Theory and experiment of MEMS tunable lasers

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ABSTRACT

This doctoral thesis focuses on the theoretical studies and experimental implementations of three types of tunable lasers using the microelectromechanical systems (MEMS) technology. A discretely tunable laser is first developed, including new theoretical models for the extremely short cavity and discrete wavelength tuning, and a MEMS prototype fabricated by deep etching on a silicon-on-insulator wafer. It can be tuned over 13.5 nm within 1 ms. Secondly, a continuously tunable laser is developed, including a modified theory and a fabricated MEMS laser. A continuous tuning range of 30.3 nm is obtained. Finally, an injection-locked laser subsystem is developed by integration of single MEMS laser components. A new generalized theory is established and a MEMS injection-locked laser is demonstrated. Locking states with a SMSR > 50 dB and all optical switching up to 50 MHz are achieved. In summary, the developed MEMS lasers exhibit many advantages such as small size, fast tuning speed, and high mechanical stability, and would find wide applications in optical communications, biomedical studies, and military defense.

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Theory and Experiment of MEMS Tunable Lasers

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School of Electrical & Electronic Engineering

A thesis submitted to the Nanyang Technological University
in fulfilment of the requirement for the degree of
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2006

观其著者以知微，察其显者而见隐，此格物致知之要道也

– 刘伯温 (公元 1311 - 1375)

The one who observes largeness conceives the microscopic; the one who notices obviousness infers the concealed, and such is the key path towards attainment of true knowledge.

by Bowen Liu (1311 – 1375)

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.

09 May 2006
Date

Zhang Xuming
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Signature:

SUMMARY

This doctoral study focuses on the theoretical and experimental development of tunable lasers using the microelectromechanical systems (MEMS) technology. More specifically, three laser schemes have been investigated: the discretely tunable external-cavity laser, the continuously tunable external-cavity laser, and the injection-locked laser.

In the development of the discretely tunable lasers, a new extended feedback model is first developed, which accounts for the extremely short cavity and medium feedback in the MEMS lasers, for which the conventional weak-feedback models fail. Then, the theory of discrete wavelength tuning is established, and, for the first time, explains clearly the transition between the continuous tuning and the mode hopping. This transition has long been observed in the experiment but cannot be interpreted using the available analyses. A MEMS discrete laser with an improved configuration is finally fabricated by deep etching on a silicon-on-insulator wafer. It has a dimension of 1.5 mm $\times$ 1 mm and can be tuned to sweep over 13.5 nm within 1 ms. The experiment matches the analysis in various aspects such as tuning range, mode spacing and mode stability.

The study of the continuously tunable lasers begins with the adaptation of the conventional theory to account for special concerns of the MEMS lasers, such as short cavity length and pre-aligned component position. It is proven that in the Littrow lasers a fixed pivot has only limited tuning range, which is opposite to some studies in literature. It is newly found that the carrier dependent change of the gain medium refractive index, which is commonly neglected, significantly affects the wavelength tuning range. Based on the theoretical study, a MEMS laser is designed, fabricated and tested. It has a

dimension of $2.0 \text{ mm} \times 1.5 \text{ mm} \times 0.6 \text{ mm}$, and can be tuned continuously over 30.3 nm at a resolution of 0.05 nm/V^2 . As a comparison, another laser designed by the conventional theory has a tuning range of only 5.9 nm.

A new generalized theory for injection locking is developed based on the concept of injection seeding. It can be used to analyze locking properties on various conditions such as strong injection power, multiple external injections and multi-mode slave laser, which are not covered by the previous analyses but are important in some new applications. In the experiment, a MEMS injection-locked laser is prototyped by the integration of a continuously tunable laser with a Fabry-Perot laser. Locking states with a side mode suppression ratio $> 50 \text{ dB}$ have been obtained, and all optical switching up to 50 MHz has also been demonstrated. Other static properties such as the influences of the polarization, injection power and misalignment have been investigated as well. The generalized model predicts the laser characteristics such as critical detuning, increase of total output power, maximum red shift, threshold injection power and gating threshold to be 0.31 nm, 38%, 0.27 nm, -23.1 dBm and 2.3 dB, respectively, as compared to the measured data of 0.295 nm, 30%, 0.29 nm, -21.9 dBm and 2.0 dB, respectively. The reasonable agreement has verified the effectiveness of the generalized model.

The successful implementation of the three MEMS lasers has evidenced the effectiveness of the MEMS technology to the tunable lasers in enhancing the specifications. It has also shown that different physical considerations may arise as the external cavity is downscaled to microns.

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CHAPTER 1

INTRODUCTION

1.1 Motivation

This PhD project is highly motivated by the foresight that the performance of the external-cavity tunable lasers (ECTLs) can be improved significantly by the use of the microelectromechanical systems (MEMS) technology, whose miniaturization not only paves the way for technological innovations, but also incubates physical discoveries [1, 2].

Wavelength tunable lasers are of great importance to many applications such as biophysics and environmental engineering. Especially in optical communications, they have become the key enabler for the dense wavelength division multiplexing (DWDM) systems and the all optical networks (AONs). They not only improve the functionalities of the networks, but also cut the cost. For example, combined with the passive wavelength routers, the tunable lasers are capable of switching and routing the optical signals in the full-mesh AONs without the need for optical crossconnects (OXC)s [3]. And wavelength-based virtual networking in DWDM networks can be implemented by the use of programmed wavelength tunable lasers [4]. In addition, with the help of wavelength converters, tunable lasers are able to realize source-determined optical switching and routing even in a large scale AON [5]. The DWDM system needs light

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sources at multiple wavelengths standardized by the International Telecommunication Union (ITU) G694.1 (spaced by 100 GHz, 50 GHz, 25 GHz or the multiple) to improve the transmission capacity in optical fibers [6]. Therefore, the inventory cost and volume can be saved by the use of tunable lasers to replace the wavelength-fixed laser sources.

There are mainly three approaches to realizing the wavelength tuning – temperature tuning, current tuning and mechanical tuning. All these approaches involve the change of the effective length of the light path of the laser cavity. Temperature and current tuning approaches vary the refractive index of the laser internal cavity by changing the temperature and the current density, for example, in multisection distributed feedback lasers (DFBs) and sampled grating distributed Bragg reflector lasers (DBRs) [7, 8]. The speed of the temperature tuning is very slow since it takes time for the temperature to evenly distribute within the laser gain medium. The tuning range is also very small due to the weak temperature dependence (about $0.02 \text{ nm}^\circ\text{C}$). In addition, high temperature tends to damage the laser easily, and the wavelength is very sensitive to the environment. These drawbacks make it unsuitable for many applications. The current tuning method has fast tuning speed, but it suffers from large power fluctuation, and it has also very limited wavelength tuning range due to small achievable change of refractive index. In contrast, mechanical tuning avoids these problems associated with the laser medium by introducing an external cavity and modifying the external cavity length directly [9]. Among all the technological options, ECTL has led itself to the main stream due to its advantages of simple configuration, wide tuning range, spectrum purity, high output power and single mode operation. Furthermore, the presence of external cavity yields a number of performance enhancements such as narrow linewidth ($\sim 1 \text{ KHz}$) and

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high sidemode suppression ratio (> 30 dB). In ECTLs, the wavelength tuning is obtained by the mechanical movement (rotation and/or translation) of a mirror and/or grating, and it requires a movement accuracy of less than one tenth of the wavelength. Conventional ECTLs have to use complicated mechanical structures (e.g. bearings, levers, hinges, piezomechanical translators and feedback servos) to obtain the required movements, which make the laser systems bulky, slow and less mechanically reliable [10-12]. As shown in Table 1.1, a conventional laser typically has a sweeping speed as slow as 2 s and a size as big as $400 \times 450 \times 200 \text{ mm}^3$ [13] though it has favorable wavelength resolution and accuracy.

Table 1.1 Comparison of the typical specifications of conventional tunable laser with MEMS tunable laser.

Specifications	Conventional [13]	MEMS Laser
Tuning speed	2 s	1 ms
Dimension	400 x 450 x 200 mm cube	1.5 x 1.0 x 0.6 mm cube
Tuning range	40 nm	10 - 60 nm
λ resolution	$< 0.01 \text{ nm}$	0.04 nm
λ accuracy	$\pm 0.1 \text{ nm}$	$\pm 0.02 \text{ nm}$
λ repeatability	$\pm 0.05 \text{ nm}$	$\pm 0.02 \text{ nm}$
Peak power	4 mW	1.5 mW
IC Integration	External, hybrid	Single chip

The development of the MEMS technology has opened up a new opportunity for the ECTLs [14-19]. Similar to the integrated circuit (IC) process, the MEMS technology makes use of the spin coating, mask, photolithographic patterning, deposition and etching techniques to fabricate the devices on standard wafers (e.g. silicon wafers and silicon-on-

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insulator wafers) [21-22]. The MEMS fabrication has one more release step to remove the sacrificial layers. After the releasing, part of the MEMS structure becomes floating and thus allows for mechanical movement such as bending, torsion, translation and rotation. Applying the MEMS technology to the ECTLs would have the benefits in various aspects such as batch fabrication (i.e. cost reduction), compact size (whole device in millimeter scale), fine feature size (in micron scale) and accurate mechanical motion (accuracy in nanometer scale, resulting in high wavelength resolution). In addition, the laser specifications can be improved significantly [15-19]. As shown in Table 1.1, MEMS tunable lasers have much fast tuning speed (~ 1 ms) compared with the conventional lasers. The wavelength tuning range can be very large (> 10 nm) since the external cavity of the MEMS ECTLs can be very short (~ 10 μm) in comparison to the typical cavity length of 1 cm to 1 mm in the opto-mechanical ECTLs. Since the MEMS fabrication is IC compatible, it is easy to integrate the MEMS devices with the IC monitoring/controlling circuits onto a single chip. Moreover, owing to the photolithography, different parts of the MEMS devices are pre-aligned at high resolution, it makes it simple to assemble the MEMS structures with some external components such as semiconductor laser chips and optical fibers [15-19]. In contrast, the opto-mechanical ECTLs requires complicated assembly and tedious fine adjustment.

In addition to all the technical benefits mentioned above, the MEMS also leads to physical difference to the ECTL. Although the MEMS and the conventional ECTLs follow the same general physical principle, they have different behaviors in the details. Some dominant factors in the conventional ECTLs become insignificant in the MEMS counterparts, and vice versa. For example, the range of the discrete tuning is found to be

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inversely proportional to the length of the external cavity. The tuning range can be quite large in the MEMS lasers that allow for very short cavity. However, it is too small for any practical use in the conventional ECTLs that have long cavity. Besides, the dispersion of the gain medium during the wavelength tuning is negligible in the long cavity conventional ECTLs, however, it would induce mode hopping in the MEMS ECTLs if not properly designed. For this reason, the design theories of the MEMS lasers need double-check with the traits of the MEMS taken into account.

Many applications make use of discrete wavelengths, for example, the DWDM networks. It is preferable to use discretely (i.e. stepwise) tunable lasers for such applications. On one hand, the speed of the discrete tuning is much faster than that of the continuous tuning. On the other hand, the discrete tuning can lock the wavelengths at the desired positions while the continuous tuning suffers from serious wavelength drift, and thus needs fine adjustment and feedback control. Discrete tuning can be achieved by mode locking in the Fabry-Perot (FP) lasers [23], by discretely tuned filters [24], and by vernier effect between the laser FP lasers and the external filters [25]. External-cavity lasers provide another option by controlling the external feedback [26].

Continuously tunable lasers are more versatile. They are indispensable for many applications such as spectroscopy, bio analysis and lab equipment. Compared with the discretely tunable laser, the continuously tunable laser has more complicated configuration and high requirement for the motion control. Recently, some researchers have investigated the continuous tuning using a MEMS mirror [17-27], and have also tried to fabricate the grating using the deep etching and have obtained favorable performance [28]. MEMS mechanical flexure to provide a complicated motion has also

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been reported [29, 30]. However, in the previous works, the MEMS mirrors/gratings are only part of the devices and are hybridly integrated with other bulky components such as coupling lenses and actuators. Although the tuning speed can be improved, the overall size of the lasers remains quite large. Actually, the MEMS technology allows fabricating the mirrors/gratings, the micro-actuators and the coupling micro-optics all on single chip. With this purpose, a fully single-chip integrated continuously tunable laser will be developed in this PhD project.

One of the drawbacks of the ECTLs is that the output power cannot be very high in comparison to the bare laser chip since it is difficult to obtain high coupling efficiency between the laser internal cavity and the external gratings/mirrors. And also, the metal-coated surface would be burnt if the power goes beyond certain limit. Although the bare laser chip can provide high power, it is not tunable. And the output is commonly multiple longitudinal mode. As a result, the beam quality is not good and in turn it makes fiber coupling challenging. One preferred solution is the injection locking, which uses a MESM tunable laser to lock the wavelength of a bare laser chip. The resulted output of the bare laser chip inherits the wavelength, phase and good beam quality from the tunable laser while maintaining its own merit of high output power [31-33]. In addition to the high power application, the injection-locked laser is also very useful in optical networks for coherent communication, all optical switching and wavelength conversion etc. [34-36]. Another new application is the miniaturized atomic clocks, in which the MEMS injection-locked lasers act as wavelength-stabilized light sources. Same as the MEMS discretely/continuously tunable lasers, the MEMS injection locking lasers would also bear the advantages of single-chip integration, compact size and fast tuning speed etc.

