hour. Then the substrates are unidirectionally rubbed with a soft cotton fabric with light pressure and the rubbing direction is parallel to the intended prism vertex. Spacers were fixed at a predetermined position on one of the substrates and

machined to give uniform thickness. A program control drawing machine is used to draw the sealing border instead of the silk printing system which is normally used in mass production lines. The sealant material is ultraviolet sealant 91 of Norland products. In order to form the prism, the sealant thickness of the borders is different. The two substrates were carefully assembled together and spacers are at a fixed distance from the vertex. The rubbing directions of the two substrates are antiparallel to each other. The sample cell is put into a transparent plastic bag and exposed to the UV light under vacuum environment. After the adhesive border is cured, the prism angle is locked. Then, the LC Merck E63 ($\Delta n = n_e - n_o = 1.744 - 1.5172$) is filled into the cavity by the air pressure. The filling speed should be controlled and not too fast, otherwise the alignment layer may be destroyed by the LC flow. After that, the injection hole was sealed using UV sealant A-720. The whole cell is then heated to 90°C , which is higher than the clearing point of the LC E63 to make the LC isotropic. Then the cell is slowly cooled to room temperature. The dimension of the deflector is $32\text{mm} \times 52\text{mm}$ and the active region is $5\text{mm} \times 32\text{mm}$. All together four LC deflectors are fabricated and the one with largest prism angle is chosen to be used as the tuning element in the tunable ECL. Figure 4.6 shows the custom-fabricated LC deflector.

Figure 4.5 Schematic diagram representing process steps of a LC deflector fabrication: (a) Cleaned ITO glass; (b) Spin coating Polyimide at 4krpm for 30s; (c) Bake at 200°C for 60 mins; (d) Rub mechanically, the rubbing direction of the two substrates antiparallel to each other; (e) Put the spacer on one of the substrate at predetermined position; (f) Deposit UV-cured optical adhesive on the other substrate and then assemble the cell ; (g) Fill LC into the cavity and seal the injection hole.

Figure 4.6 The photograph of custom-fabricated LC deflector.

4.2.3 Characteristics of LC deflector

The fabricated LC deflectors have a clear aperture diameter of 5mm and wedge angle of 0.022rad. The NLC used is Merck E63, which has a manufacturer-specified birefringence of 0.2272 at a room temperature of 25°C and $\lambda = 589.3\text{nm}$. The NLC birefringence depends on the operating wavelength. Typically, for NLCs with large birefringence in the visible bands, the birefringence decreases by ~15%-20% from the visible to near-IR band [82]. Hence, according to equation (4.9) the theoretical maximum deflection angle in near-IR band is calculated to be about 4.22mrad.

Figure 4.7 shows the setup to measure the insertion loss of the chosen LC deflector. A tunable laser (AQ4321D, ANDO) is used as the input light source. The output wavelength is 1550nm. The light is coupled by an optical fiber, the output of which is collimated to 100 μm in diameter by a collimating lens. The light passing through the deflector will be collected by a broadband power meter (13PEM001, Melles Griot). First, the output power from the collimator P_1 is measured. Then after insertion of the LC deflector, the output power P_2 is obtained. The insertion loss is given by

$$10 \log_{10} \left(\frac{P_2}{P_1} \right) = 10 \log_{10} \left(\frac{1.89}{2.0} \right) = -0.25\text{dB}.$$

Figure 4.7 the schematics of the optical setup for measuring the insertion loss.

Due to the large aperture and the thickness of the NLC layers, the response time of the fabricated LC deflector is in the order of 1 s . The response time is mainly determined by the thickness and viscosity of the LC. Large thickness and high viscosity correspond to long response time. Therefore the response time can be improved by using LCs with high birefringence and low viscosity. It can also be improved through varying the LC deflector parameters such as the smaller thickness and clear aperture.

4.3 Single Mode External Cavity Laser with LC Deflector

An electronically tunable ECL that uses an electronically optical tuning mechanism based on a LC deflector combined with a reflection grating is proposed.

4.3.1 Configuration

The configuration of the electronically tunable ECL is shown in Figure 4.8. It consists of a gain chip, and a free space region with a collimating lens, a LC deflector and a diffraction grating. The laser employs a Littrow configuration to get relatively high feedback and to minimize the external-cavity length. The light from the back facet of the gain chip is coupled to an optical fiber to monitor the laser output. The collimating lens coupled the light from the front facet of the gain chip through the LC deflector to the diffraction grating [83].

Figure 4.8 Schematic view of the proposed tunable ECL based on an LC deflector.

4.3.2 Basic Principle

For the proposed tunable ECL, through applying voltage to the LC deflector, the light beam is deflected and consequently changes the incident angle to the grating. The tuning mechanism is based on the wavelength-dependent angular sensitivity combined with the angular deflection from the LC deflector.

Figure 4.9 shows the detailed tuning model of the proposed tunable ECL. For the Littrow configuration, the grating equation is

$$\lambda = 2a \sin \theta . \tag{4.10}$$

Where λ is the operational laser wavelength, which depends on the incident angle of the beam on the grating ' θ ' and the grating period ' a '. As the voltage applied to the deflector increases, the light beam is deflected, and consequently, the angle of incidence onto the grating is changed.

Figure 4.9 Detailed tuning model of the tunable ECL.

Let the initial incident angle onto the grating be θ_1 . With an increase in the applied voltage, the incident angle changes from θ_1 to θ_2 . As the incident angle is varied, $\Delta\theta = \theta_2 - \theta_1$, the emission wavelength is tuned.

Assuming $\Delta\theta$ is very small, the wavelength variation can be expressed as

$$\begin{aligned}\Delta\lambda &= \lambda_2 - \lambda_1 = 2a \sin \theta_2 - 2a \sin \theta_1 \\ &= 4a \cos\left(\frac{\theta_1 + \theta_2}{2}\right) \sin\left(\frac{\Delta\theta}{2}\right) \approx 2a \cos \theta_1 \Delta\theta, \quad (4.11)\end{aligned}$$

where $\Delta\theta = \theta_2 - \theta_1$.

4.3.3 Experimental Results of the Single Mode Tunable ECL with LC Deflector

Based on the previous analysis, a tunable ECL was designed. The components, including a gain chip, collimating lens and grating are chosen according to the requirements.

4.3.3.1 Characteristics of the Gain Chip

The gain chip is a stripe-guide-multiple-quantum-well InGaAsP/InP device having dimensions of $300\mu m \times 250\mu m \times 100\mu m$ (length $\times$ width $\times$ height) from DenseLight, Singapore (DL-CG 5053R). The facet facing the lens is AR coated and has a residual reflectivity of 0.16%. The back facet has an HR coating with a reflectivity of 90%. It has a nearly circular cross section with far-field divergence angle of 35° in the plane parallel and vertical to the contact surface. The gain profile of the gain chip with an injection current of 50mA is shown in Figure 4.10, which is obtained by measuring the amplified spontaneous emission (ASE) spectrum. The 3-dB width of the gain chip is $\sim 50\text{nm}$ (1520-1570nm). It is observed that there is a certain oscillation in the curve. It is likely due to the interference of the parasitic reflection of two facets of the gain chip [84].

Figure 4.10 Gain curve of the gain chip by measuring the ASE spectrum.

4.3.3.2 Characteristics of the Lens and Grating

The most critical component for determining the feedback strength is the intracavity collimating lens. A general requirement for strong feedback in extended configurations is that the collimating lens must transform the Gaussian beam waist at the gain medium facet into another waist at the surface of the external mirror as shown in Figure 4.11 [16].

