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MICROMACHINED TUNABLE LASER SOURCES - DESIGN, FABRICATION AND EXPERIMENTS

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A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of
Doctor of Philosophy

2010

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Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

08-Nov-2011

Date

Cai Hong

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SUMMARY

This doctorate thesis focuses on the design, fabrication and experiments of micromachined tunable laser sources using microelectromechanical systems (MEMS) technology. Specifically, three different types of micromachined tunable laser schemes are investigated: external cavity tunable lasers, coupled-cavity tunable lasers, and injection-locked lasers.

For the external cavity tunable lasers (ECTLs), physical and mathematical models of external Fabry-Pérot (FP) cavity based tunable lasers are derived. A feedback model for predicting wavelength tuning is established. Besides, a micro-optical system is designed to provide an effective coupling external cavity for optical performance enhancement. A bi-directional comb-drive actuator is designed. It provides the micro-mirror with flexibility of linearly displacement and enables fine wavelength tuning. Additionally, a deep reactive ion etching (DRIE) fabrication process is developed for tunable lasers fabrication on a silicon-on-insulator wafer.

For the coupled-cavity lasers (CCLs), an equivalent model of micromachined CCLs is derived. Further incorporation of threshold condition analyses enables the prediction of the improved device performance. Based on the theoretical study, a micromachined CCL with micro-mirror configuration is designed and fabricated. The measured tuning speed is 1.2 μ s. It can tune over 51.3 nm while maintaining single longitudinal mode with an average side mode suppression ratio (SMSR) > 19 dB.

For the injection-locked lasers (ILLs), a theoretical model of micromachined ILL is developed to analyze the optical locking properties such as stability and hysteresis. The micromachined injection-locked laser is designed and fabricated. According to experimental results, locking states with a SMSR of more than 25 dB,

all optical switching up to 100 MHz and a lockable spectrum range of 41.24 nm are achieved. Locking properties are examined and analyzed. The effects of injection power and wavelength detuning are also investigated.

Three different types of micromachined tunable lasers are designed, fabricated and experimented. The successful implementations of these micromachined lasers further confirm the effectiveness of MEMS technology to tunable lasers in enhancing the specifications and performances.

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CHAPTER 1

INTRODUCTION

1.1 Motivation

This PhD research topic is motivated by the potential of microelectromechanical systems (MEMS) technology in improving the performance of tunable lasers. The miniaturization of MEMS technology not only paves the way for technological innovations, but also incubates physical discoveries. Specifically, MEMS technology has enabled the evolution of tunable lasers from large desk-top devices into transistor-sized ones with low cost, high capacity, high reliability and stability.

Wavelength tunable lasers have attracted considerable research interest for some time [1-3]. They are used as light sources for many applications, ranging from fiber optic telecommunication systems to broadband sensors. They are the key enabler for dense wavelength division multiplexing (DWDM) systems and all optical networks (AONs) in optical communications. For example, combined with passive wavelength routers, tunable lasers are capable of switching and routing optical signals in full-mesh AONs in the absence of optical crossconnects (OXC) [2]. Such capability of passive wavelength switching becomes particularly important when thousands of different optical channels are involved in large-scale all-optical switching. Indeed, tunable lasers with simple tuning method, wide tuning range, small size and high integration have grown into a critical research topic.

There are mainly three different tuning methods such as temperature tuning, current tuning and mechanical tuning. The principle of tuning lies on varying the effective length of light path within a laser cavity. The temperature and current tuning methods vary the refractive index of the laser internal cavity by changing temperature and current density, respectively. Examples include multisection distributed feedback lasers (DFBs), distributed Bragg reflector lasers (DBRs) and coupled-cavity tunable devices [4-6]. The temperature tuning method bears inherent limitations of slow tuning speed and small tuning range because it takes time for the temperature to transmit within the laser active region (especially in cooling process). The lasers temperature dependent coefficient is typically very small ($\sim 0.02 \text{ nm}^\circ\text{C}$). Additionally, a higher temperature also tends to deteriorate the laser performance and stability. The current tuning method has fast tuning speed, ideal single-mode and tuning performance, but it suffers from large power fluctuation, and limited wavelength tuning range due to small changing range of refractive index. The mechanical tuning method avoids these problems by introducing an external cavity to the laser and modifying the length of the external cavity directly [7]. Among all the three different methods, the external cavity tunable laser (ECTL) is leading the main stream because of simple configuration, wide tuning range, high spectrum purity, large output power and single mode operation. Furthermore, ECTL has other advantages such as narrow linewidth ($\sim 1 \text{ kHz}$) and high sidemode suppression ratio ($> 30 \text{ dB}$). In general, the wavelength tuning of ECTLs is obtained by using a mechanically movable (rotation and/or translation) mirror or grating. Usually, the movement accuracy of less than one tenth of the wavelength is required. It is challenging for the conventional ECTLs, which have to use complicated mechanical structures such as bearings, levers, hinges, and piezomechanical translators to meet

the accuracy requirement. The conventional ECTLs are bulky, slow and exhibit less mechanical reliability [8-10]. For example, a conventional ECTL is as big as $400 \times 450 \times 200 \text{ mm}^3$ [11], and the switching time is as slow as 2 s. A comparison between the conventional ECTL and the MEMS tunable laser is shown in Table 1.1.

Table 1.1 Comparison of a typical conventional tunable laser with a MEMS tunable laser.

Specifications	Conventional tunable lasers [11]	MEMS based laser [12] PHOENIX™ 1000
Dimension	$400 \times 450 \times 200 \text{ mm}^3$	N.A.
Tuning range	38 nm (1528 nm -1563 nm)	40 nm (1515 nm -1565 nm)
Linewidth	10 MHz	1.0 MHz
Side mode suppression ratio	45 dB	50 dB
Switching time	2 s	2 ms
Output power	13 dBm	10 dBm
Relative intensity noise	-135 dB/Hz	-152 dB /Hz
Packaging	Hybrid packaging	Single chip packaging

In MEMS technology [13-19], deep reactive ion etching (DRIE) represents a breakthrough for MEMS tunable lasers. Various configurations with different external cavities such as external reflectors (i.e. mirrors, etalons and gratings), optical-coupling systems, laser chips (cleaved or coated), and integration methods (single-chip or hybrid) have been investigated. For instance, wavelength tuning can be achieved by mode locking in the Fabry-Perot (FP) lasers [13], or by discretely tuned filters [14], or by Vernier effect between the FP laser diodes and external filters [15]. ECTLs provide

another solution by controlling the external feedback [16]. The miniaturization of ECTLs using MEMS technology has attracted attention from MEMS research society, and some have even led to commercial success [17-19]. One of the key components of MEMS ECTLs is to use MEMS structures and actuation for wavelength tuning. Indeed, MEMS has its natural synergy with ECTLs in various aspects. For example, the length of a typical semiconductor chip is a few hundred micrometers, which is close to the overall size of a MEMS device (typically 1 mm, including all the function blocks such as microactuators and suspensions). The wavelength of most tunable lasers ranges from 0.4 μm to 2 μm , which is of the same order of magnitude as the MEMS fine feature. Some types of lasers require a displacement within a half wavelength to obtain the whole tuning range [17, 18], and such displacement can be easily performed by microactuators. In addition, the high precision and stable movement of the MEMS structures enable fine-tuning of the lasing wavelength with high repeatability. Moreover, micromechanical structures make it feasible to form extremely short external cavities ($<100\text{ }\mu\text{m}$), which is usually difficult for bulky optical components. Most applications such as optical communications and biomedical studies require tunable lasers with a wide tuning range ($>40\text{ nm}$), continuous or stepwise wavelength tuning, short response time ($<1\text{ ms}$), high accuracy/repeatability, high reliability/stability, light weight, easy integration and low cost. The introduction of MEMS to tunable lasers brings in significant improvement in most of these specifications. The small dimension of MEMS makes lasers light-weighted and portable, and further facilitates the formation of large arrays with enhanced mechanical-related properties such as tuning speed, tuning resolution and mechanical reliability/stability. The photolithography of MEMS fabrication process gives accurate positioning/alignment, batch fabrication, easy and compatible

integration with IC devices and low fabrication cost. Such fabrication not only provides MEMS mechanical flexures with complicated motions, but also allows the integration of mirrors/gratings, micro-actuators and coupling micro-optics onto a single chip. More importantly, the ability to construct short cavities makes it very promising to obtain a wide tuning range. MEMS technology provides a unique solution for simple, integrated and widely tunable lasers.

Although the MEMS tunable lasers and the conventional ECTLs follow the same general physical principle, they have different engineering behaviors. For example, the range of discrete tuning is found to be inversely proportional to the length of the external cavity. The tuning range can be quite large in MEMS ECTLs that possess very short cavity, which is too small for the conventional ECTLs. Besides, the wavelength tuning ability may not be so sensitive to coupling efficiency in the conventional long cavity ECTLs, and high coupling efficiency is relatively easy to achieve with advanced bulky optical components. However, the coupling efficiency is crucial for the MEMS tunable lasers because their external cavity length is in the micro-scale. It poses a fundamental challenge for the MEMS tunable lasers to achieve large wavelength tuning range.

Although the MEMS ECTLs have advantages over some other laser configurations, the wavelength tuning speed of the ECTLs is still limited by the mechanical motion of the external reflectors. Furthermore, their tuning range is limited by the inherent gain medium characteristics. Those limitations can be relaxed or removed mostly by using coupled-cavity laser configurations. Traditional coupled-cavity utilizes an all-active two-section Fabry-Pérot design with an intermediate etched groove to provide a coupled-cavity tunable structure [6, 20-23]. As the principle of such coupled-cavity lasers (CCLs) is based on the combination of free

carrier plasma effect and Vernier effect, large wavelength tunability at high speed is reasonable. However, the challenge remains in obtaining the optimal cavity coupling and phase matching at the same time, especially when the two coupled cavities have fixed cavity gaps as predetermined during fabrication. A better solution is to provide an adjustable gap for the coupling between the coupled-cavities. This potential solution will be explored and optimized in the PhD research work.

One of the drawbacks of the MEMS ECTLs is that output power cannot be very high compared to a bare laser chip since it is difficult to obtain high coupling efficiency between the laser internal cavity and external gratings/mirrors. A metal-coated surface can be burnt if power goes beyond certain limit. Although the bare laser chip provides high power, it is not tunable. Output commonly shows multiple longitudinal modes. As a result, the beam quality is not good and in turn it makes fiber coupling challenging. One preferred solution is to use injection locking where a MEMS tunable laser is used to optically lock the wavelength of the bare laser chip. This approach enables the resulted output of the bare laser chip to inherit the wavelength, phase and good beam quality from the tunable laser while maintaining high output power [24-26]. In addition to power enhancement, bandwidth is reduced and stability is improved. Besides high power applications, this MEMS injection-locked laser is also very useful in optical networks for coherent communication, all optical switching, wavelength conversion and all optical logic operation [27-29]. Another application is miniaturized atomic clocks, where the MEMS injection-locked laser is used as wavelength-stabilized light source. Comparable to the MEMS external cavity tunable lasers, the MEMS injection-locked lasers also bear the advantages of single-chip integration, compact size and fast tuning speed.

In summary, while MEMS technology helps to improve the performance of the tunable lasers at low-cost, it also facilitates the integration of the whole device onto a single chip. Overall, the MEMS-based tunable laser solution has been a goal actively pursued by both academia and industry, and is chosen as the topic of this thesis.

1.2 Objectives

The main objective of this research is to develop high performance MEMS-based tunable lasers. Three types of MEMS-based tunable lasers in different configurations will be developed, such as (1) external cavity tunable laser, (2) coupled-cavity tunable laser, and (3) injection-locked laser. The primary target is to improve wavelength tuning speed, wavelength purity and tuning stability. The investigation includes theoretical analyses, fabrication development and experimental study. The theoretical models and analyses for the three different tunable lasers will provide guidance in the designs of the corresponding tunable lasers, both mechanical and optical. A deep RIE (DRIE) process will be developed for fabricating the micromachined tunable lasers in this PhD project. The experimental studies will be carried out for characterizations and performance evaluations of the three micromachined lasers.

The MEMS external cavity tunable laser consists of a FP laser diode, an actuated curved mirror, an optical fiber and an output collection fiber. All components are integrated onto a single chip. A three dimensional (3D) micro-optical coupling system is proposed to improve optical coupling and wavelength tuning range. A fundamental analytical model of the wavelength tuning is derived. MEMS DRIE

fabrication processes are developed for the designed chips. The experimental results are discussed and compared with the theoretical analyses.

The coupled-cavity laser mainly consists of two identical laser chips and a movable parabolic mirror, through which an effective optical coupling between the two chips can be obtained by adjusting the gap between the two chips. The design theory is studied, and the effectiveness of the adjustable air gap is measured. Then, issues related to tunability such as tuning speed and wavelength tuning range are addressed.

The micromachined injection-locked laser consists of a micromachined external cavity tunable laser and a normal FP laser diode. The theoretical study of the injection locking focuses on the stability and hysteresis of the micromachined laser properties. The micromachined injection-locked laser is fabricated and integrated onto a single chip. The experimental results on the locking characteristics under single and multiple injections in various aspects are discussed, including the effect of wavelength detuning and optical power, bistability and all optical switching applications.

1.3 Major contributions of the thesis

The major contributions of this PhD thesis lie in various aspects of the theoretical analyses, designs, fabrications, and experiments of the three different types of MEMS tunable lasers. The details are listed below:

- 1) An extended feedback model for predicting the wavelength tuning is developed for the tunable laser that employs a micromachined movable mirror as the external reflector. This extended model is versatile and covers a large feedback range. Since most MEMS tunable lasers work under weak or

medium intensity optical feedback, the extended model is more suitable for MEMS tunable lasers (See Chapter 3).

- 2) A novel three dimensional (3D) micro-optical system, which employs a rod lens and a curved mirror is designed. Such a combination enables the formation of a highly effective coupled external cavity over a large range of cavity length, without the need of using conventional bulky optical components. The feedback coupling efficiency of such external cavity design can be improved by 10 times as compared to that of the conventional flat-mirror design. For the first time such a high coupling efficiency is achieved using micro-optical components (See Chapter 3).
- 3) Deep reactive ion etching (DRIE) fabrication processes are developed for MEMS tunable lasers. These DRIE processes can be used to fabricate high-aspect-ratio suspended structures and used for many other MEMS devices applications (See Chapter 3).
- 4) A MEMS external cavity tunable laser is designed, fabricated, integrated and characterized, with all the MEMS structures fabricated by the DRIE on a silicon-on-insulator wafer. The integrated laser has a layout of $1.5 \text{ mm} \times 1 \text{ mm}$ (not including the full length of the optical fiber) and can be tuned to sweep a wavelength range of 14.05 nm (See Chapter 3).
- 5) The theoretical model, with special reference to the micromachined coupled-cavity lasers, is developed. Particularly, the additional incorporation of the threshold condition analysis enables a precise prediction of the laser performance. It is shown that the MEMS coupled-cavity laser is able to obtain a wide wavelength tuning range with a low threshold when the

coupling gap between the two cavities is optimized. Improved by electrical tuning, the tuning speed of a coupled-cavity laser is much faster than that of the mechanically tuned ECTL (See Chapter 4).

- 6) A single chip micromachined coupled-cavity tunable laser is fabricated and experimentally characterized. The laser can be tuned over 51.3 nm while maintaining a single longitudinal mode with a side mode suppression ratio (SMSR) > 19.0 dB. The measured wavelength switching time is 1.2 μ s (See Chapter 4).
- 7) It is found and confirmed that the proposed MEMS design with an actively adjustable gap can solve the fundamental problem of phase matching in the conventional coupled-cavity lasers which have a predetermined gap. In Chapter 4, the importance of such actively adjustable gap is verified. The proposed MEMS design gives single mode output with high SMSR, improved mode selectivity and high output stability (See Chapter 4).
- 8) A generalized model of the optical injection locking is developed, and the static and dynamic properties are investigated. The model is valid for the full-scale variation ranges of optical injection power and injection current. It is able to deal with the case of multiple injections to a multimode laser and the evolution of the locking from the unlocked state to the fully locked state. Especially, it takes into account the effects of injection power ratio and wavelength detuning on the operating characteristics of injection locking lasers. The generalized model has the potential of analyzing some emerging applications such as injection-locking-based all optical switching, wavelength conversion, and optical data processing (See Chapter 5).

- 9) A micromachined injection-locked laser device is designed and fabricated. A MEMS tunable laser and a FP laser chip are integrated onto a chip. It can obtain a SMSR > 25 dB, with a lockable spectral range as wide as 41.24 nm. It is found that a higher optical injection power results in an increase of the bistable loop bandwidth (See Chapter 5).
- 10) In the experimental investigation of MEMS injection-locked laser, all-optical switching is achieved by using both control optical pulses and data optical pulses to lock the FP slave laser. After injection locking, data pulses are suppressed when the control signal is in the “on” state, and data can pass through when the control signal is in the “off” state. All-optical switching up to 100 MHz is demonstrated. Such a switching speed is much faster than the typical micromechanical optical switching time of the order of milliseconds (See Chapter 5).
- 11) An all-optical logic NOR logic gate is designed based on the micromachined injection-locked laser, and the proof-of-concept is demonstrated for the potential applications of MEMS-based all-optical logic operations. Such simple and efficient MEMS approach will find potential applications in next-generation optical communications (See Chapter 5).

1.4 Organization of the thesis

The thesis is organized into six chapters. The introduction of the thesis covers the motivation, objectives, and major contributions as presented in this chapter. The motivation section explains why and how the PhD research is carried out. The objectives state the main focus of this thesis, and the contributions section lists the

innovations and the important findings in both the theoretical and technological aspects.

In Chapter 2, literature of micromachined tunable lasers research, including categories of external-cavity, coupled-cavity and injection-locked lasers, is reviewed. All such important background work provides the guidance and impetus for the research, and also lays the technological foundations on which the work of this thesis is built.

In Chapter 3, design, fabrication and experiments of micromachined external cavity tunable lasers are presented. The theoretical analysis focuses primarily on an extended feedback model for the prediction of the wavelength tuning. A three dimensional (3D) micro-optical system for the external cavity laser is proposed to improve the optical coupling and wavelength tuning capability.

In Chapter 4, the design, fabrication and experiments of coupled-cavity tunable laser using MEMS technology are elaborated. The theoretical analysis considering the threshold condition and the adjustable gap is developed to optimize the wavelength tuning range. The experimental results of the coupled-cavity tunable laser are discussed. The tuning properties of the laser verify the effectiveness of the tuning method and the significance of the MEMS enabled adjustable gap.

Chapter 5 presents the design, fabrication and characterization of micromachined injection-locked lasers. The theoretical model of the injection-locked lasers is derived and discussed. Various locking properties, such as the lockable spectral range, the critical detuning and the hysteresis during the change of injection power are discussed. New features in the experiment are observed and explained. A show case of all-optical NOR logic gate is presented based on the micromachined injection-locked lasers.

Chapter 6 concludes and highlights the major contributions of this thesis.
Recommendations of the future work follow.

CHAPTER 2

LITERATURE SURVEY

This chapter presents a review of micromachined tunable lasers technologies, as foundations to microelectromechanical systems (MEMS) based tunable lasers to be developed in this thesis. A general survey on various aspects of tunable lasers is firstly presented, including the basic principles, research milestones, current problems and opportunities for different configurations of external cavity tunable lasers, coupled-cavity lasers and injection-locked lasers. Additionally, the pros and cons of various existing wavelength tuning methods available are discussed and compared. The second part of this chapter focuses on the review of developments and recent progresses on micromachined tunable lasers. All such ground work therefore lays foundation for the contributions of this thesis in the development of MEMS-based tunable lasers.

2.1 Basic principles of tunable lasers

Tunable lasers refer to lasers whose output wavelength (or frequency) can be adjusted by certain means. Lasers wavelength tuning started to attract research attention soon after the invention of lasers and boomed up in the following decades as they are indispensable for a wide range of applications, including optical communications, biophysics and bioengineering, spectroscopic analysis and military applications. Especially, in the 1990s, telecommunication and information applications began to drive significant investments into the field of tunable lasers to

support the perceived need for dynamic networks and wavelength reconfigurability in wavelength division multiplexing (WDM) systems. Thus, wavelength tunable lasers are among the key components to build reconfigurable optical networks and in demand of cost-effective and compact telecommunications infrastructures. Particularly, the provision of laser sources with precise emission wavelengths becomes a great challenge in setting up any WDM network. Furthermore, a broadband tunable laser with high purity emission spectrum is a versatile tool for many sensing applications. However, free-running laser diodes usually tend toward simultaneous operation in many closely spaced longitudinal modes, yielding a multi-mode emission spectrum. To achieve single frequency operation, a special wavelength selection mechanism is required to be built into the laser diode. On the other hand, although the wavelength of the laser diodes can be tuned by changing temperature or injection current, such as in distributed feedback (DFB) lasers [30], distributed Bragg reflector (DBR) lasers [31], sampled-grating DBRs (SG DBR) [32], superstructure grating DBRs (SSG DBR) [33] and vertical cavity surface emitting lasers (VCSELs) [34], these tuning approaches have limited usage in practical applications due to small spectral tuning range and/or limited output power. The easiest way to obtain a widely-tunable laser is perhaps to make a DFB array. However, with an increasing number of lasers, there is a trade-off between tuning range and output power due to increasing losses in couplers [35]. An alternative solution is to place a diode laser in an external resonant cavity comprising a wavelength selector within the laser system. In contrast to the above mentioned tunable lasers, the external-cavity tunable laser (ECTL) has attracted significant interests since it can provide large tuning range, continuous wave (CW) tuning, high output power and high wavelength accuracy while maintaining single longitudinal

mode with a considerable narrow linewidth (~ 1 kHz) and a reasonable high side-mode suppression ratio (SMSR > 30 dB). Typically, the ECTL contains a cleaved facet on one side and an external reflector (usually a grating or a mirror) on the other side. Emission at the desired wavelength is achieved by properly adjusting the reflector, and wavelength tuning is realized by moving the reflector to change the effective length of the laser cavity. Therefore, selection and tunability of the emission wavelength by external control can be executed without the complications associated with the variation of temperature or pumping level.

For ultrahigh-capacity and coherent optical fiber transmission communication system, it is desirable to have a tunable laser source that emits at one single frequency even under high-bit rate direct modulation. At the same time, the tuning speed of the laser is also essential. For instance, the tunable lasers must switch wavelengths within a few nanoseconds for all-optical packet switching. Such a criterion will favor tunable laser types that are controlled electronically as compared to the ones that have thermal or mechanical tuning element. For this reason, coupled-cavity lasers and optical injection-locked lasers have been widely investigated. Besides, further improvements on laser performance and development of new applications have been derived from these lasers designs, since they can provide many important features, including laser linewidth reduction, mode hopping suppression, mode partition noise reduction and various modulation performance improvements.

2.1.1 External cavity tunable lasers

The first external-cavity laser, constructed by a GaAs diode with one facet anti-reflection (AR) coated and a flat mirror as the external reflector, was presented in 1964 [36]. Initially, the mirror function was not to tune the wavelength but to extend

the cavity length to lower the beat rate for linewidth measurements. However, it provided a simple and fundamental configuration for the development of tunable lasers. The truly external-cavity lasers were invented shortly after the invention of semiconductor lasers. The numerous virtues that ECTLs now owe, mainly developments in the field of Fabry-Pérot (FP) laser cavities or strictly speaking semiconductor optical amplifiers (SOAs), are promising. This is why they are still the subject of interest and research, and their properties are continuously improved in pace with the general progress in semiconductor technology and optoelectronics.

Figure 2.1 shows the schematic diagrams of different configurations of the ECTLs. In general, an ECTL consists of a FP laser cavity with a mirror-like rear facet (with or without AR coating), a lens element, and a reflector. Output from the FP laser cavity is collimated and redirected backwards. Among various features, when the external cavity is long, an additional intra-cavity lens with a large numerical aperture will help to collect most of the divergent light emitted from the FP laser cavity. The reflector provides optical feedback to excite lasing in the cavity. Additionally, by changing the position of the reflector, the frequency and spectrum of the emission are perturbed, leading to wavelength tuning while wavelength dependent reflectivity of the reflector enforces single frequency operation of the system. The mirror configuration shown in Fig. 2.1(a) is one of the “standard” designs [8, 18, 37-39] because of its simplicity. Since the flat mirror is not a dispersive component, the spectrum of this type generally has multiple longitudinal modes output. Even though the injection current may be well controlled to maintain a single mode operation during the wavelength tuning, SMSR is relatively low and output power is limited as well. Besides, wavelength tuning is not continuous [37, 39].

Discrete tuning of mirror configuration ECTLs has strict requirements for both the injection current and mechanical stability of the mirror, which are difficult to meet for conventional lasers based on bulky mechanics. The conventional lasers usually have a long external cavity (>1 cm), which limits the wavelength tuning range. A promising solution is to miniaturize the laser structure so that the cavity length can be shortened while stability is improved at the same time.

Other two principal designs of ECTLs systems include diffraction gratings as dispersive wavelength selector, named as Littrow due to the Littrow retro-diffraction geometry, shown in Fig. 2.1(b) [40-43], and Littman or grazing-incidence configurations, shown in Fig. 2.1(c) [44-47]. The lasing wavelength in each of these schemes is determined by the centre of the grating dispersion curve, which is given by

$$m\lambda = d(\sin \varphi_i + \sin \varphi_d) \quad (2.1)$$

where m denotes diffraction order, λ is the centre wavelength, d is the grating pitch, φ_i is the incidence angle, and φ_d is the diffraction angle.

In the Littrow configuration, the front facet of the FP cavity (or semiconductor gain medium) is AR coated, and the output is collimated onto a diffraction grating. The incident optical mode on the grating is retroreflected back into the FP cavity from an external cavity. Wavelength tuning is accomplished by rotating and/or translating the grating, while the output wavelength is determined by a combination of the standing-wave condition (i.e., cavity length) and the centre wavelength of the feedback grating (i.e., grating angle). Alternatively, in the Littman configuration, the incident light on the grating is diffracted onto the mirror that retroreflects the light via the grating back to the FP cavity. The method of double pass through the grating per

Fig. 2.1 Schematic diagrams of various ECTLs configurations: (a) elementary ECTL consisting of a gain medium (SOA/FP), collimating optics and two mirrors, with the mirror on the rear facet covered by a high reflectivity coating (HR) [39], (b) Littrow ([40-43]), (c) Littman ([44-47]), (d) electro-optic filter ([52]), (e) acousto-optic filters([53]), (f) etalon wavelength selective mirror ([54]), (g) Bragg waveguide ([55]), (h) multichannel SOA ([57]), and (i) multichannel SOA with phase shift section (PS), and Rowland grating ([58]).

cavity round trip favors the cavity wavelength sensitivity, leading to improved side-mode suppression.

Although the characteristics of both Littrow and Littman configurations depend on a particular design, the Littrow design with a mechanically rotated and translated bulk grating is probably more widely used [48-51]. This could be due to the relatively more complicated configuration and higher optical requirements of the Littman design, which involves double dispersing. Additionally, the AR coating of the front facet in the Littman configured FP laser cavity provides lower reflectivity than that required in the Littrow configuration.

The linewidth of the operating ECTLs mode and the wavelength tuning range are among the most important parameters for the lasers designs. An external cavity with a grating in Littrow mount produced a linewidth of 10 kHz [59]. Such linewidth was later reduced to as low as 300 Hz by detuning the external cavity feedback phase from the resonance with the field reflected from the AR-coated facet of the SOA [60].