1.2 Objectives

The main objective of the study is to develop tunable lasers using the MEMS technology, including both the theoretical investigations and experimental implementations. To make full use of the MEMS technology, three types of lasers are to be investigated: (i) wavelength discretely tunable laser; (ii) wavelength continuously tunable laser; and (iii) injection locked laser. The choice of these three tunable lasers follows the logics that the laser configurations are from simple to complicated, the implementations from easy to challenging, and the integrations from the level of single component to the level of multi-component subsystem. Nevertheless, the latter ones are based on the former ones, for example, the continuously tunable laser shares the similar fabrication, actuation and integration/packaging with the discretely tunable laser, while the injection-locked laser directly use the continuously tunable laser as part of the subsystem.

The discretely tunable laser consists of a MEMS actuated mirror, a laser diode and an optical fiber; all are integrated in a single chip. For simplicity of the device, the focus lens and the other micro-optics are to be avoided by using very short cavity and curve-shaped mirror. The theory and condition for discrete tuning will be analyzed, and based on which, the laser will be designed. The MEMS part will be fabricated using deep reactive ion etching (DRIE), and then will be integrated with the laser diode and the optical fiber. The experiment will be carried to verify the analysis and to showcase the advantage of the MEMS.

The continuously tunable laser mainly consists of a laser diode, a grating and some micro-optics for optical coupling. The facet of the diode facing the grating should

be anti-reflection (AR) coated to suppress the influence of the cavity of the diode itself and to improve the purity and quality of the output optical spectrum. Similar to the discretely tuning, an optical fiber is for output and the whole device should be single-chip integrated. The design theory of the continuous tuning should be reexamined with the concern of the MEMS. In the experiment part, the effectiveness and efficiency of the MEMS grating and the MEMS coupling optics should be first tested since they are the key component for wavelength tuning. The experiment results will be compared to the theoretical study.

The theoretical study of the injection locking will focus on developing a new theory for multiple-injected multi-mode lasers based on the concept of injection seeding. A MEMS injection-locked laser will be fabricated and integrated onto a single chip with a MEMS continuously tunable laser as the master. The experiment will be carried out to investigate the locking properties under single and multiple injections in various aspects, such as the influence of the wavelength detuning, all optical switching, influence of the injection power, misalignment, and polarization etc.

1.3 Major contribution of the thesis

The major contribution of this PhD project lies in various aspects of the theory, design and implementation of the three types of the MEMS tunable lasers, as detailed below:

- (i) A new extended feedback model for the wavelength tuning has been developed for the tunable laser that employs a mirror as the external reflector. Compared with the conventional weak feedback model that is valid only for very weak

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optical feedback, the extended model is more versatile and covers a large range of feedback from very weak to medium. Since most MEMS lasers work under weak to medium optical feedback, the extended model is more suitable (See Chapter 3).

- (ii) The theory of discrete wavelength tuning has been established. The theory, for the first time, explains the transition between the continuous tuning and the mode hopping. This transition has been observed in the experiment but cannot be interpreted using the available analyses. The theoretical study also reveals that the discrete tuning becomes dominant under the conditions of weak external feedback and short external cavity (See Chapter 3).
- (iii) An improved configuration of discretely tunable laser has been proposed and analyzed. It employs a curved mirror as the external reflector instead of a flat mirror. The feedback coupling efficiency of the curved-mirror design is estimated to increase by 10 times than that of the conventional flat-mirror design (See Chapter 3).
- (iv) A MEMS discretely tunable laser has been designed, fabricated and characterized. 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 13.5 nm within 1 ms. The experiment matches the theoretical analysis in various aspects such as tuning range, mode spacing and mode stability (See Chapter 3).
- (v) The theory for the grating-tuned lasers has been reexamined and then been adapted to account for special concerns of the MEMS lasers, such as short cavity

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length and pre-aligned component position. It is shown that in the MEMS Littrow lasers a mode-hop-free wavelength tuning requires a moving pivot, or in the other word, a fixed pivot has only limited tuning range, which is opposite to the claim in some previous analyses that the tuning range is unlimited if the pivot position is chosen following certain rule (See Chapter 4).

- (vi) It is newly found that the carrier density dependence of the gain medium refractive index significantly affects the wavelength tuning range, which is neglected in some previous analyses. With this effect taken into account, the wavelength tuning range can be significantly improved. In the example in Chapter 4, the range is increased from 19.5 nm to 55.0 nm (See Chapter 4).
- (vii) A single-chip MEMS continuously tunable laser has been fabricated by deep reactive ion etching on a silicon-on-insulator wafer. The laser has a dimension as small as $2.0 \text{ mm} \times 1.5 \text{ mm} \times 0.6 \text{ mm}$, and can be tuned continuously over 30.3 nm at a resolution of 0.03 nm/V^2 . As a comparison, another MEMS laser designed according to the conventional theory has only a tuning range of 5.9 nm. This might be the first demonstration of single-chip integrated continuous laser (See Chapter 4).
- (viii) A new generalized model has been developed to investigate the static properties of the injection locking based on the concept of seeding. It is advantageous over the previous analyses in various aspects. It is valid for the whole range of injection power and injection current, unlike the previous small signal models that are based on the small signal condition. It is able to deal with the case of multiple injections to a multimode laser, and the evolution of the locking from

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the unlocked state to the fully locked state, which are not covered by the previous analyses. The superior capabilities of the generalized model make it potential for analyzing some emerging applications such as injection-locking-based all optical switching, wavelength conversion, optical data processing, coherent communications, and high power lasers. (See Chapter 5).

- (ix) An injection lock laser device has been designed and fabricated based on the MEMS tunable lasers. It is formed by integrating a MEMS tunable laser (as the master) and a FP laser chip (as the slave) with the MEMS tuning/coupling structures on a SOI substrate. The prototype has a dimension of $3\text{ mm} \times 2\text{ mm} \times 0.6\text{ mm}$. It can obtain a side mode suppression ratio $> 50\text{ dB}$, much higher than the typical values of 20 dB in literature.
- (x) Locking depth, a definition to gauge the locking quality, has been proposed. Its value always falls into 0 to 100%, which stands for the unlocked state and the perfect locked state, respectively. With this definition, the locking quality can be studied quantitatively (See Chapter 5).
- (xi) The influence of polarization angle on the injection locking has been measured. This property has not been reported and cannot be explained by the available injection-locking theories, which took for grant implicitly that the polarization direction had been well aligned (See Chapter 5).
- (xii) All optical switching has been achieved using both the control optical pulses and the data optical pulses to lock the FP slave laser. After injection locking, the data pulse is suppressed when the control pulse is on, and the data can pass through when the control is off. Thus, the switching can be implemented on the native

optical form. The control and the signal are square waves at 1M Hz and 50 MHz, respectively. Such a switching speed is much faster than the typical micromechanical optical switches at the level of milliseconds (See Chapter 5).

1.4 Organization of the thesis

The thesis is structured into six chapters. An introduction to the thesis is given in Chapter 1, which covers the motivation, objective, and major contributions. The motivation part explains why and how the PhD projection is to be carried out. The objective states the main focus of the research. And the contribution part lists out the findings and innovations on both the technological level and the physical level.

In Chapter 2, the MEMS tunable lasers are reviewed, including the discretely, continuously and injection-locked types. It provides a background for and a technological roadmap to the research. The injection locking technology is also surveyed within the scope of the theoretical development and applications.

In Chapter 3, the theory and experiment of wavelength discretely tunable laser are presented for the potential applications in the wavelength division multiplexing systems. The theoretical studies include an extended feedback model for the wavelength shift of the laser modes, and an explanation to the discrete wavelength tuning. It also derives the condition under which the discrete tuning becomes dominant. The design, fabrication, and experiment are then detailed along with the comparison of theoretical studies.

In Chapter 4, the theory and experiment of continuous wavelength tuning using MEMS technology are elaborated. The new theory optimizes the pivot position for the Littrow grating by taking into account the reduction of the effective grating reflectivity

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and the refractive index change during the wavelength tuning. The analysis is then incorporated into a single-chip MEMS continuously tunable laser. The tuning property of the laser is used to verify the effectiveness of the theory.

Chapter 5 covers the theory and experiment of the MEMS injection-locked laser. The rate equations for the new generalized model is derived and discussed, followed by the experimental implementation of the MEMS injection-locked laser. The locking properties of the laser are measured in various aspects such as the lockable spectrum range, the critical detuning and the hysteresis during the change of the injection power, the tolerance for the misalignment, the detuning, the polarization, the slave response to the pulsated injection, and the all optical switching. New features observed in the experiment are examined and explained qualitatively and quantitatively.

Finally, the last chapter concludes the major findings of this PhD projection, and recommends some works for further study.

CHAPTER 2

LITERATURE SURVEY

This chapter is to present a roadmap to the MEMS lasers to be developed in this thesis. A general survey on various aspects of the tunable lasers will be presented in Section 2.1, including the basic principles, milestones, current problems and possible opportunities of the discretely tunable lasers, continuously tunable lasers and injection-locked lasers. Section 2.2 will focus on the recent progress of applying the MEMS technology to the tunable lasers.

2.1 Basic knowledge of tunable lasers

Tunable lasers refer to the lasers whose output wavelengths (or frequency) can be adjusted by certain means. Wavelength tuning of the lasers started to attract the research attentions soon after the invention of the laser, and boomed up in the following decades driven by the intense demand of various applications, including the optical communications, biophysics and bioengineering, spectroscopic analysis, and military applications. Although the wavelength of diode laser can be tuned by changing the temperature and injection current, for example, in multisection distributed feedback lasers (DFBs) and sampled grating distributed Bragg reflector lasers (DBRs), these tuning approaches have limited uses due to small tuning range and/or limited output power. In contrast, the external-cavity tunable laser has attracted significant interests since it can

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provide large tuning range, continuous wave (CW) tuning, high output power and excellent wavelength accuracy while maintaining single longitudinal mode. Also, the presence of external cavity yields a number of performance enhancements such as narrow linewidth (~ 1 KHz) and high sidemode suppression ratio (> 30 dB). Typically, an external-cavity laser has a gain medium to provide the optical amplification and an external cavity formed by a reflector. The wavelength tuning is realized by moving the reflector to change the effective length of the laser cavity. This is the key idea of the external-cavity tunable lasers. According to the tunability of wavelength, the external-cavity lasers can be simply categorized into two types: continuous tunable laser and non-continuous tunable laser. The former can scan over a certain wavelength range while the latter cannot. Among the non-continuous lasers, discrete wavelength tuning is of special interest for the DWDM networks, which use standardized wavelength grids for transmitting the light signals in the optical fibers. For this reason, this study focuses on the discretely tunable lasers and the continuously tunable lasers.

2.1.1 Discretely tunable lasers

The first external-cavity laser was presented by Crowe and his colleague in 1964 [37]. The laser chip was a GaAs diode with one facet AR coated, and a flat mirror was used as the external reflector. For notation simplicity, this configuration is named as mirror configuration. Although their initial intention was not to tune the wavelength but to extend the cavity length to lower the beat rate for linewidth measurement, which was soon replaced by more accurate Fabry-Perot (FP) interferometry, the simple mirror configuration has become one of the “standard” designs [10, 14, 15, 18-19]. Since the flat mirror is not a dispersive component, the spectrum of this type of tunable laser generally

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has multiple longitudinal modes. Even though the injection current may be well controlled to maintain single mode operation during the tuning, the side mode suppression ratio (SMSR) is low and the output power is also limited. Besides, wavelength tuning is not continuous [15, 18].

Non-continuous tuning has been realized in many practices, for example, using coupled cavity lasers in Coldren's works [20]. However, purely discrete tuning using the external cavity formed by a mirror remains untouched. One reason is that the discrete tuning has strict requirement for the injection current and the mechanical stability of the mirror, which is difficult for the conventional lasers constructed by bulky mechanics. Another more important reason is that the conventional lasers have long external cavity (> 1 cm), which limits the wavelength range of discrete tuning to be negligibly low. A promising solution is to miniaturize the laser structure to shorten the cavity length and to improve the stability at the same time.

2.1.2 Continuously tunable lasers

In later 1960's, the tunable dye lasers were on the central stage of laser research driven by the exciting applications for the material spectroscopy, which required high spectrum purity such as single mode, narrow linewidth, and continuous tuning etc. To overcome the problems of wavelength tuning discontinuity and multiple longitudinal mode associated with the flat mirror, the gratings were introduced to the tunable lasers as a dispersive external reflector. Bradley *et al.* used a blazed grating arranged in Littrow configuration in a dye laser (the laser configuration is thus named as Littrow configuration) and obtained 10 nm wavelength tuning by rotating the grating [38, 39]. Another Littrow pulsed high-power dye laser was also reported to tune a large range from

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437.5 nm to 642.0 nm with a linewidth of only 0.3 nm [40]. Further works were carried out to improve the specifications such as Hänsch's Littrow dye laser having 0.04 nm linewidth [41].