Figure 4.11 Intracavity beam transformation by coupling optics [16].

The output beam from the gain chip has a divergence angle $\theta_v = 35^\circ$, as shown in Figure 4.11. For the Gaussian intensity profile the $1/e^2$ point is 1.7 times the FWHM value. The collimating lens should have a sufficiently large numerical aperture (NA) to capture the beam output to these points, that is

$$NA \geq \sin\left(\frac{1.7}{2}\theta_v\right) = 0.50.$$

The chromatic aberration refers to the variation of the focal length of a lens with wavelength. Since ECLs operate over a wide wavelength range and the position of the collimating lens is critical to laser performance, a collimating lens exhibiting small chromatic aberrations should be chosen.

According to the requirements described above, a diffractive-aspheric hybrid lens from Thorlabs (350781C-C) was chosen. The lens is designed to keep the chromatic aberrations minimized over the entire C and L band (1500-1650nm). It has an AR coating for 1500-1650nm with a reflectivity less than 0.5%. Its numerical aperture is 0.55 and the focal length is 4.5mm.

According to equation (4.11), the tuning range is proportional to the grating pitch. Hence a 600 lines/mm reflection ruled diffraction grating GR13-0616 (Thorlabs) is chosen. The blaze angle is $28^{\circ}41'$ at 1600nm. The diffraction efficiency is about 80% for the beam whose polarization direction is perpendicular to the rules of the grating. The grating filter passband $\Delta\lambda$ is determined by $\Delta\lambda = \lambda / N$, where λ is the wavelength of the laser and N is the number of grooves illuminated on the grating. The laser intracavity beam incident on the grating was estimated to be about 2.5mm in diameter. The passband is calculated to be about 0.9nm.

4.3.3.2 Performance of the Tunable ECL with LC Deflector

The ECL is set up and mounted upon a baseplate. The gain chip and the optical fiber are packaged together with an external-cavity length of $\sim 3\text{cm}$. A laser diode controller LDC500 (Thorlabs) is employed to inject current to the gain chip. The

light from the back facet of the gain chip is collected and analyzed by the optical spectrum analyzer (MS9701B, Anritsu). Firstly, the lens is fixed to collimate the output of the gain chip. Then the grating is mounted on a manufactured 3-axis rotational stage and carefully adjusted to feed the first order diffraction light back to the gain chip. Thus a fixed wavelength Littrow external cavity laser as shown in Figure 4.12 is set up. Figure 4.13 shows the fiber-coupled output spectrum of the fixed wavelength ECL. The threshold current of the laser is 25mA. The lasing wavelength is 1528.6nm and the SMSR is ~30dB.

Figure 4.12 The Littrow ECL with fixed wavelength.

Figure 4.13 Output spectrum of the fixed wavelength ECL.

CHAPTER FOUR

In order to tune the wavelength, the LC deflector is inserted in the external cavity. The rubbing direction of the LC deflector is parallel to the output polarization direction of the gain chip. The distance from the LC deflector to the grating is 18mm. Through slightly adjusting the grating, the tunable ECL is set up. A controllable dc-balanced 20kHz square waveform is applied to the LC deflector by a function generator (33250A, Agilent). A lower frequency ac voltage degrades the performance of LC deflector because the LC molecules fluctuate [2]. Figure 4.14 shows the set-up of the tunable ECL system. The initial output spectrum is shown in Figure 4.15. The oscillation wavelength is 1526.28nm when no voltage is applied to the LC deflector. According to the grating equation, the initial incident angle θ_i is calculated to be 27.2°.

Figure 4.14 The set up of the tunable ECL system with the LC deflector.

Figure 4.15 Spectral characteristic of the tunable ECL:
The initial wavelength is at 1526.28nm.

Figure 4.16 shows the various output spectra at different applied voltages to the LC deflector (V_{DEF}) with an injection current of 55mA to the gain chip. The output maintained at a single longitudinal mode over the entire tuning range.

Figure 4.16 Output power spectra at 11 different applied voltages.

The power from the fiber is $\sim 1\mu W$, which is mainly due to the high reflectivity of the back facet of the gain chip and low fiber coupling efficiency. The output beam from the grating has a power of 0.06mW. The variation of the output wavelength with the change of applied voltage is shown in Figure 4.17. When the applied voltage reaches $V_{DEF} = 2.5V$, the refractive index of the LC begins to change and resulted in a shift of the wavelength. With increasing voltage, the lasing wavelength increases. When the voltage increases to 9.5V, the oscillation wavelength is 1538.52nm as shown in Figure 4.18 and ceases to change any more with any further increase of V_{DEF} . A total tuning range ($\Delta\lambda$) of 12nm is obtained. Based on equation (4.11), the maximum steering angle ($\Delta\theta$) of the LC deflector is calculated to be 4.0mrad. It agrees well to the theoretical maximum deflection angle of 4.22mrad. According to equation (4.9), the birefringence of the LC E63 is calculated to be 0.1825 in the near-IR band, which is within the 15%-20% decreasing range of the birefringence in the visible band.

Figure 4.17 Laser wavelength versus the applied voltage to the LC deflector

Figure 4.18 Output spectrum with 9.5V applied voltage to the LC deflector.

The SMSR is measured by checking the spectrum. The SMSR is more than 30dB over the whole tuning range as plotted in Figure 4.19.

Figure 4.19 SMSR as a function of the wavelength.

Figure 4.20 shows the fiber coupled power versus the injection current. It can be seen that the threshold current is 39mA, beyond that the output power increases linearly with the increase in injection current. When the injection current is larger than 75mA, the fiber-coupled power begins to saturate.

Figure 4.20 Fiber coupled power versus injection current.

From equation (4.9) and equation (4.11), it can be seen that the tuning range is proportional to the prism angle α and the birefringence. Therefore the tuning range can be improved by using higher birefringence and a larger prism angle. Considering that the response time will also increase as the prism angle increases, a multistage LC deflector can be applied to improve the tuning range.

4.4 WDM-Channel-Selected Tunable External Cavity Laser

In order to satisfy the requirement of the applications of channel reconfiguration and assignment in DWDM systems, the laser wavelengths of the tunable lasers need to be

tuned to match the ITU grids. Based on the tunable ECL discussed in the previous section, a WDM-selectable tunable ECL with an ITU etalon and a LC deflector as the tuning elements is proposed.

4.4.1 Configuration

The tunable ECL consists of a gain chip and a free space region with a collimating lens, a fixed etalon, a LC deflector and a diffraction grating as shown in Figure 4.21. The external cavity is formed by the back facet of the gain chip and the diffraction grating (600 grooves/mm, $28^{\circ}41'$ blaze at 1600nm). The gain chip is stripe-guide multiple-quantum-well InGaAsP/InP device. The back facet has a high reflection coating with a reflectivity of 90%. The light emitted from the back facet is coupled to an optical fiber to monitor the laser output. The facet that faces the collimating lens is AR coated and has a residual reflectivity of 0.16%. The collimating lens is AR coated, has a focal length of 4.55mm and a numerical aperture of 0.55. An etalon is inserted in the external cavity to act as a frequency-periodic transmission filter reference to the ITU 100GHz grid. That implies the etalon has selective transmission peaks over the 100GHz ITU channels. Then the beam is incident onto a LC deflector, which is used to control the incident angle of the beam onto the grating electronically. The grating rulings are perpendicular to the output polarization direction of the gain chip, which is parallel to the rubbing direction of the LC deflector. The diffraction efficiency of the grating (Thorlabs, GR13-0616) is about 80%.