Tuning may not necessarily turn out to be continuous since quite often mode-hopping is hidden in the recorded spectrum. Nevertheless, true continuous tuning over a wide band has been reported in a number of cases [61-66]. Furthermore, to ensure the same mode being selected by the grating during the tuning, the cavity length must be properly adjusted. Rotating the grating together with its linear translation has been commonly used for such purpose [63, 67]. A classic solution is using a motorized translation stage to simultaneously vary the cavity length and rotate the grating [49]. In another approach, a continuous tuning range of 50 GHz in the range of 1510-1560 nm was achieved by combining rotation-translation of the grating using three independent piezoelectric transducers (PZT) that controlled the grating rotation and the cavity length [68]. The combined effect of simultaneous translation and rotation can also be achieved in a single motion by rotating the grating about a remote point located in precisely chosen place [46, 61-62, 64-66]. In general, the tuning spectral

range depends on the FP laser cavity/SOA gain spectrum, AR coating and configuration of the ECTLs. A literature survey in the field of ECTLs is given in Table 2.1.

Despite all difficulties, investigations of various hybrid grating external-cavity lasers (e.g. in Littrow/Littman configuration) continue to be pursued mainly due to their outstanding spectral performance, such as single frequency operation and broad continuous tuning ranges. Besides, the ECTL configuration has the merit that it may be employed regardless of the laser material, which enables to build laser operation at any wavelength in the wide range extending from UV up to far-infrared.

Table 2.1 Summary of the literature survey of the ECTLs research

Year	Laser set-up configuration	Center λ (nm)	Tuning range (nm)	SMSR (dB)	Output power (mW)	Refs.
1964	Mirror					[36]
1968	Littrow	760	10			[40]
1978	Littman	600				[44]
1983	Littrow (M)	1500	55	50	3	[59]
1986	Littrow (M+PZT)	1260	15	30		[63]
1990	Littrow (M)	1500	242	42	45	[69]
1991	Littrow (M)	1300	160	40	40	[70]
1993	Littrow (M)	852	35	20	1000	[71]
1996	Littman (M)	825	40		6.5	[49]
1996	Mirror (MEMS)	1550	20			[39]
1998	Littrow(M+PZT)	780	20		80	[48]
2004	Mirror (MEMS)	1550	13.5	13	1	[72]
2005	Littman (MEMS)	1544	40		16	[73]
2005	Fixed LC tunable mirror	1550	35	50	32	[54]
2006	Waveguide external cavity	1553		40	7	[55]
2007	Voltage-tuned liquid-crystal cladded subwavelength resonant grating	1530	7	30	>1	[56]

Notes: LC- liquid crystal, M- moved by motors, MEMS- microelectromechanical systems, PZT- piezoelectric actuators, SMSR- side mode suppression ratio.

The advantages offered by the ECTLs have turned out to be a sufficient argument to implement these devices to series production. The designs which are currently available in the market, in general, follow classic technical solutions using mobile bulk gratings with the external cavity in Littrow or Littman configurations. Special effort is made to obtain highly stabilized operation and continuous tuning. Also, some particularly interesting developments are focused on increasing the laser output power without sacrificing single frequency operation and tunability. For example, a compact design of ECTL [74] was capable to emit an excellent beam reaching 1 W output power in the wavelength range from 775 to 785 nm. The laser output signal could be modulated up to 100 MHz and tuned mode-hopping-free across 15 GHz at the rate of 1 kHz when using a piezoelectric actuator.

Notwithstanding of the effort in improving the lasers with mobile bulk diffraction grating, some challenges remain to be overcome. They include mechanical and thermal stability of the laser, high wavelength selectivity and wide range mode-hopping-free tuning. Any lateral translations of the FP laser chip can result in variations in the optical gain in the cavity and induce rather complicated changes in the laser output, while axial translations of the chip perturb the resonant frequencies of the compound cavity of the laser. Stabilizations of the grating and remaining optical components are required for the same reasons. Besides, laser temperature control is essential since temperature changes may give rise to variations in gain spectrum and optical path length within the diode itself.

In many cases, the speed at which the laser can be tuned is also essential. Mechanical tuning maybe in this respect beyond consideration, but other tuning methods may offer a satisfactory solution.

2.1.2 Coupled-cavity lasers

For ultrahigh-capacity and long-distance single-mode optical fiber communications systems in the 1.3 μm -1.7 μm wavelength range, it is desirable to have a semiconductor laser based light source that emits stably at one single frequency under high-bit rate direct modulation. Unfortunately, conventional free-running FP semiconductor lasers operate in multilongitudinal modes when directly modulated. In addition, for long-distance transmissions longer than 150 km with specially designed dispersion-shifted fibers, the allowed spectral width has to be less than 1.5 nm. For a conventional laser diode operating at 1550 nm and having a cavity length of 250 μm , the longitudinal mode spacing is around 1.5 nm. Thus, for such systems single-longitudinal mode spacing is required. Furthermore, a light source with a wide wavelength range is always preferred. Consequently, the alternative is to produce semiconductor laser-based sources that operate stably in a single longitudinal mode even under high-bit-rate direct modulations. This solution has the important advantage that not only a low loss 1550 nm region can be utilized, and it also opens up the possibility of truly wideband transmission. Hence, considerable effort has been focused on the development of semiconductor lasers based sources with better longitudinal mode control under modulation.

The realization of coherent optical-fiber transmission systems that utilize frequency modulation (FM) or phase modulation (PM) is another area of intense interest [75-78]. However, it is difficult to develop such systems due to the lack of suitable frequency tunable lasers and a stable single-frequency local oscillator. Besides frequency tunability, the laser also needs to be mechanically compact and must emit stably at one single frequency. Previous approaches include the use of electro-optic frequency modulators, either integrated or discrete devices in external-

cavity semiconductor lasers, and the direct modulation of injection current. Envelope spectrum shifts of 0.4 Å and 20 Å can be obtained by electro-optic effect or by threshold gain variation through the modulation of effective mirror reflectivity. However, the major drawback of this scheme is the difficult procedure involved in fabricating such complicated integrated structures. Directly modulating the injection current of the conventional diode to obtain FM is simple, but the frequency shift is very small. This is because the FM arises from index modulation due to carrier density modulation, and the carrier density should be pinned at the threshold value. This results in a relatively small frequency shift with the change of the modulation current.

An alternative method is the use of coupled-cavity laser (CCL) configurations, which provide practical, electronically controllable, tunable and single-frequency output. Traditional coupled-cavity lasers consist of two or more optical cavities separated by air gaps sufficiently narrow to allow optically coupling in between. Variations in the current flowing through either one of the cavities change that cavity's refractive index, and therefore the cavity optical length. The total mode structure is subsequently modified, which provides a simple and convenient method of spectral tuning. The operating mode of the compound device is determined by the interaction of the permitted modes within the individual sections and the coupling mechanism between them. Thus, modes from each cavity, spectrally superposed will constructively interfere and become the enforced modes, while the others will destructively interfere and become suppressed. Additionally, thanks to the Vernier effect, such coupled-cavity lasers achieve a very wide wavelength-tuning range.

The concept of coupled-cavity resonators for longitudinal mode selection was proposed as early as 1962 [79-80] for gas lasers applications. Though this concept is

available and it is also known that semiconductor laser diodes employing one FP cavity usually lase in multi-longitudinal modes, no rigorous effort was made to apply this coupled-cavity concept to semiconductor lasers for mode selection until the 1980s [6, 81-82]. There are several reasons for this. First, there was little demand for truly single-frequency semiconductor laser diodes until the advent of very low-loss, single-mode fiber in the 1550 nm region. Second, there was no practical technology for fabricating multi-coupled cavity laser diodes whose total lengths were only in the order of 200 μm - 400 μm which were suitable for mass production. Third, there was a general belief that the length ratio of the two coupled cavities and their air gap separation were crucial in achieving optimal mode selection. Finally, even if single-longitudinal-mode operation can be achieved in coupled-cavity semiconductor lasers diodes, its stability with respect to changes in biasing currents would be limited.

Nevertheless, in 1968, Kosnocky and Connely [83] developed two coupled broad-area diodes by cracking a single diode into two halves when techniques capable of implementing multiple coupled cavities in semiconductor diodes were available and their purpose was to study optical amplification. Later on, with the same concept of forming coupled-cavity, Allen *et al.* demonstrated single-longitudinal-mode operation with their broken lasers under CW operation, although no independent biasing of the two optically coupled diodes was possible [84]. However, this technique is applicable to one diode chip at a time. Furthermore, the cracked diodes must remain soldered to the metal plate and cannot be transferred to another more suitable heat-sink mounting and electrical package. This technique, therefore, is not suitable for mass production. More importantly, the resulting device could not be adjusted to optimize the intensity ratio of the selected mode relative to the undesired modes since there is no independent biasing. It not only precludes the ability of

independent electronic tuning, but also precludes any possibility of an electrical feedback loop to stabilize the device against parameter drift during operation. Another fabrication technique uses either wet or dry etching to form the reflecting mirror, constructing coupled-cavity scheme. For example, monolithic two-section lasers were fabricated by dry etching and chemical etching [6]. This technique is capable to accurately control the gap spacing between two separate sections. However, mirrors formed by such etching do not have high quality as those formed by cleaving along crystallographic planes. Additionally, the mirrors usually are not perfectly parallel to the end facets that are formed by cleaving. As a result, an alternative technique for forming cleaved-coupled-cavity (C^3) lasers by a simple variation in usual cleaving procedures employed in production process is proposed [85-87]. It is compatible with mass-production processing procedures. C^3 lasers can be freely transported and bonded to any desirable heat sink and packaged as usual. One major advantage is that all facets are formed by cleaving along crystallographic planes, yielding excellent flat mirrors perfectly parallel to each other for each cavity. Furthermore, complete electrical isolation between the two individual diodes is enabled in such design, leading to independent electrical biasing control. Theories of such coupled-cavity lasers have been well established [88-91]. More recently, other various approaches of realizing tunable coupled-cavity lasers have been proposed, involving in the form of a Y-laser [92-95], the introduction of one-dimensional distributed Bragg reflector [96] or photonic crystals [97], and coupled cavities based on distributed feedback lasers [98]. However, the mode selectivity of the Y-lasers is insufficient for stable single-mode operation with good side mode suppression.

Thus, it is still challenging to obtain optimal cavity coupling and phase matching at the same time. This is particularly true when the two coupled cavities

have fixed cavity gaps as predetermined during the fabrication. The etched cavity gaps have to be finely controlled during the fabrication. The fixed gap is not adaptive to the variations of working conditions such as change in environmental temperature and may lead to unstable single-mode operation and limited mode selectivity. Hence, a micromachined coupled-cavity laser is proposed to overcome these problems for the CCLs practical applications.

2.1.3 Injection-locked lasers

Injection locking is a technology of locking the free-running oscillation state of the resonant object (i.e., oscillator, termed as *slave*) by injecting an external radiation (termed as *master*). The locking phenomenon can occur between oscillators. It is believed that such phenomenon was first observed in two swinging pendulums by the Dutch scientist Christian Huygens in the 1600s. People did not start to realize the complexity and beauty relative to nonlinearly coupled oscillators until the beginning of nonlinear dynamic study. The application of injection locking for electrical oscillators was pioneered by Van der Pol in 1927 [99], who injected an external signal into a self-sustained RLC oscillator and found that, when the injection frequency gets close to the RLC frequency, the oscillation suddenly occurs only at the injection frequency, and the beating between the injection and intrinsic RLC oscillation disappears correspondingly. In 1946, the first paper describing a theoretical study and the application of the locking technique in electronics and communications was presented by Adler [100]. Similarly, he found that the original oscillation frequency of a free-running oscillator can be locked to the frequency of an injection oscillator with a constant phase value. Such a locking concept was adapted to laser oscillators [101, 102] soon after the invention of the laser. The first optical injection locking was

demonstrated by using one HeNe laser to lock another one [101]. Early theoretical works for injection locking focused mostly on the general theory [102-107] while theoretical and experimental investigations on optical injection locking in the 1970s have been focused on the understanding of physical phenomena. Tang and Statz [102] applied the Van der Pol equation into the laser field, but ignored the inversion density. Although Pantell took into account the inversion density and presented a more general analysis using a field equation and a rate equation, but neglected the refractive index change with the carrier density [103]. Finally in 1982, a milestone work was presented by Lang [107], who not only synthesized the previous studies and developed a small signal theory for the multimode semiconductor lasers, but also reported an asymmetric tuning curve and a peculiar dynamical instability of an injection-locked diode laser. Subsequently, Lang's theory was extensively employed and proven in many theoretical and experimental studies [108-114]. For instance, in 1985 Mogensen *et al.* [106] presented a thorough theoretical and experimental investigation of locking conditions and stability properties. However, the small signal approximation and the combination of the effect of all the side modes into one mode would limit its validity in many cases such as large single and strong side modes. On the other hand, more and more work was devoted to theoretical studies and analyses for specific applications [115-121]. For example, a detailed study of the locking bandwidth and relaxation oscillations was given by Petitbon *et al.* [122]. Cassard and Lourtioz developed the analysis for injection-locked high-power pulsed lasers by treating the locking as the competition between the injection- and noise-driven fields [26]. Injection locking for Q-switched lasers was also investigated [123]. Further work was also reported with topics on locking the single-mode slave lasers [109], strong injection [124], locking conditions/stabilities [125], and lockable range [126-

127]. Particularly, driven by the significant development of optical networks, injection of multiple lasers was studied extensively. For example, the work of Hörer and Patzak who presented a large-signal analysis for wavelength conversion using two injection lasers simultaneously [111]. Cai *et al.* proposed the generation of DWDM channels using multiple optical injections and studied the associated crosstalk, noise and stability [112]. All-optical regenerators and optical transmitters were also investigated using two side-mode locking method [113-114]. The theory for chaos synchronization was established by Murakumi by treating the slave as a driven damped oscillator [124-125].

Besides significant theoretical work, tremendous amount of efforts were devoted to the investigations of injection-locking for communication applications. It can be traced back to the early 1980s, when well-engineered semiconductor lasers became available as the transmitters in communication systems. Semiconductor lasers are naturally advantageous for injection locking since they present a low Q factor cavity with a broad passband (tens of GHz) and an even broader gain region (~ 10 THz), which makes the injection locking applications easy and stable. The typical function of injection locking to the semiconductor lasers can be roughly categorized into two types: (i) improving the characteristics of slave lasers, and (ii) synchronizing the master and the slave. For the applications in the field of coherent optical communications, Kobayashi *et al.* using AlGaAs lasers demonstrated stable single-mode operation of FP lasers [130] and phase modulation (PM) in an injection-locked laser through frequency modulation (FM) of a master laser [105]; Yamamoto *et al.* applied this technology for receiver design [77]. Applications to the digital communication systems were also successfully conducted since the chirp of injection-locked lasers can be greatly reduced [115-117, 121, 131]. It was later discovered that

injection locking can also improve the laser intrinsic frequency response [134] and laser spectral narrowing [135]. Since the 1990s, more advantages in the injection-locked lasers over free-running lasers have been achieved, including modulation bandwidth enhancement [108, 136-148], resonance frequency increase [124, 144-147], nonlinear distortion reduction [148-150], relative intensity noise (RIN) reduction [108, 145, 151-154], and link gain improvement [155]. Later on, more and more applications using the injection-locking technique have been found. These include radio-over-fiber (ROF) [156], millimeter-wave generation, wavelength conversion, pulse reshaping, and un-cooled transmitters [157].

One of the potential applications of injection-locked lasers is for all-optical switching [27-28, 158-159]. The switch consists of a slave FP laser and a tunable master laser. The switching function is accomplished by using the master laser to lock (or not lock) the slave laser. As a result, the route of data signals can be switched. Another interesting application is the micromachined atomic watch [160-163]. Usually a ^{133}Cs atomic clock needs a pair of laser sources to excite the atoms between two hyperfine energy levels through a nonlinear mechanism called coherent population trapping (CPT) [164-167]. The lasers should have stable emission wavelengths, very narrow linewidth (~ 10 MHz) and very high modulation rate (~ 10 GHz). Injection locking provides an easy approach to meet such requirements. On the other hand, to downscale the atomic clock, shrinking down the laser sources is desirable. A good solution is to miniaturize the injection locked lasers and integrate them onto a single chip. The major developments in injection locking technology, especially its applications to semiconductor lasers for optical communications, are summarized in Table 2.2.

Table 2.2 Milestones of the injection locking research

Year(s)	Main accomplishment	Researcher(s)
1600s	Observation of synchronization between two pendulums	C. Huygens
1927	Earliest theoretical treatment of the locking of electrical oscillators	Van der Pol [99]
1946	First theoretical foundation on locking phenomena in electric oscillators	R. Alder [100]
1966	First demonstration of optical injection locking in lasers (two HeNe lasers)	Stover and Steier [101]
1980-1982	<ul style="list-style-type: none"> - Injection locking of semiconductor lasers (in ALGaAs lasers) - Single-mode operation of FP lasers - Phase modulation using injection-locked lasers 	Lang <i>et al.</i> [106] and Kobayashi <i>et al.</i> [105, 127]
1982	Report an symmetric tuning curve and a peculiar dynamical instability	Lang <i>et al.</i> [107]
1984	<ul style="list-style-type: none"> - Dynamic linewidth reduction - Chirp reduction 	Lin <i>et al.</i> [131]
1987-1988	Effect of optical injection of high bit-rate signals on semiconductor lasers pumped slightly below threshold	Kawaguchi <i>et al.</i> [132, 133]
1995-1996	<ul style="list-style-type: none"> - Relative intensity noise (RIN) reduction - Modulation bandwidth enhancement 	Simpson <i>et al.</i> [108]
1998	First demonstration of nonlinear distortion reduction by optical injection locking	Meng <i>et al.</i> [148, 149]
2000	Injection locking of distributed Bragg reflector (DBR) lasers	Lee <i>et al.</i> [136]
2002	Injection locking of vertical cavity surface emitting lasers (VCSELs) at 1550 nm	Chang <i>et al.</i> [110]
2004	35 GHz bandwidth for modulation in 1.3 μ m semiconductor lasers	Hwang <i>et al.</i> [142]
2006	Demonstration of 72 GHz resonance frequency and 44 GHz bandwidth of injection-locked 1.55 μ m DFB lasers	Lau <i>et al.</i> [144]
2008	107-GHz resonance frequency of injection-locked 1.55- μ m VCSELs demonstration	Zhao <i>et al.</i> [169]

The prominent advantages that injection-locked lasers can provide over free-running lasers are attractive. First of all, the noise of the slave laser can be greatly reduced [169]. The additional light coming from the master laser competes for the same carriers with all the slave laser modes. Therefore, under the same current

injection rate, the competition results in the reduction of carriers and gain available for spontaneous emission and fluctuations. This directly leads to a lower noise floor.

Secondly, the output laser linewidth can be reduced [135, 170-171]. Inside a laser, the strongest mode gets most of the gain and suppresses the rest. When the slave laser is locked, its main lasing mode is coherent with the light from the master laser and becomes stronger than the free running mode. Additionally, when the master laser is less noisy and more stable, there will be less phase fluctuation for the slave laser due to its phase locking to the master source. Combining the domination of the available gain and the phase noise reduction, the new locked mode exhibits a reasonably sharper linewidth. On the other hand, when the slave laser is initially multi-mode, the additional injection might promote single mode operation, or at least improve the side mode suppression ratio.

Third, various modulation performance improvements [110, 115-117, 136, 172-174] can be obtained; especially, the problem of frequency chirp during modulation can be mitigated. In fact, this might be one of the most important reasons which motivated researchers in the early 80's to explore this subject. Typically, the lasing wavelength is determined by the round trip phase condition and the gain available for the candidate modes. Due to the non-perfect clamping of the carriers to its threshold density, the fluctuation of the carriers manifests itself as wavelength variation via the Kramer-Kronig relation. When the slave laser is injection-locked, the locking provides an additional mechanism to prevent the laser wavelength drifting away from its CW value. It is an approach independent from the slave laser design to stabilize the laser wavelength.

Another interesting consequence of injection locking is the improvement on the laser bandwidth [108, 136-144]. Due to the presence of the external light, the gain available for slave laser modes is suppressed. Effectively, the threshold of the locked mode is reduced compared to its free-running case. Since the gain and carrier density relation can be approximated by a log function, the differential gain is larger if the threshold carrier density is lower. Besides, the higher photon density of the locked mode will enhance the stimulated emission and suppress spontaneous emission. The simultaneous presence of all these factors implies a higher resonance frequency of an injection-locked laser system. In addition, lasers under certain injection locking conditions can provide a variety of functionalities that might be useful, but not achievable by the free-running lasers [118-120, 175-181].

2.2 Micromachined tunable lasers

Among most conventional tunable lasers, the problems are mainly related to their cavity length and size. A long cavity imposes physical constraints on the wavelength tuning range, while the bulky size results in engineering inconveniences such as low mechanical stability, slow tuning speed, less portability, and high power consumption. To tackle these problems, microelectromechanical systems (MEMS) technology has been introduced to miniaturize tunable lasers [8, 18, 37-39].

About three decades ago, two papers, one on the micromechanical spatial light modulator (SLM) array [182] and another on the silicon torsional mirror [183], were published. Thirty years later, a blooming field known as microelectromechanical systems (MEMS) was born. It is one of the key enabling technologies for the “dynamic” processing of optical signals. The first market driver of optical MEMS was

DMD projection display [184-185]. The applications of optical MEMS in telecommunications started in the 1900s [186-187]. Early efforts have been focused on the development of optical MEMS devices and fabrication technologies [188-191]. As telecommunications boomed in the late 1990s and early 2000s accelerated the maturation of the technology, a wide range of MEMS based components were taken from laboratories to reliable products that meet Telcordia qualifications. As time goes by, the developed technology is available for new applications in communications and other areas [192].

MEMS technology has natural synergies for applications in tunable lasers. For instance, in order to tune over the whole wavelength range, the mirror in ECTLs needs to be moved along small distances of around one wavelength, which is easily achievable using MEMS. The precision and stable movement of microactuators enables fine-tuning of the laser's emission wavelength. The small size of micromachined mirrors yields high tuning speed, and also makes on-chip integration of ECTLs feasible. In addition, the micromachined tunable lasers yield high compactness, low fabrication cost, low power consumption and easy integration with IC control circuits. In the following section, the applications of MEMS to the three different types of tunable lasers are reviewed separately.

2.2.1 MEMS external cavity tunable lasers

The combination of a semiconductor laser diode with an external cavity mirror may be considered as a classic design for ECTLs in the MEMS technology [38-39, 72, 194]. A MEMS-based ECTL usually consists of three core parts: a gain medium for optical amplification, an external reflector (mirror or grating) plus a microactuator for wavelength tuning, and an optical coupling system in between.

Limited by the availability of fabrication techniques, the early work used simple flat mirrors as the external reflector, making continuous wavelength tuning impossible. The applications of MEMS in tunable lasers did not receive much attention until a MEMS tunable laser was demonstrated using bulk micromachining and nickel electroplating [39, 193]. In this work [193], a silicon flat mirror was fabricated by etching a single crystalline wafer along the (110) direction using KOH, since the large difference between the etching rates of the (110) and (111) crystallographic directions resulting in vertical sidewalls. The mirror is supported by the cantilever beam, and the laser diode (LD) is aligned very close to the mirror. For such original work, neither the mirror is coated with any high reflection material, nor is the LD coated with AR. With an extremely short external cavity of 10 μm , the device could only have the tuning range of 3 nm. Although the performance is not favorable, it inspires the great potential of applying MEMS technology in the tunable lasers. Later, the performance is improved by electroplating a nickel mirror using a patterned photoresist as the mold [39]. The cavity length is further reduced to $< 5 \mu\text{m}$, and the LD chip is AR coated, leading to a 20 nm wavelength tuning range.

A surface micromachined 3D mirror was also proposed for the ECTLs [38] and a surface micromachined ECTL, with the cavity length of 10 μm and a 16 nm wavelength tuning range, is later accomplished [18]. The device has a footprint of 2 mm $\times$ 1.5 mm, which fully demonstrates the compactness of the MEMS lasers. Another MEMS laser was also reported which employed a surface micromachined FP filter as the external reflector and obtained a 4 nm tuning range [195]. One interesting tunable laser configuration, by using tunable micromachined FP interferometer device to achieve discrete wavelength tuning was also demonstrated. An array of DFB laser stripes was used as the laser source and a MEMS tilting mirror selected one DFB as

the output. Coarse tuning was realized by rotating the mirror to select one of the stripes, while the fine tuning was performed with temperature control resulting in a tuning range of 33.2 nm at a step of 50 GHz and an output power of 20 mW.

Although the described approaches look promising, it is commonly observed that the wavelength does not change smoothly through the tuning range and mode-hopping occurs in the mirror configuration lasers. At the same time, with the progress of MEMS fabrication process, especially of the deep reactive ion etching (DRIE) process, it became possible to pattern complicated profiles, and thus produce highly qualified micro-optical components (e.g. curved mirrors and gratings). Hence, the traditional continuously tuning ECTL configurations, Littrow and Littman, are therefore feasible to be realized using the MEMS technology. In both configurations, the MEMS grating element is employed as a reflector within the external cavity. Such realizations provide most of the MEMS advantages such as compact size, batch fabrication and easy integration.

Academic research on MEMS implementations of Littrow [62, 196] and Littman [197] ECTLs has focused on the development of accurate alignment actuators which can provide stable, mode-hop-free tuning after initial alignment. For example, the research toward the single chip integration was pushed forward by using deeply etched gratings for Littrow MEMS lasers [196], in which a special MEMS flexure was proposed for continuous tuning. Although that work focused on hybrid integration of the MEMS gratings with bulky external components, it showed the possibility to fabricate micro-optic components using the same process as for the MEMS actuators.

Table 2.3 Milestones of the MEMS tunable lasers research

Year (s)	Config. type	Fab. method	Tuning range	Description
1995	Mirror	Bulk	3 nm, discrete	External mirror without metal coating, wavelength @ 855 nm, external cavity 10 μm , [193]
1996	Mirror	Electro-plating	20 nm, quasi-continuous	Nickel mirror, laser chip AR-coated, wavelength @ 1550 nm, external cavity < 5 μm , [39]
1996	Mirror	Surface	-	Proposed a 3D mirror for external-cavity laser, [38]
1999	Mirror	Surface + bulk	4 nm, quasi-continuous	A micromachined FP interferometer as the external mirror, LD chip AR-coated, wavelength @ 980 nm, external cavity 25 μm , [195]
2001	Mirror	Surface	16 nm, quasi-continuous	A 3D mirror, wavelength @ 1540 nm, external cavity 10 μm , tuning speed 1 ms, size 2mm $\times$ 1.5 mm, [18]
2003	Littrow	DRIE	120 nm	A special MEMS flexure for grating movement, a MEMS grating, LD AR-coated, wavelength @ 1550 nm, [194]
2003	Littman	DRIE	42 nm, continuous	DRIE comb drive to rotate a silicon mirror, laser chip AR-coated, hybrid integrated with optical components, wavelength @ 1550 nm, tuning speed 15 ms, the first commercialized MEMS laser, [198-199]
2004	Mirror	DRIE	13.5 nm, discrete	A curved mirror, wavelength @ 1550 nm, external cavity 66 μm , tuning speed 1 ms, size 1.5 mm $\times$ 1 mm, the first single-chip integrated MEMS tunable laser, [72]
2005	Littrow	DRIE	30.3 nm, continuous	A rotatable blaze grating, laser chip AR coated, hybrid integration, wavelength centered @1530 nm, device size 2.5 mm $\times$ 1.5 mm $\times$ 0.6 mm. [62]

In contrast, commercial developments, which have mostly adopted the Littman configuration to achieve better side-mode suppression, have incorporated two or more degrees of freedom in the actuator design so that both initial alignment and

compensation for cavity dispersion can be controlled by the MEMS structures [19, 198]. A successful example is that of a hybrid integration of the MEMS continuously tunable laser [198]. In their design, a vertical mirror transported by a DRIE fabricated MEMS actuator is employed for wavelength tuning. Favorable results were achieved, such as 40 nm tuning range, 7 dBm output, 55 dB side mode suppression ratio and 5 mm $\times$ 5 mm size. It is the first commercialized MEMS laser. These types of lasers have excellent stability and optical characteristics. However, the mirror is only for the tuning and it is hybrid integrated with the other bulky components such as the grating and the beam splitter; while the tuning time is 15 ms, which is relatively long compared to other MEMS lasers [159]. The development of MEMS external cavity tunable lasers in literature is summarized in Table 2.3.