The involvement of the grating places strict requirement for the motion control. The grating should be translated to change the cavity length for wavelength tuning; at the same time, it should be rotated to change grating diffraction angle for wavelength filtering. However, theoretical analysis for optimizing the tuning range remained untouched until McNicholl's work that provided a straightforward explanation [42]. The Littrow laser was abstracted into a mirror and a grating. The mirror and the grating represent the two ends of the overall laser cavity. The length between the mirror and the grating in the optical axis is equal to the original laser internal cavity length plus the external cavity length. If the rotation center of the grating is right at the intersection of the mirror and the grating, the roundtrip phase accrual is a constant independent of the grating angle and the wavelength. In this way, the returned wave is able to maintain a constant phase relative to the incident wave throughout the wavelength tuning, and thus the wavelength of the laser cavity mode can always track the diffraction wavelength of the grating. In the other word, the wavelength tuning is always continuous.

Although McNicholl's study was based on the geometric optics and scalar diffraction theory, it was proved correct by several other analyses later [43-46] and many laser implementations. However, McNicholl's study neglected the cavity length change due to the dispersive property of the laser medium and the optical lens, which is acceptable in the bulky opto-mechanical lasers since the laser cavity length is much longer than the dispersion induced change.

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Another laser configuration was proposed by Littman and his colleagues in a series of works (named as Littman configuration) [47-50]. Their initial purpose was to narrow the linewidth of dye lasers and to obtain single longitudinal mode [47, 48], and later the configuration was extended to the wavelength tuning of dye lasers [49]. The same configuration was also demonstrated to tune the semiconductor lasers [50]. The Littman laser comprises a gain medium (e.g. dye cell), a blazed grating and two mirrors [50]. The laser from the gain medium is first projected to the blazed grating and is then steered to the tuning mirror by diffraction. It is reflected back to the grating and is finally diffracted again back into the gain medium. The 0th order of the grating diffraction can be used as the output. The wavelength tuning is achieved by rotating the grating about a pivot. To tract the grating diffraction wavelength over the entire tuning range, the pivot position should be chosen in such a way that the parameters satisfy the following conditions:

$$\lambda = \frac{2}{N} L(\phi) = \frac{2}{N} [l_f + l_t(\phi)] \quad (2.1)$$

$$\lambda = \frac{x}{m} (\sin \theta_0 + \sin \phi) \quad (2.2)$$

where $L(\phi)$ is the optical cavity length, l_f is the distance from the grating to the fixed mirror, and l_t is the distance from the grating to the tuning mirror, N is the mode number, x is the grating pitch, m is the diffraction order, θ_0 is the incidence angle, and ϕ is the diffraction angle. If the pivot center is chosen as the intersection of the surface planes of the end mirror and the grating, then $L(\phi)$ can be expressed as

$$L(\phi) = l_f + l_p \sin \phi \quad (2.3)$$

Substitute Eq. (2.3) into Eq. (2.1) and then compare with Eq. (2.2), it reveals once

$$l_f = l_p \sin \theta_0, \quad (2.4)$$

the tracking is achievable exactly for all accessible wavelengths. In the other word, the wavelength tuning is always continuous by proper choosing the mechanical movement of the grating. Similar to the Littrow theory, this analysis is also based on geometric optics and scalar diffraction theory. When the size of the cavity becomes small, some other effects such as the Gaussian expansion of the laser beam and the dispersion of gain medium should be taken into account.

2.1.3 Injection-locked lasers

Injection locking is a technology for locking the oscillation state of a resonance cavity (named as the slave) by injecting an external coherent radiation (named as the master). It was pioneered for the electrical oscillators by Van de Pol in 1927 [51], who considered to inject an external signal into a self-sustained RLC oscillator and found that when the injection frequency goes close to the RLC frequency, the oscillation suddenly occurs only at the injection frequency and the beating between the injection and the intrinsic RLC oscillation disappears correspondingly. The injection locking soon found its applications in the microwave oscillators [52, 53] and was then extended to the laser oscillators [54-56]. In 1964, Lamb built up a semi-classical theory to describe the operation of a multimode laser parameterically and to investigate various laser behaviors such as threshold condition, frequency pulling/pushing, and mode competition etc [57]. Although Lamb borrowed the idea of external injection in explaining the frequency locking of the laser modes, he did not really study the laser behavior under external injection. However, Lamb's laser theory provided a common base for most of the later

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theoretical investigations of the injection locking. Early theoretical works for injection locking focused mostly on the general theory [54, 58-61] while the recent works tend to target more at the analyses for specific applications [33, 62-68]. Tang and Statz [54] applied the Van der Pol equation into the laser field, but the inversion density was eliminated. 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 [58]. The same problem occurred in some other works that were developed specifically for the injection locking of semiconductor lasers [59, 60]. A milestone work was presented in 1982 by Lang, who synthesized the previous studies and developed a small signal theory for the multimode semiconductor lasers [61]. Lang's theory has been extensively used and proven in many theoretical and experimental studies [63-66, 69-71]. 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 signal and strong side modes. Further works were also reported with focus on strong injection [67], on the locking conditions/stabilities [69], on locking the single mode slave lasers [70], and on lockable range [72-73]. Later, theoretical studies for specific applications have attracted considerable attentions. For example, 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 [33]. Injection locking for Q-switched lasers was also investigated [62]. Recently, injection of multiple lasers has been studied broadly for optical networks. Hörer and Patzak presented a large-signal analysis for wavelength conversion using two injection lasers simultaneously [63]. Cai *et al.* proposed the generation of DWDM channels using multi-

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line optical injection and studied the associated crosstalk, noise and stability [64]. All-optical regenerators and optical transmitters were also investigated using two side-mode locking method [65, 66]. The theory for the chaos synchronization was established by Murakumi by treating the slave as a driven damped oscillator [67, 68].

Fig. 2.1 Concept of injection locking to a semiconductor laser.

The conceptual model for the injection locking is shown in Fig. 2.1. The external injection couples an electrical field E_{ext} at a frequency ν into the internal cavity of the Fabry-Perot laser diode. E_0 stands for the electrical field of the laser cavity, and Ω is oscillation frequency. $\omega(n, \Omega)$ is the resonant frequency of the cavity mode, which is dependent on the excited carrier density n and the oscillation frequency Ω . It should be noted that although ν , ω and Ω stand for the frequencies related to the laser cavity, they are different in such a way that: ν is the frequency of the external injection, Ω is the real frequency of the locked output, and ω is the nominal frequency defined by the refractive index $n(n, \Omega)$ and the cavity length L_d as

$$\omega = \frac{\pi M c_0}{n L_d}, \quad (2.5)$$

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where M is an integer representing the mode number and c_0 is the light velocity in vacuum.

Based on the Lamb's semi-classical laser theory [57], the state inside the FP cavity can be expressed by the field equation and rate equations as given by [61]

$$\frac{dE_0(t)}{dt} = \frac{1}{2} [G(n) - \Gamma] E_0(t) - j[\omega(n) - \nu] E_0(t) + \kappa E_{\text{ext}}, \quad (2.6)$$

$$\frac{dn}{dt} = -\gamma_s n - G(n) \cdot [E_0(t)^2 + N_u(t)] + P, \quad (2.7)$$

$$\frac{dN_u(t)}{dt} = [G(n) - \Gamma] N_u(t) + \gamma C_{\text{sp}} n, \quad (2.8)$$

where $E_0(t) = E_0 \exp(-j\omega t)$ is the time-varying electrical field in the laser cavity, $G(n)$ stands for the modal gain that is dependent on the carrier density, and Γ is the cavity loss that is regarded as a constant in the locking. κ is a proportionality constant for the external injection given by $\kappa = \frac{c_0}{2\eta L_d}$, which represents the average contribution of the external field E_{ext} to the propagating wave inside the laser cavity. It is noted that E_0 and E_{ext} are slow varying fields in contrast to the fast varying term $\exp(-j\omega t)$. γ_s is the inverse carrier lifetime, and C_{sp} is the ratio for the spontaneous emission into the oscillating mode. P is the carrier injection rate per unit volume determined by the injection current density J , active layer thickness d , and electric charge e as $P = \frac{J}{ed} \cdot N_u(t)$ denotes the photon density of the possible unlocked neighboring mode.

Equation (2.6) is the rate equation accounting for the amplitude and phase (i.e. the frequency/wavelength) of the electrical field. The first term on the right side stands for the net gain of the electrical field after a roundtrip, the second for the frequency pulling

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between the injection and the laser mode, and the last for the contribution of the external injection. Eq. (2.7) is the rate equation for the excited carrier density. On the right side, the first term is the decay of the carrier due to limited lifetime, the second for the carrier loss that is converted into photons, and the last one for the current injection. Eq. (2.8) is the rate equation for the photon density of the unlocked neighboring mode. The first term accounts for the roundtrip gain, and the second for the contribution from the spontaneous emission.

These rate equations describe the interactions inside the laser cavity and provide profound physical insight of the injection locking mechanism. Many theoretical works are based on the standard form or certain modification of such equations [61, 63-66, 69-71]. However, there are some drawbacks in these equations:

- (i) In Eq. (2.6) the external injection at ν (named as the seeded mode) is considered degenerated into the laser mode at Ω (named as the targeted mode). That is, there is no seeded mode in the laser output. However, it is observed in the experiment the seeded mode always presents in the output, and becomes dominant when the slave is well locked.
- (ii) The degeneration of the seeded mode makes it impossible to study the progress of locking from the unlocked state to the fully locked state (for example, by changing the wavelength of the injection).
- (iii) The rate equation of Eq. (2.6) is valid only for small signal conditions (i.e., the injection current is slightly over the laser threshold and the laser injection is weak). In the real applications of high power lasers and all optical switching, commonly the lasers are far beyond the threshold and the injection is strong.

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- (iv) The rate equation assumes only one external injection. It cannot deal with the case that multiple injections are injected to a multi-mode slave.

Injection locking has wide applications to the lasers. Semiconductor lasers are naturally advantageous for injection locking since they have 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 easy and stable. The function of the injection locking to the semiconductor lasers can be roughly categorized into two types: (i) improving the characteristics of the slave, and (ii) synchronizing the master and the slave. For the former, the locking is able to improve the properties of the slave laser in spatial, spectral and time domains. For example, the high power lasers are commonly multiple longitudinal mode and have wide diverging angle. Using a low-power single-mode laser as the master, the high power lasers are able to obtain much higher power level but have single wavelength, high SMSR, narrow linewidth and diffraction-limited beam quality [32, 33, 62, 74]. Tuning of the master can lead to the wavelength tuning of the slave (though tuning may not cover the full wavelength range). For high-speed modulation (i.e. time domain), the injection locking can be used to assure single-mode operation [74, 75] and to reduce the mode partition noise [76]. Additionally, it can significantly broaden the modulation bandwidth and flatten the modulation response [77, 78]. Such performance improvement has made the injection locking widely applied to the practice of the high power lasers and the optical communications [32-34, 62, 74, 79-81]. On the other side, the synchronization of the master and slave in wavelength, phase and chaos state has led the injection locking into broad applications in the coherent communications [36, 82].

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One of the latest applications of the injection locking is the all optical switching [34, 35, 81], which is achieved by simultaneous injection of three signals: a data signal, a control signal, and a CW stabilizer signal, into a FP slave laser. As the CW signal is for stabilize the slave when there is no control signal or data signal, it is not involved in the optical switching process. The wavelength and power of the signals are chosen such that the slave is always injection locked by one of the signals in the following priority: the control signal, the data signal, and the CW stabilizer signal. That is, in the presence of the control signal, the slave will be fully locked by the control signal despite the existence or absence of the data signal. Therefore, the data signal is suppressed, i.e. it is turned off. In the absence of a control signal, the data signal will lock the slave, i.e. it is turned on. In this way, the optical data signal can be switched by the control signal in the optical form, without the need for the conventional optical- electronic-optical conversion. The function of the CW stabilizer signal is to suppress the FP modes of the slave when the intensities of both the data signal and control signal are low.

Another novel application is the micromachined atomic wristwatches [83-86]. Commonly 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) [87-90]. The laser source is modulated by a local oscillator and is then shined through a gas cell of ^{133}Cs . When the laser wavelength and the modulation frequency are properly adjusted, the absorption of the gas cell is minimized due to the CPT. A photodetector measures the laser power and then feedback to the oscillator to maintain the minimum absorption. As the oscillation frequency is directly related to the transition between the hyperfine energy states, it is used as the timing signal. The lasers

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should have stable wavelength, very narrow linewidth (~ 10 MHz) and very high modulation rate (~ 10 GHz). Injection locking provides an easy method to meet the requirements. As the vapor cell of the atomic clock is miniaturized [85] and the overall size of the atomic clocks is downscaled, the laser sources should also be shrunk accordingly to the size of millimeters. However, conventional injection-locked lasers are bulky and require complicated driving and adjusting mechanism, making them not realistic for the atomic wristwatches. A good solution is to miniaturize the injection-locked laser and to integrate it on a single chip.

2.2 Development of MEMS tunable lasers

It can be seen from the previous discussions that the problems of the conventional tunable lasers are mainly related with their cavity length and size. The long cavity length puts the physical constrain of 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 etc. To tackle these problems, Microelectromechanical systems (MEMS) technology has been introduced to miniaturize the lasers [15, 91-93].

MEMS is an acronym of microelectromechanical systems. It can be seen from its name that the MEMS technology is a fusion of microelectronics, micromechanics and microsystems. The “micro” means the feature size of the MEMS devices is on the scale of $1\text{ }\mu\text{m}$. The “microelectronics” reflects that the MEMS borrows the fabrication process of microelectronic integrated circuits and can be interfaced to the electronic drives and control mechanism. The “micromechanics” implies that the MEMS devices work by the

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mechanical movement (bending, torsion, rotation and translation and so on) of certain parts, which is the most obvious difference between the MEMS and the IC. The “microsystems” indicates that the MEMS technology can provide system-level integration of the MEMS components with the components of the other technologies such as micro-optics, photonics and fluidics etc. [21].