Figure 4.21 Schematic diagram of the WDM-selectable tunable ECL.

4.4.2 Basic Principle

Etalons are narrowband wavelength filters. The main features of etalon are low wavefront distortion and low insertion loss. The basic working principle of a etalon is the interference of multiple beams.

The etalon consists of two partially transmitting mirrors that are separated by a distance d . The inner surfaces of the plates are designed to be partially reflecting and the outer surfaces are antireflecting. The equation for the transmission of the etalon is [33]

$$T(\lambda) = \frac{1}{1 + \frac{4R}{(1-R)^2} \sin^2(\phi/2)}. \quad (4.12)$$

Where R is the reflectivity of the plates, ϕ is the roundtrip phase change of the light beam. If any phase change at the mirror surfaces is ignored, then

$$\phi = \frac{4\pi n_e d_e \cos \theta_e}{\lambda}, \quad (4.13)$$

where n_i is the cavity refractive index, λ is the wavelength of the light, d_e is the distance between the etalon plates. θ_e is the angle of incoming light. The resonance wavelength is expressed as:

$$m\lambda_e = 2n_id_e \cos \theta_e . \tag{4.14}$$

The Free Spectral Range (FSR) value of the etalon can be expressed by [33]

$$\Delta v = \frac{c}{2n_id_e \cos \theta_e} . \tag{4.15}$$

where c is the velocity of light.

Figure 4.22 Transmission curve of the ITU etalon.

A 100GHz solid etalon (Casix, China) was chosen for the configuration and the reflectivity of the plates is 40%. Equation (4.14) shows that by changing the incident

angle θ_e , the resonance wavelength can be tuned to match the ITU wavelength exactly. Figure 4.22 shows the simulated transmission curve of the etalon whose transmission peaks match the ITU grids.

Through changing the applied voltage to the LC deflector, the incident angle to the grating is changed and the feedback wavelength of the grating is aligned to the transmission peak of the etalon corresponding to the desired ITU channel. As discussed in the previous section, with increasing applied voltage, the wavelength variation can be expressed as:

$$\Delta\lambda = 2a \cos \theta_0 \Delta\theta,$$

where a is the grating period, θ_0 is the initial incident angle to the grating when no voltage is applied to the LC deflector, $\Delta\theta$ is the change of the incident angle.

The cavity length of the tunable laser is designed to be 3cm, and the mode spacing is ~5GHz. The mode spacing variation caused by the change of the external cavity length is very small and can be considered negligible. Hence, when one ITU channel is selected by the feedback wavelength from the grating, there are always longitudinal modes within ± 2.5 GHz of the selected ITU channel. Due to the gain difference made by the fixed etalon between the neighboring modes, only the mode that is nearest to the selected ITU channel will lase.

4.4.3 Performance of the WDM-Selectable Tunable External Cavity Laser

The tunable ECL is set up and mounted upon the base plate. Figure 4.23 shows the setup of the WDM selectable tunable ECL. The gain chip and the optical fiber are packaged together with an external-cavity length of ~3cm. Laser diode controller LDC500 (Thorlabs) is employed to inject current to the gain chip. A controllable square waveform is applied to the LC deflector by a function generator (33250A, Agilent). The light from the back facet of the gain chip is collected and analyzed by the optical spectrum Analyzer (MS9701B, Anritsu).

Figure 4.23 The setup of the WDM selectable tunable ECL.

The etalon acts as a periodic filter of which the transmission peaks are aligned to the ITU grid channels and is fixed. By changing the applied voltage to the LC deflector, the reflection wavelength of the grating is aligned to the transmission peak of the

etalon corresponding to the desired ITU channel. The etalon is responsible for the sidemode suppression of the adjacent cavity modes of the lasing peak. The wavelength dependent reflectivity of the grating suppresses the cavity modes further away from the lasing peak.

The initial output of the tunable ECL is shown in Figure 4.24. The oscillation wavelength is 1531.88nm, which corresponds to one of the ITU wavelength. The SMSR is 38.52dB. As the applied voltage to the LC deflector changed, single-longitudinal-mode laser operation has been demonstrated over 19 channels from 1531.88 to 1546.12nm. The spectra of these channels with an injection current of 55mA to the gain chip are shown in Figure 4.25. The output beam from the grating has a power of 0.05mW.

Figure 4.24 Spectral characteristic of the WDM selectable tunable ECL: the initial lasing wavelength is 1531.88nm.

Figure 4.25 The laser output spectra for 19 ITU channels.

The variation of the output wavelength with the change in applied voltage is shown in Figure 4.26. The oscillation wavelength is 1531.88nm when no voltage is applied to the LC deflector. When the applied voltage V_d reaches 2.45V, the lasing wavelength shift to the next channel. By increasing the V_d , the lasing wavelength can be tuned to successive ITU channels. When the applied voltage V_d reaches 14.4V, the oscillation wavelength is 1546.12nm as shown in Figure 4.27, which is the last channel that the current tunable ECL can be tuned. The tuning range is limited by the deflection angle of the LC deflector.

Figure 4.26 The ITU wavelengths versus the applied voltage.

Figure 4.27 Output spectrum with 14.4 V applied voltage to the LC deflector.

The SMSR is measured by checking the spectrum. Figure 4.28 shows the SMSR versus the different channel wavelength. The SMSR is about 35dB over the whole tuning range. Compared to the tunable ECL described in the previous section, the SMSR is improved by the insertion of the etalon.

Figure 4.28 The SMSR of the 19 wavelength channels.

Table 4.1 shows the performance of the tunable ECL including lasing wavelengths versus the applied voltage, the SMSR value and the error of the lasing wavelength with respect to the ITU grid. It can be seen that the output central wavelength of the tunable ECL is within $\pm 0.02\text{nm}$ ($\pm 2.5\text{GHz}$) of the ITU grids, which satisfy the requirement of the DWDM application [63]. Based on this table, by calibrating the applied voltage to the LC deflector, the tunable ECL can be used as a digital tuning system with output matching the desired ITU wavelength.

Table 4.1 The performance of the WDM tunable ECL.

Channel #	Applied voltage (V)	Lasing wavelength (nm)	SMSR (dB)	Error (nm)
1	0	1531.88	38.52	-0.02
2	2.45	1532.68	34.86	0.00
3	2.55	1533.48	35.01	+0.01
4	2.74	1534.24	37.26	-0.01
5	3.07	1535.04	34.97	0.00
6	3.12	1535.80	35.78	-0.02
7	3.42	1536.60	36.34	-0.01
8	3.52	1537.40	34.59	0.00
9	3.69	1538.20	35.10	+0.01
10	3.84	1538.96	36.29	-0.02
11	4.21	1539.76	36.48	-0.01
12	4.46	1540.56	36.01	0.00
13	4.87	1541.34	33.08	-0.01
14	5.33	1542.12	36.04	-0.02
15	6.07	1542.92	35.25	-0.02
16	6.68	1543.72	35.97	-0.01
17	8.30	1544.52	36.63	-0.01
18	10.50	1545.32	34.58	0.00
19	14.40	1546.12	37.69	0.00

Figure 4.29 shows the fiber coupled power versus the inject current of the WDM-selectable tunable ECL. It can be seen that the threshold current is 45mA, which is larger than that of the tunable ECL 39mA with LC deflector because of the insertion losses of the etalon. Beyond that, the output power increases linearly with the increase in injection current and when the injection current reaches 75mA, the coupled power saturates.

Figure 4.29 Fiber coupled power versus injection current.