2.2.2 Micromachined coupled-cavity lasers

One of the main advantages of micromachining technology is the opportunity for system-level integration, leading to the developments of on-chip mechanical components that can be integrated with a laser chip. With the advancement in the MEMS fabrication techniques, it has been found that the devices realized by micromachining are more robust and reliable, without sacrificing lithographic resolution and surface quality. A two-section micromachined coupled-cavity laser in long-short configuration (i.e. there is a big difference in terms of cavity length between the two coupled cavities) was first developed [199]. It is formed by micromachining an optical-quality groove/gap near to the back facet of a commercial laser. Discrete wavelength tunability over 30 Å and continuous tunability over 2.8 Å are demonstrated, while maintaining operation in a single longitudinal mode and exhibiting superior SMSR. However, for the fixed cavity gap CCLs, it has been

shown that cavity gap width and location are critical to the performances of CCLs. This requires not only accurate control of the gap spacing, but also a high quality of the micromachining fabrication process, such as minimized etched surface roughness and lithographic resolution limits. Furthermore, a compact GaAs micromachined coupled-cavity laser diode, where a microbeam resonator was monolithically integrated with two LDs and a photo-diode by micromachining, was developed for optical communication and optical-sensing systems applications [200].

Micromachined coupled-cavity lasers have been also investigated in the form of vertical cavity surface emitting lasers (VCSELs). For instance, a developed tunable VCSEL based on semiconductor coupled-cavity design [201], whose operating wavelength is centered around 1300 nm. It consists of a quantum-dot semiconductor cavity and a micromachined suspended deformable membrane as the top mirror. By electrostatically modulating the air-gap between the deformable membrane and the semiconductor cavity, resonant wavelength can be tuned. Such device is compact, with single longitudinal mode output in a circular beam profile. However, the main challenges for tunable VCSELs are single-mode output power limitations, chirp, long-term reliability of the tuning mechanisms, and the cost of volume manufacturing.

2.2.3 Micromachined injection-locked lasers

MEMS technology provides not only a means to fabricate micro components, but also a substrate for integration and packaging of the tunable lasers. The fusion of the MEMS technology and external cavity tunable lasers has led to the innovation of many laser devices, as presented in Section 2.2.1. Initially, the introduction of the MEMS technology to the injection-locked laser was mainly focused on using movable MEMS films to tune the wavelength of the VCSEL, which is under external injection

[202]. For that purpose, a tunable VCSEL device was grown on InP substrate with a DBR mirror at the bottom and a GaAs/AlGaAs mirror on the top. The top mirror was attached to an electrostatically actuated MEMS cantilever for wavelength tuning. External injection was applied to the VCSEL to improve the laser performance. It provided 30 GHz modulation bandwidth, and a 25 dB increase in spur free dynamic range (SFDR).

Another type of micromachined injection-locked laser (ILL) using MEMS fabrication was also demonstrated [159]. The device integrated both a MEMS Littrow-configuration tunable laser (master) and a FP multimode laser chip (slave) in an external injection scheme, with a dimension of 3 mm $\times$ 2 mm $\times$ 0.6 mm. Measurement on single and multiple injections to the slave laser were both reported. Benefiting from the injection locking technique and MEMS technology, these devices achieved stabilization with a side mode suppression ratio of 55 dB and a range of fully locked state (FLS) of 0.16 nm. Furthermore, they demonstrated an all optical switching at a rate of 100 MHz.

Compared with the traditional ILLs, which are mostly based on bulky, free-space optical components (e.g. lenses, prisms) and complicated fiber optic components [27], the MEMS ILLs possess some competitive advantages, such as on-chip integration. Many high performance MEMS components can be integrated onto a single system, making it more functional and powerful. The advantage of compactness offers the whole integrated system with a shrinking volume of several cubic millimeters or even smaller, making it portable for field applications and efficient for large array constructions.

Although the implementation of the injection-locked lasers using the MEMS technology is under development, the progress of tunable lasers and MEMS integration has been preparing the conditions for the break-through. Further exploration in the field will open up new applications.

2.3 Summary

This chapter provides an overview of reported research work on micromachined tunable lasers which summarize:

- 1) The principles and achievements of previous work on external cavity tunable lasers, coupled-cavity lasers and injection-locked lasers.
- 2) Development and research challenges of these three different types of micromachined tunable lasers. The review showed that the application of MEMS in tunable lasers not only leads to many engineering benefits such as high tuning speed, compact size and easy integration, but also leaves broad space for exploration and improvement regarding the physics of such device, such as theoretical studies, as well as realizations of innovations in device operations and functions. The review of this chapter provides an overview of the technological base required as a foundation for the three types of MEMS tunable lasers to be discussed in the subsequent chapters and affirms the high potential of MEMS-based devices as a way toward optic/photonic integration implementations.

CHAPTER 3

MEMS EXTERNAL CAVITY TUNABLE LASERS

The objective of this chapter is to investigate micromachined external cavity tunable lasers, both theoretically and experimentally. The theory and the principle of operation of micromachined tunable lasers are studied, by developing a feedback model, a wavelength tuning model and a three dimensional (3D) optical coupling design. The theoretical study of the feedback model is then used to predict the wavelength shift of the laser mode. Further interpretation of the wavelength tuning theory provides a theoretical guidance for design optimization of MEMS tunable lasers. Design of the 3D optical system has a longer external cavity length (e.g. 10 ~ 150 μm), which not only provides a high coupling effective cavity but also yields a large tuning range. It involves no bulky optical components such as lenses and reflectors in comparison to the conventional external cavity lasers. A mechanical design of an electrostatic comb-drive micro-actuator is explored. Experiments focus on the fabrication and characterization of the MEMS tunable laser. A deep reactive ion etching (DRIE) fabrication process for high aspect ratio silicon structures is presented and discussed. Based on the experimental results, various aspects of the specifications of the tunable laser, such as tuning range, mode spacing and mode stabilities are discussed.

3.1 Architecture of MEMS external cavity lasers

Fig. 3.1 Generic architecture of the MEMS external cavity tunable laser.

Figure 3.1 shows the schematic illustration of a generic micromachined external cavity laser, which consists of a laser gain medium, an external cavity and a micromachined tuning part. The internal cavity is either a semiconductor Fabry-Pérot (FP) laser chip with the cleaved facets acting as mirrors or a chip provides optical gain for the guided optical mode. The optical coupling part serves as a path for the laser beam to propagate between the internal cavity and the external reflector. The design of the optical coupling part is crucial to achieve an effective optical coupling between the laser gain and the external cavity, which further determines the laser tuning characteristics. The micromachined tuning part provides the actuation of the external reflectors to change the external cavity length and optical coupling efficiency, so as to enable the wavelength tuning. In the following sections, the theoretical analysis of wavelength tuning, micro-optical coupling and actuator tuning are discussed separately.

3.2 Theory of wavelength tuning in external cavity tunable lasers

Before moving into the study of the external cavity lasers, some clarifications are made. The terms “frequency” and “wavelength” are used in different occasions, but they are treated as the same since they have a strict one-to-one relation. It is usually more convenient to use the term “frequency” in the analysis and the term “wavelength” in the experiment. Some assumptions and conditions for the wavelength tuning theory development are made to derive the external feedback model. These are:

- 1) The bare laser chip for the external-cavity laser is a normal multi-longitudinal mode FP chip,
- 2) The reflectivity of the external mirror is wavelength independent,
- 3) The length of the external cavity is shorter than the effective optical path length of the internal cavity,
- 4) The mirror translation is relatively small compared to the initial external cavity length,
- 5) The mode with minimum threshold gain oscillates while the others are suppressed. Thus, when the laser is operated slightly over the threshold (for example, less than 28% above the threshold current), the laser output can be single mode owing to the homogeneous broadening even though the laser is a FP laser which usually has multiple longitudinal modes, and
- 6) The laser chip has only the fundamental transverse mode.

3.2.1 Effects of optical feedback in external cavity

Generally, the output of the external cavity laser depends on both the amplitude and phase of the external optical feedback [81, 203-213]. The essence of the external optical feedback is to increase the quality factor of the laser resonator, consequently narrowing the linewidth and stabilizing the laser wavelength. Previous studies have shown that the external optical feedback strongly affects the properties of semiconductor lasers in terms of lasing threshold, output power, linewidth, and laser spectrum [205].

A typical design of a MEMS-based external cavity tunable laser consists of a FP laser diode and an external cavity formed by a reflective mirror, as shown in Fig. 3.2 (a). The laser diode provides the FP cavity and the optical gain, while the mirror can be translated to change the external cavity length. The external feedback model of the FP laser with an external cavity is based on the three-mirror model [5, 213] as shown in Fig. 3.2 (a). F_1 , F_2 and F_3 denote the two facets of the FP laser and the external mirror, respectively. r_1 and r_2 are the amplitude reflection coefficient of the laser facets F_1 and F_2 , respectively. r_3 represents the effective amplitude reflection coefficient of the external mirror, which takes into account all the losses in the external cavity, including the mirror reflectivity, diffraction loss, scattering loss and mode-mismatching coupling loss, but excluding the Fresnel reflection at the laser end facet. d and L stand for the laser cavity length and the external cavity length, respectively, and n is the effective refractive index of the laser internal cavity material.

Fig. 3.2 Analytical model for the wavelength tuning of the external cavity tunable laser: (a) Schematic diagram of the external cavity tunable laser, and (b) equivalent model.

Usually, r_3 is much smaller than r_2 , and for this type of MEMS external cavity tunable laser configuration, $r_2 r_3 \ll 1$ [5]. Therefore, the multiple reflection effect within the external cavity can be neglected. An initial electric field $E_0(t)$ inside the laser cavity undergoes a roundtrip within both the cavity of $F_1 - F_2$ and the extended cavity of $F_2 - F_3$ and becomes $E(t)$, which is given by [213]

$$\begin{aligned}
 E(t) = & r_1 r_2 \exp \left\{ -j4\pi\nu \frac{nd}{c} + (g - \gamma)d \right\} E_0(t) \\
 & + r_1 (1 - R_2) r_3 \exp \left\{ -j4\pi\nu \frac{nd + L}{c} + (g - \gamma)d \right\} E_0(t)
 \end{aligned} \tag{3.1}$$

where $E_0(t)$ is the initial electric field, c denotes the light velocity in vacuum, ν is the optical frequency, the term $(1 - R_2)$ accounts for the light transmission through F_2 , with $R_2 = r_2^2$, g is the linear gain per unit length due to the stimulated emission inside the laser internal cavity, and γ accounts for any optical loss per unit length within the internal cavity.

The three-mirror model is not very convenient for theoretical analysis. Therefore, it is simplified into an equivalent two-mirror model, as shown in Fig. 3.2 (b). The reflection from F_3 can be combined with that of F_2 , yielding an effective reflectance r_{2eff} , as given by [214]

$$\begin{aligned} r_{2eff} &= r_2 + \frac{(1 - R_2)}{r_2} \sum_{k=1}^{\infty} \left[r_2 r_3 \exp \left\{ -j4\pi\nu \frac{L}{c} \right\} \right]^k \\ &= \frac{r_2 + r_3 \exp \{ -j2\pi\nu\tau_L \}}{1 + r_2 r_3 \exp \{ -j2\pi\nu\tau_L \}} \\ &= R_{2eff} \exp(-j\phi_L) \end{aligned} \quad (3.1a)$$

where τ_L is the roundtrip delay of the external cavity, given by $\tau_L = 2L/c$. R_{2eff} and ϕ_L represent the amplitude and phase of the effective reflectance r_{2eff} , respectively. When $r_2 r_3 \ll 1$, $R_{2eff} = r_2 \sqrt{1 + \xi^2 + 2\xi \cos(2\pi\nu\tau_L)}$, where $\xi = (1 - R_2)r_3/r_2$ is the coupling efficiency between the external cavity and the laser cavity. In the case of one round trip, the effective reflectance can be simply characterized by

$$\begin{aligned} r_{2eff} &= r_2 + \frac{(1 - R_2)}{r_2} r_2 r_3 \exp \left\{ -j4\pi\nu \frac{L}{c} \right\} \\ &= r_2 + (1 - R_2) r_3 \exp \{ -j2\pi\nu\tau_L \} \end{aligned} \quad (3.1b)$$

Therefore, the electric field can be rewritten as

$$E(t) = r_1 r_{2eff} \exp \left\{ -j4\pi\nu \frac{nd}{c} + (g - \gamma)d \right\} E_0(t) \quad (3.2)$$

For a stationary stable laser oscillation, the amount of light amplified by the stimulated emission should be equal to the total losses in the lasing system [5], yielding

$$r_1 r_{2eff} \exp \left\{ -j4\pi\nu \frac{nd}{c} + (g - \gamma)d \right\} = 1 \quad (3.3)$$

When the amplitude and the phase are separated, it yields

$$r_1 R_{2eff} \exp[(g - \gamma)d] = 1 \quad (3.4a)$$

$$\phi(\nu) = \phi_L + 2\pi\nu\tau_d = 2m\pi, m \text{ is an integer} \quad (3.4b)$$

where $\phi(\nu)$ denotes the roundtrip phase of the laser beam after traveling through the internal cavity and external cavity, τ_d is the roundtrip delay of the laser internal cavity, as given by $\tau_d = 2nd/c$.

By solving the above basic equations for laser oscillation under a weak optical feedback condition ($\xi \ll 1$) [5], the required excess gain Δg and the total roundtrip phase change $\Delta\phi(\nu)$ for the laser system in the presence of the feedback can be expressed respectively as [213, 215]

$$\Delta g = g - g_0 = -\frac{\xi}{d} \cos \phi_{ext} \quad (3.5)$$

and

$$\Delta\phi(\nu) = 2\pi(\nu - \nu_0)\tau_d + \xi\sqrt{1 + \alpha'^2} \cdot \sin[2\pi\nu\tau_L + \arctan(\alpha')] \quad (3.6)$$

where $\phi_{ext} = 4\pi\nu(L/c)$ denotes the external phase, g_0 is the linear gain in the absence of the feedback, $\Delta\phi(\nu)$ represents the deviation of the oscillation phase $\phi(\nu)$ from $2m\pi$, ν_0 is the laser emission frequency without feedback, $\alpha' = \alpha/\Gamma$, α is the linewidth enhancement factor, and Γ is the optical confinement factor.

3.2.2 Frequency shift under optical feedback

It is known that the phase condition in the presence of the feedback determines the oscillating frequency of the external cavity laser, as described by Eqs.

(3.3) and (3.4). To achieve a stationary oscillation, the phase condition requires $\Delta\phi(\nu) = 0$ (Eq. (3.6)) and it leads to

$$\Delta\phi(\nu) = 2\pi(\nu - \nu_0)\tau_d + \xi\sqrt{1 + \alpha'^2} \cdot \sin[2\pi\nu\tau_L + \arctan(\alpha')] = 0 \quad (3.7)$$

A parameter C is defined as

$$C = \frac{\tau_L}{\tau_d} \xi \sqrt{1 + \alpha'^2} \quad (3.8)$$

which represents the external feedback strength.

In the case of weak feedback ($C \ll 1$), the phase change ($\Delta\phi(\nu)$) versus the emission frequency (ν) is a monotonic function, which results in only one solution for $\Delta\phi = 0$ and thus a single emission frequency. Assuming that $2\pi\Delta\nu\tau_L \ll 1$, then Eq. (3.7) could be solved using a first-order approximation. The solution of the emission frequency ν can be derived as

$$\nu = \nu_0 - \frac{C \sin[\phi_{ext} + \arctan(\alpha')]}{2\pi\tau_L \{1 + C \cos[\phi_{ext} + \arctan(\alpha')]\}} \quad (3.9)$$

The frequency shift ($\Delta\nu$) can be further expressed as

$$\Delta\nu = \nu - \nu_0 = -\frac{C \sin[\phi_{ext} + \arctan(\alpha')]}{2\pi\tau_L \{1 + C \cos[\phi_{ext} + \arctan(\alpha')]\}} \quad (3.10)$$

Eq. (3.10) shows a periodic relation between the frequency shift and the external phase. It implies that the value of C cannot be larger than 1 (i.e. $C < 1$). Otherwise, the denominator term can be 0, which causes instability or coherence collapse.

For a small value of C , the variation of the frequency shift versus the external phase is shown in Fig. 3.3, where the central line represents the oscillation frequency of the solitary laser ($C = 0$). It shows that for the same external cavity, the frequency

Fig. 3.3 Frequency shift versus external phase at different levels of the external feedback strength C .

shift increases with the external feedback strength. In other words, higher feedback coupling efficiency would increase the wavelength tuning range of the external cavity tunable laser. Moreover, it is evident that the frequency shift is a repetitive function with one period corresponding to an optical displacement of $\lambda/2$. When C is $\ll 1$, the frequency shift is close to a sinusoidal waveform; when C becomes close to 1, the output becomes sawtooth-like.

3.2.3 Frequency tuning range of external cavity lasers

3.2.3.1 External cavity length and external feedback effects

Based on the Eq. (3.10), the frequency shift can be simplified as

$$\Delta\nu = K \times \frac{C \sin[\theta]}{1 + C \cos[\theta]} \quad (3.11)$$

where

$$K = -\frac{1}{2\pi\tau_L} \quad (3.11a)$$

$$\theta = \phi_{ext} + \arctan(\alpha') \quad (3.11b)$$

By analyzing Eq. (3.11), the maximum frequency shift can be expressed as

$$\Delta\nu_{\max} = \frac{C}{2\pi\tau_L\sqrt{1-C^2}} \quad (3.12a)$$

and the minimum frequency shift can be expressed as

$$\Delta\nu_{\min} = -\frac{C}{2\pi\tau_L\sqrt{1-C^2}} \quad (3.12b)$$

Then, the total frequency tuning range ($\Delta\nu_{total}$) of the external cavity laser is given by

$$\Delta\nu_{total} = \Delta\nu_{\max} - \Delta\nu_{\min} = \frac{C}{\pi\tau_L\sqrt{1-C^2}} \quad (3.12c)$$

Substitute Eq. (3.8) into Eq. (3.12c), the maximum frequency shift of the external cavity laser can be given by

$$\Delta\nu_{total} = \frac{\sqrt{1+\alpha'^2}}{\pi\tau_d\sqrt{\left(\frac{1}{\xi}\right)^2 - \frac{4(1+\alpha'^2)}{c^2\tau_d^2}L^2}} \quad (3.13)$$

Substitute Eq. (3.5) into Eq. (3.13), the total frequency shift can be simplified as

$$\Delta\nu_{total} = \frac{A}{\pi\sqrt{\left(\frac{1}{r_3}\right)^2 - \tau_L^2 A^2}} \quad (3.14a)$$

where factor A represents

$$A = \frac{(1 - R_2)\sqrt{1 + \alpha^2}}{r_2 \tau_d} \quad (3.14b)$$

According to Eq. (3.14a), there are two parameters affecting the maximum frequency shift of the external cavity laser. The first parameter $\tau_L (2L/c)$ represents the effect of the external cavity length (L). When the cavity length is increased, the frequency shift ($\Delta \nu_{total}$) of the external cavity laser is increased. The second parameter r_3 represents the effective amplitude reflection coefficient of the external mirror. When r_3 is increased, the external coupling efficiency is increased, and then the maximum frequency tuning ($\Delta \nu_{total}$) is widened.

Figure 3.4 illustrates the graphs relative to the dependence of frequency shift on the external cavity length at different levels of coupling. It indicates that the frequency shift is wider when the external cavity length is increased. When the external feedback coupling is stronger, the frequency shift increases quickly. For instance, when $\xi = 1.4$, the frequency shift increases sharply as the external cavity length becomes longer. On the contrary, when $\xi = 1.0$, the corresponding frequency shift increases by a very low slope ($\sim 8 \times 10^{-4}$ THz/ μm), even though the external cavity length is extended from 70 μm to 170 μm . At different values of ξ , when the external cavity is not long enough, for instance $L < 95 \mu\text{m}$, the frequency shift is small and the curves are flat.

Fig. 3.4 Frequency shift versus external cavity length at different values of coupling effect ξ .

The relationship between the frequency shift and the external feedback strength is shown in Fig. 3.5. It can be seen that the maximum frequency shift ($\Delta\nu_{total}$) is increased when the cavity length (L) and the external feedback strength (C) are increased. For short external cavity lengths such that $L \leq 90 \mu\text{m}$, the maximum frequency shift increases slowly with the external feedback strength. For long external cavities such that $L \geq 140 \mu\text{m}$, the frequency shift greatly increases. In some cases such that $C > 0.06$ and $L > 140 \mu\text{m}$, it reaches very high level.

According to Figs. 3.4 and 3.5, there are two ways to increase the frequency shift: (1) increasing external cavity length, and (2) enhancing the external coupling strength.

Fig. 3.5 Frequency shift versus external feedback strength at different values of external cavity length L .

3.2.3.2 Wavelength tuning range of external cavity lasers

In practical experiments it is more convenient to work to use the wavelength tuning range ($\Delta\lambda_r$) and external coupling efficiency (η_{ext}). Since $\nu = c/\lambda$, then

$$\Delta\lambda = -\frac{\lambda^2}{c} \Delta\nu \quad (3.15)$$

Based on Eqs. (3.6), (3.10) and (3.15), the expression of the wavelength tuning range is derived. The wavelength tuning range as a function of the external cavity length and the external coupling efficiency is given by

$$\Delta\lambda_r = \frac{A_0 \eta_{ext}}{\sqrt{1 - B_0 L^2 \eta_{ext}^2}} \quad (3.16)$$

where A_0 and B_0 are variables combining the other parameters of the tunable lasers, as given by

$$A_0 = \frac{t_2^4 \lambda^2 \sqrt{1 + \alpha^2}}{\pi c r_2 \tau_d} \quad (3.16a)$$

$$B_0 = \frac{4t_2^8 (1 + \alpha^2)}{c^2 r_2^2 \tau_d^2} \quad (3.16b)$$

$$t_2^2 = \frac{r_2 \xi}{r_3} \quad (3.16c)$$

$$\eta_{ext} = r_3 / t_2^2 \quad (3.16d)$$

From Eq. (3.16), it can be seen that the wavelength tuning range is increased by increasing the external cavity length and the coupling efficiency. For different cavity lengths, the relationship between the tuning range and the coupling efficiency is shown in Fig. 3.6. For the short cavity length of 10 μm (e.g. flat mirror reflector), the tuning range is less than 5 nm even for $\eta_{ext} \rightarrow 1$. For a longer cavity length of 70 μm (e.g. curved mirror reflector), the tuning range is still limited and requires high coupling efficiency. In contrast, for the long cavity of 220 μm , the tuning range increases greatly at the coupling efficiency of $\sim 35\%$ (i.e. let the denominator $1 - B_0 L^2 \eta_{ext}^2 = 0$ in Eq. (3.16)). These conditions are considered for the external cavity laser design and can serve as a good guideline for the control of laser operations.

Based on the theoretical analyses, the external feedback strength (C) and the external cavity length (L) are the key factors in determining the frequency shift and the wavelength tuning range of the external cavity laser. Therefore, these two factors are highly significant for the design of MEMS external cavity lasers.

Fig. 3.6 Wavelength tuning range versus external coupling efficiency for different external cavity lengths.

3.3 Micro-optical design

This section focuses on the micro-optical design of the external cavity of the MEMS tunable laser. The fundamental mathematical expressions of the beam propagation and coupling of the micro-optics are introduced. Then, the optical designs of the external cavity of the external cavity laser are elaborated. Finally, the simulation and optimization of the micro-optical design are discussed.

3.3.1 Micro-optical coupling

The tunability of the MEMS tunable lasers is mainly determined by the properties of the external cavity such as the type of external reflectors and feedback strength. Among them, the coupling effect of the external cavity tunable laser is of great importance. In other words, both higher coupling efficiency and longer external cavity are necessary to obtain large tuning range for the MEMS tunable lasers. To

estimate the coupling effect, optical modeling has to be conducted. Hence, the mathematic equation governing the optical coupling is studied.

3.3.1.1 Propagation of Gaussian laser beams

In general, laser beam propagation can be approximated by assuming that the laser beam has an ideal Gaussian intensity profile, corresponding to the theoretical TEM_{00} mode. In TEM_{00} mode, the beam emission from a laser begins as a perfect plane wave with a Gaussian transverse irradiance/intensity profile as shown in Fig. 3.7.

The following formulae describe the Gaussian beam spreading as it propagates [216]. Even if the Gaussian TEM_{00} laser beam wavefront is made perfectly flat at some plane, it would quickly acquire curvature and begin spreading in accordance with

Fig. 3.7 Gaussian distribution: (a) Gaussian irradiance distribution, and (b) Gaussian beam intensity profile.

$$w(z) = w_0 \left[1 + \left(\frac{\lambda z}{\pi w_0^2} \right)^2 \right]^{1/2} \quad (3.20)$$

and

$$R(z) = z \left[1 + \left(\frac{\pi w_0^2}{\lambda z} \right)^2 \right] \quad (3.21)$$

where z is the propagation distance relative to the plane where the wavefront is flat, λ is the wavelength of light, w_0 (also known as beam waist) is the radius of the irradiance contour at the plane where the wavefront is flat, $R(z) \rightarrow \infty$, $w(z)$ is the radius after the wave has propagated a distance of z , and $R(z)$ is the wavefront radius of curvature after propagating over a distance of z . The plane $z = 0$ marks the location of a Gaussian beam waist (w_0). Simultaneously, as $R(z)$ asymptotically approaches z for longer distance, $w(z)$ asymptotically approaches the value defined by

$$w(z) \approx \frac{\lambda z}{\pi w_0} \quad (3.22)$$

In this case, the difference between Eqs. (3.20) and (3.22) is quite small. For example, when $z = 30 \mu\text{m}$, $\lambda = 1.55 \mu\text{m}$, $w_0 = 1.75 \mu\text{m}$, the difference of the values given by Eqs. (3.20) and (3.22) is around 1%.