MEMS technology has natural synergism with tunable laser. The wavelength of tunable laser is around 1 μm , which is on the same scale of the MEMS fine feature. Since the photon has no mass, which is easy for the MEMS devices to operate. For some tunable lasers, to tune over the whole wavelength range, it needs the mirror to displace about one wavelength, which is easy for MEMS. The precision and stable movement of the microactuators enables fine-tuning of the wavelength. The small size of the micromachined mirrors yields high tuning speed and also makes it feasible to form the extremely-short-external-cavity tunable lasers. 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 part, the application of the MEMS to the three type of laser will be reviewed separately. It is noted that the MEMS external-cavity tunable lasers surveyed here do not include the vertical cavity surface emitting lasers (VCSELs).

2.2.1 MEMS discretely tunable lasers

The tunable laser is among the early applications of the MEMS technology [15, 91]. Due to the limit of fabrication, the early works had to use simple flat mirrors as the external reflector, making the continuous tuning impossible. Those lasers were tuned mostly by a mixture of continuous and discrete change, and thus can be roughly put into

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the category of discretely tunable lasers. The application of MEMS to tunable laser was pioneered by Uenishi using the bulk micromachining and the nickel electroplating [15, 91]. In his work, a silicon mirror was formed by etching a single crystalline wafer along (110) direction using KOH, the very different etching rate between the (110) and (111) directions resulted in vertical sidewalls [91]. The mirror was supported on a cantilever beam fabricated in the same process. The laser diode (LD) chip was aligned very near to the mirror to form an extremely short cavity of 10 μm . Since the mirror was not coated with any high reflection material and the LD chip was not AR coated, the obtained wavelength tuning range was only 3 nm, and the tuning was dominated by mode hopping (i.e. discrete tuning, or in the other word, stepwise tuning). Although the performance was not favorable, it inspired the great potential of MEMS technology to the tunable lasers. Later, Uenishi *et al.* improved the performance by electroplating a nickel mirror using the pattern thick photoresist as the mold [15]. The cavity length was further reduced to $< 5\mu\text{m}$, and the LD chip was AR coated. A 20 nm wavelength range was obtained by a quasi-continuous tuning (i.e., partially continuous and partially discrete).

Surface micromachined 3D mirror was also proposed for the ECTLs by Kiang *et al.* [14]. The resolution and stability of mechanical movement were evaluated for the purpose of MEMS lasers, however, it was not really applied to the lasers. A surface micromachined ECTL was later accomplished [18]. The cavity length was only 10 μm . A wavelength range of 16 nm was obtained by quasi-continuous tuning at a sweep speed of 1 ms. The device had a footprint of only 2 mm $\times$ 1.5 mm, which fully demonstrated the compactness of the MEMS lasers. Another MEMS laser was also reported by Sidorin *et al.* [16], which employed a surface micromachined FP filter as the external reflector and

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obtained only 4 nm tuning range. Pezeshki *et al.* demonstrated an interesting configuration of discretely tuning [16]. An array of DFB laser stripes was used as the laser source and a MEMS tilting mirror was used to select one of the DFB as the output. Coarse tuning is realized by rotation the mirror to select one of the stripes while the fine tuning is by temperature control. It obtained a tuning range of 33.2 nm at a step of 50 GHz and an output power of 20 mW.

2.2.2 MEMS continuously tunable lasers

With the progress of MEMS fabrication, it has been found that the deep etched structures are more robust and reliable than the other methods while without sacrificing the feature resolution and surface quality. Especially, the deep reactive ion etching process is capable of patterning complicated profile, allowing for the fabrication of microlenses and gratings. The trend was reflected in the MEMS lasers, most of which have since then been developed based on the DRIE. The integration of MEMS lasers also divides into two directions, hybrid integration and single-chip integration. The former chooses to directly copy the structures of the conventional tunable lasers, and to use the MEMS structure to replace the bulky tuning mechanics. It is a straightforward method to obtain fast tuning speed, but the overall size cannot be reduced since the bulky optical components (focus lenses, prisms etc) remain. The latter prefers to fabricating most of the tunable laser components using the MEMS process, to integrating the whole laser onto a single chip. It enjoys most of the MEMS advantages such as small size, batch fabrication, and easy integration, and thus represents the trend of the further development. However, the optical quality of the MEMS fabrication components is still not comparable to that of the conventional optics.

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A successful example of hybrid integration was presented by Iolon Inc in their MEMS continuously tunable laser [27, 92], which was in a Littman configuration. A vertical mirror transported by a deep etched MEMS actuator was employed for the wavelength tuning [93]. Favorable results were achieved, such as 40 nm tuning range, 7 dBm output, 55 dB side mode suppression ratio, 20 pm wavelength accuracy and 5 mm × 5 mm size. It is the first MEMS laser that leads to commercial success. However, the mirror was only for the tuning and was hybridly integrated with the other bulky components such as the grating and the beam splitter etc. since the mirror and the actuator were quite large and thus had large mass, the tuning speed between two wavelength (not sweeping the whole range) was 15 ms, which is relatively slow compared with the other MEMS lasers.

The research toward the single chip integration was moved forward by the Syms and Lohmann's works on the deep etched gratings for the Littrow MEMS lasers [28-30], in which a special MEMS flexure was proposed for continuous tuning. The MEMS grating was evaluated separately for the laser tuning, and exhibited acceptable diffraction efficiency and filtering property. Although their works still focused on hybridly integrating the MEMS gratings with bulky external components, it showed the possibility to fabricate the micro-optics using the same process for the MEMS actuators.

2.2.3 MEMS injection-locked lasers

The introduction of the MEMS technology to the injection-locked laser was mainly focused on using the movable MEMS film to tune the wavelength of the VCSEL, which is under external injection [94]. In this work, a tunable VCSEL device is grown on InP substrate with a DBR mirror at the bottom and a GaAs/AlGaAs mirror on the top.

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The top mirror is attached to an electrostatically actuated MEMS cantilever for wavelength tuning. External injection is applied to the VCSEL to improve the performance. It obtained 30 GHz modulation bandwidth, 25 dB increase in spur free dynamic range (SFDR), 7× relaxation oscillation frequency and 5-10 dB increase in modulation efficiency.

Although direct implementation of the injection-locked lasers using the MEMS technology is mere untouched, the progress of tunable lasers and the MEMS integration has been preparing the conditions for this break-through.

2.3 Summary

In conclusion, this chapter briefs the principles and previous works of the discretely tunable lasers, the continuously tunable lasers and the injection-locked lasers. It shows the fusion of MEMS and lasers not only leads to many benefits in the engineering level such as fast tuning speed, small size and easy integration, but also leaves broad space for the improvement in the physics level such as new theoretical studies and new phenomena. The review of this chapter provides an overview of the technological base for the three types of MEMS lasers to be discussed in the next three chapters.

CHAPTER 3

MEMS DISCRETELY TUNABLE LASERS

The objective of this chapter is to investigate discretely tunable external-cavity lasers using the MEMS technology, both theoretically and experimentally. As one of the three types of lasers to be developed in this thesis, the discretely tunable laser is chosen as the first one due to its relatively simple configuration. In this chapter, the theoretical studies will present an extended feedback model and then a theory of discrete wavelength tuning, while the experiment part will focus on the fabrication and characterization of a MEMS discretely tunable laser by integration of a deep-etched curved mirror with a Fabry-Perot (FP) laser chip and an optical fiber.

The structure of this chapter is as follows. First, the extended feedback model will be derived for predicting the wavelength shift of the laser mode comb in Section 3.1. This is to accommodate the needs for analyzing the MEMS lasers that work under medium optical feedback since the conventional models are mostly valid only for very weak feedback. Secondly, the theory of discrete wavelength tuning in external-cavity lasers will be developed in Section 3.2. It is to provide a theoretical guidance for achieving discrete-tuning-dominant lasers and an interpretation to the observed tuning behavior (alternation of continuous tuning and discrete tuning with the length change of external cavity). Next, the MEMS fabrication process will be discussed in Section 3.3 with special concerns on dry etching, high aspect ratio and notching effect etc. Finally, experiment

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issues of the MEMS discretely tunable laser will be elaborated, including the design, integration and characterization. The experimental data will be used to verify the theoretical studies in various aspects such as tuning range, mode spacing and mode stability.

3.1 Theory of wavelength tuning via external cavity

Before the start of analysis, some clarifications should be made. The terms “frequency” and “wavelength” will be both used in different occasions in this chapter, but they will be regarded as the same since they have strict one-to-one relation. Commonly it is more convenient to use the “frequency” in the analysis and the “wavelength” in experiment. In addition, the wavelength tuning theory is developed based on the following conditions and assumptions:

- (i) FP laser condition: The bare laser chip for the external-cavity laser is a normal multi-longitudinal mode FP laser.
- (ii) Non-dispersive mirror condition: The external reflector is a mirror whose reflectivity is wavelength independent, unlike the gratings to be used in the other types of tunable lasers.
- (iii) Short external-cavity length condition: The length of the external cavity is smaller than the effective length of the internal cavity.
- (iv) Short mirror translation condition: The mirror translation is relative small compared with the initial external-cavity length.
- (v) Homogeneous assumption: The mode with minimum threshold gain oscillates while the others are suppressed. When the laser is operated slightly over the

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threshold (for example, 28% over the threshold current), the laser output can be single mode owing to the homogeneous broadening even though the laser is a FP laser that usually has multiple modes.

Fig. 3.1 Analytical model for the wavelength tuning of the external-cavity laser.

3.1.1 Variation of laser gain and phase with mirror translation

The schematic diagram of a tunable laser is shown in Fig. 3.1. It consists of an internal cavity representing a laser chip and a passive external cavity formed by a mirror. According to the FP laser condition and the non-dispersive mirror condition, the laser chip provides a FP cavity and optical gain, the mirror is non-dispersive and can be translated to change the external cavity length.

The extended feedback model of the FP laser with external cavity is based on the three-mirror model [8, 95] as shown in Fig. 3.1. F_1 , F_2 and F_3 denote the two facets of the FP laser and the external mirror, r_1 and r_2 are real numbers representing the amplitude reflectances of F_1 and F_2 , respectively, while r_3 denotes the effective amplitude reflectance of the external mirror F_3 . However, r_3 is not directly the reflectance of mirror

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as the coupling losses due to the mirror misalignment and the spreading of laser beam should be taken into consideration. μ_e is the effective refractive index of the laser internal cavity, and d and L stand for the lengths of the laser internal cavity and the external cavity, respectively. The reflection from the external mirror can be treated by combining it with the reflection of the laser end facet F_2 as shown in Fig. 3.1, yielding an effective reflectance r_{2eff} given by [96]

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

where ν is the frequency of the diode laser, τ_L is the roundtrip delay of the external cavity given by $\tau_L = 2L/c_0$, and c_0 denote the light velocity in vacuum. R_2 and ϕ_L are the notations represent the amplitude and phase of the effective reflectance r_{2eff} , respectively.

Assume $r_2 r_3 \ll 1$, the multiple reflections in the external cavity are neglected.

Then R_2 and ϕ_L are expressed by

$$R_2 = r_2 T \quad (3.2)$$

$$\phi_L = \arcsin[\xi \sin(2\pi\tau_L \nu)/T] \quad (3.3)$$

and

$$\xi = r_3(1 - r_2^2)/r_2 \quad (3.4)$$

$$T = \sqrt{1 + \xi^2 + 2\xi \cos(2\pi\tau_L \nu)} \quad (3.5)$$

where ξ is the relative reflectance of the external mirror and T is a variable having a period of $1/\tau_L$.

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

$$E_1 = E_0 r_1 r_{2eff} \exp[-j2\pi\tau_d\nu + (g - \gamma)d] \quad (3.6)$$

where E_1 is the amplified field, $\tau_d = 2\mu_e d / c_0$ is the roundtrip delay of the internal cavity, and g and γ represent the modal gain and loss of the internal cavity respectively. To obtain a stationary laser oscillation, the amplitude and phase conditions should be met [8], yielding

$$r_1 R_2 \exp[(g - \gamma)d] = 1 \quad (3.7)$$

$$\phi = \phi_L + 2\pi\tau_d\nu = 2\pi m, \quad (m = \text{integer}) \quad (3.8)$$

where ϕ denotes the roundtrip phase of the laser beam after traveling through the internal cavity and external cavity.

Based on the amplitude condition (see Eq. (3.7)), the threshold difference of the modal gain Δg due to the optical feedback is given by

$$\Delta g = -\ln(T)/d \quad (3.9)$$

where $\ln$ represents the natural logarithm.