4.6 Summary

The design and fabrication of a LC deflector is presented. By changing the applied voltage to it, the beam can be deflected. Later, a tunable ECL based on the LC deflector in combination with a reflection grating is designed and presented. Applying voltage to the LC deflector changes the angle of incidence to the grating, leading to the wavelength tuning of the laser diode. A wavelength tuning range of

12nm and a SMSR of more than 30dB were obtained with a driving voltage of less than 10V. Finally, based on the tunable ECL with LC deflector, a WDM-selectable tunable ECL is demonstrated, which includes a fixed etalon in the lasing cavity. The device only requires one parameter to tune the wavelength to match ITU grid. By changing the voltage to the LC deflector, the lasing wavelength can be tuned to 19 wavelength channels of 100GHz spacing. The driving voltage of the LC deflector is less than 15V and the power consumption is less than 4.5mW. The SMSR of each channel is about 35dB.

Compared to the electro-optic tunable ECLs listed in Table 2.1 and Table 2.2, the tunable ECLs illustrated here are simple in structure, has low power consumption, and allows for low-cost fabrication that can be compatible with standard processing.

CHAPTER FIVE

TUNABLE EXTERNAL CAVITY LASER BASED ON LC-FPI AND FINE TUNER

5.1 Introduction

This chapter describes the details of the tunable ECL based on liquid crystal Fabry-Perot interferometer (LC-FPI) and Fine tuner. The theoretical analysis of the LC-FPI and fine tuner are presented to determine the parameters of the structure. The fabrication process and the characteristics of the tuning elements are highlighted. The design and the tuning principle of the tunable ECL will be explained. The experimental setup and the performance of the tunable laser will also be discussed.

5.2 Liquid Crystal Fabry-Perot Interferometer

An optical wavelength-selective filter with wide tuning range, narrow bandwidth, and low loss will be key component for tunable ECL. Various tunable wavelength-selective filters have been actively studied [85]. Among them, a Fabry-Perot interferometer (FPI) filter using nematic liquid crystal as the active cavity material has several practical advantages including a simple structure and low voltage drive, as well as economy and adequate optical filter performance [2, 86, 87]. Hence, It is chosen as the tunable filter in the tunable ECL design.

5.2.1 Theoretical Design of LC-FPI

Figure 5.1 The structure of the liquid crystal Fabry-Perot interferometer.

The schematic structure of an LC-FPI is shown in Figure 5.1. A homogenously aligned nematic LC layer is sandwiched between two glass plates, on which alignment films, ITO transparent electrodes, and dielectric films are designed to be deposited at the respective surfaces. Since the ITO film has a loss at the wavelength of $1.5 \mu m$, the ITO electrodes must be placed outside the cavity. The outer sides of the substrates are made antireflecting and the resonance wavelength of LC-FPI is given by

$$m\lambda_m = 2nl \cos \theta_i, \quad (5.1)$$

where n is the refractive index of the liquid crystal, l is the distance between two substrates, θ_i is the incident angle to the LC-FPI and m is an integer. In order to prevent the beam lasing off the surface of the LC-FPI, the LC-FPI is tilted slightly with respect to the resonator axis and θ_i is significantly small. The resonance frequency occurs at

$$\nu_m = m \left(\frac{c}{2nl \cos \theta_l} \right) \quad (5.2)$$

where c is velocity of light.

Liquid crystals are known to have a large refractive index anisotropy, which means there is a large difference between n_e (extraordinary refractive index) and n_o (ordinary refractive index). Without applying any voltage signal, the LC molecules are aligned parallel to the glass substrates, shown in Figure 5.2(a). When an electric field is applied, the LC molecules become tilted as shown in Figure 5.2(b). The refractive index gradually changes from n_e to n_o with increasing voltage for an incident light polarized parallel to the LC molecules. Thus, the resonance wavelength shifts gradually from $2n_e l \cos \theta_l / m$ to $2n_o l \cos \theta_l / m$, the tuning range is $2\Delta n l \cos \theta_l / m$. For light polarized vertically to the LC molecules, with the increasing voltage the refractive index does not change and the resonance wavelength does not shift [2].

Figure 5.2 LC molecules of the LC-FPI (a) with no voltage and (b) with voltage.

In this design, the tuning range of the proposed LC-FPI depends on the free spectral range (FSR) of LC-FPI. The FSR is required to be equal to the tunable range. It is desired that the tuning range be larger than one of the ITU bands, which is 40nm. Therefore, from the theory of FPI, there exists

$$\Delta\lambda = \frac{\lambda_0^2}{2nl \cos \theta_i} . \quad (5.3)$$

Where λ_0 is assumed to be $1.55\mu m$, l is the distance between two substrates, n is the refractive index of the liquid crystal, which is usually around 1.5, then

$$l \leq \frac{\lambda_0^2}{2n\Delta\lambda \cos \theta_i} \Rightarrow l \leq 20\mu m . \quad (5.4)$$

As the response time of the liquid crystal is proportional to the square of l , a nematic liquid-crystal layer of approximately $10\mu m$ thickness lying between two glass plates is chosen. From equation (5.3), the FSR of such a LC-FPI is 80 nm.

The FSR, which is the spacing of the resonance wavelength peaks, can also be expressed as:

$$FSR = \frac{\lambda_m}{m+1} . \quad (5.5)$$

From equation (5.1) and equation (5.5), for the LC-FPI with a cavity gap of $10\mu m$ the resonance wavelengths λ_{19} and λ_{20} are 1.58 and $1.50\mu m$. Here the n of the LC is assumed to be 1.5.

The tuning range of LC-FPI is $\lambda_m \Delta n / n$. A larger tuning range can be obtained by using LC with a large Δn . The simulated result for the dependence of the tuning

range on Δn is shown in Figure 5.3. The experimental values may be smaller than the simulation values because the LC molecules close to the surface may not realign even when sufficient voltage is applied. In order to obtain a tuning range of 80nm, the liquid crystal used is MLC-7800-100 ($n_e = 1.6060, n_o = 1.4911$), which has a birefringence of 0.1149.

Figure 5.3 Simulated results for the dependence of the tuning range on Δn .

Since the θ_i is significantly small, it can be ignored during the simulation. The transmission equation of a LC-FPI is given by [2]

$$T(\lambda) = \frac{T_{\max}}{1 + (4/\pi^2)F^2 \sin^2(2\pi nl/\lambda)} \quad (5.6)$$

where λ is the wavelength, F is the total finesse, and $T_{\max}$ is the maximum transmittance at the resonance wavelength. The total finesse (F) of an FPI is

determined by two finesesses: the reflection finesse (F_R) and the surface-defect finesse (F_S). F_R is determined by reflectivity of the substrate and cavity loss, and F_S is determined by the surface of the substrates. The total finesse F is given by [2]

$$\frac{1}{F^2} = \frac{1}{F_R^2} + \frac{1}{F_S^2} \quad (5.7)$$

Assuming that the substrate surface is free of defects, the transmittance $T_{\max}$ and the reflection finesse F_R are expressed as

$$T_{\max} = \frac{(1-R)^2 \tau}{(1-R\tau)^2}, \quad (5.8)$$

$$F_R = \frac{\pi\sqrt{R\tau}}{1-R\tau}, \quad (5.9)$$

$$\tau = \tau_M \times \exp(-\beta l), \quad (5.10)$$

where R is the reflectivity of the substrate, $1-\tau_M$ is the loss of the mirror, and β is the absorption coefficient of the LC.