The beam propagation/coupling of the external cavity laser can be shown schematically in Fig. 3.8(a). For the convenience of the optical analytical model, the equivalent schematic diagram is shown in Fig. 3.8(b), where the optical system can be any linear optical elements (such as a lens or a mirror) or their combination. Suppose the original laser emitting beam is B_1 , after propagation through the optical system, it

Fig. 3.8 Schematic diagram of the laser beam propagation and coupling: (a) Laser beam propagation/coupling in the external cavity laser, and (b) equivalent diagram of (a).

is reshaped to be either a focused beam B_2 or a diverging one B_3 . To mathematically describe such transformation, a ray transfer matrix M can be defined as

$$M = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \quad (3.23)$$

where the elements A , B , C , and D correspond to the elements of ABCD law.

A complex beam parameter, q , is introduced. It gives the information on the radius of the propagating Gaussian beam $w(z)$ and the radius of the wavefront curvature $R(z)$. It can be expressed as [217]

$$\frac{1}{q(z)} = \frac{1}{R(z)} - j \left[\frac{\lambda}{\pi w(z)^2} \right] \quad (3.24)$$

After the Gaussian beam q_1 propagates through an optical system, by the transformation rule of ABCD law, the beam is expressed as

$$q_2 = \frac{Aq_1 + B}{Cq_1 + D} \quad (3.25)$$

where q_1 and q_2 are the beam parameters in the input and output planes of an optical system as shown in Fig. 3.8 (b) described by its ray (ABCD) matrix. From Eq. (3.24), it indicates that when $R(z)$ approaches infinity such that $R(z) \rightarrow \infty$, the real part of $1/q(z)$ is zero. In other words, the beam waist is located at the position of z .

3.3.1.2 Coupling of Gaussian laser beams

The Gaussian optical field distribution is shown in Fig. 3.9. It should be noted that this schematic is valid for many optical arrangements, such as fiber-to-laser and laser-to-laser optical couplings. The first beam is referred as the laser source (w_{0s}) and the second as the receiver beam mode (w_{0r}).

The x component (E_x) of the field vector can be expressed as [37]

$$E_x(x, y, z) = E_1 \frac{w_{0s}}{w(z)} \exp \left\{ -i[kz - \phi(z)] - r^2 \left[\frac{1}{w^2(z)} + i \frac{k}{2R(z)} \right] \right\} \quad (3.26)$$

Fig. 3.9 Analytical model for the laser beam optical field distribution.

where E_1 is the laser output field's amplitude at the origin position ($x=0, y=0, z=0$), r is the radius from position (x, y, z) to the z axis (i.e.

$$r = \sqrt{x^2 + y^2})$$

$$k = 2\pi n / \lambda \quad (3.27a)$$

$$\phi(z) = \tan^{-1} \left(\frac{\lambda z}{\pi n w_{0s}^2} \right) \quad (3.27b)$$

$$w^2(z) = w_{0s}^2 \left[1 + \left(\frac{\lambda z}{\pi n w_{0s}^2} \right)^2 \right] \quad (3.27c)$$

$$R(z) = z \left[1 + \left(\frac{\pi n w_{0s}^2}{\lambda z} \right)^2 \right] \quad (3.27d)$$

where w_{0s} is the waist radius of the emitting beam, z denotes the distance of propagation, n is the refractive index, and λ is the wavelength of light.

After the emitted beam goes through the gap and the optical system, it reaches the laser facet. Similarly, the x' component $E_{x'}$ of the field vector can be expressed as

$$E_{x'}(x', y', z') = E_1 \frac{w_{0s}}{w(z')} \exp \left\{ -i[kz - \phi(z')] - r'^2 \left[\frac{1}{w^2(z')} + i \frac{k}{2R(z')} \right] \right\} \quad (3.28)$$

where r' is the radius from position (x', y', z') to the z' axis

$$\phi(z') = \tan^{-1} \left(\frac{\lambda z'}{\pi n w_{0r}^2} \right) \quad (3.29a)$$

$$w^2(z') = w_{0r}^2 \left[1 + \left(\frac{\lambda z'}{\pi n w_{0r}^2} \right)^2 \right] \quad (3.29b)$$

$$R(z') = z' \left[1 + \left(\frac{\pi n w_{0r}^2}{\lambda z'} \right)^2 \right] \quad (3.29c)$$

By combining Eqs. (3.28) and (3.29), there are

$$E_x(x, y, z) \Big|_{z'=0} = E_1 \frac{w_{0s}}{w(Z_0)} \exp \left\{ -i[kZ_0 - \phi(Z_0)] - (x'^2 + y'^2) \left[\frac{1}{w^2(Z_0)} + i \frac{k}{2R(Z_0)} \right] \right\} \quad (3.30)$$

$$E_{x'}(x', y', z') \Big|_{z'=0} = E_1 \frac{w_{0s}}{w_{0r}} \exp \left\{ - (x'^2 + y'^2) \left[\frac{1}{w_{0r}^2} \right] \right\} \quad (3.31)$$

The coupling between two Gaussian mode beams is determined by separation, offset, and angular misalignment. Then, the coupling coefficient η_c at $z'=0$ between the two Gaussian beams can be expressed as [37, 38]

$$\eta_c = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} E_x(x, y, z) \Big|_{z'=0} \times E_{x'}^*(x', y', z') \Big|_{z'=0} dx' dy' \quad (3.32)$$

and the power transmission coefficient can be written as

$$T_c = \frac{\left| \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} E_x(x, y, z) \Big|_{z'=0} \times E_x^*(x', y', z') \Big|_{z'=0} dx' dy' \right|^2}{\int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} |E_x(x, y, z) \Big|_{z'=0}|^2 dx' dy' \times \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} |E_x^*(x', y', z') \Big|_{z'=0}|^2 dx' dy'} \quad (3.33)$$

where $E_x^*(x', y', z')$ is the conjugate of $E_x(x', y', z')$.

3.3.2 Butt coupling methods

Although theoretically the beam coupling efficiency could be very high, a simple and efficient coupling within the laser external cavity is always very challenging. Various methods have been proposed since the development of laser diodes for optical communications. With the development of MEMS technology and fabrication techniques, more methods have emerged. However, none seems to be an ideal solution.

Butt coupling using a flat mirror as the reflector is the simplest way of realizing the external cavity, as shown in Fig. 3.10 (a) [218]. The mirror is usually coated with a thin layer of gold and its surface is a plane perpendicular to the optical axis of the emitting laser beam. The mirror is then brought close to the laser facet and aligned with the emitting beam.

Fig. 3.10 Schematic of the MEMS tunable lasers with different external mirrors:

(a) Flat mirror, and (b) curved mirror.

Fig. 3.11 Comparison of coupling efficiency versus different external cavity lengths.

Typically, the efficiency of the butt coupling using a flat mirror is fairly low, and longer external cavity would suffer even higher losses. As can be seen from Fig. 3.10(a), the laser beam is divergent in both parallel and transverse directions. To improve the mirror reflection back to the diode laser, a curved mirror has been suggested as shown in Fig. 3.10(b) [72]. Although it could only focus the back-reflected beam in the horizontal plane, the coupling efficiency can be increased significantly. The details of the simulation results and discussions are as follows.

Based on the analytical model (Eqs. (3.26) – (3.33)) presented in last section, the relations among coupling efficiency, external cavity length, laser wavelength, and mirror rotation angle can be obtained. The feedback coupling efficiencies for two different MEMS mirrors designs are compared in Fig. 3.11. In the simulation, the curved mirror has a curvature of 66 μm , the wavelength is 1.55 μm , the reflectivity of the mirror surface is assumed to be 100%; and the laser beam is taken as an elliptical Gaussian shape with the beam waist in major and minor axes of 1.75 μm (w_{0x}) and 1.53 μm (w_{0y}), respectively. Based on the simulation results, in Fig. 3.11, the coupling efficiency of the curved mirror can reach from 4% to 8.2% when the mirror moves

Fig. 3.12 Comparison of coupling efficiency versus different laser wavelength.

back and forth within $\pm 8 \mu\text{m}$ with respect to the original position. In contrast, the efficiency of the flat mirror can be 0.5% - 0.6%. As a result, compared to the flat mirror, the curved mirror provides higher coupling efficiency (more than 7%) for the external cavity laser design.

The dependence of the coupling efficiency on the laser wavelength is shown in Fig. 3.12. When the laser wavelength changes from $1.25 \mu\text{m}$ to $1.85 \mu\text{m}$, the coupling efficiency of the curved mirror case drops from 10% to 7%, whereas that of the flat mirror case reduces from 1% to 0.5 %. This also proves that the curved mirror provides higher coupling efficiency for different wavelengths.

Position misalignments, including angular misalignment and x -/ y - axis position misalignment between laser diode and external mirror, deteriorate the coupling efficiency. For instance, the angular misalignments in the x - z plane may significantly reduce the coupling efficiency, as shown in Fig. 3.13. Therefore, some

Fig. 3.13 Schematic diagram of the coupling efficiency of angular misalignment.

concerns should be taken into consideration to reduce the misalignment effect during the MEMS actuator design.

The effects of the angular misalignment on coupling efficiencies for different cavity configurations are illustrated in Fig. 3.14. The curved mirror can focus the beam with a higher coupling efficiency as compared to the flat mirror. However, once the curved mirror has an angular misalignment, such as $\theta = 3^\circ$ in Fig. 3.14(c), the reflection beam is directed away from the laser beam axis. Therefore, a small angular misalignment of the curved mirror may result in a large reduction of the coupling efficiency. On the other hand, the flat mirror has a large tolerance to this angular misalignment as it has no focusing effect. Based on the analytical model, the influence of the rotation angle θ is shown in Fig. 3.15. The curved mirror can provide the coupling efficiency from 8.2% to 7% when the tolerance of θ is $\pm 0.5^\circ$. Its coupling efficiency is close to 0 when θ is deviated by approximately $\pm 3^\circ$. However, the flat mirror has nearly a constant efficiency of 0.7% over the θ deviation of $\pm 3^\circ$.

Fig. 3.14 Schematic diagrams of the beam propagation in the external cavity with angular misalignment, for the curved mirror and the flat mirror.

Fig. 3.15 Comparison of the coupling efficiencies of the curved mirror and the flat mirror in the presence of the angular misalignment θ .

In summary, according to the simulation results, the curved mirror is approximately 10 times more efficient than the flat mirror in terms of coupling efficiency when the misalignment is not very serious. On the other hand, the coupling efficiency of the flat mirror is low, although it is not very sensitive to the angle and position misalignment.

3.3.3 3D micro-optical design

In section 2.2, according to the theoretical analysis, the importance of the coupling efficiency and the external cavity length to the wavelength tuning range of an external cavity laser has been emphasized. Both factors are significant for the design of MEMS tunable lasers. In the following section, the 3D optical coupling design is presented.

3.3.3.1 3D micro-optical system

A 3D optical system for MEMS external cavity tunable laser is designed as shown in Fig. 3.16. The external cavity consists of a rod lens and a reflective curved mirror. In the design, an optical fiber is used as a rod lens. The rod lens is employed to collimate and focus the laser beam in a vertical direction while the curved mirror collimates the laser beam in the horizontal direction. The beam divergence is greatly limited in both directions because the collimating directions are normal to the beam propagation direction.

Fig. 3.16 Schematic of the tunable laser with 3D micro-optical external cavity: (a) Top view, and (b) side view.

3.3.3.2 Simulation of the 3D micro-optical system

After the Gaussian beam is transferred by the external cavity (between the laser diode and the reflective mirror), which can be represented by the transfer matrix M , the beam radius and wavefront/phase curvature can be calculated by using the ABCD Gaussian beam propagation law (i.e. Eq. (3.25)). As shown in Fig. 3.17, the Gaussian beam entering the optical system can be described by the q parameter as $q = L_1 + iz_0$ (where $z_0 = \pi w_0^2 / \lambda$), and at the exit plane the Gaussian beam emerges with the beam parameter q' as $q' = -L_3 + iz_0'$, with $z_0' = \pi (w_0')^2 / \lambda$.

Fig. 3.17 Schematic diagram of Gaussian beam propagation through the 3D optical system.

In the 3D micro-optical system design, the transfer matrix of M (in Fig. 3.17) is expressed as

$$M = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \frac{2-n_f}{n_f} & \frac{2R}{n_f} \\ \frac{2(1-n_f)}{n_f R} & \frac{2-n_f}{n_f} \end{bmatrix} \quad (3.37)$$

In order to couple the feedback beam to the original emitting beam mode so as to obtain high coupling efficiency of the external cavity, the design parameters L_1 , L_2 , and L_3 must satisfy the following conditions

$$L_2 = 2R \quad (3.38a)$$

$$L_3 = -\frac{(AL_1 + B)(CL_1 + D) + ACz_0^2}{C^2 z_0^2 + (Cz_0 + D)^2} \quad (3.38b)$$

$$z_0' = z_0 \frac{CL_3 + A}{CL_1 + D} \quad (3.38c)$$

$$z_0' = z_0 \quad (3.38d)$$

where L_1 is the distance between laser facet and the fiber surface, and L_3 is the distance between the fiber surface and the mirror. The conditions of Eqs. (3.38a) –

(3.38d) imply that L_1 and L_3 are the locations of the beam waist of the initial and the transformed Gaussian beams, respectively. R is the radius and n_f is the refractive index of the fiber, respectively.

The beam patterns of back-reflected beams for different external cavities are compared in Fig. 3.18. The original beam emitted from the laser diode has an elliptical shape (beam radii of $1.75\ \mu\text{m}$ and $1.53\ \mu\text{m}$) as shown in Fig. 3.18 (a). In the cases of flat and cylindrically curved mirrors, the external cavity lengths are $10\ \mu\text{m}$ and $66\ \mu\text{m}$, respectively. Their reflected beams are reshaped to $5.9\ \mu\text{m} \times 6.6\ \mu\text{m}$ and $1.75\ \mu\text{m} \times 42.6\ \mu\text{m}$ as shown in Figs. 3.18 (b) and (c), which are far from the initial beam size and thus results in low coupling efficiency. In contrast, the 3D micro-optical system is able to focus the laser beam back to $1.75\ \mu\text{m} \times 1.53\ \mu\text{m}$ (Fig. 3.18(d)) even though the external cavity length is chosen to be $220\ \mu\text{m}$.

Fig. 3.18 Comparison of the beam patterns at the laser facet: (a) Original laser emission, (b) reflected beam by the flat mirror ($L = 10\ \mu\text{m}$), (c) by the curved mirror ($L = 66\ \mu\text{m}$), and (d) by the 3D micro-optical system ($L = 220\ \mu\text{m}$).

Based on the simulations and coupling concerns, the design parameters of the 3D micro-optical system of the MEMS tunable laser are: $L_1 = 50 \text{ } \mu\text{m}$, $R = 30 \text{ } \mu\text{m}$, $L_3 = 82 \text{ } \mu\text{m}$, and $L = 220 \text{ } \mu\text{m}$, where L is the total external cavity length ($L = L_1 + 2n_f R + L_3$).

3.4 Mechanical design

For mechanical design of micromachined tunable lasers, microactuators play a key role in moving mirrors to tune wavelength. The MEMS actuator design is discussed in this section.

Many different types of microactuators based on various actuation mechanisms have been successfully developed, including electrostatic [219-225], thermal [226-229], piezoelectric [230-234], magnetic [235, 236], scratch drive actuators (SDA) [237, 238], and so on [239-241]. Based on the literature survey, different types of MEMS actuators are summarized in Table 3.1.

Table 3.1 Comparison of different types of MEMS actuators

Mechanisms	Force	Speed	Displace. range	Compatibility	Repeatability
Electrostatic	Low	High	High/low	High	High
Electromagnetic	High	Low	High	Low	High
Piezoelectric	High	High	Low	Low	High
Thermal	High	Low	High	High	Low
Surface tension	Large	Low	High	High	Low

Compared with electrostatic comb-drive actuators, thermal-actuators are too sensitive to ambient temperature. Electromagnetic actuators, on the other hand, are much more complicated in terms of fabrication as their device structures require special materials which are not compatible with the complementary metal oxide semiconductor (CMOS) fabrication process. Although other actuation mechanisms could provide large forces or fast speeds, electrostatic actuators are much more suitable for the MEMS external cavity tunable lasers due to the feature of fast speed, high compatibility, and easy fabrication [219]. Particularly, electrostatic actuators can be simply fabricated using the established silicon IC processes and can be easily integrated with electronic components. Meanwhile, other advantages of high repeatability, low power consumption and easy control make the electrostatic actuators most suitable for single chip integrated MEMS devices. Especially, the lateral comb-drive actuators exhibit better stability characteristics over long ranges of in-plane translation, accurate position control and easy drive, which are critical to the MEMS external cavity lasers. Additionally, microactuators can be easily designed for linear operation over a large displacement range. As a result, comb-drive actuators are selected for the MEMS external cavity tunable lasers.

3.4.1 Electrostatic comb-drive actuators

Electrostatic comb-drive actuators provide in-plane actuation. The principle of comb-drive actuation is illustrated in Fig. 3.19. The typical comb-drive actuator consists of a stationary set and a movable set of inter-digitated comb-fingers and a folded suspension beam. For each pair of fingers, one finger is fixed and the other one

Fig. 3.19 Principle of the linear electrostatic actuation: (a) Movement of fingers, and (b) analytical model of a pair of fingers.

is movable, separated by a gap as shown in Fig. 3.19 (b). Particularly, the latter is attached to a mechanical spring that provides the restoring force to counteract electrostatic force. By charging the two plates with equal and opposite charges (e.g. $+Q$ and $-Q$), the electric field will generate attractive forces between the two plates, causing the movable comb to move toward the stationary one. The final steady position is controlled by a balance between the electrostatic force and the mechanical restoring force from the compliant suspension. Commonly, the suspension makes use of double-folded beams. When the DC voltage V is applied between the movable and fixed combs, the electrostatic force induces in the movable comb a certain displacement Δx , as given by [242]

$$\Delta x = \frac{n \epsilon t}{g k_x} V^2 \quad (3.34)$$

where n is the number of finger pairs, ϵ is the dielectric constant of the medium, t is the thickness of comb fingers, g is gap spacing between adjacent fingers, and k_x represents the stiffness of suspension beams.

3.4.2 Bidirectional comb-drive actuators

The comb-drive actuators can be designed for bidirectional actuation so that the total deflection range is doubled without impacting the side stability. Such an approach also makes the tunable laser design more flexible. The schematic diagram of a bidirectional actuator consists of three series (two sets) of comb-like fingers, with fingers partially overlapping with each other, as shown Fig. 3.20. The middle series are free to move in opposite directions, while the other two series are fixed. The folded beam is employed as the suspension beam. Its lateral stiffness is expressed as [242]

$$k_x = \frac{2EtW_b^3}{L_b^3} \quad (3.35)$$

where t is the thickness of the beam, L_b and W_b are the length and width of the beam, respectively, and E is the Young's modulus. The corresponding parameters are indicated in Fig. 3.20 (b). Combining Eqs. (3.34) and (3.35) gives, the lateral displacement Δx

$$\Delta x = \frac{F}{k_x} = \frac{n\varepsilon}{2Eg} \left(\frac{L_b}{W_b} \right)^3 V^2 \quad (3.36)$$

From Eq. (3.36), the ratio of the length and width of the folded beam affects the displacement much more than the gap and finger numbers. It indicates that the displacement is also proportional to the square of the applied DC voltage.

Fig. 3.20 Schematic diagrams of the bidirectional comb-drive actuator: (a) Overview of the actuator, and (b) comb-drive set.

3.5 Fabrication process on SOI substrate

MEMS devices are fabricated using the process steps similar to those in integrated circuit manufacturing, including photolithography, wet and dry etching, oxidation, diffusion, low-pressure chemical vapor deposition (LPCVD) and sputtering deposition. Among the candidate technologies for MEMS fabrication, such as bulk

micromachining, surface micromachining and reactive ion etching (RIE), the RIE technology is the most practical one owing to the availability of fabrication facilities and its technological merits, for example, high selectivity, anisotropy, arbitrary structure profiles, easy integration and simple process.

The DRIE fabrication processes not only produce high aspect ratio structures but also facilitate different designs of MEMS structures. State-of-the-art DRIE tools are capable of etching deep silicon structures with aspect ratios exceeding 50:1, high selectivity to photoresist ratios exceeding 100:1. While fundamental process capability has been improved, there have been parallel developments in etching rate and productivity. It provides a means of etching silicon at high rate with excellent anisotropy; silicon etch rate higher than 20 $\mu\text{m}/\text{min}$ is routinely achieved in MEMS manufacturing.

A reliable DRIE process on a silicon-on-insulator (SOI) wafer is developed for the tunable laser fabrication. The SOI wafer consists of a top silicon layer as the structure layer, a buried oxide layer and a silicon substrate. The oxide layer can be used for micromachining in two ways: sacrificial buffer and etch-stopper. For the first role, the buried oxide layer can be easily removed by wet chemical etching in HF. With the DRIE process, a free standing structure and highly vertical profiles can be achieved. The oxide layer can also be used as an etch-stopper when anisotropic etching in KOH or dry etching is applied. Additionally, it can be used for electrical isolation. As the movable mirror and micro-lenses may have arbitrary profiles, crystal-orientation-dependent wet etching is not suitable. Dry etching is thus preferred due to the advantages it offers: crystal-orientation-independent etching, high resolution, no stiction, better fabrication control and smaller features [243-244]. The

SOI wafers used for the MEMS tunable lasers have a 75- μm -thick silicon structure layer, a 2- μm -thick silicon dioxide buffer layer, and a 475- μm -thick handling silicon substrate.

The DRIE process flow, as shown in Fig. 3.21, is developed for the MEMS tunable lasers. Some special requirements are carefully addressed. For example, electrical connections are essential to applying an injection current to the laser diode and an electric potential to the actuator. The etched sidewall requires high verticality and smoothness, especially for the mirror surface that requires high reflectivity. The etching depth is large enough for the mirror to cover the diverged light beam from the laser chip and to allow the insertion of normal single mode fibers as the input and output coupling. In addition, dicing lines need to be fabricated by the etching process for the convenience of wafer dicing, in order to expose the fiber grooves for packaging and integration.

The aluminum electrodes are patterned and sintered for low ohm contact with silicon, as shown in Fig. 3.21 (a). Those electrical pads are patterned on the substrate (SOI) firmly for the wire bonding of MEMS packaging. Then, the hard mask (e.g. silicon dioxide) is deposited, and the microstructures including comb-drive actuators, fiber grooves and dicing lines are patterned by lithography and hard mask etching process. In addition, an even thicker photoresist (PR) layer is deposited and patterned not only for protecting the patterned hard mask (SiO_2 layer), but also for patterning the dicing lines as shown in Fig. 3.21 (b). Such multi-layer patterning method is used to etch the deep dicing lines from 75 μm (structure layer) down to the buried oxide layer, while keeping all the other parts of the microstructures protected. A first deeper DRIE etches through the device layer where the microstructures patterned on the hard

Fig. 3.21 Schematic diagram of the DRIE process flow in silicon-on-insulator wafers.

mask oxide layer are protected by the patterned PR layer, and then continues by partially etching the handle substrate silicon layer. Then, the PR layer is stripped as shown in Fig. 3.21 (c). By this means, the lithography onto deep trenches is prevented and the accuracy of the functional structure is guaranteed. Later, by exposing the patterned hard mask to proceed with the microstructures fabrication, another step of deep etching of the device layer down to the buried oxide buffer layer is carried out. It is noted that the trenches with sufficient width are etched down to the buried oxide

layer, while the narrow trenches are not yet completely etched, with the dicing lines further deepened, as shown in Fig. 3.21 (d). To prevent notching at the bottom of the wide trenches, PECVD dioxide is then employed to cover the top surfaces, bottoms and sidewalls of the trenches, as shown in Fig. 3.21 (e). In order to continue etching for the other trenches, an anisotropic oxide etching step is performed, using an Applied Materials P5000 Mark II to remove the laterally deposited oxide layer in a CHF_3 based etchant as shown in Fig. 3.21 (f). After that, the DRIE is processed again until the narrowest trenches are completely etched through (Fig. 3.21 (g)). To free the movable structures and to remove the oxide layer, wet release with buffered oxide etchant (BOE) is performed (Fig. 3.21 (h)). Lastly, the microstructures are covered by the shadow mask for metal deposition to the selected areas, such as mirror surfaces (Fig. 3.21 (i)). As a result, the functional optical components such as mirrors are coated with 0.2- μm of gold in order to obtain highly reflective surfaces. The sputtering processes for thin-film deposition are naturally energetic and generally do not require additional heat input to generate good morphology. In this case, the Au coating on the mirror surface is done by the BLAXER sputtering system (Sitek Process Solution Inc). In addition, an adhesion layer of Ti is initially deposited before the Au surface coating. The sputtering conditions for Ti/Au are: Ti $\sim 300 \text{ \AA}$ thick as adhesion layer, power 1.5 kW, argon gas flow 100 sccm, deposition rate 133 $\text{\AA}/\text{min}$; Au (0.2 μm), power 1.0 kW, argon gas flow 30 sccm, deposition rate 333 $\text{\AA}/\text{min}$. Due to the notching effect, the gold on the sidewalls of the trench could be well isolated from that on the bottoms and neighboring sidewalls, ensuring the desired electrical isolation between different parts of the structures.

The process flow is arranged in such an order that the electrical pads are first fabricated, followed by the formation of the very deep dicing line; MEMS structures

are then patterned, etched, released and metal coated. Finally, the wafer is ready for dicing to small dies and then packaged with the laser chips and optical fibers. This process can also be simplified further in various ways according to the applications and different designs.

The deep RIE process is key to the MEMS tunable laser fabrication. More details are discussed below. The DRIE process is performed by using the Surface Technology Systems (STS) inductively coupled plasma (ICP) deep etching systems. The method employs successive alternations of etching/passivation steps in a plasma etching system. The passivation step coats the silicon sidewalls with a protective polymer film to prevent lateral etching. In the etching step, the polymer is firstly removed from the base of the etching structures, and then the underlying silicon is etched away at a high rate. In this way, the etched sidewalls can be very vertical. The vital part of this process is the high-density plasma that is capable of providing sufficient etchant species and polymer precursors. The STS etching system is designed to offer high aspect ratio anisotropic etching by alternative steps of etching and sidewall passivation. The ICP source offers high-plasma density and operational stability at 13.56 MHz. Additionally, this system uses a high density low pressure (HDLP) system to reduce the ion collision probability since the sheath thickness decreases at higher ion density and the ion mean free path increases at lower pressure [245]. In this way, the ion directionality is improved and this enhances the anisotropy control. The main reaction gases are SF_6 for etching and C_4F_8 for passivation.

As DRIE is a cyclic process of etching and passivation, various combinations of the etch and passivation steps affect the overall etch rate, trench profile and sidewall qualities. Hence, a trade-off among the above features has been made during

the process design. As a result, settings of platen power, durations of the etching and passivation cycle, process pressure, gas flow rate and temperature are major issues in the process optimization.