From Eq. (3.8), the total roundtrip phase change $\Delta\phi$ due to the frequency change is given by

$$\Delta\phi = \phi_L + \frac{4\pi d}{c_0} \Delta(\mu_e \nu) \quad (3.10)$$

3.1.2 Variation of wavelength with mirror translation

The effective refractive index μ_e changes with the frequency variation since the optical feedback alters the carrier density n in the internal cavity. Adopting the derivation procedure in Chapter 9 of Ref. [8], the change $\Delta\mu_e$ can be expressed by

$$\Delta\mu_e = \frac{\partial\mu_e}{\partial n}(n - n_0) + \frac{\partial\mu_e}{\partial\nu}(\nu - \nu_0) \quad (3.11)$$

where n_0 is the threshold carrier density. The carrier density variation induces the change of the material gain Δg_{mat} as given by [8]

$$\frac{\partial\mu_e}{\partial n}(n - n_0) = \alpha \frac{\partial\mu_e''}{\partial n}(n - n_0) = -\alpha \frac{\partial g}{\partial n} \frac{c_0}{4\pi\nu}(n - n_0) = -\frac{\alpha c_0}{4\pi\nu} \Delta g_{\text{mat}} \quad (3.12)$$

where μ_e'' denotes the imaginary part of the complex refractive index of the internal cavity, α is the linewidth enhancement factor defined by $\alpha = \partial\mu_e / \partial\mu_e''$, and μ_e'' is related

to g by $\mu_e'' = \frac{c_0}{4\pi\nu} g$ (from Eqs. (2.41) and (2.42) of Ref. [8]).

It should be noted that in Eqs. (3.7) and (3.9), the gain is modal gain, while in Eq. (3.12) it is material gain. The relationship is given by

$$\Delta g = \Gamma \Delta g_{\text{mat}} \quad (3.13)$$

where Γ is the optical confinement factor. This difference significantly alters the value since Γ is generally quite small (e.g. 0.1) [97], but it has long been neglected in the previous studies that dealt with the similar cases [8, 19, 95].

It can be derived from Eqs. (3.11) and (3.13) that

$$\Delta(\mu_e \nu) = \nu \Delta\mu_e + \mu_e (\nu - \nu_0) = -\frac{\alpha c_0}{4\pi\Gamma} \Delta g + \bar{\mu}_e (\nu - \nu_0) \quad (3.14)$$

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where $\bar{\mu}_e$ is the group effective refractive index in the internal cavity given by [8]

$$\bar{\mu}_e = \mu_e + v \cdot \frac{d\mu_e}{dv} \quad (3.15)$$

Substituting Eqs. (3.9) and (3.14) into Eq. (3.10), it has

$$\Delta\phi = 2\pi t_d (v - v_0) + \phi_L + \phi_g \quad (3.16)$$

where $t_d = 2\bar{\mu}_e d / c_0$ is the group roundtrip delay in the internal cavity, and ϕ_g denote the roundtrip phase change due to the gain variation given by

$$\phi_g = \alpha' \ln(T) \quad (3.17)$$

where $\alpha' = \alpha / \Gamma$.

To achieve a stationary oscillation, the phase condition Eq. (3.10) requires

$\Delta\phi = 0$, yielding

$$\begin{aligned} v - v_0 &= - \frac{\phi_g|_{v=v_0} + \phi_L|_{v=v_0}}{2\pi t_d + \left. \frac{\partial \phi_g}{\partial v} \right|_{v=v_0} + \left. \frac{\partial \phi_L}{\partial v} \right|_{v=v_0}} \\ &= - \frac{T_0^2}{2\pi} \cdot \frac{\alpha' \ln(T_0) + \arcsin[\xi \sin(2\pi\tau_L v_0) / T_0]}{t_d T_0^2 + \tau_L \xi [\xi + \cos(2\pi\tau_L v_0) - \alpha' \sin(2\pi\tau_L v_0)]} \end{aligned} \quad (3.18)$$

where $T_0 = T|_{v=v_0}$ represents the value of T at $v = v_0$. This is one of the key analytical results in this chapter, and is unique in comparison to previous analyses [8, 18, 95, 96].

3.1.3 Comparison of the extended feedback model with the conventional weak feedback model

It is noted that the Eqs. (3.9), (3.16) and (3.18) are derived under the assumption that $r_2 r_3 \ll 1$, which is rather different from the weak optical feedback condition $\xi \ll 1$

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that was widely used [18, 95, 96]. However, they are also available for deducing the weak optical feedback condition. Assume $\xi \ll 1$, Eqs. (3.9), (3.16) and (3.18) becomes

$$\Delta g = -\xi/d \cos(2\pi\tau_L\nu) \quad (3.19)$$

$$\Delta\phi = 2\pi_d(\nu - \nu_0) + \xi\sqrt{1+\alpha'^2} \sin[2\pi\tau_L\nu + \arctan(\alpha')] \quad (3.20)$$

$$\nu - \nu_0 = -\frac{C \sin[2\pi\tau_L\nu_0 + \arctan(\alpha')]}{2\pi\tau_L[1 + C \cos(2\pi\tau_L\nu_0 + \arctan(\alpha'))]} \quad (3.21)$$

where $C = (\tau_L/t_d)\xi\sqrt{1+\alpha'^2}$ represents the external feedback strength. Eqs. (13) – (15) are the same as those given in Refs. [8] and [95] when α' is replaced by α (as mentioned above, the optical confinement factor was not taken into account in their analysis).

In this chapter, the terms “weak feedback” and “medium feedback” are used to represent the cases of different feedback strengths, while the terms “extended feedback model” and “weak feedback model” represent the two different models. The weak feedback model is valid only in the case of weak feedback, while the extended feedback model covers both the weak and medium feedbacks.

In the tunable lasers using micromachined mirrors, r_3 may not be so weak (e.g. $r_3 = 0.15$) due to the short external cavity. If the end facet F_2 is coated with dielectric anti-reflection films, r_2 can be reduced to a lower value (e.g. $r_2 = 0.2$). In this example, $r_2 r_3 = 0.03 \ll 1$ while $\xi = 0.72$ does not meet the condition of $\xi \ll 1$. Here a simple classification is given that the conditions of $\xi \leq 0.1$ and $0.1 < \xi < 0.8$ are regarded as the weak feedback and medium feedback respectively while other represents strong feedback. The values of 0.1 and 0.8 are chosen somewhat arbitrarily. Physically, ξ represents the amplitude ratio of the light reflected by the facet F_2 to the light

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transmitting to the external cavity and then re-entering the internal cavity (only one round). When $\xi \leq 0.1$, the light energy fed back from the external cavity is much smaller than that by the facet F_2 of the internal cavity. It is a weak feedback. When $\xi > 0.8$, coherence collapse may be easy to occur [95], which invalidate the analysis. In the micromachined tunable lasers that work in extended feedback region, Eqs. (3.9), (3.16) and (3.18) are more suitable.

Fig. 3.2 Comparison of the extended feedback model and the weak feedback model in predicting the gain variation with the change of external cavity length ($\xi = 0.72$). a.u. represents arbitrary unit.

In order to compare the difference of the extended feedback model and the weak feedback model, the weak feedback model is extended to the extended feedback region. The threshold gain difference induced by the optical feedback varies as the length of external cavity changes. The predictions by both models are compared in Fig. 3.2 (assuming $\xi = 0.72$). Both predictions have a period of $\lambda/2$, as implied by Eqs. (10) and

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(13). However, the extended back model gives out a larger gain increment $\Delta g_{\max} = -\ln(1 - \xi)/d$ and a smaller gain reduction $\Delta g_{\min} = -\ln(1 + \xi)/d$ compared with those $\Delta g_{\max} = \xi/d$ and $\Delta g_{\min} = -\xi/d$ predicted by the weak feedback model. The discrepancy of these two models increases with the increases of ξ . In addition, the extended feedback model predicts broad valleys in the curve of threshold gain difference. When the external mirror is initially adjusted to the valley regions, the threshold gain changes very small with the change of external cavity length. Thus the output light intensity of the dominating mode is stable. However, the small slopes of the gain valleys are harmful for the side mode suppression.

The wavelength variations predicted by Eqs. (3.18) and (3.21) are illustrated in Fig. 3.3 to compare the extended model with the weak model. The weak model shows a cosine-like relation between the wavelength tuning and the external cavity length, while the extended model has sharp valleys and smooth peaks. This implies that in the micromachined tunable laser the wavelength can be tuned slowly with the movement of external mirror if the light is initially adjusted to one of the smooth peaks, and rapidly if to one sharp valley. In the extended feedback model, the achievable maximum and minimum wavelengths are smaller than those predicted by the weak model. However, the extended model gives larger tuning range (i.e. the achievable maximum wavelength minuses the minimum) than the weak model does. Based on Eqs. (3.18) and (3.21), the wavelength tuning range given out by the two models are compared in Fig. 3.4. For small relative reflectance ξ , the two models match very well. While ξ increases, the extended model tends to give a larger tuning range than the weak model does.

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Fig. 3.3 Comparison of the wavelength variation predicted by the extended feedback model and the weak feedback models ($\xi = 0.72$). a.u. represents arbitrary unit.

Fig. 3.4 Comparison of the wavelength tuning ranges predicted by the extended and the weak feedback models (a.u. represents arbitrary unit).

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In the tunable lasers that use micromachined mirrors to form external cavities, the short distances between the mirrors and the laser facets are found to be inducing significant feedbacks. Under this circumstance, the extended feedback model should be adopted instead of the weak feedback model to avoid large discrepancy in analyzing the tuning characteristics.

3.2 Theory of discrete wavelength tuning

It is noted that the usefulness of the extended feedback model lies in its versatility in handling both weak and medium feedback strengths, which are the normal working conditions of short-cavity MEMS external-cavity lasers. However, in dealing with purely discrete tuning, the weak-feedback model is adopted due to two reasons. One is its simplicity; the other is that it is later proven that purely discrete tuning requires the condition of weak feedback.

Since the mirror is a non-dispersive component, the laser output may contain one or several of its cavity modes (i.e. single longitudinal mode or multiple longitudinal mode). The extended feedback model developed above is to predict the continuous wavelength tuning of any of the laser modes. It does not take into account the mode hopping. However, it is commonly observed in the experiment that during the tuning the laser would experience a small range of continuous tuning, then suddenly jumps to the adjacent mode (discrete tuning). In this section, this continuous-then-discrete-tuning phenomenon will be explained theoretically by monitoring the tuning behavior of one laser mode, and then the conditions for a discrete-tuning-dominant wavelength tuning will be derived.

3.2.1 Laser modes and frequency shift

According to Eq. (3.6), the gain and the light frequency at threshold can be expressed as

$$2\pi\tau_d\nu_m + \phi_L = 2\pi m \quad (m \text{ is an integer}) \quad (3.22)$$

$$g_{th} = \gamma - \ln(r_1 R_2)/d \quad (3.23)$$

where ν_m is the longitudinal mode of the laser cavity. Eqs. (3.22) and (3.23) govern the laser output in such a way that the former defines the possible output frequencies (i.e. laser modes) while the later determines the gain of each mode. According to the homogeneous assumption, the mode having lowest gain is selected for oscillating.

The amount of continuous tuning is the frequency shift of the laser modes relative to their original positions when there is no external cavity. According to Eq. (3.11), the change of refractive index is given by [98]

$$\mu_e - \mu_{e0} = \frac{c_0 \alpha'}{4\pi\nu_m} (g_{th} - g_{th0}) \quad (3.24)$$

where μ_{e0} and g_{th0} are the effective refractive index and the gain without external cavity, respectively.

Substitute Eq. (3.24) into Eq. (3.23), yielding

$$\nu_m = \frac{1}{2\pi} [2\pi m + \alpha' \ln(R_2/r_2) - \phi_L] \cdot \Delta\nu_s \quad (3.25)$$

$$\nu_m - \nu_{m0} = \frac{1}{2\pi} [\alpha' \ln(R_2/r_2) - \phi_L] \cdot \Delta\nu_s \quad (3.26)$$

where $\Delta\nu_s = c_0/(2\mu_{e0}d)$ is the original mode spacing of the laser (s for spacing), and

$\nu_{m0} = mc_0/(2\mu_{e0}d)$ represents the m^{th} laser mode without external cavity. Eq. (3.25)

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describes the possible frequencies of the laser output, and Eq. (3.26) expresses the relative frequency shift of any laser mode relative to its original position. It is noted that the frequency shift is continuous with the mirror translation.

By substituting R_2 and ϕ_L in Eqs. (3.2) and (3.3) into Eq. (3.26), it would yield an accurate but complicated expression of the laser frequency shift. To get a more straightforward physical understanding, the expression is simplified under the condition of weak external feedback, i.e. $\xi = r_3(1 - r_2^2)/r_2 \ll 1$. In this case, $r_2 r_3 = \xi \cdot [r_2^2 / (1 - r_2^2)] \ll 1$ if r_2 does not approach to 1 (i.e. not high-reflection coated). Therefore, $R_2 \approx r_2 [1 + \xi \cos(2\pi\tau_L \nu_m)]$ and $\phi_L \approx \xi \sin(2\pi\tau_L \nu_m)$. Using these relationships, Eq. (3.26) can be further simplified to be

$$\nu_m - \nu_{m0} = \frac{\xi \sqrt{1 + \alpha'^2}}{2\pi} \cos\left(2\pi\tau_L \nu_m + \frac{\pi}{2} - \arctan(\alpha')\right) \cdot \Delta\nu_s \quad (3.27)$$

Although ν_m appears in both sides of Eq. (3.27), its variation relative to the original mode spacing is limited in a small range as expressed by

$$-\frac{\xi \sqrt{1 + \alpha'^2}}{2\pi} \leq \frac{\nu_m - \nu_{m0}}{\Delta\nu_s} \leq \frac{\xi \sqrt{1 + \alpha'^2}}{2\pi} \quad (3.28)$$

In case of the weak feedback $\xi \ll 1$ and the short external cavity length $L_0 < \mu_e d$, the continuous frequency shift is small, and

$$2\pi\tau_L (\nu_m - \nu_{m0}) \leq \frac{\xi L_0 \sqrt{1 + \alpha'^2}}{\mu_e d} \ll 1 \quad (3.29)$$

Therefore,

$$\nu_m - \nu_{m0} \approx \frac{\xi \sqrt{1 + \alpha'^2}}{2\pi} \cos\left(2\pi\tau_L \nu_{m0} + \frac{\pi}{2} - \arctan(\alpha')\right) \cdot \Delta\nu_s \quad (3.30)$$

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The continuous shifts of the m_1^{th} , $(m_1-1)^{\text{th}}$ and $(m_1-2)^{\text{th}}$ laser modes are shown in Fig. 3.5 (a) (m_1 is an integer). They change periodically at a pitch of about $\lambda_0/2$ while maintaining a fixed phase difference of about $2\pi L_0/(\mu_{e0}d)$ (corresponding to a difference of $L_0\lambda_0/(2\mu_{e0}d)$ in the L axis). L_0 and λ_0 are, respectively, the initial external cavity length and the laser output wavelength without external feedback. The thick solid lines represent the frequencies that have minimum threshold gain (to be discussed later).