The full width at half maximum (FWHM) is given by

$$\text{FWHM} = \frac{\text{FSR}}{F}. \quad (5.11)$$

The performance of the LC-FPI can be estimated from the above equations. It can be seen that the large scattering and absorption of the intracavity causes low transmittance, low finesse and large FWHM. Kawachi *et al.* reported that the absorption coefficient of LC was 0.5cm^{-1} at the $1.55\mu\text{m}$ band [71]. For a cavity gap

of $10\mu m$, the LC loss is estimated to be 5×10^{-4} . The mirror loss is estimated to be 6×10^{-4} [2].

In the design, the substrate reflectivity is chosen to be 93.5% for a cavity gap of $10\mu m$. The reflection finesse is calculated to be 46 and the simulated maximum transmittance is 97%. The surface defect finesse depends on the curvature, waviness, roughness and parallelism of the substrates. Based on reference [2], the defect finesse is taken as 150 for the simulation, and then the total finesse F can be calculated to be 44. The transmission curve of the LC-FPI is shown in Figure 5.4.

Figure 5.4 The simulated transmission curve of the LC-FPI.

In the above theoretical simulation, the effect of the ITO electrode is ignored. The transmittance of ITO transparent electrode is close to 100% in the visible wavelength

band. The transmittance decreases with the increasing of the wavelength above $1.0\ \mu\text{m}$. In the design, a thin ITO electrode is deposited on the glass substrate with a transmittance of about 96% for the near infrared band. Thus the actual transmittance of the LC-FPI is expected to be reduced by 8% due to the ITO loss.

5.2.2 Fabrication of LC-FPI

The proposed LC-FPI is fabricated in Class 1000 clean room. The schematic of LC-FPI fabrication is shown in Figure 5.5. The two substrates are Bk7 glass. The transparent electrode and the dielectric mirror with reflectivity of 93.5% are deposited on the inner side of the substrates. The outer sides are AR coated with reflectivity less than 0.2% for near infrared band. The substrates are then cleaned with standard glass cleaning process that includes ultrasonic cleaning with detergent, ultrasonic cleaning and spray with DI water and thermo-dry. The Sunever 130 (SE-130) alignment layer is spun coated to the substrates at 3000rpm for 30 seconds and baked in the oven at 200°C for 60 minutes. The substrates are rubbed mechanically. A program control drawing machine is used to draw the sealing border on one of the substrate. The sealant applied is a mixture of $10\ \mu\text{m}$ spacers in epoxy sealant XN21-S. A dry type spacer spraying machine is employed to apply spacers of $10\ \mu\text{m}$ to the other substrate. Two substrates are assembled together and the rubbing direction of the two substrates are antiparallel to each other. The epoxy sealing border of the cell is cured at $150\ ^{\circ}\text{C}$ for 90 minutes using a hot press machine. MLC-7800-100 is filled into the cell by the air pressure. Since the uniformity of the cell gap of the LC-FPI is critical for its performance. Before the end seal, the LC cell is vacuum pressed to adjust the cell gap uniformity. A-720 UV sealant is used to cure the

injection hole. Then the whole cell is then heated to 105 °C which is higher than the clearing point of the liquid crystal to make it isotropic. The cell is then slowly cooled to room temperature. The size of fabricated LC-FPI is 35mm×32mm and the clear aperture diameter is about 20mm. Three LC-FPIs were fabricated as shown in Figure 5.5 and their optical characteristics were examined. Figure 5.6 shows the photograph of the fabricated LC-FPI.

Figure5.5 Schematic diagram representing process steps of LC-FPI fabrication: (a) Clean the substrate; (b) Spin coating polyimide; (c) Bake the polyimide; (d) Rub the alignment layer mechanically; (e) Draw the sealant with spacers on one substrate and spray spacers to another; (f) Mate two substrates and cure the adhesive; (g) Fill in LC to assemble a cell.

Figure 5.6 The photograph of the custom- fabricated LC-FPI.

5.2.3 Characteristics of LC-FPI

The experimental setup for the optical characterization of the LC-FPI is illustrated in Figure 5.7. A super luminescent diode from an Optical Spectrum Analyzer (Anritsu MS9701B) is used as broadband light source and has a peak wavelength at 1530nm. The bandwidth of the light source is $\cong 90\text{nm}$. The light is coupled by a fiber collimator of $100\text{ }\mu\text{m}$ in diameter. Since the optical properties of the LC-FPI are dependent on the polarization of the input light, a polarizer is placed in front of the LC-FPI. The polarization direction of the polarizer is parallel to the rubbing direction of the LC-FPI. The LC-FPI sample is mounted on a rotational stage and carefully adjusted to tilt slightly with respect to the resonator axis. The light passing through the LC-FPI sample will be collected by a fiber coupler and analyzed by the optical spectrum analyzer (OSA). The transmission spectra of the filters are measured when different voltages are applied. Square wave AC voltage with a frequency of 20kHz is applied to the LC-FPI using a function generator (Agilent

33250A). A lower frequency ac voltage degrades the LC-FPI performance because the LC molecules fluctuate.

Figure 5.7 Schematic diagram of the experimental setup for optical characterization of LC-FPI.

All the three fabricated LC-FPIs are tested using the same experimental setup. The transmission spectra of the LC-FPIs are shown in Figure 5.8 (a)-(f).

(a)

(b)

Transmission spectrum of #1 LC-FPI (a) FSR = 67.5nm (b) FWHM=1.56nm

(c)

(d)

Transmission spectrum of #2 LC-FPI (c) FSR = 67.8nm (d) FWHM=1.8nm

(e)

(f)

Transmission spectrum of #3 LC-FPI (e) FSR = 67.7nm (f) FWHM=3.0nm

Figure 5.8 Transmission spectra of the three LC-FPIs.

Table 5.1 shows the performance of all the three LC-FPIs with respect to Figure 5.7 (a-f). It can be seen that the #1 LC-FPI has the smallest FWHM and highest Finesse. Hence it is chosen to be the tunable filter in the external cavity. The measured FSR value is lower than the simulated results. This is because the actual cavity thickness of the LC-FPI is about $11.1\text{ }\mu\text{m}$ which is larger than $10\text{ }\mu\text{m}$. The decrease in finesse compared to the calculated value could be due to the deviation of the cavity thickness that is caused by the non-uniform substrate surface and the insufficient parallelism between two substrates.

Table 5.1 The performance of the three LC-FPIs.

LC-FPI	FSR (nm)	FWHM (nm)	Finesse (F)
Simulated results	80	1.82	44
#1	67.5	1.56	43.2
#2	67.8	1.8	37.5
#3	67.6	3	22.5

Figure 5.9 shows the tuning characteristics of the LC-FPI #1. The threshold voltage of the LC-FPI is 1.8V. When the applied voltage exceeds the threshold voltage, with the increasing of the voltage, the resonance wavelength decreases.

The insertion loss of the LC-FPI is measured to be about 4.9dB. The response time of the LC-FPI depends on the cavity gap, and the LC material. It required a longer time to tune from shorter to a longer wavelength because the turn-off time of the LC is longer than the turn-on time. The response time of the LC-FPI is measured to be

about 125ms. The response time can be improved by choosing a LC with smaller viscosity-to-elasticity (η/K) ratio [2].

Figure 5.9 Resonance wavelength versus applied voltage.

If tuning is done by LC-FPI alone, severe degradations SMSR will be observed whenever modes are about to hop. In order to satisfy both continuous tuning and high SMSR over the tuning range, a fine tuner is proposed to be used together with the LC-FPI. The function of the fine tuner is to change the optical length of the tunable ECL, which in turn changes the resonance frequency of the external cavity modes.