Based on the DRIE processes conditions, the microstructure layouts and design rule are developed in this project. Two important issues between design and fabrication processes are considered. First, the microstructures along with the distribution of the overall structures may lead to different consequences even under the same etching conditions. For etch patterns with different opening sizes, etching rates vary according to the effect of aspect ratio resulting in RIE lag (also known as loading effect). The etch rates vary drastically with the reduction of the width of etch openings. More specifically, the etch depth increases with broader etch openings. Such variations in etch rates with respect to the aspect ratios and the etch opening sizes arise as a result of several etch mechanisms (e.g. the ion and kinetic neutral shadowing effect and the electrical charges accumulation effect on etch surface), while the most prominent one would be the transportation of etch reactants towards/away from the etch surface. In this case, a higher charge density at the bottom of smaller trenches results in higher probabilities of repelling away the incoming charged reactive species, which reduces or even prohibits further etch actions eventually. Second, the notching effect of silicon at the interface of the structure and the buried oxide is considered. The former charge accumulation effect also occurs simultaneously with notching. To solve both critical problems (loading and notching), an optimized fabrication process was therefore developed, as described in Fig. 3.21. By dividing the deep etching into more steps, the DRIE steps are associated with auxiliary oxide deposition and lateral oxide removal steps intercalated in between. In

this way, the notching effects are mostly ameliorated while trenches with different openings finally reach the same etching depth.

3.6 Experimental results and discussions

In this section, experiments and characterizations of the micromachined external cavity tunable laser are discussed. Firstly, the optical performances of the 3D micro-optical system are evaluated, including the beam reshaping effect and the coupling efficiency. Then, the coupling efficiencies of the three different designs are compared and discussed. Finally, the experimental results of wavelength tuning of the tunable laser, as well as its tunability and mode stability, are presented and discussed.

3.6.1 MEMS tunable laser

The MEMS tunable laser is fabricated by using the DRIE process, as shown in Fig. 3.22. A single mode fiber (SMF) is assembled in the external cavity as a lens. The cylindrical lens within the external cavity has a diameter of 60 μm and a focal length of 46.9 μm . It is fabricated by etching a standard SMF-28 optical fiber (diameter 125 μm) using 49% HF. The curved mirror has the curvature radius of 220 μm , which is driven by the electrostatic comb-drive actuator. The wavelength tuning of the tunable laser is achieved by changing the length of the external cavity between the laser diode and the curved mirror.

Fig. 3.22 SEM image of the MEMS tunable laser using a 3D micro-optical system.

3.6.2 Beam reshaping and optical coupling

The curved mirror is coated with a 0.2- μm -thick gold layer to improve its reflectivity. The effectiveness of the curved mirror and the cylindrical fiber lens are measured by capturing the transformed beam patterns using an infrared CCD camera. When it is focused just by only the curved mirror, the beam size in the horizontal direction is maintained while that in the vertical direction is elongated, as shown in Fig. 3.23 (b). When it is focused only by the rod lens, the beam in the horizontal direction is elongated while in the vertical direction the shape is maintained, as shown in Fig. 3.23 (c). Moreover, both patterns indicate that the irradiance around the center part is decreased compared to the original pattern, as shown in Fig. 3.23 (a). The beam irradiance distributions are shown in Fig. 3.23. The original laser emission has an elliptical distribution as shown in Fig. 3.23 (a). As it can be seen, the peak distribution of the irradiance, thus most of the emitted power is concentrated in When it is focused by both the curved mirror and the rod lens, the transformed beam is again elliptical (as shown in Fig. 3.23 (d)), with a shape which closely matches with the

Fig. 3.23 Experimental results of the beam patterns for different external cavities corresponding to different focus states: (a) Initial laser emission, (b) cavity with the curved mirror, (c) cavity with the rod lens, and (d) 3D micro-optical system.

original pattern in terms of beam size and irradiance distribution. In this latter case it is clear that the 3D micro-optical system has improved coupling efficiency as compared to the cavity including the curved mirror or the rod lens.

The experimental results of the measurements of coupling efficiency in the 3D micro-optical system are shown in Fig. 3.24. The coupling efficiencies of different external cavities were compared, including the cavities with the flat mirror and the curved mirror. Fig. 3.24 shows that the 3D micro-optical system achieves a power coupling efficiency of 46.5%, which is much higher than what is obtained with the flat mirror (1%) and the curved mirror (8.5%). It is important to note that the original cavity lengths for the flat mirror, the curved mirror and the 3D optical system are 10 μm , 66 μm and 220 μm , respectively. When the cavity length is changed by translating the curved mirror, the efficiency of the 3D micro-optical system drops gradually from 46.5% to 16%. It drops from 8.5% to 1% within a cavity length change of 6 μm for the curved mirror. However, the coupling efficiency does not change significantly for the flat mirror. Based on the previous simulation results as shown in Fig. 3.6, the corresponding tuning range for 1% and 8.5% coupling

Fig. 3.24 Measurement results of the coupling efficiency versus the length of the external cavity.

efficiencies are 0.05 nm and 0.47 nm, respectively. The tuning range of the tunable laser can be very wide for the coupling efficiency of 46.5%, although the real tuning range may be limited by other factors such as the gain spectrum and the injection current level.

3.6.3 Wavelength tunability and mode stability

The position of the curved mirror is controlled by applying a driving voltage to the comb-drive actuator. The mirror displacements are measured by first recording the images using a CCD camera (AVC 561) and then correlating the images using MatLab codes. The measured actuation relationship for the curved mirror is shown in Fig. 3.25. When the driving voltage is 15.8 V, the mirror displacement can reach 3 μm. The external cavity length is about 220 μm initially. When actuated, the mirror moves away from the laser diode, which results in an increase in the external cavity

Fig. 3.25 Experimental result of the curved mirror displacement vs. applied voltage.

length. The detection fiber is located in a U-shaped groove etched on the silicon layer. The end of the fiber is placed close to the emitting window of the laser diode, which ensures a simple butt-coupling with a sufficient efficiency for characterization. With regard to the butt-coupling, the fiber core has a diameter of $8.2\ \mu\text{m}$ and the laser output has diameters of $1.75\ \mu\text{m} \times 1.53\ \mu\text{m}$ in an elliptical shape. Although the efficiency of the butt-coupling is less than 20%, it is simple and without additional coupling lenses. The coupled power is typically 1 mW. When it is measured by using a tapered fiber (TSMJ-X-1550-9/125-0.25-7-5-26-2-AR, OZ Optics), the coupling efficiency can be increased to more than 40%. However, it is less tolerant to packaging misalignment. With respect to the optical coupling between the laser diode and the curved mirror, the optical axis is approximately $30\ \mu\text{m}$ lower than the upper edge of the curved mirror. At the position of the curved mirror, the laser beam has dimensions of about $74\ \mu\text{m} \times 84\ \mu\text{m}$ in diameters. The curved mirror is larger than $120\ \mu\text{m}$ in the horizontal direction, but could partially reflect the laser beam in the

vertical direction, and thus introduces a loss of 3.4 dB. The surface roughness of the mirror due to the etching and gold coating is 40 nm (RMS) in the top 40 μm part of the mirror. In the bottom part, it becomes rough. As a result, such roughness would cause additional loss by scattering.

The laser diode is made of multiple-quantum-well InGaAsP/InP material with the dimensions of $300\text{ }\mu\text{m} \times 300\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$, and the emitted wavelength is around 1.55 μm . The laser facets are normally cleaved (i.e. $r_2 = 0.56$). A Seastar Optics LD-2000 laser diode driver is used as the current source. The effective reflectance of the curved mirror is evaluated to be $r_3 = 0.03$ by measuring the threshold current variation while translating the curved mirror.

The wavelength tuning property of the MEMS tunable laser is shown in Fig. 3.26. The injection current is kept at 21.4 mA, which is 28% over the threshold current 16.7 mA. At this level, the tunable laser can be operated in continuous wave (CW) mode without additional heat sink. Meanwhile, due to homogeneous broadening, it is able to maintain single longitudinal mode when it is tuned to different wavelengths. The spectra of different output states are shown in Fig. 3.26.

Fig. 3.26 Measured laser spectra at different mirror driving voltages.

The spectrum is measured by an Advantest Q8384 Optical Spectrum Analyzer. Various wavelengths are detected each time, with an output power about 1 mW. The side mode suppression ratio is more than 20 dB. Fig. 3.27 shows the measured wavelength tuning with respect to the mirror displacement. In the experiment, the laser spectra are measured at different mirror driving voltages, and then the corresponding driving voltages are converted into mirror displacements. The emission wavelength is initially at 1549.45 nm. When the displacement of the curved mirror is increased by 0.1 μm , the output wavelength is tuned by 1.3 nm as shown in Fig. 3.27 (b). The wavelength is shifted by less than 0.01 nm within the mirror displacement of 0.07 μm . Further movement of the curved mirror makes it suddenly drop to 1542.45 nm (the shortest wavelength). After that, the wavelength appears at the positions of the laser modes, and is increased by a constant step of 1.3 nm. A tuning range of 14.05 nm, from 1542.45 nm to 1556.5 nm, is obtained by tuning the laser to 11 modes. It is noticed that multimode output occurs in the positions beyond the tuning range. This is mostly due to the laser gain profile. The weak modulation of the gain threshold is not strong enough to keep only one oscillating mode while suppressing the others, especially when the laser needs to transit from the maximum emission wavelength mode to the minimum. The measurement shows that further displacement of the curved mirror results in periodical wavelength changes, which matches the theoretical prediction. The mirror translation corresponding to one period is half of the initial wavelength. The sudden drop and stepwise increase of the wavelength are the evidence of discrete wavelength tuning.

The MEMS structures including the curved mirror and the actuator have a resonant frequency of 2.5 kHz. It takes less than 1 ms to switch from one wavelength

Fig. 3.27 Measured wavelength tuning relationships: (a) Wavelength tuning, and (b) example of output spectra. (measurement resolution: 0.01 nm)

to any of the other wavelengths. The MEMS comb-drive actuator was tested for lifetime. It operated for more than 24 hours under a square-wave driving signal at 200 Hz, which corresponds to about 17 million cycles, yet no obvious degrading has been observed in the structure and in the dynamic response of the comb-drive. Such a comb-drive actuator was also operated in an open environment for five days. No obvious performance degrading is noticed. These life tests proved that the MEMS-tunable lasers are robust and reliable.

It is also observed that outside the multimode regions, the output at any wavelength is stably single mode when the mirror is translated within a certain region. This stability region corresponds to a range of $0.05 \mu\text{m} - 0.07 \mu\text{m}$. Two adjacent modes are excited once the mirror moves out of this region, and thus mode competition occurs. In such case, one mode becomes weaker while the adjacent one keeps increasing. However, their relative power varies randomly, and the laser output therefore becomes unstable. The length of the unstable region is approximately $0.01 \mu\text{m}$. Within the stability region, the threshold gain of the stable mode is apparently

lower than that of its adjacent. On the other hand, at the edges of this region, the gain difference between two adjacent modes becomes very small. Additionally, random effects such as thermal/current/gain fluctuations play their roles.

The micromachined tunable laser demonstrated other merits. For example, the laser has high mechanical stability and wavelength repeatability since the laser mode does not change when the external mirror moves within the stability regions. Wide tuning range can be obtained by applying a short external cavity design. The laser configuration is simple and does not require external optical lenses and gratings. The change of the external cavity is simply a translation in contrast to the complicated mechanical movement in the continuously tuning lasers [45, 246] (e.g. the conventional laser has complicated design of actuator with very high driving voltage (e.g. ± 140 V) and low tuning range (e.g. ± 2.5 degrees mirror rotation). The external reflector needs only to travel for a distance less than one wavelength to sweep the whole tuning range, giving high-sensitivity output tuning. Another advantage is that all the longitudinal modes are automatically aligned to the ITU grids if the initial output is deliberately adjusted to an ITU wavelength and the mode spacing is selected to match the ITU grid interval, resulting in no further wavelength conversions. The MEMS tunable laser is able to reach specification of a wide tuning range (e.g. 20 – 30 nm), which is sufficient for many fibre-optic communication applications. On the other hand, the MEMS tunable laser has also some weaknesses including power fluctuation during tuning, low power in single-mode operation. Because the single mode output can be obtained when the injection current is not too high (typically less than twice of the threshold current), the resulted output power is therefore low (typically about 1 mW). Outside a certain wavelength range, the gain of the laser

modes drops to such a low level that a weak modulation of the threshold gain is no longer strong enough to support their oscillations.

3.7 Summary

This chapter focuses on theoretical analysis, optical designs, mechanical designs, DRIE fabrication and experiments of the micromachined external cavity tunable lasers. The theoretical analysis explores the optical feedback model, which predicts the wavelength tuning range and also guides external-cavity lasers designs. The optical and mechanical designs of the MEMS tunable lasers are investigated to improve the coupling efficiency, wavelength tuning range and tuning stability. More specifically, a 3D micro-optical coupling system is designed to increase coupling efficiency and wavelength tuning range. In addition, deep reactive ion etching (DRIE) fabrication processes are developed for the fabrication of the MEMS tunable lasers on a SOI wafer. Experiments show that the 3D optical system improves the coupling efficiency up to 46.5%, which is much larger than the conventional design of curved-mirror tunable laser [45]. Discrete tuning is also measured in constant steps of 1.3 nm over eleven wavelength positions, with a tuning range of 14.05 nm.

The advantages of the MEMS tunable lasers are as follows:

- 1) The capability to construct very short resonant cavity. This paves the way for a large tuning range.
- 2) The inclusion of MEMS in tunable lasers downscales bulky lasers, leading to many engineering merits in terms of batch fabrications and low power consumption. It also opens up space for utilizing new physical methods. However, as the wavelength tuning is intrinsically based on the mechanical translation of the mirror, the switching time is

typically limited at millisecond level. Although such a speed is sufficient for many applications, there are still intense demands on faster tuning, perhaps in the scale of micro-seconds or even nanoseconds in high-speed advanced applications in the future. Hence, new mechanisms and methods for speeding up the tuning of MEMS-based lasers should be further explored and investigated.

CHAPTER 4

MICROMACHINED COUPLED-CAVITY LASERS

The micromachined external-cavity tunable laser, studied in the previous chapter, demonstrated wavelength tuning by means of movable micro-mirrors. In this chapter, micromachined coupled-cavity lasers are presented. The objective is to seek a different physical mechanism for fast wavelength tuning while maintaining easy implementation using MEMS technology. Specifically, this chapter utilizes coupled-cavity laser configuration to achieve short tuning time at micro-second level.

This chapter starts with the theoretical studies of coupled-cavity lasers (CCLs), first presenting a brief introduction of the fundamental form of coupled-cavity lasers (two-section coupled-cavity lasers). Then, essential physical mechanisms behind the large wavelength tunability at high tuning speeds are investigated, including the free carrier plasma effect and the Vernier effect. This is followed by the development of coupled-cavity laser theoretical model. The additional incorporation of threshold condition analysis allows more precise prediction on the improved performance. Based on the theoretical studies and analyses, the integrated micromachined coupled-cavity lasers, particularly with an adjustable gap enabled by a parabolic mirror, is designed and fabricated. Finally, experimental results and tuning characteristics are elaborated.

4.1. Theory of wavelength tuning in the coupled-cavity lasers

Fig. 4.1 Schematic diagram of a two-section coupled-cavity laser.

4.1.1. Working principle of the coupled-cavity laser

A typical CCL is formed by coupling two or more laser cavities, which can be fabricated by etching a narrow groove inside a cleaved single chip [6] or by employing cleaved-coupled-cavity structures [85]. The general two-section coupled-cavity laser is shown schematically in Fig. 4.1. The dominant oscillation mode of the CCL is determined by the interference of the electromagnetic (EM) fields in all optical cavities involved. Separate electrical contacts to the two cavities allow a desirable electronic control of the output spectrum by adjusting the individual cavity gains and refractive index via the input currents. The additional degree of freedom in this two-section geometry also permits amplitude adjustment when the output wavelength is changed. The CCL configuration is particularly suitable for longitudinal mode selection and stabilization.

However, technical challenges remain to obtain, at the same time, optimal cavity coupling and phase matching. When the two coupled cavities are fixed by the

cavity gap as predetermined by the fabrication, the fixed gap is not adaptive to the variations of working conditions (such as environmental temperature change) and may lead to unstable single-mode operation and limited mode selectivity [88, 91, 247].

Based on the CCL working principle, this chapter aims to innovate an actively adjustable cavity gap using MEMS technology to realize a micromachined CCL configuration. The active adjustment of the cavity gap provides optimal phase matching and mode selection by using a micromachined movable mirror, with high compactness and easy integration.

Figure 4.1 schematically shows a general two-section coupled-cavity laser that consists of two standard Fabry-Pérot (FP) laser diode with different cavity lengths, which are mutually self-aligned and closely coupled in-line via an air junction to form a two-cavity resonator. Ideally, the active strip/waveguide of each diode is precisely aligned with respect to the other in a straight line. All the reflecting facets are formed by cleaving along crystallographic planes. Hence, the two chips are perfectly flat and parallel to each other, and then the complete electrical isolation of the two individual FP diodes is therefore achieved.

In general, the electronic wavelength tuning for wide tuning range at high speed is due to both the nonlinear relationship between gain and carrier density, and the rather linear dependence between refractive index and carrier density. Therefore, a quite large wavelength tuning can be accomplished.

4.1.2. Free-carrier plasma effect

The physics behind this electrical control of a laser's emission spectrum is the free carrier plasma effect [248]. It is widely used to change the refractive index, and consequently to tune the wavelength even in a very wide range. Yet this effect requires a sustained electric power supply.

For the fundamental FP cavity, the resonance condition can be expressed as

$$\lambda_N = \frac{2n_{eff}(\lambda_N)L}{N} \quad (4.1)$$

where N is the longitudinal mode number, λ_N represents the wavelength for mode number N , L is the laser cavity length, and $n_{eff}(\lambda_N)$ is the effective refractive index. By investigating the resonance condition, it is obvious that the comb-modes in a laser resonator/cavity may be tuned by the electrical control of the effective refractive index. Accordingly, the cavity of length L with an electronically controllable effective refractive index may serve as the basic tuning element to perform the shift of the comb-mode spectrum.

Considering the wavelength tuning achieved with a certain effective refractive index change Δn_{eff} as induced by the electronic control current, the tuning range $\Delta\lambda_{tune}$ can be estimated by

$$\frac{\Delta\lambda_{tune}}{\lambda_N} = \frac{|\Delta n_{eff}|}{n_{eff}} \quad (4.2)$$

The refractive index change Δn caused by the injection of electron-hole plasma into a semiconductor is mainly due to the density of the free carriers, while the

spectral shift of the absorption edge also contributes to Δn [249-250]. In this case, the real part of the refractive index change is given by [249]

$$\Delta n_r = -\frac{e^2 \lambda^2}{8\pi^2 c^2 n \epsilon_0} \left(\frac{1}{m_e} + \frac{1}{m_h} \right) \rho \quad (4.3)$$

where m_e and m_h denote the effective masses of the injected electrons and holes, respectively, e is the electronic charge, λ is the optical wavelength, n is the refractive index of the semiconductor, ϵ_0 is the permittivity of free space, ρ is the free electron concentration, which is equal to the free hole concentration, and c is the vacuum speed of light. In addition to the real part, the imaginary part of the refractive index is also changed by Δn_i , yielding an additional optical loss, as expressed by

$$\Delta n_i = -\frac{e^2 \lambda^2}{8\pi^2 c^2 n \epsilon_0} \left(\frac{1}{m_e^2 \mu_e} + \frac{1}{m_h^2 \mu_h} \right) \rho \quad (4.4a)$$

and

$$\alpha_{pl} = -2k_0 \Delta n_i = -\frac{e^3 \lambda^2}{4\pi^2 c^3 n \epsilon_0} \left(\frac{1}{m_e^2 \mu_e} + \frac{1}{m_h^2 \mu_h} \right) \rho \quad (4.4b)$$

where μ_e and μ_h are the mobilities of electrons and holes, respectively. The mobilities are related to the effective masses, as expressed by

$$\mu_{e,h} = e \tau_r / m_{e,h} \quad (4.5)$$

where τ_r is the dielectric relaxation time (typically in femtosecond timescale). Even when the injected electron-hole pairs recombination process is taken into consideration, such a plasma effect which modifies the refractive index still needs a few nanoseconds. As a result, switching time of the coupled-cavity lasers can be expected to be of the order of a few nanoseconds.

4.1.3. The Vernier effect and wavelength tunability

Fig. 4.2 Schematic of the laser structure where each end reflectivity has a comb characteristic.

To further extend the tuning range beyond $\frac{\Delta\lambda_{tune}}{\lambda_N} = \frac{|\Delta n_{eff}|}{n_{eff}}$, the *Vernier effect*

is used to exploit the full width of the gain window of semiconductor laser chips. The Vernier effect has been used in high-resolution distance measurements. When the laser structure has a comb-like reflection characteristic at each end, as the two combs

Fig. 4.3 Schematic of the cavity used as reflector.

have different periods, the Vernier effect can be utilized to expand the tuning range of the laser as illustrated in Fig. 4.2. The first comb has a period of $\Delta\lambda$ while the second comb has $\Delta\lambda - \delta\lambda$. When the position of one of the combs is shifted by $\delta\lambda$, the wavelength of coincidence is also shifted by $\Delta\lambda$. As an example of a reflector with the comb characteristic, we assume one facet is replaced by a cavity with field reflection coefficients r_1 and r_2 , refractive index n_1 , and length L_1 as shown in Fig. 4.3.

Based on the transfer matrix method, the reflection coefficient of the cavity is given by

$$r_1' = r_1 + \frac{(1 - r_1^2)r_2'}{1 + r_1r_2'} \quad (4.6)$$

where

$$r_2' = r_2 \cdot \exp\left(-j \frac{4\pi}{\lambda} n_1 L_1\right) \quad (4.6a)$$

The phase term in Eq. (4.6a) gives constructive or destructive interference and leads to a wavelength dependence on the magnitude of r_1' , with maxima spaced by

$$\Delta\lambda_1 = \frac{\lambda^2}{2n_{g,1}L_1} \quad (4.6b)$$

where $n_{g,1}$ is the group index of the cavity. This is exactly the same as the expression for the FP cavity mode spacing.

In a first example, assume that the individual reflection coefficients are the same as shown in Fig. 4.4, with a value of 0.1. When $\lambda = 1550$ nm, $n_1 = n_{g,1} = 3.47$, and $L_1 = 250$ μ m, then $\Delta\lambda_1 = 1.38$ nm. For the second case, if the refractive index is

Fig. 4.4 Cavity reflections as functions of the wavelength, with the normalized product of the two reflectivities shown as a bold curve.

the same as in case one, but the cavity length $L_2 = 280 \mu\text{m}$, $\Delta\lambda$ is changed to 1.24 nm. The reflection curves of the two cases are shown in Fig. 4.4. When both end reflectivities have a comb characteristic, the product of the reflectivities will have a wavelength selective pattern, as presented by the bold curve. When the refractive indices are identical, and n_g is the group index for the cavity, the beat period $\Delta\lambda'$ is given by

$$\Delta\lambda' = \frac{\lambda^2}{2n_g(L_2 - L_1)} \quad (4.6c)$$

In this case, separate electrical control of each individual cavity facilitates the alignment of the loss minima of the two cavities. As a result, the selected laser mode has optimal suppression of spurious modes.

When the CCL structure has comb-like reflection ends, but different periods, the Vernier effect can be utilized to expand the tuning range. The basic principle of the

CCL is illustrated schematically in Fig. 4.5. According to the resonance condition of the optical cavity, a set of potential longitudinal modes of the lasing chip (Fig. 4.1) of the CCL can be given as

$$\lambda_M = \frac{2n_{eff}L}{M} \quad (4.7)$$

where λ_M is the longitudinal mode wavelength that is essentially reciprocal to the corresponding mode number M , n_{eff} is the effective group refractive index of the FP cavity, and L is the cavity length.

Subsequently, the comb-like spectrum of the lasing chip (i.e., the lasing cavity in Fig. 4.1) has an almost to constant mode spacing ($\Delta\lambda_1$), which is given by

$$\Delta\lambda_1 = \frac{\lambda_0^2}{2n_{eff1}L_1} \quad (4.8)$$

where λ_0 is the wavelength in vacuum, n_{eff1} represents the effective group refractive index. L_1 is the cavity length of the lasing chip.

Similarly, the mode spacing ($\Delta\lambda_2$) of the tuning chip (i.e., the tuning cavity in Fig. 4.1) can be expressed as

$$\Delta\lambda_2 = \frac{\lambda_0^2}{2n_{eff2}L_{eff2}} = \frac{\lambda_0^2}{2(n'_{eff2}L_2 + n_{air}d)} \quad (4.9)$$

where n_{eff2} and L_{eff2} represent the effective group refractive index and the cavity length of the combined tuning cavity, respectively, L_2 is the cavity length of tuning chip, n_{air} represents the air refractive index, and d is the cavity gap distance between the two chips. As a different driving currents result in a different effective group refractive index values, the mode spacings of the lasing chip and the tuning chip could be

different even though they may have the same cavity length. When the mode spacings $\Delta\lambda_1$ and $\Delta\lambda_2$ are slightly different, the spectral spacing (Λ) of the neighboring enforced/aligned mode is expressed as [85]

$$\Lambda = \frac{\Delta\lambda_1 \cdot \Delta\lambda_2}{|\Delta\lambda_1 - \Delta\lambda_2|} = \frac{\lambda_0^2}{2|n_{eff1}L_1 - n_{eff2}L_{eff2}|} \quad (4.10)$$

The different mode spacings of the lasing and tuning chips are represented schematically by the solid and dashed lines in Figs. 4.5 (a) and (b), respectively. Since the two cavities are coupled, those cavity modes that coincide spectrally will interfere

Fig. 4.5 Mechanism of the wavelength tuning in the coupled-cavity laser. The solid and dashed lines correspond to the different injection current applied to the tuning chip: (a) Possible modes of the lasing chip, (b) possible modes of the tuning chip, (c) coincident modes of the coupled-cavity, (d) laser gain profile, and (e) coupled-cavity laser output spectrum.

Fig. 4.6 Schematic illustration of the wavelength tuning through the Vernier effect. When only one of the refractive indices is changed at a time, the lasing is limited to a symmetric range around the center wavelength λ_0 .

constructively and become the reinforced FP modes of the coupled-cavity resonator, as shown in Fig. 4.5(c). It is noticed that Λ can be significantly larger than either of the original individual FP chip mode spacing (see Fig. 4.5 (c)), when the difference between $n_{eff2}L_{eff2}$ and $n_{eff1}L_1$ is sufficiently small. When Λ is generally larger than the spectral width of the laser gain window (Fig. 4.5 (d)), it allows only one coincident mode to oscillate as shown in Fig. 4.5 (e). In this way, the laser output is stabilized at single-longitudinal mode.

A schematic representation of the tuning behavior of the coupled-cavity laser is shown in Fig. 4.6. It is shown that the tuning characteristic is not continuous. The wavelength jumps between discrete values. The total tuning range is limited by the coincidence spacing as given by Eq. (4.10).

The direct wavelength tuning over a large range achieved in the CCLs can be explained using the Vernier effect. During the wavelength tuning operation, the lasing chip provides potential modes while the tuning chip selects one mode to oscillate. The tuning current applied to the tuning chip is always below the threshold, thus the tuning chip acts as an etalon. The variation of the tuning current changes the effective refractive index through the free carrier plasma effect, resulting in a wavelength shift in $\Delta\lambda_2$. Generally, the carrier density in the cavity is related to the injected current density, and it is a nonlinear function of the injected current, increasing sublinearly below laser threshold and remaining constant above. For example, when the lasing chip is biased with an injection current (I_{lasing}) above the lasing threshold, an increase of tuning current (I_{tuning} , below the threshold) results in a change in the carrier density of the tuning chip. Correspondingly, Δn_{eff2} decreases. Therefore, the modes of the tuning cavity shift towards shorter wavelengths. Furthermore, when wavelength tuning is realized by the free carrier plasma effect in the tuning chip, the tuning time is expected at the level of micro-seconds or even nano-seconds [88]. In addition, these tuning mechanisms explain how the CCL can always operate in a highly stabilized single-longitudinal mode even under high-speed direct amplitude or frequency modulation.