3.2.2 Transition between continuous and discrete tuning

It is observed in the experiments that the wavelength changes continuously within a certain range, jumps to the adjacent mode (i.e. discrete tuning), and then changes continuously and jumps again [15, 18]. The transition between the continuous and the discrete tuning appeared in the whole tuning wavelength range. This transition can be attributed to the mode selection mechanism that only the mode with lowest gain can be oscillated (i.e. homogeneous assumption).

Under the weak feedback condition, the variation of gain can be expressed as

$$g_{th} - g_{th0} = -\ln(R_2/r_2)/d \approx -\xi \cos(2\pi\tau_L\nu_m) \quad (3.31)$$

where $g_{th0} = \gamma - \ln(r_1r_2)/d$ is the gain without external cavity. The threshold gain varies periodically with the mirror translation as shown in Fig. 3.5 (b). Similar to the continuous shift, the threshold gain has a pitch $\lambda_0/2$ and a fixed phase difference of $2\pi L_0/(\mu_{e0}d)$ between the adjacent laser modes.

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Fig. 3.5 Frequency tuning with the change of external cavity length. (a) Continuous frequency shift; (b) variation of threshold gain; and (c) output frequency after taking into account the transition between the continuous tuning and the discrete tuning. a stands for $\xi\sqrt{1 + \alpha'^2} \Delta\nu_s / (2\pi)$.

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To investigate the transition between the continuous and the discrete tuning with the translation of the mirror, here as an example, assume when $L = L_1$ and $m = m_1$, it happens to have

$$\tau_{L_1} \nu_{m_1} = p \quad (p \text{ is an integer}) \quad (3.32)$$

According to Eq. (3.31), the m_1^{th} mode has the lowest gain and therefore becomes the dominant oscillating mode. If the mirror displaces slightly to be $L = L_1 + \Delta L$ (assume ΔL is not large enough to cause mode hopping), the phase terms of the m_1^{th} and the $(m_1-1)^{\text{th}}$ mode become

$$\tau_{L_1+\Delta L} \nu_{m_1} = p + 2\Delta L/c_0 \quad (3.33a)$$

$$\tau_{L_1+\Delta L} \nu_{m_1-1} = p + 2\Delta L/c_0 - 2(L_1 + \Delta L)\Delta \nu/c_0 \quad (3.33b)$$

where $\Delta \nu$ is the current mode spacing.

To keep the gain of the m_1^{th} mode lower than that of the $(m_1-1)^{\text{th}}$ mode, it should satisfy that

$$\Delta L < L_1/(2m_1 - 1) \quad (3.34)$$

In general,

$$|\Delta L| < \Delta L_c/2 \quad (3.35)$$

where $\Delta L_c = L_0 \lambda_0 / (2\mu_e d)$ represents the critical range within which the laser mode does not change (c for critical).

The thick solid lines in Fig. 3.5 (b) indicate the regions within which the minimum threshold gain is obtained. It can be seen that one laser mode, for instance, the m_1^{th} mode, has the minimum threshold gain when the mirror translation within $L_0 - \Delta L_c/2$ and $L_0 + \Delta L_c/2$. Accordingly, the output frequency is tuned continuously

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following the thick solid lines in Fig. 3.5 (a), as also shown in the zoomed view in Fig. 3.5 (c). With the further translation of the mirror, the $(m_1-1)^{\text{th}}$ mode obtains the minimum threshold gain and gets oscillated. As a result, the output frequency changes abruptly, and then continuous and abruptly again as shown in Fig. 3.5 (c). The alternation of the continuous and the discrete tuning makes the laser sweep the whole tuning range.

3.2.3 Properties of discrete-dominant tuning

A discrete-tuning-dominant laser should have the drifts of mode position and mode spacing well suppressed, that is,

$$\xi \sqrt{1 + \alpha'^2} / 2\pi \ll 1 \quad (3.36)$$

which requires $\xi \ll 1$, i.e. the weak feedback condition. From the derivation above, it also requires the short external cavity $L_0 < \mu_{e0}d$.

The frequency range of discrete tuning is determined by the gain threshold. According to Eq. (3.31), the tuning range ν_r and the number M_r of all the possible laser modes are given by

$$\nu_r = c_0 / (2L_0) \quad (3.37a)$$

$$M_r = \mu_{e0}d / L_0 \quad (3.37b)$$

It implies that short external cavity length has large tuning range. In the conventional tunable lasers, the external cavity length commonly ranges from centimeters to meters. The discretely tunable range is too small to have any practical use. In contrast, the MEMS lasers have external cavity length from several microns to hundreds microns. It supports a discretely tuning range as large as tens of nanometers. This is one of the fundamental advantages of the MEMS lasers compared to the conventional lasers.

3.3 Deep reactive ion etching (DRIE) process

The tunable lasers commonly consist of mirrors, gratings and lenses etc., thus the fabrication should be able to produce high-quality optical components. In addition, it should allow for packaging laser chips and optical fibers. Among the candidates for fabricating the MEMS tuning structures, such as the bulk micromachining, surface micromachining and deep etching, the deep etching is most practical owing to the available fabrication facilities and the technological merits, for example, large aspect ratio, high verticality, easy fabrication of lenses and gratings, easy integration and simple process. Compared with the normal silicon wafer, the silicon-on-insulator (SOI) wafer possesses the merits of predefined thickness, simple process, fewer masks and easy electrical isolation. As the mirrors, gratings and microlens may have arbitrary profiles (i.e., layouts), the crystal-orientation-dependent wet etching is not suitable. Gaseous dry etching is thus preferred owing to the advantages of crystal orientation independence, high resolution, no stiction, and better fabrication control. Consequently, all the MEMS structures in this chapter are fabricated on the SOI wafers by the deep reactive ion etching (DRIE) process [99]. The SOI wafer has a silicon structural layer (75 μm thick) and a SiO_2 buffer layer (2 μm thick) on a handling silicon wafer (475 μm thick). In the discussions below, the process flow will be presented with the special concerns for the MEMS tuning structures of the tunable laser, followed by a detailed discussion on the DRIE etching and release.

As a process flow for the MEMS tunable lasers, it should take into account some special requirements. For example, electrical connections are needed to apply an injection current to the laser chip and a potential to the actuator. The etched sidewall should be vertical, smooth and highly reflective to act as a good mirror surface. The etching depth should be large enough to cover the diverged light beam from the laser chip and to allow normal single mode fibers as the output coupling. In addition, dicing lines should be

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etched out for easy separation of the wafer in order to expose the fiber grooves for packaging and integration. With these issues taken into account, the designed process flow is outlined in Fig. 3.6. (i) A layer of gold ($0.2\ \mu\text{m}$ thick) is patterned and then sintered for a good ohm contact with silicon as shown in Fig. 3.6 (a). This is to provide the electrical pads, which are bound to the substrate firmly enough for the wire bonding in later MEMS packaging. (ii) A layer of SiO_2 is deposited, patterned and then protected by a layer of photoresist as shown in Fig. 3.6 (b). The SiO_2 layer will be used as the hard mask for patterning the microstructures later. (iii) Multi-layer patterning method is used to etch the deep dicing lines by $75\ \mu\text{m}$ down to the buried oxide layer while all the other part of the structural layer is protected (see Fig. 3.6 (c)). (iv) The exposed buried oxide is removed. Then further etching into the handling silicon wafer about $50\ \mu\text{m}$ is performed to deepen the dicing lines (see Fig. 3.6 (d)). (v) The protection layer of photoresist is stripped to expose the hard mask, whose pattern is then transferred to the structural silicon layer by the deep etching (see Fig. 3.6 (e)). At the same time, the dicing lines are further deepened and have a total depth of about $200\ \mu\text{m}$. To free the movable structures, a step of dry release is performed. (vi) Lastly, a layer of gold ($0.2\ \mu\text{m}$ thick) is deposited on the sidewalls as shown in Fig. 3.6 (f). This is realized by first depositing a gold layer ($0.2\ \mu\text{m}$ thick) and then etching back this layer from the top. In this way, the gold on the top surface is removed (the electrical pads are kept un-etched) while that on the sidewalls remains. The metal coating is done on the BLAZER sputtering system from Sitek Process Solutions Inc. The sputtering conditions for Ti/Au are: (1) Ti $\sim 300\text{\AA}$ thick as adhesion layer, power 1.5kW , argon gas flow $100\ \text{Sccm}$, deposition rate $133\text{\AA}/\text{min}$; (2) Au ($0.2\ \mu\text{m}$), power 1.0kW , argon gas flow $300\ \text{Sccm}$, deposition rate $333\text{\AA}/\text{min}$. The step coverage (the ratio of the thickness of a film over a side wall to the thickness in a flat top area) for this Au deposition is about 50%. The inclusion of the etching back is to guarantee better electrical isolation. Due to the notching effect associated with the SOI

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wafer, the gold on the sidewalls of a trench could be well isolated from that on the bottom. However, as the notching effect is dependent on the trench width and depth, the electrical isolation may not exist for some structures if the gold layer is not very thin. For this reason, the etching back is necessary.

Fig. 3.6 Process flow of the deep reactive ion etching for the MEMS lasers.

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In brief, 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; the MEMS structures are then patterned and metal coated. Finally, the wafer is ready for dicing to small dies and then integrating with the laser chips and optical fibers.

As the DRIE process is key to the fabrication, more details are discussed. In this study, the surface technology systems (STS) inductively coupled plasma (ICP) deep etch machine is employed for the high aspect ratio anisotropic etching through alternative steps of etching and sidewall passivation. This technique uses high density low pressure (HDLP) system, which reduces the probability of ion collision and improves the ion directionality for better control of anisotropy. The ICP source provides the most stable and widest operating window at 13.56 MHz. To obtain high etching depth, the pre-etched trench is first deposited with a polymer passivation layer on all the surfaces and sidewalls, then the base of the trench is removed to expose the bottom silicon while maintaining the sidewall protection layer. The exposed silicon is etched down, followed by another round of passivation and etching. In this way, it guarantees that the etching occurs only in vertical direction. The main reaction gases are SF_6 for etching and octafluorocyclobutane (C_4F_8) for passivation.

The dry release of the MEMS structures is realized by utilizing the notching effect. Although wet etching (e.g., 49% HF) can be used, the dry release is preferable as it avoids the capillary-force-induced stiction problem. The DRIE makes use of alternative etch and passivation to attain the deep trenches. Although the sidewall is covered by the polymerized CF_2 , this thin layer cannot protect the sidewall from etching by the high energy ions repelled from the exposed silicon dioxide layer, which is actually the cause

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of notching (i.e., undercutting). However, the thin sidewall spacer oxide film can resist the etching. The dry release makes use of the notching effect to undercut the bottom of moving structures while using the coverage of the spacer oxide to control the depth.

Fig. 3.7 Configurations of MEMS tunable lasers. (a) A flat mirror is used as the external reflector; (b) a curved mirror is used as the external reflector.

3.4 Experimental results and discussions

3.4.1 Improved design of laser configuration

A typical configuration of MEMS lasers is shown in Fig. 3.7 (a), in which a flat mirror is used as the external reflector [15, 18, 19], a diode laser as the gain medium and a butt-coupling optical fiber as output. Commonly, no external coupling optics is allowed in the MEMS chips due to space limitation and alignment difficulty. However, this configuration suffers from low feedback coupling efficiency since the laser light diverges at a large angle (typical 30 – 40 degree). To obtain acceptable coupling efficiency, extremely short external cavity has to be used (10 – 20 μm) [15, 18], which would give rise to other problems. An improvement is to replace the flat mirror with a concave

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mirror as shown in Fig. 3.7 (b). The concave surface helps to focus the diverging laser light, and therefore improves the feedback efficiency. As the concave surface remains to be a challenge to deep etching process, a curved shape might be suitable. The curved mirror converges the laser light in one direction while leaving it diverging in the other direction. Even so, the coupling efficiency can be significant improved.