5.3 Fine Tuner

For tunable ECLs, the resonance wavelength occurs at $2n_cL/m$, where n_c is the refractive index of the laser cavity, L is the length of the whole laser cavity, c is the velocity of light, and m is an integer. Hence, the longitudinal mode interval of a tunable ECL is $c/2n_cL$.

The function of the fine tuner is to adjust the resonance wavelength within a longitudinal mode interval by changing the optical length of the cavity.

5.2.1 Theoretical Design of Fine Tuner

The proposed fine tuner configuration is as shown in Figure 5.10. A nematic LC layer is sandwiched between two glass plates, on which alignment films, indium tin oxide (ITO) transparent electrodes, are deposited. An electric field is applied to the LC via ITO electrodes deposited upon the inner sides of the glass plates. The outer sides are coated with an antireflective coating. It can be seen that the main difference between LC-FPI and the fine tuner is that the LC-FPI has a high reflection coating on the top of ITO layer.

Figure 5.10 The structure of the fine tuner.

When the voltage is applied, the refractive index of the LC gradually changes from n_e to n_o , which results in the change of optical length of the tunable ECL cavity. Assuming the incident beam is normal to the fine tuner, hence the resonance frequency can be expressed as:

$$\nu_m = \frac{mc}{2(n_c L_0 + n_{lc} l_f)} \quad (5.12)$$

where n_{lc} is the refractive index of the liquid crystal in fine tuner, L_0 is the constant part of the laser cavity length, l_f is the cavity length of fine tuner, and $n_c L_0 + n_{lc} l_f = n_c L$. Hence,

$$\delta \nu_m = \frac{m c l_f}{2(n_c L_0 + n_{lc} l_f)^2} \delta n_{lc} \quad (5.13)$$

In order to obtain continuous tuning, the tunable range of the fine tuner should be larger than a longitudinal mode interval of the external cavity modes, so

$$\frac{m c l_f}{2(n_c L_0 + n_{lc} l_f)^2} \delta n_{lc} > \frac{c}{2(n_c L_0 + n_{lc} l_f)} \Rightarrow \frac{2l_f}{\lambda_m} \delta n_{lc} > 1 \quad (5.14)$$

Take $\lambda_m = 1.55 \mu m$, from equation (5.14),

$$\delta n_{lc} \cdot l_f > 0.775 \mu m \quad (5.15)$$

For a given Δn of liquid crystal of about 0.2, from equation (5.15), l_f is calculated to be greater than $3.875 \mu m$. Due to the available spacer size of $3 \mu m$, $6 \mu m$, $10 \mu m$ and $30 \mu m$, a thickness of $6 \mu m$ is selected for the LC layer in the design.

5.2.2 Fabrication and Performance of Fine Tuner

The fabrication process of the fine tuner is similar to that of the LC-FPI. For the fabricated fine tuner, the substrates are made of ITO glass. The outside of the substrates is AR coated with the reflectivity less than 0.2% for near infrared band. The SE-130 alignment layers are deposited on these glass substrates. The rubbing directions of the two substrates are antiparallel. Spacers of $6\text{ }\mu\text{m}$ are used to create the cavity gap of the fine tuner. The nematic LC used is Merck E63 ($n_e = 1.7444, n_o = 1.5172$). Figure 5.11 shows the fabricated fine tuner. It has a clear aperture diameter of 20mm and its measured insertion loss is about 0.2dB. The response time is measured to be about 27ms.

Figure 5.11 The photograph of the custom-fabricated fine tuner.

5.4 Single Mode External Cavity Laser with Fine Tuning

A tunable ECL based on a tuning mechanism combining coarse tuning and fine tuning is proposed. The LC-FPI is used to obtain mode-hopping tuning and the continuous tuning can be fulfilled by the fine tuner. The electronically tunable ECL

has wide tuning range, and is simple in structure for easy fabrication. Based on the discussion in chapter 4, the gain chip and the collimating lens are chosen.

5.4.1 Configuration

The schematic diagram of the proposed electronically tunable ECL based on LC elements is shown in Figure 5.12. The gain chip is a stripe guide multiple-quantum-well InGaAsP/InP device having a dimension of $300\mu m \times 250\mu m \times 100\mu m$ from DenseLight, Singapore. The back facet has a high reflection coating and a reflectivity of 90%. The light from the back facet is coupled to an optical fiber to monitor the laser output. The facet that faces the lens is antireflection coated and has a residual reflectivity of 0.16%. The lens collimates the output of the gain chip to the free space mode of the external cavity. The collimating lens is antireflection coated, has a focal length of 4.55mm and a numerical aperture of 0.55. An electro-optically tuned Fabry-Perot interferometer, made of liquid crystal, creates multiple-beam interference inside the laser cavity and exhibits a transmission peak to determine the lasing wavelength. The tuning is achieved by changing the voltage applied to it. A fine tuner is proposed to slightly modify the cavity length to get the continuous tuning within a longitudinal mode interval. It assists in tuning the wavelength in a small amount to avoid mode-hopping caused by the cavity modes. A partial-reflection coated exit mirror with reflectivity of 85% (Photonik, Singapore) feeds part of the beam back to the gain chip to complete the lasing cavity and allows the rest of the beam passing through the mirror.

Figure 5.12 Schematic diagram of tunable ECL based on LC elements.

5.4.2 Basic Principle

The wavelength tuning of the tunable ECL is the combination of the mode hopping and continuous tuning as shown in Figure 5.13. The LC-FPI is the coarse tuner, which fulfills the tuning based on mode hopping. By changing the applied voltage to the LC layer, the transmission peak of the LC-FPI can be controlled. Continuous tuning can be achieved by the fine tuner. It varies the cavity length to shift the positions of cavity modes. Hence the wavelength can be tuned smoothly within a longitudinal mode interval. The wavelength selection is done in the following way. The transmission peak of the LC-FPI is tuned by changing the applied voltage. Then the applied voltage to the fine tuner is tuned so that one of the cavity modes is aligned optimally to the LC-FPI's transmission peak.

Figure 5.13 Schematic of the wavelength selection principle of the tunable ECL using LC elements.

As the gain of the semiconductor medium is strongly coupled to its index of refraction, threshold gain ripple caused by the diode-cavity etalon effect gives rise to a number of undesirable phenomena such as bistability, tuning nonlinearities, and in some cases axial mode instabilities [16]. In order to avoid these problems, it is very desirable to operate a tunable external cavity laser in the strong feedback regime. On the other side, strong external feedback also improves the ability to obtain single-mode oscillation without mode-hopping instability and the fidelity with which the oscillation wavelength tracks the peak feedback wavelength. As for the extended cavity feedback model shown in Figure 2.3, for strong feedback it needs $r_3^2 \gg r_2^2$. For the design, the facet faces the collimating lens is AR coated with a reflectivity of 0.16%, that is $r_2^2 = 0.16\%$.

For the tunable ECL, one-way coupling efficiencies for good large-aperture coupling lenses are typically in the range of 50%-70%. Therefore, assuming no other intracavity losses the maximum round-trip feedback efficiency is limited to the range of 25% to 50% by the coupling lens [16]. The insertion losses of the LC-FPI and the fine tuner are 4.9dB and 0.2 dB. Hence, the round-trip insertion loss from the tuning element is 10.2dB. In order to get high feedback efficiency and allow part of the beam passing through mirror as the output, a partial reflection mirror with a reflectivity of 85% is chosen. Then the overall feedback efficiency is about 4%.