Some practical limitations associated with the Vernier effect in tunable lasers are:

- (a) The coincidence spacing must be comparable to the width of the gain spectrum, or the modes at neighboring coincidences must be suppressed by some other methods.
- (b) The cavity gain difference must be sufficient to suppress the other modes.

- (c) The phase condition must be satisfied. In other words, the round-trip phase of the desired mode should be controlled to be a multiple of 2π .

4.1.4. Equivalent model and threshold conditions

Based on the physical principle, the analytical model of the micromachined CCL is derived. An equivalent model of the CCL is shown in Fig. 4.7(a). It consists of two FP chips separated by an air gap (or cavity gap). F_{1a} , F_{1b} , F_{2a} and F_{2b} denote the facets of two FP chips where 1 refers to lasing chip, and 2 refers to tuning chip. r_1 , r'_1 , r_2 and r'_2 are the reflectances of F_{1a} , F_{1b} , F_{2a} and F_{2b} , respectively. g_1 , g_{air} and g_2 describe the roundtrip gains inside the lasing chip, the air gap and the tuning chip, respectively. L_1 , L_2 and d are the corresponding chip cavity length/ air gap.

In general, cavity 2 can be treated as an active étalon modulating the loss of the FP modes in the cavity 1 via an equivalent mirror which combines the effects of cavity 2 and the cavity gap. Therefore, the micromachined CCL configuration can be further simplified into a single-cavity scheme as shown in Fig. 4.7(b), where R is the reflectance of F_{1a} ($R = r_1$), and G describes the roundtrip gain inside the lasing chip ($G = g_1$).

Fig. 4.7 Schematic of the micromachined coupled-cavity laser analytical model: (a) Two Fabry-Pérot cavities based coupled-cavity laser model, and (b) the equivalent model of the coupled-cavity laser.

The coupling between the two cavities is characterized by a general effective reflectance, R_{eff} , which is given by [214, 251]

$$R_{eff} = \frac{r'_1 (1 - r_2 r'_2 g_2) - g_{air} (r_2 - r'_2 g_2)}{1 - r'_1 r_2 g_{air} - r_2 r'_2 g_2 + r'_1 r'_2 g_{air} g_2} \quad (4.11a)$$

where the roundtrip gain within the cavity gap is

$$g_{air}(d, \lambda) = \exp(-2\alpha_{air}d - j4\pi d/\lambda) \quad (4.11b)$$

and α_{air} denotes the optical loss coefficient. Similarly, the roundtrip gain within the tuning cavity is given by

$$g_2(n_2, \lambda) = \exp(-2\alpha_2 n_2 L_2 - j4\pi n_2 L_2/\lambda) \quad (4.11c)$$

where, α_2 and n_2 denote the absorption coefficient and the refractive index of the tuning chip, respectively. With this effective reflectivity (R_{eff}), the lasing chip of the micromachined CCL is modulated as a function of the refractive index of the tuning chip (n_2) and the distance of the cavity gap (d). Therefore, the gain condition for the micromachined CCL lasing can be expressed as [214]

$$g(d, n_2, \lambda) = \alpha_m - \ln[R|R_{eff}(d, n_2, \lambda)|]/L_1 \quad (4.12)$$

where α_m is the internal loss of the lasing cavity. By varying the injection current to the tuning chip, its refractive index (n_2) is changed. As a result, the gain of the micromachined CCL is modulated.

Fig. 4.8 Effective mirror reflectivity R_{eff} as a function of the wavelength: (a) $d = (2k)\lambda/4$, and (b) $d = (2k+1)\lambda/4$.

Fig 4.8 illustrates the plots of the effective reflectivity R_{eff} , where d is equal to either an odd or even multiple of $\lambda/4$. In these cases, the vertical lines represent the unperturbed possible modes of cavity 1. In Fig. 4.8 (a), the maxima of the R_{eff} are steeper, leading to a good side-mode suppression. In other words, the reflectivity peaks can serve a useful purpose in narrowing the oscillation bandwidth of the wide-band laser cavity. In contrast, the maxima of R_{eff} are flat due to the anti-resonant

second cavity, leading to poorer adjacent side mode suppression, as shown in Fig. 4.8 (b). Therefore, the cavity gap d is close to an integer number of $\lambda/2$ for best spurious mode discrimination over a range of gains.

Fig. 4.9 Threshold gain modulation as a function of the wavelength: (a) Threshold gain versus the wavelength, when $d = d_0$, (b) $d \neq d_0$, and (c) the threshold gain shifts with the change of effective refractive index induced by the variation of the tuning current.

Fig. 4.9 illustrates the threshold gain modulation introduced by the effective reflectivity R_{eff} and the importance of the gap distance d . The analysis is one-dimensional with single transverse mode propagation, and second-order effects such as lateral hole-burning, are neglected. As shown in Figs. 4.9 (a) and (b), the periodicity of the threshold gain (solid line) is determined by the cavity length of the tuning chip, while the cavity gap controls the bottom envelope (dashed line). Only the wavelengths falling on the bottom envelope and covered by the shadow are the possible oscillating modes which are strongly supported by the tuning cavity. Among those modes, the one which can match the lasing cavity supporting mode will be the final lasing mode of the micromachined CCL, with the condition of lower threshold gain required (see Fig. 4.5 (d)). Eqs. (4.9), (4.10) and (4.11) indicate that the cavity gap coupler is also a resonant cavity, so the two-cavity laser really has three cavities. Thus, the couple amplitude and phase can be controlled independently by the cavity gap design. When the cavity gap is set to an optimal distance such that $d = d_0$, only one of matching modes falls in the “shadow window”, generating the single mode lasing output. Otherwise, an unsuitable gap with $d \neq d_0$ provides out of phase feedback for the two laser cavities, resulting in several “shadow windows” as shown in Fig. 4.9 (c), which causes any matching modes loading in these windows to be one of the outputs. Such unsuitable gap results in multi-mode and unstable output. Consequently, the optimal cavity gap increases the tunability and selectivity of the micromachined CCL. On the other hand, when the tuning current (ΔI) is changed, the refractive index (Δn_2) is varied, which shifts the threshold, as shown in Fig. 4.9 (c). During the operation of the micromachined CCL, the tuning chip introduces an optical feedback to the lasing chip, causing the cavity gain ($g_{th(CCL)}$), as given by Eq. (4.12) to be highly modulated. Particularly, with the adjustable cavity gap, it widens

up the “cavity gain window”, as indicated by the shadow in Fig. 4.5 (d). Hence, this modulation is the key to obtain a large tuning range. In addition, it enhances the mode selectivity, which is related to the side-mode suppression ratio (SMSR). The previous investigation of SMSR of the FP cavity laser reveals that the spectral selection of the semiconductor gain characteristic is not sufficient to provide a reasonable single longitudinal-mode operation, particularly when the mode wavelength is tuned. Nevertheless, in the case of the micromachined CCL, discrimination of side modes is based on misalignment of resonant modes between the tuning chip and the lasing chip. The narrower the threshold gain peaks, the better the mode selectivity between adjacent modes. Therefore, it is concluded that the tuning current not only causes wavelength tuning, but also improves the wavelength tuning range and mode selectivity. When the output reaches a stable single-mode state, it will tolerate a certain amount of mirror displacement and tuning current change. By estimation, the tolerance to the mirror displacement is of $\pm 0.2 \mu\text{m}$ and the tolerance to the tuning current is $\pm 0.06 \text{ mA}$.

4.2. Micromachined tunable coupled-cavity lasers

Based on the theoretical model and analysis, the design guidelines of the micromachined tunable coupled-cavity laser are as follows:

- (a) The two cavity lengths should be comparable with each other for a wide tuning range as limited only by the gain window,
- (b) The gap d should be close to an integer number of $\lambda/2$ for best spurious side mode suppression over the whole wavelength tuning range, and

- (c) Separate injection current control for the individual cavity can provide the necessary alignment of a desired laser mode for optimal spurious suppression.

The design of the micromachined tunable coupled-cavity laser is depicted schematically in Fig. 4.10. The micromachined CCL consists of two identical chips and a movable parabolic mirror [252]. The two chips are standard FP chips, which are denominated as lasing chip and tuning chip. The lasing and tuning chip are optically coupled through the parabolic mirror, but electrically isolated. In this case, two sets of electrodes are available for the FP chips, where the lasing chip has a constant current (above the threshold) injection and the tuning chip has a variable current (below the threshold) injection. Therefore, each chip has independent electrical control, which facilitates separate control of the carrier concentrations in the two individual FP chips. According to the operation principle of the CCL as discussed in Section 4.1, there is an optimal cavity gap length between the two chips in order to obtain a stable single-mode output with high spectral purity. The movable parabolic mirror is designed for the cavity gap adjustment and modification to its optimal value. It should be noted that no further mirror movement is required once the output stable single mode is obtained. The wavelength tuning is achieved by varying the driving current of the tuning chip, while keeping the position of the micro mirror. In contrast to many developed micromachined tunable lasers, the wavelength tuning speed of the CCL is not limited by the mechanical response [61, 72, 253].

The parabolic mirror is a symmetrically arranged pair of parabolic parts, whose foci are positioned at the two adjacent facets of the chips, respectively. Based on geometric optics, the beams from the focus point of a parabola are collimated by

Fig. 4.10 Schematic diagram of the micromachined tunable coupled-cavity laser.

Table 4.1 Design parameters of the micromachined tunable coupled-cavity laser

Parameters	Design values
Lasing/ tuning chip dimensions (length $\times$ width $\times$ height)	$250 \times 300 \times 100 \mu\text{m}^3$
Chip facet reflectivity	$\sim 30 \%$
Threshold current (I_{th})	$10 \sim 15 \text{ mA}$
Tuning current	$0 \sim 80\% I_{\text{th}}$
Lasing current	$\sim 1.2 I_{\text{th}}$
Central wavelength (λ_0)	1550 nm
Initial air gap distance (d_0)	$403 \mu\text{m}$
Parabolic mirror curvature	$y^2 = 4px$ (where $p = 250 \mu\text{m}$)
Mirror open angle	60° degree
Mirror movement	$\pm 10 \mu\text{m}$
Actuator voltage	$0 \text{ to } 15 \text{ V}$

actually two-dimensional and has the focusing/collimation effect only in the horizontal plane, nevertheless it provides sufficient coupling. In addition, the coupling efficiency is not sensitive to the horizontal translation of the mirror, as confirmed in a recent study [252]. The design parameters of the micromachined tunable coupled-cavity laser are summarized in Table 4.1.

4.3. Experimental results and discussions

In this section, the fabrication process of the prototype of the micromachined CCL is discussed and experimental results are discussed.

4.3.1. Fabrication processes

Based on the theoretical analysis, a micromachined tunable coupled-cavity laser is designed and a prototype is fabricated using deep RIE processes. The fabricated micromachined CCL is shown in Fig. 4.11. It includes a parabolic mirror, a comb-drive actuator for mirror actuation, some trenches for the twin FP chips and coupling fiber, which are fabricated simultaneously on a SOI wafer using the DRIE process. The SOI wafer has a 100- μm -thick structure layer, a 2- μm -thick insulator silicon oxide layer and a 675- μm -thick substrate. The process flow is the same as that in Section 3.5. In the final process step, the MEMS structures are selectively coated with a 0.2- μm -thick aluminum layer. Such selective coating is used by a shadow mask. The aluminum coating improves the reflectivity of the mirror and provides the electrical connections for driving the FP chips. Following the fabrication, the twin chips are then assembled and soldered onto the MEMS substrate. Finally, the output fiber is inserted and glued into the etched groove. Each chip of the twins is made of

multiple-quantum-well InGaAsP/InP materials with straight waveguide and has dimensions of $250\ \mu\text{m} \times 300\ \mu\text{m} \times 100\ \mu\text{m}$. The chip facets are normally cleaved surfaces with reflectivity R of 29%. The effective reflectance of the mirror including the optical coupling loss is evaluated to be $R' = 0.03$ by measuring the threshold current variation while moving the curved mirror [214]. Following $y^2 = 4px$ (where $p = 250\ \mu\text{m}$), the two parts of the parabolic mirror are designed. The parabolic mirror has an open angle of 60° relative to the chips so as to cover 99% of the power. Moreover, in order to reduce the deformation of the mirror surface, a frame structure is employed to strengthen the parabolic curvature.

Fig. 4.11 SEM images of the micromachined coupled-cavity laser: (a) Overview of the device, and (b) close-up of the comb-drive micro-actuator.

The experimental setups include two laser drivers and 5-axis precision fiber stages. In the experiment, a bare MEMS laser sample with two chips and an optical fiber is placed on a 5-axis stage for positioning, and an optical fiber is aligned by another 5-axis stage for coupling the output light. Four probes positioned by 3-axis stages are employed to apply the injection current to the separated twin chips individually and one more probe is employed for fine alignment adjustment of the tuning chip to the lasing chip. A microscope is used to observe the operation of the CCL assembling. Other used equipments were an oscilloscope for monitoring the junction voltage of the laser chip, an optical power meter, and an optical spectrum analyzer. The whole experimental set-up is fixed to an optical table. When the twin chips and fibers are packaged and wire bonded, adjustment stages are not necessary.

When the driving voltage is applied to the comb drive, the comb fingers produce an electrostatic force between the moving fingers and the fixed fingers, and thus generate electrostatic force to push the mirror. The position of the parabolic mirror is therefore controlled by applying an electrostatic voltage to the comb-drive microactuator as shown in Fig. 4.10 (b). Such adjustment ensures a precise control of the cavity gap between the two chips. The measurement results of the electro-mechanical properties of the actuators show that a displacement of 18 μm is obtained with an applied voltage of 10 V. The displacement of the movable mirror increases with the driving voltage.

4.3.2. Characterization of the micromachined CCL

Before evaluating the optical performances of the micromachined CCL, the lasing chip and the tuning chip are characterized separately. Each chip is a strip-guide

multiple-quantum-well InGaAsP/InP device with dimensions of $250\ \mu\text{m} \times 300\ \mu\text{m} \times 100\ \mu\text{m}$. The original output spectrum of the lasing chip, with an injection current of 14.1 mA (above the threshold of 12 mA) is shown in Fig. 4.12 (a). The beam quality is measured through a beam profiler. The far-field beam profile is shown having a nearly circular cross section, with the far-field divergent angles of 30.4° and 31.3° in the planes parallel and vertical to the contact surface, respectively. The spot size is $1.63\ \mu\text{m} \times 1.58\ \mu\text{m}$. It is observed that the single chip operates in a multi-longitudinal-mode regime, and the beam has a single transverse mode, with nearly Gaussian intensity distribution. After the two chips are assembled onto the MEMS substrate to form the micromachined CCL, the output spectrum is then characterized. In the experiment, the lasing current is kept constant at 14.1 mA while the tuning current is varied. The environmental temperature is maintained constant at $27 \pm 1\ ^\circ\text{C}$ with an additional heat sink. The output spectrum of the laser driven by lasing current of 14.1 mA is stable and repeatable as shown in Fig. 4.12 (b). In addition, laser characterization has been carried out with and without temperature control by using a thermoelectric cooler (TEC). It is observed that the output power is reduced and the output wavelength becomes unstable when the environmental temperature is too high. The optimal cavity gap d_0 is experimentally determined by moving the parabolic mirror back and forth while monitoring the output spectrum until a single-longitudinal-mode output is obtained. The group shown in Fig. 4.12 (b) exemplifies the single-longitudinal-mode spectrum when the tuning current is 8.6 mA, with $\lambda = 1567.7\ \text{nm}$ and SMSR = 24.5 dB. The gap d_0 is estimated to be approximately $400\ \mu\text{m}$. When the cavity gap is moved away from its optimal region ($d = d_0 \pm 0.2\ \mu\text{m}$), the output spectrum of the micromachined CCL becomes multi-longitudinal mode again as shown in Fig. 4.12 (c). Such a gap is not suitable as d allows the two chips to

Fig. 4.12 Output spectra of the micromachined CCL in different states: (a) Original multi-mode output of the single chip, (b) single-mode output spectrum when the cavity gap is optimal ($d = d_0$), and (c) multi-mode spectrum when the cavity gap is not optimal ($d \neq d_0$).

work independently instead of affecting each other, even though they are optically coupled. This proves that the gap between the two chips is the key for mode matching and wavelength selection. It is also observed that the SMSR of the single mode output of the micromachined CCL (~ 24.5 dB) is higher than the peak value (~ 17 dB) of the single chip.

4.3.3. Wavelength tunability

The tuning current is varied from 5.7 mA to 10.8 mA to study the wavelength tunability. The lower limit is set at 5.7 mA because the output is not single mode when the tuning current goes lower. The upper limit is set at 10.8 mA so that the tuning chip is maintained below the threshold state. Under these operation conditions, a stepwise wavelength tuning from 1540.5 nm to 1591.8 nm ($\Delta\lambda = 51.3$ nm) is obtained with the tuning step of 1.3 nm. The tuning time for one interval is only 1.2 μ s. The overlapped spectra of all single-mode outputs are shown in Fig. 4.13 (a). The output power of the CCL is from -20 dBm to -12 dBm with the corresponding tuning current varying from 5.7 mA to 10.8 mA. It can be seen that the middle of the tuning range has high SMSR (e.g. > 25 dB) as compared to the two extremes (e.g. < 20 dB). The middle range is shown in Fig. 4.13 (b), where the output wavelength is tuned from 1551.2 nm to 1569.1 nm as a result of the change of tuning current from 7.05 mA to 8.91 mA. The average SMSR of 22 dB is measured. Based on the experimental results, the single mode output at any wavelength is stable when the tuning current is varied within ± 0.06 mA. On the other hand, the single mode output remains stable as long as the mirror displacement is kept less than 0.2 μ m. Such tolerance is in good agreement with the estimations of the tolerance based on the theoretical analysis. It shows that

the micromachined CCL scheme can operate with a high degree of wavelength stability.

Fig. 4.13 Measurement results of the wavelength tuning of the micromachined CCL: (a) Stepwise wavelength tuning from 1540.5 nm to 1591.8 nm with a tuning step of 1.3 nm, and (b) wavelength tuning from 1551.2 nm to 1569.1 nm.

Fig. 4.14 Measured output versus the tuning current: (a) Output wavelengths and SMSR versus the tuning current, and (b) light intensity output versus the tuning current with different driving lasing currents.

Fig. 4.15 Measurement result of the transient response of the wavelength tuning when rise time is 1.6 μ s and fall time is 1.2 μ s.

The measured outputs are shown in Fig. 4.14. The output wavelength and SMSR are tuned by varying the tuning current as plotted in Fig. 4.14 (a). Initially, the output wavelength is 1540.5 nm when the tuning current is 5.7 mA. When the tuning current increases, the output wavelength increases to 1591.8 nm. The SMSR is as small as 19.0 dB at the beginning and increases with higher tuning current until it reaches its maximum of 25.9 dB. After that, the SMSR drops again. Further increase in the tuning current results in a reduction in the output power, when the lasing current is kept constant. The trend is reasonable since output power and SMSR are primarily determined by the gain profile of the lasing chip, which bends down at both ends of the gain spectrum.

Although the lasing current can be increased to boost the output power, such increase is limited to be less than 4 mA for single mode output. As shown in Fig. 4.14 (b), the output power increases with the tuning current when the lasing current is kept at a low level ($I_{lasing} = 14.1$ mA, $I_{threshold} = 12$ mA). When the lasing current is

increased to a certain threshold such that $I_{lasing} = 20.0$ mA, the output power jumps to a higher level and its magnitude increases proportionally when the tuning current is applied on the tuning chip. The laser output becomes multi-longitudinal mode when the tuning current is above 8.67 mA, as indicated by “*” marks in Fig. 4.14 (b). Multi-longitudinal mode output is observed when the lasing current is increased further, beyond the control of the tuning current. It is observed that the output wavelength experiences a red-shift at a rate of 1 nm/mA, but the tuning range and the SMSR are not significantly affected.

Figure 4.15 shows the transient response of the wavelength tuning by monitoring the output power of two wavelength modes $\lambda_1 = 1562.9$ nm and $\lambda_2 = 1572.5$ nm. In this way, the switching of the wavelengths is reflected by the change in the optical power. When a step-up signal of I_{tuning} is applied, the power of λ_1 is reduced quickly, while that of λ_2 is increased. The fall time is $t_{fall} = 1.2$ μ s, corresponding to the reduction in the output power from 90% to 10%. The rise time is $t_{rise} = 1.6$ μ s, corresponding to the increase in output power from 10% to 90%. Switching is much faster than what is obtained by thermal or mechanical tuning, which is typically in the time scale of milliseconds [61, 253]. It should be noted that the present switching speed is not limited by the CCL device but by the slow current pulse source (2520 Pulsed Laser Diode Test System) and optical detector (Newport 818-IR, rise time < 1 μ s) used in the experiment. Hence, due to the fast response of free carrier plasma effect, the speed of the CCL is expected to be at the level of nanoseconds.

4.4. Summary

The designs, theoretical analyses and experimental studies of the micromachined coupled-cavity laser are presented in this chapter. In the structural design, this laser utilizes an actively adjustable cavity gap between fixed lasing and tuning laser chips, as enabled by a MEMS parabolic mirror. The design solves the fundamental problem of the phase matching in the conventional coupled-cavity lasers that have predetermined cavity gaps during the semiconductor processes, and significantly enhances the wavelength tuning range, the spectral purity and the mode stability. The analysis examines physical mechanisms of free carrier plasma effect and Vernier effect. Theoretical relationships between laser parameters and their characteristics are developed. Particularly, the use of the Vernier effect greatly simplifies the physical picture and mathematical formulation of wavelength tuning behaviors. The analysis draws important guidelines to the parametric design of coupled-cavity lasers. Among them, it is optimal to have a cavity gap of an integer multiple of half wavelengths. Otherwise the output has low side mode suppression and might go to multi-longitudinal mode or even become unstable. This in turn verifies the importance of having an adjustable cavity gap. In the experimental studies, the micromachined CCL is fabricated using DRIE processes and two diode chips and optical fibers are assembled onto a chip. It measures a wide tuning range of 51.3 nm, from 1540.5 nm to 1591.8 nm, while maintaining single longitudinal mode with a SMSR > 19.0 dB. The output power is approximately -20 dBm to -10 dBm. The measured wavelength tuning time is 1.2 μ s. The usage of the adjustable cavity gap between the lasing and tuning lasers is verified to be efficient and crucial in obtaining optimal discrimination against adjacent modes, improving mode selectivity

and output stability. Compared with conventional fixed cavity gap coupled-cavity lasers, the proposed micromachined coupled-cavity laser overcomes the phase mismatching and mode instability problems, while maintain the merit of high-speed wavelength tuning.

The micromachined coupled-cavity laser showcases a synthesis of MEMS with photonic devices. On one hand, MEMS incorporates movable structures to overcome the fundamental limits of conventional coupled-cavity lasers, and thus drastically enhances its performance. On the other hand, applications of the coupled-cavity mechanism break the limits of previous mechanically and thermally tunable MEMS lasers. It broadens the wavelength tuning range from 10 nm to 50 nm, and boosts the switching time from 1 ms to 1 μ s or even shorter. Moreover, MEMS technology provides a multifunctional platform for the integration of a complicated system within a compact footprint.

CHAPTER 5

MICROMACHINED INJECTION-LOCKED LASERS

The objective of this chapter is to develop a micromachined injection-locked laser (ILL), which employs a master laser to optically lock a multi-mode slave laser. This chapter includes theoretical analysis, device design, fabrication and experiments followed by discussions. Based on the wavelength tuning theory, the theoretical model of the micromachined injection-locked laser is derived.

This chapter begins with the theoretical study of the mechanism of optical injection locking to provide an insight into diode laser injection-locking properties. The theoretical model describing the interaction between injected field and slave laser field is developed and discussed. Both static and dynamic properties of the injection-locked lasers, such as stability and hysteresis are investigated in details. Specifically, the effects of both injection power ratio and wavelength detuning on the ILL operating characteristics are considered. Next, the experimental results, including locking characteristics under single and multiple injections are elaborated. Finally, a case study of all-optical logic gates using the micromachined injection locked laser is designed and demonstrated.

Fig. 5.1 Schematic diagram of the injection-locked laser.

5.1 Theoretical study of injection locking

A standard optical injection-locked laser consists of two optical sources, a master laser and a slave laser, as shown in Fig 5.1. In this system, external light emitting from the master laser is injected and coupled into the slave laser.

5.1.1 Principle of optical injection locking

According to the mechanism of the injection-locked lasers, the slave laser can be stably locked or behave chaotically depending on system parameters and injection conditions involved. When the injection locking conditions are satisfied, the frequency of the slave laser is locked by the master laser with constant phase offset. Basically, two important injection locking parameters are considered:

- (1) The frequency detuning Δf is the frequency difference between the master and the free-running slave laser, such as $\Delta f = f_{ML} - f_{SL}$;
- (2) The injection ratio R is the ratio between injected power from the master laser and lasing power of the free-running slave laser, such as $R = P_{inj} / P_{SL}$. It also represents the external injection strength.

The injection locking range with respect to the injection ratio (injection strength) and the frequency detuning is known as Arnold tongue in nonlinear dynamics [254]. The idea can be visualized as the plot in Fig. 5.2. When the injection strength (R) is constant, different detuning within the locking range corresponds to different initial possible lasing modes of the slave laser, resulting in the final output lasing mode being locked at a different particular mode among all the possible modes of the slave laser. Even though the slave laser is locked to the frequency of the external source within the locking range, the locked point could be different with different combinations of the initial frequency detuning (Δf) and injection strength (R). The description above delineates the general pictures of injection locking. It is much more complicated in a real system where the Arnold tongue has more features than the two simple lines.

Fig. 5.2 Arnold tongue for a simple oscillator (master laser) locked to another one (slave laser). The locking range (shaded area) is symmetric in detuning from the slave oscillator nature frequency f_{SL} and large at a strong external injection level.

Fig. 5.3 Schematic diagram of total slave laser intensity, including the amplified spontaneous emission and amplified injected field versus the frequency detuning.

The injection locking dynamics can be described by the coupled rate equations, which represent the field amplitude, field phase, and carrier number of the slave laser under optical injection. The detailed theoretical and experimental investigations of optical injection will be discussed in this chapter. Here, an overview of the fundamental physics of injection locking is discussed. Fig. 5.3 illustrates the evolution of the intensity of the slave laser under optical injection when frequency detuning values are varied while the injection ratio R is constant. It can be seen that the spontaneous emission of the slave laser is significantly suppressed throughout the locking range, resulting in a great reduction of the relative intensity noise (RIN) of the injection-locked laser. The intensity of the injection-locked laser also changes with the frequency detuning.

Figure 5.4 shows the schematic of a typical optical spectrum of a free-running laser without external optical injection and an injection-locked FP laser. The external injections from the master laser at different wavelengths are named as the “master

modes”, as shown in Fig. 5.4 (a). Among all the multiple longitudinal modes of the slave laser in the free-running state, named as “slave modes”, those close to the master modes are defined as the “targeted modes”, while the rest are named as “side modes”, as shown in Fig. 5.4 (b). These two independent types of modes can be both observed in an unlocked state. Only when the master modes are sufficiently close to the target modes and tuned within the injection locking range, the master modes suppress all the others leaving only the injection-locked modes as peaks, as shown in Fig. 5.4 (c).