For a simple comparison between the two configurations, assume perfect mirrors and no angular and lateral misalignments between the laser and the mirrors. The coupling efficiencies of the flat mirror and the curved mirror can be estimated based on the insertion loss analysis of Gaussian beam [99], as expressed by

$$R_{3\text{flat}} = T_2 \left(1 + \frac{L^2 \lambda^2}{\pi^2 w_x^4} \right)^{-\frac{1}{2}} \left(1 + \frac{L^2 \lambda^2}{\pi^2 w_y^4} \right)^{-\frac{1}{2}} \quad (3.38a)$$

$$R_{3\text{curved}} = T_2 \left(1 + \frac{L^2 \lambda^2}{\pi^2 w_y^4} \right)^{-\frac{1}{2}} \quad (3.38b)$$

where $R_{3\text{flat}}$ and $R_{3\text{curved}}$ are the effective coupling efficiencies in the flat mirror configuration and the curved mirror configuration. T_2 is the transmittance of the laser facet, w_x and w_y are, respectively, the laser beam waists in the horizontal and vertical directions. As an example, with an external cavity length of 66 μm , the flat mirror leads to a feedback coupling efficiency of about 2% while the curved mirror gives about 10%. Other parameters used in the example are: the laser spot size is 1.75 μm and 1.53 μm in elliptical shape, the laser wavelength is 1.55 μm , and the transmittance of the laser facet is 70%. Therefore, the curved mirror configuration is preferred since its higher coupling efficiency places lower requirement for alignment accuracy in the laser integration compared with the flat mirror configuration.

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To compare the two laser configurations at the presence of the position misalignment, detailed coupling analysis is developed based on the Collins integral [100] and the mode coupling theory [101]. The former calculates the transformation of the emitted laser field by the mirror (either curved mirror or flat mirror) while the latter works out how much percentage of the power of the transformed laser can be coupled back into the laser internal cavity. The analytical model of the mirror coupling is shown in Fig. 3. 7. The mirror can be either a curved mirror or a flat mirror. The curved mirror has the curvature in the x_1 - z plane while keeping straight in the y_1 - z plane. The calculation has three steps: (1) ray transfer matrix; (2) coordinate system conversion, and (3) mode coupling. Following this sequence, the coupling efficiency of the laser configuration is estimated as detailed below.

Fig. 3.8 Analytical model for the coupling efficiency of the mirror at the presence of misalignment.

(i) Ray transfer matrix of curved mirror

To calculate the coupling efficiency using the Collins integral, the ray matrix of the curved mirror is first to be derived. Suppose the initial light field $E_1(x_1, y_1)$ emitted from the laser chip can be expressed as

$$E_1(x_1, y_1) = \sqrt{\frac{2}{\pi w_x w_y}} \exp\left\{-\frac{x_1^2}{w_x^2} - \frac{y_1^2}{w_y^2}\right\} \quad (3.39)$$

where the coordinate system (x_1, y_1) is on the end facet of the laser as shown in Fig. 3.8.

The term $\sqrt{\frac{2}{\pi w_x w_y}}$ is to normalize the input power to be 1.

According to Collins integral [100], the transformed laser field $E_1(x_4, y_4)$ is given by

$$E_4(x_4, y_4) = \frac{-j \exp\{jkL\}}{\lambda \sqrt{\det(\vec{B})}} \iint E_1(x_1, y_1) \times \exp\left\{j \frac{\pi}{\lambda} \left[\vec{r}_1' (\vec{A} \vec{B}^{-1}) \vec{r}_1 + \vec{r}_4' (\vec{D} \vec{B}^{-1}) \vec{r}_4 - 2 \vec{r}_1' \vec{B}^{-1} \vec{r}_4 \right] \right\} dx_1 dy_1 \quad (3.40)$$

where λ is the wavelength, k is the wavenumber defined by $k = \frac{2\pi}{\lambda}$, L is the distance

from the laser end facet to the mirror center, and the plane $((x_4, y_4))$ is perpendicular to the central line of the reflected light and its origin is in the (x_1, y_1) plane (as shown in Fig.

3.8). For the matrices and vectors, $\vec{r}_1 = \begin{pmatrix} x_1 \\ y_1 \end{pmatrix}$, $\vec{r}_4 = \begin{pmatrix} x_4 \\ y_4 \end{pmatrix}$, $\vec{B}^{-1} = \text{inv}(\vec{B})$, and $\det(\vec{B})$ is the

determinant. $\vec{A}$, $\vec{B}$ and $\vec{D}$ are 2×2 matrices defined by

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$$\begin{pmatrix} \vec{A} & \vec{B} \\ \vec{C} & \vec{D} \end{pmatrix} = \vec{M} \quad (3.41)$$

here $\vec{M}$ is a 4×4 matrix that stands for the overall ray transfer matrix for the laser field transformations including the propagation from the facet to the mirror, rotation of the mirror, tilting of the mirror, reflection and focus of the mirror, and the propagation from the mirror to the (x_4, y_4) plane. It can be expressed by

$$\vec{M} = \vec{M}_{\text{fs}}(L_0) \cdot [\vec{R}^{-1}(\alpha) \cdot \vec{T}(\theta) \cdot \vec{R}(\alpha)] \cdot \vec{M}_{\text{fs}}\left(\frac{L_0}{\cos(2\theta)}\right) \quad (3.42)$$

where $\vec{M}_{\text{fs}}(L)$ is the ray transfer matrix for the free space propagation of a distance L , and $\vec{R}(\alpha)$ for the rotation about the z axis by an angle α (as shown in Fig. 3.8), as given by

$$\vec{M}_{\text{fs}}(L) = \begin{pmatrix} 1 & 0 & L & 0 \\ 0 & 1 & 0 & L \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (3.43a)$$

$$\vec{R}(\alpha) = \begin{pmatrix} \cos \alpha & \sin \alpha & 0 & 0 \\ -\sin \alpha & \cos \alpha & 0 & 0 \\ 0 & 0 & \cos \alpha & \sin \alpha \\ 0 & 0 & -\sin \alpha & \cos \alpha \end{pmatrix} \quad (3.43b)$$

$\vec{T}(\theta)$ is the matrix representing both the mirror reflection/focus and the mirror tilting by an angle θ about the y axis. For the curved mirror and the flat mirror, $\vec{T}(\theta)$ can be expressed as

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$$\vec{T}_{\text{curved}}(\theta) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ \frac{-2 \cos \theta}{\rho} & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (3.43c)$$

$$\vec{T}_{\text{flat}}(\theta) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (3.43d)$$

Fig. 3.9 Analytical model for the coordinate system conversion and the phase compensation.

(ii) Coordinate system conversion on laser facet

With the Eqs. (3.39) – (3.43d), the laser field in the plane (x_4, y_4) can be obtained. However, to couple the laser field $E_4(x_4, y_4)$ into the laser internal cavity, the coordinate system (x_4, y_4, z_4) should be converted to the coordinate system (x_1, y_1, z) following the rules below

$$\begin{aligned} x_4 &= [x_1 - L \sin(2\theta)] \cos(2\theta) \\ y_4 &= [y_1 - L \sin(2\beta)] \cos(2\beta) \end{aligned} \quad (3.44a)$$

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The projection of (x_4, y_4, z_4) into (x_1, y_1, z) would result in distance change as given by

$$\begin{aligned}\Delta z_x &= [y_1 - L \sin(2\beta)] \sin(2\beta) \\ \Delta z_y &= [y_1 - L \sin(2\theta)] \sin(2\theta)\end{aligned}\quad (3.44b)$$

Therefore, when $E_4(x_4, y_4)$ in the (x_4, y_4, z_4) system is converted into $E_4(x_1, y_1)$ in the system (x_1, y_1, z) , a phase change should be compensated as follows

$$\Delta\phi = k(\Delta z_x + \Delta z_y) \quad (3.44c)$$

(iii) Feedback coupling efficiency using mode coupling method

According to the mode coupling theory [101], the power efficiency E_0 of $E_4(x_1, y_1)$ being coupled into the laser internal cavity can be obtained by mode-overlap integral as given by

$$\begin{aligned}E_0 &= \frac{\left| \int \int_{-\infty}^{\infty} E_4(x_1, y_1) E_1^*(x_1, y_1) dx_1 dy_1 \right|^2}{\int \int_{-\infty}^{\infty} |E_4(x_1, y_1)|^2 dx_1 dy_1 \cdot \int \int_{-\infty}^{\infty} |E_1^*(x_1, y_1)|^2 dx_1 dy_1} \\ &= \frac{\left| \int \int_{-\infty}^{\infty} E_4(x_1, y_1) E_1^*(x_1, y_1) dx_1 dy_1 \right|^2}{\int \int_{-\infty}^{\infty} |E_4(x_1, y_1)|^2 dx_1 dy_1}\end{aligned}\quad (3.45)$$

where $E_1^*(x_1, y_1)$ is the conjugate of $E_1(x_1, y_1)$, which has unit power.

Based on the above analytical model, the feedback coupling efficiencies of the curved mirror and the flat mirror is compared for different types of misalignment. In the simulation, the curved mirror has a curvature of 66 μm , the wavelength is 1.55 μm ; the reflectivity of mirror surface is assumed to be 100%; the laser beam is taken as an elliptical Gaussian shape with the major and minor axes of 1.75 μm and 1.53 μm , respectively. The beam size is estimated by measuring the far-field beam profile. As shown in the simulation results of Fig. 3.10 (a), the curved mirror has a feedback

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coupling efficiency ranging from 4% to 9% when the mirror moves back and forth within $\pm 4 \mu\text{m}$ relative to its original position. In contrast, the flat mirror has only 0.5% - 0.6%. When the laser wavelength changes from $1.25 \mu\text{m}$ to $1.85 \mu\text{m}$, the curved mirror produces a coupling efficiency dropping from about 12% to 7% while the flat mirror has only 1% to 0.5%. It proves that the curved mirror has much high coupling efficiency.

(a)

(b)

Fig. 3.10 Comparison of the feedback coupling efficiencies of the curved mirror and the flat mirror. (a) Changing cavity length, and (b) changing wavelength.

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Fig. 3.11 Comparison of the coupling efficiencies at different angular misalignments. (a) Rotation angle α ; (b) rotation angle β ; and (c) rotation angle θ .

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When there are certain angular misalignments α , β and θ , which are defined as shown in Fig. 3.8, the curved mirror has different performance compared to the flat mirror. As shown in Fig. 3.11 (a), when there is pure α rotation (i.e. $\beta = 0$), the coupling efficiency of the curved mirror varies between 8% and 9% when α goes to as high as ± 90 degree. With the increase of β , the peak coupling efficiency is reduced, and the efficiency drops rapidly with larger α value. However, even at $\beta = 2$ degree, the efficiency is greater than 7% when -3 degree $< \alpha < +3$ degree. It shows that the curved mirror can sustain quite large angular misalignment in the α direction. In contrast, the flat mirror provides an efficiency as low as 0.7%, but it keeps nearly constant with the increase of α . In the curve of the coupling efficiency versus β as shown in Fig. 3.11 (b), the coupling efficiency falls from 9% to 5% when the rotation angle β increases from 0 to 6 degree. It can tolerate certain angular misalignment in β . However, when there is any other type of angular misalignment, for example, $\alpha = 5$ degree and $\theta = 0.5$ degree, the toleration for β reduces drastically. The coupling efficiency would fall from its peak 6% to nearly 0 within ± 2 degree of β rotation. In contrast, the flat mirror keeps smoothly at a low level of 0.6% with the change of rotation angle β . The influence of the rotation angle θ is shown in Fig. 3.11 (c). The curved mirror can provide an efficiency from 9% to 6% when θ increases from 0 to 0.5 degree. The efficiency goes to near 0 when θ is about ± 2 degree. In contrast, the flat mirror has nearly constant efficiency at 0.6%.

In summary, the curved mirror is about 10 times more efficient than the flat mirror in coupling the feedback laser light when the misalignment is not very serious. The flat mirror has much smoother relation with the misalignment, however, its efficiency is too low. For the curved mirror, it can tolerate quite high α and moderate β , but it is very sensitive to θ .

Fig. 3.12 Overview of the MEMS discretely tunable laser.

3.4.2 Description of MEMS discretely tunable laser

With guidance of the analysis, a MEMS tunable laser has been designed and fabricated as shown in Fig. 3.12. It is formed by integration of a FP diode laser with a MEMS mirror and a single mode optical fiber. The fiber is for butt-coupling. After the fabrication, the laser chip and the optical fiber are integrated and packaged. The laser has an overall dimension of $1.5 \text{ mm} \times 1 \text{ mm} \times 0.6 \text{ mm}$ (not including the full length of the fiber). In the assembly, the laser having a contact on the top surface is placed with face down into a trench in the silicon wafer (Fig. 3.12). The bottom of the trench is connected to the wafer surface, both are gold coated. A layer of indium foil about $45 \text{ }\mu\text{m}$ thick is sandwiched between the laser and the trench bottom. This foil serves two purposes. It bonds the laser to the trench, therefore provides better ohmic contact and heat transfer. It also lifts up the optical axis of laser emission for fiber output coupling. In the experiment, two probes are employed to apply the injection current. The positive touches the wafer surface (i.e. connected to the contact surface of the laser) while the negative contacts with the other laser surface.