The coupling coefficient ξ is given by [26]

$$\xi = r_3(1 - r_2^2) / r_2 = 4.99 .$$

The external feedback strength is defined as

$$C = (\tau_L / \tau_d) \xi \sqrt{1 + \alpha_1^2} ,$$

where τ_L is round-trip delay of the external cavity given by $\tau_L = 2L / c_0$, $\tau_d = 2nd / c_0$ is the round-trip delay of the laser cavity, α_1 is a linewidth enhancement factor (typical value ranges from 4 to 7). For the gain chip the cavity length is $300 \mu m$ and the refractive index is about 3.3 [88]. The external cavity length is designed to be about 3cm. When α_1 is equal to 6, then the external feedback strength C is calculated to be 920. Since $C \gg 1$, the tunable ECL has strong external feedback.

5.4.3 Performance of the Tunable ECL with LC-FPI and Fine tuner

The tunable ECL is set up and mounted upon a baseplate. The gain chip and the optical fiber are packaged together to monitor the output of the tunable ECL. Laser diode controller LDC500 (Thorlabs) is employed to inject current to the gain chip. The light from the back facet of the gain chip is collected and analyzed by an optical spectrum Analyzer (MS9701B, Anritsu). Firstly, the lens is fixed to collimate the output of gain chip. Then the partial reflection mirror is mounted on a manufactured 3-axis rotational stage and carefully adjusted to feed the part of the beam back to the gain chip. With that an ECL with fixed wavelength as shown in Figure 5.14 is set up.

Figure 5.14 The ECL with fixed wavelength.

For the above ECL the feedback efficiency is about 42%. Figure 5.15 shows the output spectra of the ECL with an injection current of 55mA to the gain chip. The oscillation wavelength is 1515.8nm and the threshold current of the ECL is about 40mA. Since it is a strong feedback and there is no filter, the laser oscillation is fully determined by the gain profile and the external cavity longitudinal modes. The experimental results show that the SMSR is about 10dB and the oscillation wavelength is not stable.

Figure 5.15 The output spectra of the ECL with fixed wavelength.

The LC-FPI and fine tuner are then inserted into the cavity. The distance from the LC-FPI to the mirror is ~6mm. The cavity length is about 3.6cm and the external cavity mode spacing is ~4.2GHz. Two function generators (WAVETEK 90 and Agilent 33250A) are employed to apply driving voltage to LC-FPI and fine tuner respectively. The rubbing directions of the LC-FPI and the fine tuner are parallel to the output polarization direction of the gain chip. In order to prevent the beam lasing off the surface of the LC-FPI, the LC-FPI is tilted slightly with respect to the resonator axis. The optical spectrum analyzer (Anritsu MS9701B) is used to measure the output spectra of the tunable ECL. Figure 5.16 shows the setup of the developed tunable ECL based on LC elements.

Figure 5.16 The setup of the developed tunable ECL based on LC elements.

Since the insertion losses of the LC elements are large, the injection current to the gain chip needs to be high to get the system lasing. The gain profile of the gain chip with 80mA injection current is shown in Figure 5.17, which is obtained by measuring the amplified spontaneous emission (ASE) spectrum. The 3-dB width of the gain chip is ~45nm (1480-1525nm). It is observed that there is a certain oscillation in the curve. It is likely due to the interference of the parasitic reflection of two facets of the gain chip.

Figure 5.17 the gain profile of the gain chip with injection current of 80mA.

The wavelength tuning of the tunable ECL is done in two stages. First, through changing the applied voltage to the LC-FPI the lasing wavelength is tuned. Then the fine tuner is tuned such that one of the cavity modes is aligned optimally to the LC-FPI transmission peak, thus one of the longitudinal modes can be dominant and maximum SMSR can be obtained. In order to align one of the transmission peaks to the long wavelength of the bandwidth of the gain chip, the initial applied voltage to LC-FPI is $V_{FPI} = 4.7V$ and the applied voltage to the fine tuner is $V_{FT} = 8.9V$. With that, the oscillation wavelength is at 1525.52nm as shown in Figure 5.18. When the applied voltage to the LC-FPI is increased, the lasing wavelength will decrease. When the V_{FPI} increases to 13.5V and the V_{FT} is 5.2V, the oscillation wavelength is 1484.76nm as shown in Figure 5.19. With further increase of V_{FPI} , the other transmission peak of the LC-FPI begin to lase due to the gain profile of the gain chip.

Figure 5.18 The output spectra with $V_{FPI} = 4.7V$ and $V_{FT} = 8.9V$.

Figure 5.19 The output spectra with $V_{FPI} = 13.5V$ and $V_{FT} = 5.2V$.

Figure 5.20 shows the spectra obtained at different applied voltages to LC-FPI and fine tuner with an injection current of 80mA to the gain chip. Through controlling

the applied voltages to the LC-FPI and fine tuner, the output maintains single mode operation over the whole tuning range. A coarse tuning range of 40nm is obtained and the output beam from the partial reflection mirror has a power of 0.04mW. The low output power is mainly due to the low efficiency of the gain chip and the high insertion loss of the LC-FPI.

Figure 5.20 Output spectra at different applied voltages.

Figure 5.21 shows the variation of the output wavelength with the change of the applied voltage to the LC-FPI under different voltages to the fine tuner. It can be seen that the wavelength is tuned asymptotically with the increasing of the applied voltage.

Figure 5.21 Laser wavelength versus the LC-FPI voltage.

In order to demonstrate the continuous tuning between the adjacent longitudinal modes, an experiment was carried out with fixed voltage applied to the LC-FPI. Figure 5.22 gives an example of the effect of fine tuning. It also shows that by adjusting the voltage to the fine tuner, the SMSR can be improved. In this figure, the applied voltage to the LC-FPI is fixed at 8.186V. When no voltage is applied to the fine tuner, the SMSR is about 11.7dB as shown in Figure 5.22 (a). By changing the applied voltage to the fine tuner, the SMSR can be improved. It is observed that there exist two voltage values that high SMSR can be obtained while the lasing wavelengths at these two voltages remain the same. When the applied voltage to the fine tuner is 6.2V, the SMSR of 22.17dB is obtained and the peak wavelength is 1503.302nm as shown in Figure 5.22 (b). When the applied voltage to the fine tuner is 13.06V, the peak wavelength is 1503.302nm and the SMSR is about 25.12dB as shown in Figure 5.22 (c). This shows that at these two voltages, the lasing happens

at two adjacent longitudinal modes, i.e. continuous tuning over a longitudinal mode interval could be achieved through controlling the applied voltage to the fine tuner.

(a)

(b)

Figure 5.22 The output spectra of the tunable ECL (a) $V_{FT} = 0V$ (b) $V_{FT} = 6.2V$ (c) $V_{FT} = 13.06V$.

Theoretically, by controlling the applied voltages to the LC-FPI and fine tuner continuous tuning over the whole tuning range can be obtained. However, the experiments show that the gain ripples affect the tuning characteristics. There exist some wavelength gaps that the tuning cannot reach. In the future work, a phase control section can be integrated with the gain chip to control the position of the gain ripple. By controlling the applied voltages to the LC-FPI and the fine tuner, and the injection current to the phase section, fully continuous tuning over the tuning range can be obtained.

The SMSR of the lasing wavelengths is measured by checking the spectrum. Figure 5.23 shows that SMSR is about 25dB over the whole tuning range. The center wavelengths have higher SMSR than that of the side wavelengths. This is due to the gain profile of the gain chip.

Figure 5.23 SMSR as a function of wavelength.

Figure 5.24 shows the fiber-coupled power versus the injection current. It can be seen that the threshold current is 65mA. Beyond that, the output power is found to increase linearly until the injection current reaches 90mA.