Fig. 5.4 Schematic of the laser modes in injection-locked lasers: (a) External optical injections, (b) laser modes of the slave laser in the state of free-running, and (c) output laser modes of the slave laser in the state of injection-locking.

5.1.2 Theoretical analysis

Fig. 5.5 Schematic of the injection-locked model with external optical injection.

The analytical model of the injection-locked slave laser is shown in Fig. 5.5. The optical external injection is coupled into the slave laser. A model based on modified rate equations is used to describe the interaction between photons and carriers inside the slave cavity. When the external light is injected into the cavity, the system preserves the general form of the original equations, but with extra terms describing the effects of the injection [151]. The extra terms play an important role in this nonlinear dynamic system.

The equations are expressed as

$$\frac{dS}{dt} = \frac{G_0(N - N_0)}{1 + \varepsilon S} \cdot S - \frac{S}{\tau_p} + 2k_c \sqrt{S \cdot S_{inj}} \cdot \cos(\phi(t) - \phi_{inj}) + R_{sp} + F_s \quad (5.1)$$

$$\frac{d\phi}{dt} = \frac{\alpha}{2} G_0(N - N_{th}) - \Delta\omega - k_c \sqrt{\frac{S_{inj}}{S}} \cdot \sin(\phi(t) - \phi_{inj}) + \frac{F_\phi}{S} \quad (5.2)$$

$$\frac{dN}{dt} = \frac{I}{q} - \frac{N}{\tau_n} - \frac{G_0(N - N_0)}{1 + \varepsilon S} \cdot S + F_n \quad (5.3)$$

where S and S_{inj} denote the photon number and the external injected photon number, respectively, G_0 is the material gain, N_0 and N are the transparency carrier and the carrier density inside the slave laser cavity, respectively, and ε is the gain suppression factor. The first term $\frac{G_0(N - N_0)}{1 + \varepsilon S}$ on the right hand side of Eq. (5.1) is the net gain of the photon number to incorporate the gain saturation. N_{th} is the carrier density above threshold, without spontaneous emission and gain saturation, τ_p is the photon lifetime, and $\frac{1}{\tau_p}$ accounts for both the internal and the facet mirror loss.

R_{sp} represents the spontaneous emission rate, and F_s , F_ϕ and F_n denote the Langevin noise terms in photon, phase and carrier density, respectively. k_c is the coupling coefficient of the external photons into the slave cavity, while $\phi(t)$ and ϕ_{inj} are the phase inside the original cavity and the phase of the injected light, respectively. Referring to Eq. (5.2), α is the linewidth enhancement factor, and $\Delta\omega$ ($\Delta\omega = \omega_{inj} - \omega_{SL}$) is the frequency difference/detuning between the external injection light and the slave laser. I is defined as the injection current, q is electronic charge, and τ_n denotes the carrier lifetime.

It is interesting to note from Eqs. (5.1) - (5.3) that when $S_{inj} = 0$ and the noise terms are neglected, the coupled equations are reduced to the original two coupled rate equations. In other words, in such a free-running case, $S_{inj} = 0$ and $\Delta\omega = 0$, and the phase equation can be neglected in the study of the photon behavior since only photons and carriers are coupled. When the injection is switched to the on state, the new photon-phase coupling dramatically enriches the system dynamics. The coupling strength is proportional to the square root of the relative

injection intensity, and the frequency and phase differences between the external injection and the slave laser play important roles as well. In the following section, the important characteristics of an injection locked laser will be discussed.

By changing the magnitude and the optical frequency of the injected light, the slave laser operates in different regimes [176], such as stably locked to the injected laser frequency, amplitude modulated at the detuning frequency (beating), and self-pulsating at the relaxation frequency or chaotic.

5.1.3 Locking range and stability

Stability is one of the most important characteristics for the case of the injection-locked lasers. The two variables that can be changed are the external injection light intensity and the frequency detuning between the external injection and the slave laser. The interest here is therefore to find out all the possible combinations of these two parameters, or the injection locking range, within which the slave laser can be stably locked to the external master.

The locking range is different if the slave laser is constantly biased or the slave laser is under modulation. The parameter set that the steady-state slave laser locks to the master could not guarantee its stability when the slave laser is perturbed. In a complicated system such as the injection-locked laser, the dynamic stability of the entire system needs to be analyzed with advanced control theories. In this chapter, the focus is on the simple case where the slave laser is DC biased. The results of research work on dynamic stability on modulated injection-locked lasers can be found elsewhere [122].

Based on Eqs. (5.1) - (5.3), the condition to have the CW slave laser stably locked to the external master can be easily obtained. The steady-state solutions of Eqs. (5.1) and (5.2) can be obtained by setting the time-varying terms to zero, i.e. $d/dt \rightarrow 0$. When the spontaneous emission is neglected and $\Delta\phi$ is defined as $\Delta\phi = \phi(t) - \phi_{inj}$, Eqs. (5.1) and (5.2) can be re-written as

$$\frac{G_0(N - N_0)}{1 + \varepsilon S} \cdot S - \frac{S}{\tau_p} + 2k_c \sqrt{S \cdot S_{inj}} \cdot \cos(\Delta\phi) = 0 \quad (5.4)$$

and

$$\frac{\alpha}{2} G_0(N - N_{th}) - \Delta\omega - k_c \sqrt{\frac{S_{inj}}{S}} \cdot \sin(\Delta\phi) = 0 \quad (5.5)$$

If it is assumed that the system is stably locked, the phase relation between the external master and the slave laser is constant (i.e. $\Delta\phi = C_s$); the gain is approximated by removing the gain suppression factor ε , then the term related to the gain in Eq. (5.4) can be obtained as

$$\frac{G_0(N - N_0)}{1 + \varepsilon S} \cdot S - \frac{S}{\tau_p} \approx G_0(N - N_0) \cdot S - \frac{S}{\tau_p} \approx G_0(N - N_{th}) \cdot S$$

Here, N_{th} as the threshold carrier density of the free-running slave laser, therefore,

$$G_0(N - N_{th}) \approx -2k_c \sqrt{\frac{S_{inj}}{S}} \cdot \cos(\Delta\phi) \quad (5.6)$$

Substituting Eq. (5.6) into Eq. (5.5), the steady-state detuning condition can be obtained as

$$\Delta\omega = k_c \sqrt{\frac{S_{inj}}{S}} \cdot \sqrt{1 + \alpha^2} \sin(\Delta\phi - \varphi) \quad (5.7)$$

where $\varphi = \arctan(\alpha)$.

From Eq. (5.7), it is obvious that the phase difference between the locked slave laser and the external injection is determined by the ratio of the emitted intensities by the two lasers and their frequency detuning. The final phase of the slave laser's emission is locked, and lagged behind the phase of the original external injection, so that the phase influence can be expressed as

$$\Delta\phi = \arcsin\left(\frac{\Delta\omega}{k_c\sqrt{\frac{S_{inj}}{S}} \cdot \sqrt{1+\alpha^2}}\right) + \varphi \quad (5.8)$$

Due to the $\sin(\Delta\phi - \varphi)$ term on the right hand side of Eq. (5.7), the magnitude of the detuning falls within a certain range, which can be expressed as

$$|\Delta\omega| \leq k_c\sqrt{\frac{S_{inj}}{S}} \cdot \sqrt{1+\alpha^2} \quad (5.9)$$

In addition, there is an additional physical restriction on the stable locking range. The existence of the external injection light inside the slave cavity increases the stimulated emission, which consumes the carriers and reduces the gain available for all the supported modes [145]. The immediate consequences include lower laser noise and better SMSR. When the right hand side of Eq. (5.6) $-2k_c\sqrt{\frac{S_{inj}}{S}} \cdot \cos(\Delta\phi)$ is negative, then $\cos(\Delta\phi) > 0$. Therefore, the condition of locking range of the slave laser is determined as

$$-\frac{\pi}{2} \leq \Delta\phi \leq \frac{\pi}{2} \quad (5.10)$$

Combining Eqs. (5.10) and (5.8), the detuning range is therefore given by

$$-k_c \sqrt{\frac{S_{inj}}{S}} \cdot \sqrt{1 + \alpha^2} \leq \Delta\omega \leq k_c \sqrt{\frac{S_{inj}}{S}} \quad (5.11)$$

The relationship between the wavelength detuning $\Delta\lambda$ and the injection ratio with various values of parameter α for locking range are plotted in Fig. 5.6. When $\alpha = 0$, the locking range of the slave laser arises from the symmetric wavelength detuning. When $\alpha = 3$ and 6, the locking ranges come from asymmetric wavelength detuning and are increased by approximately 50% ~ 100% at the injection ratio = 10 dB. A laser with

Fig. 5.6 Analytical locking range when $\alpha = 0, 3$ and 6.

larger α has a larger stable locking range and is easier to be locked with a positive wavelength detuning. The fact that the laser is easier to be locked with a positive wavelength detuning source can be intuitively understood. With the injected light depleting the carriers inside the slave cavity, the refractive index of the gain medium increases following the Kramers-Kronig relation. The increased refractive index then causes a red shift of the slave laser wavelengths. Since the external injection light is at

the ‘red side’ of the slave cavity mode, $\lambda_{inj} > \lambda_{SL}$, for a negative frequency detuning the extra red-shift contribution from the carrier density change makes the locking process easier. The larger the α parameter, the larger the refractive index changes due to the carrier density change. Correspondingly, it makes locking possible even when the amount of positive frequency detuning is large. Experimentally, this asymmetric locking feature can be used to extract the α parameter of the slave laser by fitting the measured Arnold tongue to the theory [255].

5.1.4 Coupling coefficient

The coupling coefficient k_c of the external injection into the slave laser cavity is quite different for various laser configurations. By inspecting Eq. (5.1) the unit of k_c is found to be inverse of time. It can therefore be interpreted as the rate at which the injection field adds to the slave laser field. Alternatively, k_c can be considered as a term describing the effectiveness of the external injection in changing the effective loss, or gain inside the slave cavity. The discussion of such coupling effects on the mirror loss of the slave laser is conducted.

Fig. 5.7 Schematic analytical model of the injection-locked laser.

Consider the situation in Fig. 5.7, the external electric field E_{inj} affects the slave laser electric field E_{SL} , which is a complex electric field within the slave laser properly normalized as

$$|E_{SL}(t)|^2 = S \quad (5.12)$$

where S is the photon number within the slave laser cavity, as described in Eq. (5.1).

The slave cavity has the length of L_d , whereas the reflectivities of its two mirror facets are represented by r_1 and r_2 , respectively. The corresponding power reflectivity is $R_i = r_i^2$. Assume that the total electric field E_r , at the interface of the left side mirror, can be expressed as

$$E_r = r_2 \cdot E_{SL} + (1 - r_2^2) \cdot E_{inj} \quad (5.13)$$

The effective reflectivity of the mirror at the injection side $r_{2,eff}$ and the effective mirror loss of the cavity $\alpha_{m,eff}$ can be expressed as

$$r_{2,eff} = \frac{E_r}{E_{SL}} = r_2 + (1 - r_2^2) \frac{E_{inj}}{E_{SL}} \quad (5.14)$$

$$\alpha_{m,eff} = \frac{1}{2L_d} \ln \left(\frac{1}{r_1 \cdot r_{2,eff}} \right) = \frac{-1}{2L_d} \ln \left[r_1 r_2 \left(1 + \frac{1 - r_2^2}{r_2} \right) \right] \quad (5.15)$$

In Eq. (5.15), the ratio between E_{SL} and E_{inj} has been dropped, since the mirror loss and the photon lifetime are normalized to the unit electric field in the rate equation.

Because the effective mirror loss is changed, the photon lifetime is also modified as

$$\begin{aligned} \left(\frac{1}{\tau_p} \right)_{eff} &= v_g (\alpha_i + \alpha_{m,eff}) = v_g \left\{ \alpha_i - \frac{1}{2L_d} \left[\ln(r_1 \cdot r_2) + \ln \left(1 + \frac{1-r_2^2}{r_2} \right) \right] \right\} \\ &= \frac{1}{\tau_p} - \frac{v_g}{2L_d} \ln \left(1 + \frac{1-r_2^2}{r_2} \right) \end{aligned} \quad (5.16)$$

where v_g is the group velocity inside the slave laser and α_i is the cavity loss coefficient denoting the cavity loss due to the absorption and scattering. Obviously, the presence of the external field contributes an extra negative term to the inverse of the photon lifetime. The negative sign of this term increases the photon lifetime, which translates into an effective gain for the slave laser field. When the extra term due to the injection is defined as the coupling coefficient of the external field into the slave laser cavity, the coupling coefficient can be derived as

$$\begin{aligned} k_c &= - \left[\left(\frac{1}{\tau_p} \right)_{eff} - \frac{1}{\tau_p} \right] = \frac{v_g}{2L_d} \ln \left(1 + \frac{1-r_2^2}{r_2} \right) = \frac{c}{2nL_d} \ln \left(1 + \frac{1-R_2}{\sqrt{R_2}} \right) \\ &\approx \frac{c}{2nL_d} \cdot \frac{1-R_2}{\sqrt{R_2}} \end{aligned} \quad (5.17)$$

where n is the effective refractive index of the slave laser. For a reasonable mirror reflectivity, the coupling coefficient k_c can be further simplified [251].

5.1.5 Bistability and hysteresis

Bistability and hysteresis are important characteristics to be investigated in order to obtain a stable output from the injection-locked laser system. Assuming the two facets of the slave have the same reflectivity such that $r = r_1 = r_2$, the resulted power reflectivity is R where $R = r_1^2 = r_2^2$. Taking into account the refractive index

dependence on the injected carrier density, the relationship between the input and output optical power for slave laser can be expressed as [256]

$$P_{out} = \frac{k_c P_{in} T^2 G}{(1 - RG)^2 + 4RG \sin^2 \Theta} \quad (5.18)$$

$$G = \exp[(\Gamma g - \alpha_{s0})L_d] \quad (5.19)$$

$$g = \frac{g_0}{1 + P_{out}/P_s} \quad (5.20)$$

$$\Theta = \Theta_0 + \frac{(\mathcal{G}/2)g_0 L_d (P_{out}/P_s)}{1 + P_{out}/P_s} \quad (5.21)$$

where transmittance $T = 1 - R$; P_{in} and P_{out} are the input and output power, respectively. g is the saturated gain coefficient and g_0 denotes the small-signal gain coefficient; Γ is the optical confinement factor; and α_{s0} represents the scattering loss inside the cavity. P_s is the saturation output power of the slave. Θ and Θ_0 are the single path phase change across the slave and detuning parameter, respectively. $\mathcal{G}$ is the antiguidance factor [257] that is defined as the ratio of decrease in the real refractive index to increase in the imaginary refractive index.

For the optical bistability, Fig. 5.8 illustrates the normalized output power against the injected power for different detuning parameters Θ_0 , which corresponds to the wavelength difference, $\lambda_{m,ILL} - \lambda_{0,ILL}$, between the injection and the slave supported lasing mode. It shows that the operating properties are strongly dependent on the wavelength detuning. Especially, if there is no detuning such that $\Theta_0 = 2m\pi$ and m is integer, the injected slave system operates as a power limiter for the input range, as presented by curve “a” and there is no bistability. However, when the

Fig. 5.8 Output power (P_{out}/P_s) versus input power ($k_c P_{in}/P_s$) with different detuning (Θ_0).

wavelength detuning is introduced, a point is reached where the system becomes bistable. It suggests that the output power is a multi-valued function of wavelength detuning.

Figure 5.8 also shows a general type of bistable input-output hysteresis behavior. For example, as plotted in curve “b”, the output power of the slave only grows slowly with the increase of the injected power when the injection level is low. Once the injection level reaches a certain value marked by the first turning point, where the slave is fully locked, the output power suddenly jumps upward to the upper branch. However, when the injection power is subsequently reduced, the output power level moves down, but remains in the upper branch. Therefore, the locking state is still kept. Only until the slave goes below the locking state, its output power falls abruptly to the lower branch, as shown in Fig. 5.8. As a result, the hysteresis between the input power and output power is demonstrated. It is noticed that the portion of the input-

output curve between the two discontinuities, marked by the dashed line, corresponds to the unstable state of the output. The detailed experimental observation of the input-output hysteresis behavior is further discussed in the next section. The parameters of micromachined injection locked lasers are listed in Table 5.1.

Similar to the influence of the injection power on the output of the locked modes, the output is certainly related to the wavelength detuning. Fig. 5.9 shows the relationship between the stable output power and the wavelength detuning, $\Delta\lambda = \lambda_{in,ILL} - \lambda_{0,ILL}$, at various input powers ($k_c P_{in}/P_s$). It can be seen that the detuning curve becomes very asymmetrical with respect to $\lambda_{in,ILL} = \lambda_{0,ILL}$. Generally, for any injection power strength, the maximum output is always obtained at the positive wavelength detuning. Meanwhile, it predicts a red shift property of the injection locked laser system. Moreover, there is a corresponding wavelength detuning range for certain injection power level. When the driving current is fixed, the higher the injection power, the wider the wavelength detuning range (loop bandwidth).

Fig. 5.9 Output power (P_{out}/P_s) versus nominal wavelength detuning $[(\lambda_{in,ILL} - \lambda_{0,ILL})/\lambda_{0,ILL}]$ at different injection powers level ($k_c P_{in}/P_s$).

Table 5.1 Specifications of the FP slave laser employed in micromachined ILLs

Parameters	Design value
Peak wavelength of the slave laser λ_0	1552.8 nm
Length of the FP slave laser cavity L_d	250 nm
Width of the active gain medium w_0	1.3 μm
Thickness of the active gain medium t_0	0.5 μm
Optical confinement factor Γ	0.2
Group refractive index of InGaAsP $\bar{\mu}_e$	3.375
Reflectivity of slave laser facet r_1 and r_2	0.54
Linewidth enhancement factor α	3
Scattering loss inside the cavity α_{s0}	20 cm^{-1}
Small-signal gain coefficient g_0	240 cm^{-1}
Antiguידance factor $\mathcal{G}$	3

The reason could be that the higher limit of the detuning wavelength is determined by the locking condition. As a result, its absolute value increases when the injection power is stronger.

5.2 Fabrication processes

Based on the theoretical study of the injection-locked lasers, the micromachined ILL is designed and fabricated. The MEMS structure is fabricated on 8" SOI wafers using the DRIE process. The Si structure layer is 75 μm thick, with a buried oxide layer of 1 μm and a handle silicon substrate of 625 μm . The structure layer is deeply etched to form mirror, actuators and trenches for the laser chips and the optical fibers. An aluminum evaporation coating process is used through a shadow mask to provide bonding pads, electrical routing and mirror reflection surfaces. After completing the wafer fabrication, it is proceeded for integration and packaging. During the laser chip packaging, the laser chips is put into the MEMS trenches with

Fig. 5.10 SEM image of the integrated micromachined injection-locked tunable laser.

its P-side facing down. A layer of indium foil is sandwiched between the laser chips and the trenches on the dies. The laser chips are fixed by applying conductive epoxy. After that, the normal single mode optical fibers (Corning, SMF-28) are aligned into the fiber grooves on the dies, and then fixed by the UV-curable epoxy.

Figure 5.10 shows the SEM image of the integrated micromachined injection-locked laser. The tunable laser is used as the master laser (as developed in Chapter 3) to provide the external optical injection into the FP laser, which acts as the slave laser. An optical fiber can be used to couple the output. After the fabrication and integration, the injection-locked MEMS laser has dimensions of $3\text{ mm} \times 2\text{ mm} \times 0.8\text{ mm}$. The FP chip of the master is a stripe-guided multi-quantum-well InGaAsP/InP laser chip, with dimensions of $250\text{ }\mu\text{m} \times 300\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$. The wavelength tuning range is from 1540 nm to 1570 nm with resolution of 0.01 nm. When the output of the slave laser is injection-locked by the master laser, its wavelength tuning is achieved through the wavelength tuning of the MEMS master laser. The slave laser chip is the same as the one used for the master laser, with a threshold current around 10 mA. In

Fig. 5.11 Schematic of the experimental set-up for characterizations of the micromachined injection-locked tunable lasers.

the experiments, its typical output optical power is about -2 dBm when the slave laser is driven by a DC current at 14 mA.

The schematic of the experimental setup is shown in Fig. 5.11. The micromachined ILL is observed by a microscope. In the experiment, both the master laser and the slave laser are driven by two independent laser drivers (236 Source Measure Unit, Kaithley). The output of the master laser is directly coupled into the slave FP laser. Then, the output of the slave laser is connected to a 50/50 optical coupler (2×2 coupler), where one output branch is connected to an optical spectrum analyzer (Q8384 Optical Spectrum Analyzer, Advantest) for the spectral measurements, the other one is connected to a photo detector (2832-C Dual-Channel Power Meter + 818-IR detector head, Newport) for optical power measurements. The electrical signals of the driving current of the laser drivers and the output of the photodetector are connected to a digital oscilloscope (TDS 360, Tektronix) for waveform measurements.

5.3 Experimental results and discussions

For the characterization of the injection-locked laser, investigations include not only the parameters of the master laser, such as injection power and wavelength detuning, but also the parameters of the slave laser such as bias driving current. This section focuses on the study of the locking properties.

5.3.1 Locking properties under single external injection

The single external injection is introductive to the more complicated multiple injection case; in particular, it is not required to take into account the competition between the injected modes.

5.3.1.1. Locking states

Figure 5.12 illustrates the evolution of the slave spectrum from the free-running state to the fully locked state under single external injection from the master, in which the detuning (i.e., the wavelength difference between the targeted slave mode and the master) is changed continuously. Based on the definition, $\lambda_{0,ILL}$ is the original targeted FP mode of the slave chip under free-running condition, and $\lambda_{m,ILL}$ is the external injection optical mode. Therefore, the detuning wavelength $\Delta\lambda$ is defined by $\Delta\lambda = \lambda_{m,ILL} - \lambda_{0,ILL}$. The parameters of the slave are listed in Table 5.1. For the free-running state, the slave output has more than 30 modes with a total output power of -2 dBm. The external injection comes from the master laser with an estimated power of -4 dBm. Fig. 5.12 shows the typical injection locking progress and history. Figs. 5.12 (b)-(e) show the locking progress when the detuning $\Delta\lambda$ sweeps

Fig. 5.12 Experimental results on the injection locking process in terms of different states, showing the whole injection locking progress: (a) Starts from the free-running state, (b) far from the locked state, with negative wavelength detuning ($\Delta\lambda < 0$), (d) close to the locked state, (e) and (f) fully locked state, (g) out of locked state, (h) close to the locked state, at positive wavelength detuning ($\Delta\lambda > 0$), (i) fully locked state, (j) leaving from the locked state, (k) and (l) out of locked state again.

from a low negative value to a positive value. When the external injected mode is close to the targeted mode, the power of the neighboring mode is decreased. Accompanied by a small red-shift, the power is mostly concentrated on the targeted mode until the laser is fully locked, as shown in Fig. 5.12 (e). The locked state can be maintained with further positive wavelength detuning of the injected mode, as shown

in Fig. 5.12 (f). When it is out of the lockable range, as shown in Fig. 5.12 (g), the laser loses its fully-locked state and the previous suppressed neighboring mode is recovered. However, when the injected mode is returned back to the targeted mode, the laser cannot be locked along its “previous path”, as shown in Fig. 5.12 (h). Only when the injected wavelength detuning returns further, is the laser under the fully-locked state again (Fig. 5.12 (i)). The locked state can be kept until the wavelength detuning leaves from the locked state (Figs. 5.12 (j) and (k)) and steps out of the detuning range once again (Fig. 5.12 (l)).

Fig. 5.13 Experimental output spectra of the injection locked laser with different states: (a) Free-running state, (b) far from the locked state, $\Delta\lambda = -0.14$ nm, (c) close to the locked state, $\Delta\lambda = -0.06$ nm, and (d) fully locked state, $\Delta\lambda = 0.08$ nm.

Typical states are selected from Fig. 5.12 to discuss the laser locking progress in details, as shown in Fig. 5.13. In the free-running state, the peak power of the target mode (peak-B) at 1556.875 nm is 2.5 dB lower than the highest peak mode (peak-A), as shown in Fig. 5.13 (a). When the external injection from the master laser is -4 dBm, the output spectra of the slave laser are shown in Fig. 5.13 (b). When the detuning is varied, its output is shifted accordingly, as shown in Fig. 5.13 (c). In Fig. 5.13 (b), when the external injection mode is far from the target mode (with wavelength detuning $\Delta\lambda = -0.14$ nm), it introduces a reduction of the output power to the original slave FP modes. Especially the power of the target mode (peak-B) is most strongly affected. Meanwhile, there is a small red shift of 0.025 nm happening to the cavity modes. In Fig. 5.13 (c), when the injection mode traces closely to the target mode ($\Delta\lambda = -0.06$ nm), the red shift is increased to 0.06 nm, and most of the output power is concentrated on the injection mode and target mode, while the side modes become suppressed. When the injected mode is even closer to the target mode ($\Delta\lambda = 0.08$ nm), the laser is fully locked, as shown in Fig. 5.13 (d). The locked mode dominates over the other modes with a SMSR of 27.6 dB, in contrast to the original 5.2 dB for the free-running state. As a result, the cavity mode is shifted by 0.104 nm as compared to the original free-running mode. It is also observed that once fully injection locking is achieved, the locked mode can reach the highest output peak (P_{peak_locked}), which is 11 dB higher than that of the original highest mode in the free-running state (P_{peak_free}). The reason is that the threshold of the laser can be reduced by external optical injection, since the cavity loss can be reduced accompanied by gain reduction.

In another experimental study of the injection-locked laser, locking at the different states, linewidth reduction of the output is observed, as shown in Fig. 5.14.

Fig. 5.14 Experimental results of the injection-locked laser in different states: (a) Original multi-mode output of the slave, (b) single-mode output at the fully-locked state, and (c) red-shift due to injection locking.

When it is in the state of free-running, the slave laser has multimode output, with $\lambda_0 = 1552.94$ nm, $P_{peak} = -30.2$ dB, as shown in Fig. 5.14 (a). When the external injection is $\lambda = 1553.0$ nm, the slave laser is fully locked, presenting single-mode output ($\lambda'_0 =$

1553.01 nm, $P_{peak} = -24.5$ dB) with a SMSR of 32 dB, as shown in Fig. 5.14 (b). As expected, compared to the free-running FP resonance mode, the locked output wavelength is red shifted by 0.09 nm and its linewidth (full width at half maximum, as FWHM) is reduced to 0.075 nm, respectively, as shown in Fig. 5.14 (c). It is observed that the output power of the peak in the full-locked state is increased by 32% and the FWHM is reduced by 0.055 nm (from 0.130 nm to 0.075 nm).