Figure 5.24 Fiber coupled power versus injection current.

5.5 Summary

In this chapter, a novel tunable laser device with fine tuning is demonstrated by using an electronically controlled LC-FPI and a fine tuner. Applying voltage to the LC-FPI gets the mode hopping tuning over the tuning range. The fine tuning between the adjacent longitudinal modes can be obtained by changing voltage applied to the fine tuner. The power consumption of the LC-FPI and fine tuner is less than 10mW and 47mW respectively. The fabrication of the tuning elements is compatible with standard processing. A coarse wavelength tuning range of 40nm and an average SMSR of about 25dB were obtained with a driving voltage of less than 15V and 10V to the LC-FPI and fine tuner respectively. In order to obtain higher SMSR, LC-FPI with smaller FWHM can be used. The tunable laser system has the advantages of wide tuning range, simple structure, and low driving voltage.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This chapter concludes the research work entitled ‘Investigation on liquid crystal based tuning elements for tunable diode laser’ by highlighting the significant research findings as given below:

The basic principle and tuning mechanisms of the tunable ECLs are investigated. A literature review of the current tunable ECLs has been carried out, which suggested that electronically tunable ECLs that are simple in configuration, easy to fabricate and low in power consumption offer advantages. Due to the unique electro-optical properties of liquid crystals (LCs), the refractive indices of LCs can be tuned by low electrical signals due to the weak interactions between LC molecules. Hence, LCs were used to fabricate the tuning elements in this project.

In this context, three novel configurations of tunable ECL using LC tuning elements are presented, which are LC deflector as the tuning element, LC deflector with the ITU etalon as the tuning elements and LC-FPI and fine tuner as the tuning elements.

Theoretical design of a LC deflector was carried out based on the birefringence properties of the LC. The operational mechanism of the LC deflector basically uses

the dielectric wedge prism to achieve a voltage controlled steering angle. The LC deflector was fabricated and tested. A tunable ECL that uses an electro-optic tuning mechanism based on the LC deflector combined with a diffraction grating was proposed. Applying a voltage to the deflector steers the light beam and consequently changes the incident angle onto the grating. The wavelength tuning mechanism is based on the wavelength-dependent angular sensitivity combined with the angular deflection from the LC deflector. The tunable ECL is set up and mounted upon a baseplate. A wavelength tuning range of 12nm and a SMSR of more than 30dB were obtained with a driving voltage of less than 9V.

For the applications in DWDM systems, the laser wavelengths need to be tuned to match the ITU grids. An ITU wavelength tunable ECL is demonstrated, which includes a fixed etalon inside the cavity laser and makes use of the LC deflector. An etalon is inserted in the external cavity to act as a frequency-periodic transmission filter. Applying the voltage to the LC deflector, the lasing wavelength can be tuned to 19 wavelength channels of 100GHz spacing. The driving voltage is less than 15V and the SMSR of each channel is about 35dB. By calibrating the applied voltage to the LC deflector, the tunable ECL can be a digitally tunable system to output desired ITU wavelength. The device only requires one parameter, applied voltage to the LC deflector, to tune the wavelength matching ITU grids.

For the tunable ECLs based on LC deflector, they are simple in structure, easily operated and have low power consumption. However, the tuning speeds of the systems are slow as the response time of the LC deflector is estimated to be about 1s.

With respect to the slow tuning speed, these types of tunable ECLs find applications such as for sparing and provisioning [89].

A tunable ECL with fine tuning using LC tuning elements was demonstrated. A LC-FPI and a fine tuner are designed and fabricated. Applying voltage to the LC-FPI gets the mode hopping tuning, and the continuous tuning can be obtained by changing voltage applied to fine tuner. A coarse wavelength tuning range of 40nm and an average SMSR of about 25dB were obtained with a driving voltage of less than 15V and 10V to the LC-FPI and fine tuner respectively. The continuous tuning between the adjacent longitudinal modes was demonstrated. The tunable ECL has the advantages of high compactness, wide tuning range and low driving voltage.

6.2 Recommendations for Future Work

In order to enhance key laser performance characteristics of the tunable ECLs such as wavelength switching speed, wavelength tuning range, amplitude stability, spectral stability and output powers, the following future work are recommended:

Since the temperature controller (TEC) is not built in for the gain chip, the gain chip cannot work for a long time with high injection current. In order to improve the performance of the gain chip, a TEC can be packaged with the gain chip and optical fiber.

The response time of the LC deflector is of the order of 1s. In order to improve the tuning speed of the laser system, multi-stage LC deflector that use LCs with high

birefringence and low viscosity can be designed. By controlling the applied voltage to each stage of the deflector, large wavelength tuning range can be obtained.

For the ITU wavelength tunable ECL, the fine tuner can be added to the cavity to get the fine tuning. Through changing the applied voltage to the fine tuner, the lasing wavelength can be tuned to match to the ITU grids more accurately.

For the fabricated LC-FPI, it is polarization dependent and the response time is about 127ms. It was reported that the FPI filter can be developed using a polymer containing fine droplet of nematic LC smaller than 100nm [90]. The advantages of that FPI filter are that they are polarization independent and promote fast switching. Therefore it is worth exploring the potential of developing the FPI using other LC materials.

For the tunable ECL based on LC-FPI and fine tuner, a phase section can be introduced to control the positions of the gain ripple, thus fully continuous tuning over the whole tuning range can be achieved.

The output power of the tunable ECLs is relatively small due to the efficiency of the gain chip and the coupling efficiency of the optical fiber. A gain chip with better performance can be used to improve the output power of the laser systems. Furthermore, the coupling efficiency can be improved by using AR coated optical fiber and coupling micro-lenses at the optical fiber end.

The design principles discussed in this thesis can also be used to develop the tunable ECL for other spectral ranges by using different gain media.

The proposed tunable ECLs have the potential to be used in WDM systems. They can provide wavelengths ‘on demand’ and dynamically adapt to real time traffic pattern, facilitating wavelength addressing and switching. In addition, they help to reduce inventory by reducing the need to stock lasers for every single wavelength. The continuously tunable ECLs are also suitable as sources for gas sensing systems using absorption spectroscopy. The tunable ECLs can also be applied in depth sensitive interrogating system.

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APPENDIX

THE SPECIFICATIONS OF THE COATINGS

The specifications of the coatings including the ITO coating, the antireflection coating and the high reflection coating are given. Figure A1 shows the transmission curve of the ITO coating. It can be seen that the transmittance of the ITO for near infrared band is about 96%. The reflection curve of the antireflection coating is shown in Figure A2. The reflectivity is less than 0.2% for 1500nm-1600nm. Figure A3 shows the reflection curve of the high reflection curve. The reflectivity is about 93.5% for 1550nm-1600nm.

Figure A1. The transmission curve of the ITO coating.

Figure A2. The reflection curve of the AR coating.

Figure A3. The reflection curve of the HR coating.

LIST OF PUBLICATIONS

Journal Paper

P. Wang, L. K. Seah, V. M. Murukeshan, and Z. X. Chao. "External-cavity wavelength tunable laser with an electro-optic deflector", *Applied Optics*, Vol 45, No 34, 2006, pp 8772-8776

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L. K. Seah, V. M. Murukeshan, **P. Wang**, and Z. X. Chao. A tunable external cavity laser based on liquid crystal Fabry-Perot interferometer and liquid crystal phase shifter, *International Journal of Optomechatronics*, Vol 1, No. 1, 2007, pp63-72

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Conference Paper

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