5.3.1.2. Lockable spectral range

The experimental measurement of the lockable spectral range is shown in Fig. 5.15. In the free-running state with no external injection, the FP slave laser is driven at 9.7 mA, and the output spectrum is multimode as shown in Fig. 5.15 (a). The lockable mode at the minimum wavelength is of 1526.86 nm when the power of the single injection is fixed at -10 dBm, as shown in Fig. 5.15 (b). Any mode with shorter wavelength cannot be locked. Fig. 5.15 (c) shows locking of the mode at 1528.24 nm, which is just next to the minimum lockable mode. Then, all the longitudinal modes on the right side of the minimum wavelength are lockable up to the maximum wavelength of 1568.10 nm (being as the maximum mode), as shown in Fig. 5.15 (d). However, when it is further tuned, any mode with longer wavelength than the maximum longitudinal mode cannot be locked any more. For example, the mode at 1569.41 nm, which is adjacent to the maximum longitudinal mode, loses the locked stage, as shown in Fig. 5.15 (e). Therefore, the lockable range of the injection-locked laser is 41.24 nm, covering 31 longitudinal modes. Moreover, in the locked states, the SMSR is more than 25 dB, as shown in Figs. 5.15 (b)-(d). In addition, the peak power of the locked state is 10 dB higher than that of the free-running state, although the total power is not increased significantly. It is also noticed that the lockable spectrum

range is narrower on the left side than on the right side, which may attributed to the asymmetry properties addressed in the previous theoretical analysis.

Fig. 5.15 Experimental results of the locking range and locking process: (a) Free-running spectrum, (b) the minimum locked wavelength of 1526.86 nm, (c) locked at 1528.24 nm, (d) the maximum locked wavelength of 1568.10 nm, and (e) loss of locking at 1569.41 nm.

5.3.1.3. Injection power

When the injection power is decreased, the lockable range becomes smaller as shown in Fig. 5.16 (a). When the slave laser is driven at 9.7 mA, the critical point of injection power is of -5.3 dBm, where only the highest peak wavelength of the multimode FP spectrum can be locked. In other words, the lockable spectrum range is narrowed down to a point. Further reduction of the injection power results in no

Fig. 5.16 Effect of the injection power on: (a) the lockable spectral range, and (b) the locking depth.

lockable modes. On the other hand, when the injection power is increased, the lockable range is increased, with an upper limitation determined by the gain profile of the FP laser chip.

The effect of the injection power on the locking quality can also be evaluated through the output of the slave laser, in term of the locking depth. The locking depth σ can be expressed as

$$\sigma = \frac{\text{SMSR} - \text{SMSR}_0}{\text{SMSR}_{\max} - \text{SMSR}_0} \times 100\% \quad (5.20)$$

where σ is the locking quality in percentage, SMSR is the current side mode suppression ratio, which is determined by the power difference between the mode of interest and the maximum power among the other modes. SMSR_0 is the initial ratio in the free-running state, and $\text{SMSR}_{\max}$ is the maximum ratio in the full-locked state. According to Eq. (5.20), σ is in the range from 0 to 100%, where $\sigma = 0$ presents the free-running state and $\sigma = 100\%$ presents the fully locked state. When the injection power is either increased or decreased, the locking depth keeps flat, as shown in Fig. 5.16 (b). Only when the injection power reaches the critical point, the locking depth is changed abruptly. When the injection power is increased, the locked state cannot be obtained for power less than -5.32 dBm and locking will be kept with further power increases. On the other hand, there is a hysteresis of 0.3 dB when the injection power decreases. The locking depth drops abruptly when the power is decreased down to -5.62 dBm, and the slave laser is out of the locked state with multimode output.

5.3.1.4. Locking hysteresis and stability

Fig. 5.17 Various locking states due to the change of the driving current, while keeping the injection power constant at 0 dBm: (a) Driving current of the slave laser is 8 mA, and (b) driving current is 15 mA.

To investigate hysteresis and stability of the micromachined ILLs, the effect of wavelength detuning on the locking state is studied, as shown in Fig. 5.17. The locking is targeted at the peak mode at 1554.40 nm. Here, two cases are included: in one case the slave laser is driven at 8 mA and in the other at 15 mA. The optical injection power from the master laser is kept constant at 0 dBm. Fig. 5.17 (a) shows that in the process of gradually increasing the injection wavelength, the slave laser remains in the free running state until it reaches the critical wavelength (point *a*) and then jumps abruptly to the locking state (point *b*). It stays in the locking state and jumps back to the free running state again (*c* → *d*), because the wavelength detuning is too large. For further increase in the wavelength, the slave laser remains unlocked. In the process of decreasing the injection wavelength from an initial large positive detuning, the slave laser requires a shorter wavelength point *e* with smaller detuning to enter the locking state (*e* → *f*), and then stays in the locking state (*f* → *g*) until point *g* and jumps back to the free running state (*g* → *h*). Stable locking can be achieved in the region (*b* → *c*) for the increasing process and in the region (*f* → *g*) for the decreasing process. Two hysteresis loops *a* → *b* → *g* → *h* and *f* → *c* → *d* → *e* are observed. This hysteresis shows that the locking state is dependent on the history of the locking process. However, the stable locking is always obtained in the overlapped region, *a* → *b* → *f* → *e* as shadowed, regardless of the history of the locking process. In Fig. 5.17 (b), a similar phenomenon is observed. However, the stable detuning region is smaller while the loop bandwidth is larger. The stable ranges measure 0.124 nm and 0.026 nm for the slave driving currents of 8 mA and 15 mA, respectively. The loop bandwidth measures, $\Delta\lambda_{d \rightarrow e}|_{I=8mA} = 0.011$ nm and $\Delta\lambda_{d \rightarrow e}|_{I=15mA} = 0.014$ nm, respectively.

Fig. 5.18 Change of the locking states due to different driving currents when external injection power is lower, $P_{inj} = -10$ dBm.

Fig. 5.18 illustrates the influence of the driving current on the locking state, when the optical injection power is relatively low with $P_{inj} = -10$ dBm. When the driving current is as low as such that $I = 8$ mA and the wavelength detuning is fixed within the stable detuning range (shadow region) as shown in Fig. 5.18 (a), the fully-

locked state is obtained. However, when driving current of the slave is higher, such as $I = 15$ mA, bistability and hysteresis behavior may not be obtained by varying the wavelength detuning, as shown in Fig. 5.18 (b).

In Figs. 5.17 (a) and 5.18 (a), the driving current is 8 mA, and the optical injection to the slave laser are 0 dBm and -10 dBm, respectively. It shows that weak optical injection not only leads to an unstable fully-locked state, but also reduces the stable detuning range from 0.124 nm to 0.016 nm. A reason could be that the strong optical injection reduces the threshold, making it easier to reach the stable fully-locked state.

It can be seen that the hysteresis and bistable properties are strongly dependent on driving current, injection power and wavelength detuning. Various locking behaviors are presented. For example, under a given weak injection power, there is an unstable region ($d \rightarrow e$) between free-running and locked state for certain detuning, as shown in Figs. 5.18 (a) and (b). Furthermore, a typical dynamics spectrum corresponding to the exemplified unstable state is shown in Fig. 5.19 (c).

When the external injection power is reduced and the wavelength detuning is slightly negative or even being positive, various dynamic phenomena are observed, including chaotic oscillations. For example, Fig. 5.19 (a) shows that the output of the free-running state of the slave is multimode. When the external injection power is 0 dBm with a wavelength detuning of 0.05 nm, the target mode of the slave laser is stably injection-locked and the output shows a stable oscillation accordingly, as shown in Fig. 5.19 (b). Meanwhile, the power of the side mode is transferred to the main mode.

Fig. 5.19 Spectrum of the slave laser under different optical injection power: (a) Free-running state with multimode output, (b) locking state at the external injection of 0 dBm, and (c) unstable state at the external injection of -12 dBm.

However, when the injection strength is weak at the level of -12 dBm, it is observed that the output of the slave is unstable, with the effects including multiwave mixing and spectrum broadening of the floor, as the neighboring mode shown in Fig. 5.19 (c). In this case, when the injection intensity is changed, the resonant frequency of the cavity is therefore changed. This in turn changes the relationship between the input and output intensities in a manner which can lead to a variety of complicated bistable and multistable behaviors. Although the dynamics are not always the same for other conditions of the detuning and optical injection, they exhibit the typical feature of the chaos. In addition, corresponding to the stable and unstable oscillations of the

injection locked laser, the power of the locked mode is transferred to the side mode and the instability of the laser oscillation becomes obviously strong. However, the side mode is not excited.

The response of the slave laser to a modulated optical injection is further investigated. In the experiment, the injection wavelength is determined according to the measurements results of the fully-locked state in the static state. During the experiment, with constant output wavelength, the master laser is modulated and its output is injected to the slave laser. The slave can follow the intensity modulation of the injection signal at the modulation rate of 100 MHz, as shown in Fig. 5.20 (a). The output waveform of the slave is corresponding to the output power of the slave laser, and its power is 20% higher than that in the free-running state. However, when the modulation rate is increased to 100.2 MHz, the locking becomes unstable. The extinction ratio of the optical signal is smaller as compared to the low frequency modulation case, as shown in Fig. 5.20 (b). Furthermore, it indicates that the slave laser is not able to follow the injection variations and therefore misses some pulses. In other words, the modulation depth of the slave laser is degraded at faster modulated injection of the master. Additionally, the influence of the wavelength detuning and the injection ratio on the maximum response speed might be attributed to the pulsed injection, making the slave parameters such as the refractive index slightly different from those under the static injections.

Fig. 5.20 Slave laser output under different pulsed injection signal: (a) at 100 MHz injection modulation, the normal stable output state, and (b) at 100.2 MHz, the state with degraded output.

5.3.2 Locking properties under multiple external injections

The locking properties under multiple external optical injections are also investigated. For simplicity, two optical external injections are used, one from the master, named the control signal, while the other from another laser source, named the data signal. The spectra of the injected control and data signals shown in Fig. 5.21 (a) can be visualized when the biased driving current of the slave is turned off. The switching control signal is carried at 1555.60 nm while the data at 1557.16 nm. When the data signal is kept at the power level of -4 dBm and the control injection is off, the slave is locked with the SMSR of 23.9 dB, as shown in Fig. 5.21 (b). After the control signal is introduced and strengthened, the control mode rises gradually while the data mode decreases. When the control signal reaches -1.5 dBm, the slave is locked by the control mode, with the SMSR of more than 24 dB, as shown in Fig. 5.21 (c). When the control signal and the data signal are pulsed at 1 MHz and 100 MHz, respectively, the output waveforms in the time domain (obtained by detecting the slave laser emission) are shown in Fig. 5.21 (d). Under such modulated multiple injections, it is observed that the data signal is 'low' when the control signal is 'high', and vice versa. As the control and the data are injected in their optical forms, such optical control method has potential applications in all-optical switching, wavelength conversion and optical logic gate implementation.

Fig. 5.21 Output spectra and output waveforms of the multiple external injection locking: (a) The external injected modes of the control and the data, (b) locked solely by the data, (c) locked by the control signal with the presence of the data signal, and (d) output waveforms in the time domain of the multiple external modulation injections.

5.4 All-optical logic gates

The study of the micromachined injection-locked lasers shows attractive applications in optically modulated lasers, optical switching and logic gates. One case study of the all-optical logic NOR gate by using micromachined tunable lasers is explored in this section.

Fig. 5.22 (a) Schematic diagram of the optical logic NOR gate using the micromachined tunable lasers, and (b) principle of the logic gate process.

The schematic diagram of the micromachined optical NOR gate is shown in Fig. 5.22 (a). It consists of two micromachined external cavity tunable lasers (ECTL S_1 and S_2), a FP chip (the slave) and a λ_0 band-pass filter. During the operation, the two input signals A and B , emitted from two individual micromachined tunable lasers, are coupled into the FP chip through the coupler. As a result, the FP chip is optically

locked by the signals A and B . The band-pass filter defines the transfer window and selects the wavelength, resulting in the NOR signal at $\lambda_{0,out}$. Although signals A and B may carry different data information at different wavelengths of $\lambda_{1,in}$ and $\lambda_{2,in}$, such scheme allows simple and efficient implementation because the injection locking depends on only the optical power rather than the accurate phase matching or polarization control.

Based on the design in Fig. 5.22, the detailed explanation of the logic NOR function can be illustrated as shown in Fig. 5.23. Data A (λ_1) and B (λ_2) from S_1 and S_2 , respectively are injected into the FP chip simultaneously as shown in Fig. 5.23 (a). The FP chip basically has a multi-mode/wavelength output as shown in Fig. 5.23 (b). With the presence of either signal λ_1 , λ_2 or both, the output of the FP chip can be locked at the corresponding wavelengths as shown in Fig. 5.23 (c). The band-pass filter only allows the λ_0 signal to pass through. Therefore, the mode λ_0 is suppressed to low power level, corresponding to bit “0”, when one of the two injection signals is at high power level, corresponding to bit “1”, which includes the possible combinations “01”, “10” and “11”. Only when A and B are both “0”, the final output turns to bit “1” at λ_0 as shown in Fig. 5.23 (d), since the carrier density of the FP chip recovers all modes to high level. Therefore, the logic NOR operation is realized as shown in Fig. 5.23 (e).

Fig. 5.23 Schematic of the logic NOR function working principle based on the micromachined injection locked lasers: (a) – (d) NOR logic relation as expressed in the wavelength domain, and (e) relation between input injections and output optical power.

It should be noted that the optical logic NOR gate is implemented by the injection-locked FP chip, which also controls the output power of the signal. Generally, as long as the FP chip remains locked, the output intensity is insensitive to the large variation in the injected signal power. Moreover, based on the experimental results of the micromachined injection-locked laser, it has been verified that the signal wavelength does not need to match exactly the targeted FP mode wavelength. There is

a lockable wavelength range for the injected beam, which has been discussed in the last section. In the two states of the logic NOR gate, when the wavelength is tuned into the locking range, the output power of the FP laser (slave laser) is higher than ~ 0 dBm, corresponding to the state of “1” of the logic NOR gate. When the output power of the slave laser is lower than ~ -45 dBm, it goes to the state of “0”. Therefore, the states of the micromachined logic NOR gate are dependent on the locking state of the slave laser. In the other words, the states are determined by whether the slave laser is tuned into the locking arrange.

The overview of an assembled micromachined logic NOR gate is shown in Fig. 5.24. Two identical micromachined ECTLs (S1 and S2), each formed by a FP chip, a curved mirror and comb-drive actuator are used to generate input data separately. The coupler is driven by another comb-drive actuator to adjust its position for optimal coupling.

Fig. 5.24 SEM image of the integrated micromachined logic NOR gate.

Fig. 5.25 Output spectra of the FP chip in different states with a driving current of $1.5I_{th}$: (a) Original multi-mode output of the single chip, (b) output spectrum of the micromachined tunable lasers, with the center emission of $\lambda_0 = 1553.25$ nm and SMSR = 19.7 dB, and (c) single mode output spectrum of the injection-locked FP chip, with $\lambda_0 = 1553.34$ nm and SMSR = 26.9 dB.

In the experiments, characterizations of the injection-locked laser are shown in Fig. 5.25. Various output spectra of the FP chip at different states are measured. The driving current of the FP chip is $1.5 I_{th}$, and the threshold current I_{th} is approximately 10 mA. Initially, the single FP chip has multi-mode output, with an

emitting band of 30 nm, as shown in Fig. 5.25 (a). After the FP chip is assembled in the MEMS tunable lasers configuration, its output becomes almost single mode ($\lambda_0 = 1553.25$ nm, Fig. 5.14 (b)), though some other side modes are still seen. The output of the FP chip becomes pure single-mode emission after injection locking. As shown in Fig. 5.25 (c), the output spectra is locked to the single mode at $\lambda_0 = 1553.34$ nm, with the SMSR of 26.9 dB. Thanks to the technique of injection locking, the wavelength purity of the input data signal is not that essential in the proposed logic NOR scheme. More importantly, the output spectrum has high wavelength purity. This property is important for construction of all-optical cross connects, in which other components, like amplifiers, may degrade the spectral quality.

It is also observed that there is a red shift in the output wavelength after the FP chip is locked, for example in the case of $\Delta\lambda = 0.09$ nm. The reason might be that the optical injection into the FP chip modifies its carrier density and refractive index, leading to the FP mode shift. As a result, the wavelength detuning is observed, which is usually within the lockable wavelength range.

The static characteristics are measured for the logic NOR gate configuration. When using different input wavelengths (λ_{in}) injected into the FP chip, the output power evolution at the target wavelength λ_0 versus the injection power is presented in Fig. 5.26. For any wavelength injection (λ_{in}), the increase of its injection power causes the decrease of the output power at the target wavelength (λ_0), excluding the case of when λ_{in} is close

Fig. 5.26 Output power of the logic NOR gate versus external injection power under different injection wavelengths.

to λ_0 . For instance, at $|\Delta\lambda_2| = 0.056$ nm, when the injection power is increased from -15 dBm to 0 dBm, output power decreases substantially by -20.8 dB. It is observed that for a proper logic NOR gate operation, the injection power level of the input data signal should be either high or low enough, so as to guarantee the logic NOR operation (output state either at “1” or “0”).

For the required input power, the experiments revealed that the FP chip can be injection-locked at lower injection power when the injection signal is carried at the wavelength (λ_{in}), which has smaller wavelength detuning ($\Delta\lambda = \lambda_{in} - \lambda_0$) from the target wavelength λ_{target} . Particularly, when the output power is higher than -30.7 dBm, the FP chip is locked sufficiently and sets the logic NOR gate at high logic level “1”. In contrast, the FP chip is fully released from the locking state when the power is below -46.0 dBm. In such case, the output at λ_{out} is at low logic level “0”.

Additionally, the variation of the injection wavelength can strongly affect the operation of the logic NOR gate. Similar to the detuning properties of the single optical injection locking, the injected signals with smaller wavelength detuning requires less injection power for the switch of the logic state, from the state of “1” to the state of “0”.

The measured waveforms of different signals are presented in Fig. 5.27, in which the input and output bit rates are at 100 Mb/s. The output power is -30.7 dBm for bit “1” and -46.0 dBm for bit “0”, the corresponding extinction ratio is 15.3 dB. The waveform in Fig. 5.27 (a) represents the bit streams of the injection signal A , with a period of 001000110011101. The waveform in Fig. 5.27 (b) represents the bit streams of signal B , with a period of 000110011001010. For both two input signals, the optical power is above -28 dBm, which is sufficiently high for optical injection locking. The waveform in Fig. 5.27 (c) represents the output waveform C at $\lambda_0 = 1553.34$ nm. It has the bit streams of 100001000100000. A comparison between the measured output signal and the NOR truth table in Table 5.2 shows that it corresponds exactly to the Boolean NOR between signal A and signal B . As a result, the logic NOR function is demonstrated. The example is an attempt to realize a single-chip solution for the optical logic gate using micromachined injection-locked lasers and has high potential for optical computations in future.

Table 5.2 Truth table of the logic NOR operation

Input	A	0	0	1	1
	B	0	1	0	1
Output	$C = \overline{A + B}$	1	0	0	0

Fig. 5.27 Waveforms of the input and output signals of micromachined logic NOR gate operation.

5.5 Summary

In conclusion, the theoretical analysis, design, fabrication and experiments of the micromachined injection-locked lasers are investigated in this chapter. The micromachined injection-locked laser is fabricated by using a DRIE process on an SOI wafer. The micromachined ILLs based NOR logic gate is experimentally investigated, since it has potential future applications for optical computation and communications.

The governing equations of the injection locking system are derived, and various properties such as stability conditions, optical bistability and hysteresis in the asymmetrical tuning curve of the injection-lock laser have been studied. The condition of stably locking a slave laser to a master laser is found to have an asymmetric profile due to the presence of the linewidth enhancement factor α . For

instance, a larger α makes it easier for locking when the master laser has longer emission wavelength with respect to the slave lasers.

The micromachined injection-locked laser is designed. It consists of a MEMS tunable laser as the master laser, a FP laser chip as the slave laser, and an optical fiber for optical coupling. Single and multiple external injections are both characterized in experiments. The locking properties are examined and analyzed in both strong and weak injection regimes. Locking states with a general SMSR > 25 dB have been obtained. A measured lockable spectrum range as wide as 41.24 nm has been achieved, covering 31 longitudinal modes. The output linewidth has been reduced by 0.055 nm. As a result, the injection locking has improved the performance significantly: the SMSR increases from 5 dB to 35 dB, peak mode power is higher by 5 dB, the slave output power increases by 32%, and the linewidth reduces from 0.13 nm to 0.075 nm. In addition, hysteresis and bistability are observed in response to the variations of wavelength detuning and optical injection power. A higher injection power is helpful to increase the bistable loop bandwidth. The injection-locked based all optical switching can operate up to 100 MHz.

The micromachined injection-locked laser can provide logic functions, which inspires the development of the micromachined all-optical logic NOR gate. The effectiveness of the logic NOR function is experimentally demonstrated. The potential of such micromachined, all-optical logic function scheme allows simple and efficient implementation because the logic operation only depends on the optical power rather than the optical phase. The development of the micromachined ILL device is significant for its potential applications such as all-optical switching, wavelength conversion, and implementation of logic gates for all-optical communications.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

In this thesis, three different types of micromachined tunable lasers: (1) external-cavity tunable lasers, (2) coupled-cavity lasers and (3) injection-locked lasers are studied. Design, fabrication, and characterization for each type of the micromachined tunable lasers are presented. Theoretical models are derived and verified by experimental results. The conclusions of this thesis are listed below:

- (i) In the theoretical study of the micromachined external-cavity tunable lasers, an extended optical feedback model is developed to predict wavelength tuning performance. Compared to the conventional theories, the model developed is useful for short cavity and medium feedback strength of the external cavity tunable laser. The model also identifies the most important design issues such as coupling efficiency and external cavity length on wavelength tuning range.
- (ii) Following the theoretical analysis, an effective three dimensional (3D) micro-optical system is designed. It not only shows the advantage of coupling efficiency enhancement for the external cavity, but also enables a longer external cavity design and a wider wavelength tuning range of the tunable laser.

- (iii) Deep reactive ion etching (DRIE) fabrication processes and design rules, packaging technique are developed in this PhD project. These fabrication processes are compatible with CMOS fabrication technology.
- (iv) In the experimental study, optical fibers and bare laser chips are packaged with MEMS structures to form an integrated single chip. The experimental results of the 3D micro-optical coupling system are in good agreement with simulation results. Coupling efficiency is improved up to 46.5%. In addition, experimental results demonstrate that a tuning time of 1 ms and the wavelength tuning range of 14.05 nm have been achieved. Other specifications such as mode spacing and mode stability are also measured and discussed.
- (v) The theoretical model of the micromachined coupled-cavity lasers is derived to guide the design of the coupled-cavity laser. A special micromachined parabolic mirror is designed for the coupled-cavity laser. The optical coupling efficiency between the two cavities can be enhanced by adjusting the cavity gap using the comb-drive actuator. Compared to the external cavity tunable lasers, the micromachined coupled-cavity laser provides high output performance, such as mode selectivity, mode stability, side mode suppression, wavelength tuning range and speed.
- (vi) The parabolic mirror is fabricated by using DRIE processes. It is integrated with two bare laser chips and optical fibers onto one chip. The experimental results show that the tuning range is 51.3 nm at single longitudinal mode output and the wavelength tuning time is 1.2 μ s. The adjustable cavity gap between the two laser chips is efficient and crucial in obtaining optimal

discrimination against adjacent modes. The laser mode selectivity and output stability are also improved.

- (vii) The micromachined injection-locked lasers are developed in this thesis. The theoretical model of injection locking mechanism and the governing equations are derived. These basic conditions of stable locking are determined for an asymmetric spectral emission profile due to the presence of the linewidth enhancement factor. It is noticed that the locked state can be easily reached with a larger enhancement factor, as long as the wavelength of the master laser is longer than that of the slave laser.
- (viii) For the experimental study, a 3 mm × 2 mm × 0.8 mm prototype of the micromachined injection-locked laser is fabricated. Locked states with a side mode suppression ratio of > 25 dB are obtained under single and multiple external injections. A lockable spectrum range of 41.24 nm is achieved. In addition, hysteresis and bistability are observed in response to the variations of wavelength detuning and optical injection power. The higher injection power is increased by the bistable loop bandwidth.
- (ix) A case study of all-optical logic NOR gate based on the micromachined injection locked lasers is designed and demonstrated. The advantages of the injection-locked lasers based all-optical logic gates are easy and simple integration using MEMS technology.

The three different types of micromachined tunable lasers studied in this work are innovative and demonstrated that they can meet key specifications, such as high tuning speed, large tuning range, small size, high tuning accuracy, high stability and reliability. The advantages of micromachined tunable lasers include batch fabrication,

CMOS compatible processes and easy integration. They offer great potential for different types of tunable lasers products, such as mass production, low cost, single chip integration, high reliability and stability.

In the following section, further research work on the micromachined tunable lasers are identified and recommended to improve the specifications of the micromachined tunable lasers to meet commercial products requirements.

6.2 Recommendations

The recommendations for future research are summarized as follows

- (i) It is important to develop on-chip micro-optics to further improve the specifications of micromachined tunable lasers. A few methodologies are identified. It is noted that the deep etching-formed vertical sidewall, lenses, mirrors and reflectors which can only focus/collimate the laser beam in the horizontal plane while leaving it free in the vertical plane. Such problem severely deteriorates the optical quality and as a result, limits the tuning range and output power level of micromachined tunable lasers. Even though the designed 3D optical system has shown to solve the coupling problem partially, it is only suitable for mirror-configuration tunable lasers. A possible solution is to explore waveguide-based designs for laser beam propagation and transmission among different components, where the waveguide is able to confine and direct the propagation of light in a specific path at low loss. Another option is to fabricate micromachined optical components separately, and then package them with the main part. Alignment and related packaging have to be carefully considered.
- (ii) Rather than using classical mirror-based reflector, through the design of replacing the mirror with a distributed Bragg reflector (DBR), the external-cavity tunable laser design may take a step towards meeting more demanding requirements for potential applications, such as fast wavelength switching in optical communications. The introduction of a DBR design will improve the reflectivity (even without metal coating on the reflectors surface), enhance the wavelength selectivity and SMSR and further simplify the fabrication process

(since there is no side-wall metal coating process). Additionally, if the thermo-optical approach is employed for wavelength tuning, it will offer higher tuning speed and better stability as compared to the mechanical tuning method.

- (iii) In the fabrication process, further efforts for sidewalls etching optimization in deep reactive ion etching are needed to yield ever smoother and verticality in the MEMS reflector profiles that would further improve the optical performance of optical micromachined devices.
- (iv) The micromachined parabolic mirror indeed brings an adjustable air gap to the coupled-cavity lasers in a simple way, and significantly enhances the laser output performance in various aspects. However, without a waveguide to confine the light, a longer distance of the gap and the roughness of the mirror surface degrades the coupling between the two cavities. As a result, these cavities can be positioned in a face-to-face configuration with a short gap in between, together with some micromachined tunable filter design inserted inside the gap. Hence, the tunable filter can adjust the coupling between the two cavities and further modify the laser output. A simple way for tuning the center wavelength could be using the thermo-optical effect to control the filter operation.
- (v) Dynamic analysis of the injection locking model is a potential for design and analysis, including modes beating and chaos synchronization. The micromachined injection-locked lasers have various potential applications, for example, all optical packet/burst switches, optical logic gates and optical signal regenerators.
- (vi) The conventional configurations for dual-wavelength lasers involve complicated fabrication and/or packaging procedures. Since miniaturization

has been a continuing trend in the existing technologies toward even smaller scales, a more compacted micromachined tunable dual-wavelength laser is desired for scientific and practical applications. Therefore, the micromachined tunable dual-wavelength laser can be implemented by integrating two different DBRs with a waveguide-based coupler, or using two diffraction orders of a grating.

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