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A curved mirror is used as the external reflector as shown in Fig. 3.13. As stated above, the curved shape is to improve the feedback coupling efficiency. The mirror has a curvature radius of $66\text{ }\mu\text{m}$ and is coated with a layer of gold ($0.2\text{ }\mu\text{m}$ thick) to improve its reflectivity. The position of the mirror is controlled by applying an electrostatic voltage to a comb drive actuator. The actuation relationship is shown in Fig. 3.14. The mirror displacement increases nearly linearly with higher driving voltage, and reaches $3\text{ }\mu\text{m}$ at 30 V (displacement $\approx 0.11 \times \text{voltage}$). This linearity is unexpected, which might be due to the non-uniformity of the comb finger in the vertical direction. Due to the notching effect, the overlapping part of fingers has small separation and thus experiences less undercut in comparison of the non-overlapping part. During actuation, the initial overlapping area between the moving and fixed comb is largest at the beginning and decreases gradually with the increase of displacement. The external cavity length is about $66\text{ }\mu\text{m}$ initially. When actuated, the mirror moves away from the laser chip, and therefore the external cavity length increases. The optical fiber is placed into a U-shaped groove etched on the silicon layer down to the bottom. The end of the fiber is very close to the emitting window of the laser diode, which ensures a simple butt-coupling with an efficiency enough for the characterization. With regard to the butt-coupling, the fiber has a beam diameter of $10.4\text{ }\mu\text{m}$, which is different from that of laser output ($1.75\text{ }\mu\text{m} \times 1.53\text{ }\mu\text{m}$ elliptical shape). Although the butt-coupling has quite low efficiency (about 20% maximum), it is simple and does not need coupling lenses. Besides, the coupled power (typically 0.2 mW) is strong enough for optical characterization. A lensed fiber would increase the coupling to $> 40\%$, but presents less tolerance for packaging misalignment. With respect to the optical coupling between the laser and the curved mirror, the optical axis is about $30\text{ }\mu\text{m}$ lower than the upper edge of the curved mirror. At the position of the curved mirror, the laser beam has dimensions of about $74\text{ }\mu\text{m} \times 84\text{ }\mu\text{m}$ (in diameters). The curved mirror is large enough ($> 120\text{ }\mu\text{m}$) to reflect the laser beam in the horizontal

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direction, but has to cut off the laser beam in the vertical direction, and thus introduces a loss of 3.4 dB. The surface roughness of the mirror due to etching and gold coating is about 40 nm (RMS value) in the top 40 μm of the mirror. In the bottom part, it gets worse. Such roughness would cause additional losses by scattering.

Fig. 3.13 Close-up of the curved mirror.

Fig. 3.14 Static actuation relationship of the comb drive actuator.

Fig. 3.15 Laser spectra at different output wavelengths.

Fig. 3.16 Measured and calculated wavelength tuning relationships.

3.4.3 Experiment data of wavelength tunability

The laser chip is made of multiple-quantum-well InGaAsP/InP materials, and has a dimension of $210\ \mu\text{m} \times 300\ \mu\text{m} \times 100\ \mu\text{m}$. The laser facets are not coated (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 moving the curved mirror [102]. Using the above data, $L_0 = 66\ \mu\text{m} < \mu_{e0}d = 735\ \mu\text{m}$ and $\xi = 0.037 \ll 1$. Therefore, the tunable laser satisfies the requirements for discrete wavelength tuning.

The wavelength tuning property of the MEMS tunable laser is shown in Fig. 3.15. The injection current is kept at 25.4 mA (about 28% over the threshold current 19.8 mA). At this level, the tunable laser can be operated in continuous wave (CW) without additional heat sink. Moreover, it is able to maintain single longitudinal mode (due to homogeneous broadening) when tuned to different wavelengths. The spectra of different output states are shown in Fig. 3.15 (for convenience, “wavelength” is used instead of “frequency” in describing the experimental data). The spectrum is measured by an Advantest Q8384 Optical Spectrum Analyzer. The output power is about 1 mW, and varies with the wavelength tuning (variation < 6 dB). The suppression ratio of the side mode is > 13 dB. Fig. 3.16 shows both the measurement and the simulation of the wavelength tuning with regard to the mirror displacement. In the experiment, the laser spectra is measured at different driving voltages, and then is converted from the voltage into the mirror displacement using Fig. 3.14. The wavelength is initially at 1570.04 nm and keeps constant at very small mirror displacement. Further movement of the curved

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mirror makes it suddenly drop to 1556.56 nm (the shortest wavelength). After that, the wavelength appears at the positions of the laser modes, and increases by a constant step of 1.69 nm. A tuning range of 13.5 nm is obtained by tuning the laser to 9 modes. To obtain such a tuning range, it requires the effective reflectance of the curved mirror to be $r_3 = 0.057$ according to Eqs. (3.4) and (3.21) (correspondingly, $C = 0.92$ and $\xi = 0.17$, assuming $\Gamma = 0.1$ and $\alpha = 6$). The value of 0.057 is in good agreement with the predicted coupling efficiency 5% – 9% given in Figs. 3.10 and 3.11. Simulation predicts the measured mode positions with marginal discrepancy as shown in Fig. 3.16. According to Eq. (3.37b), 11 modes should be observed. In the positions of the 2 disappeared modes, the laser output becomes multimode as shown in Fig. 3.16. This is due to the unflatness of the laser gain curve. The weak modulation of the gain threshold is not strong enough to keep only one mode oscillating while suppress the others, especially when the laser needs to transit from the maximum output wavelength to the minimum. Measurement shows that further displacement of the curved mirror results in periodical wavelength change, which matches the theoretical prediction. The mirror translation corresponding to one period is about half the initial wavelength. The sudden drop and stepwise increase of the wavelength are the evidence of discrete wavelength tuning. Continuous wavelength change is well suppressed to be less than 0.04 nm (estimated to be 0.043 nm by Eq. (3.18) or (3.30)). 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 to any of the other wavelengths. The MEMS comb drive actuator has been tested for lifetime. It has been operated for more than 24 hours under a square-wave driving signal at 200 Hz, which corresponds to about 17 million cycles, no obvious degrading is

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observed in the structure and the dynamic response of the comb drive. Such comb drive actuator has also been operated in an open environment for five days. Although the MEMS structure has become quite dirty, its performance does not change much. The life test proves that the MEMS lasers are robust and reliable.

Fig. 3.17 Mode competition in the instable regions during discrete tuning.

3.4.4 Mode stability

It is also observed that out of the multimode regions as stated above, the output at any wavelength is stably single mode when the mirror displaces within a certain region (named as stable region, about 0.05-0.07 μm). Two adjacent modes are excited once the mirror moves out of this region, and thus mode competition occurs. Different output spectra during mode competition are shown in Fig. 3.17 (a) – (e). Among them, one mode becomes weaker and weaker while the other keeps increasing. However, they are not in time sequence. Instead, the relative power varies randomly, and therefore the laser output becomes unstable. The length of the unstable region is about 0.01 μm . This can be explained using the areas of minimum threshold gain. Within the central part of any area, the threshold gain of the current mode is apparently lower than that of the adjacent. Thus the current mode is stable. However, at the edges of the areas, the gain difference between two adjacent modes becomes very small. Random effects such as thermal/current/gain fluctuations play their roles.

In addition to the benefits come with the MEMS technology (such as batch fabrication, small size and fast speed etc), the discretely tunable laser has some special advantages. 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 stable regions. Wide tuning range can be obtained by using short external cavity. The laser configuration is simple and without the need of integrated optical lenses or gratings. The movement of the external cavity is simply a translation in contrast to the complicate mechanical movement in the continuously tuning lasers [17, 47, 48]. The external reflector needs only to displace a distance less than one wavelength to sweep the whole

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tuning range. 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. Drawbacks include power fluctuation during tuning, low power in single mode operation, and difficulty to obtain very wide tuning range. To obtain the single mode, the injection current cannot be too high (typically less than two times the threshold current). Thus the output power cannot be high (typically ~ 1 mW). As the wavelength tuning is induced by the weak feedback, the unflatness of the gain curve would fundamentally limit the tuning range. Out of a certain wavelength range, the gain of the laser modes would drop to such a low level that the weak modulation of threshold gain cannot make them oscillate.

3.5 Summary

This chapter focuses on the theories, fabrication and experiment of the discretely tunable lasers. The theoretical works first extends the conventional weak feedback model to cover the medium feedback region, which is more relevant to the MEMS lasers that have short cavity and not weak feedback strength. It is shown that the extended feedback model predicts large tuning range than the weak feedback model. Further study then reveals the tuning mechanism of and the requirement for discrete wavelength tuning. Based on the analyses, a MEMS tunable laser is designed and then characterized. The MEMS laser uses a curved mirror as the reflector instead of the common flat mirror. It improves the coupling efficiency by about 10 times. The MEMS structure is fabricated on a SOI wafer by the deep reactive ion etching process. The measurement shows that the MEMS laser can be tuned by a constant step of 1.69 nm over 9 wavelength positions. The

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comparison of the experimental results and the theoretical data shows marginal discrepancy.

This tunable laser showcases one of the important advantages of the MEMS lasers, that is, the capability to construct very short cavity. The short cavity paves the way for large tuning range, in contrast to the negligibly small tuning range in the conventional long-cavity tunable lasers. It can be seen that the inclusion of MEMS to the tunable lasers not only downscale the bulky lasers for many engineering merits such as fast speed, small size and batch fabrication etc, it also opens certain space for utilizing new physical method.

CHAPTER 4

MEMS CONTINUOUSLY TUNABLE LASERS

The lasers developed in previous chapter provide discrete wavelength tuning, however, many applications require continuously tunable lasers, such as optical communications, spectroscopy and lab equipment. To address the demands, this chapter aims at the theoretical study and experiment demonstration of wavelength continuously tunable lasers using the MEMS technology. An integrated MEMS laser will be constructed by fabricating the tuning structure using the DRIE process on a SOI wafer, and then by integrating the MEMS structures with a gain chip and an optical fiber onto a single chip. Compared with the conventional tunable lasers, the MEMS continuously tunable lasers bear two clear differences: short cavity and pre-aligned component position. For these concerns, it is necessary to reexamine the previous wavelength tuning theory and to adapt it to the MEMS lasers. For example, it is well known that the gain medium refractive index is wavelength dependent and thus the real cavity length would deviate from the nominal cavity length during the wavelength tuning. This drift of cavity length may be negligible in comparison to the long cavity (> 10 cm) in the conventional lasers, but could be significant in the short cavity MEMS lasers (~ 1 mm). Although a fixed pivot would limit the wavelength range of continuous tuning in a MEMS laser, proper choice of the pivot position may be able to counterbalance such drift and therefore to optimize the continuous tuning range.

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This chapter will start with the theoretical studies of the wavelength continuously tunable lasers, covering the design of the laser configuration, optimization of the pivot position, and comparison with the conventional design (see Section 4.1). Then, the fabrication and integration of the MEMS laser will be discussed in Section 4.2. Finally, the experimental results of the MEMS laser will be presented and then compared with the theoretical prediction.

4.1 Theory of continuous wavelength tuning

4.1.1 Design of laser configuration

Continuously tunable external-cavity lasers are typically in either Littrow or Littman configuration as shown in Fig. 4.1. In the former, the laser light from the laser diode chip is first collimated by a lens, and is then projected to a blazed grating arranged in its Littrow angle [28, 38, 42-46]. The diffracted light is again focused by the lens and is finally coupled into the internal laser cavity. This is a single-pass diffraction, that is, the laser light in the external cavity is diffracted only once. The wavelength tuning is obtained by rotating the grating. Continuous tuning (or mode-hop-free tuning) can be achieved if the pivot of the grating rotation is well chosen in such a way that the wavelength selected by the grating always matches the mode of the overall laser cavity. In the latter, the collimated laser light is diffracted by a fixed blazed grating to a mirror, the reflection goes back to the grating again and is further diffracted to the laser internal cavity [17, 48, 49]. It is obviously double-pass diffraction. The continuous wavelength tuning is obtained by rotating and translating the mirror at the same time. In both types, the wavelength tuning is realized by rotating and translating the external grating/mirror

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Fig. 4.1 Typical configurations of the continuously tunable external-cavity lasers. (a) Littrow configuration; and (b) Littman configuration.

simultaneously, which remains a challenge for the conventional bulky mechanics to achieve fast tuning speed and high reliability. The development of the MEMS technology has opened up a new opportunity to downscale a bulky tunable laser to miniaturized device while improving the tuning speed and the mechanical reliability at lower fabrication cost [15, 18, 20]. However, in the reported MEMS lasers, the MEMS technology was only used to rotate/translate the mirror while the other components such as lenses had to be hybridly integrated [17, 28]. It increased the tuning speed but did not

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reduce the overall dimension. To make full use of MEMS advantages, it is preferable to use the MEMS technology to fabricate all the necessary components such as the microlenses and gratings. Although the laser chip may have to be an exception as the silicon-based laser has not been mature, it can be later integrated into the MEMS structure. In this way, a single chip integrated MEMS laser can be obtained with many advantages such as fast speed, large tuning range, compact size, self-alignment, high mechanical reliability, batch fabrication and low cost.

For a fully micromachined ECTL, Littrow configuration may be more preferable since the Littman configuration generally needs well collimated beam projected to the blazed grating at a very large diffraction angle. It would result in very low diffraction efficiency as the deep etched microlens has vertical sidewall and therefore can only focus/collimate the light in one direction. Consequently, the Littrow configuration is chosen for the single-chip MEMS continuous tunable laser in this chapter.

4.1.2 Analysis of optimal pivot position for maximum tuning range

The design of Littrow laser can be traced back to 1960s [38] soon after the emergence of the ECTL [37]. The mode-hopping-free tuning was further studied by choosing the proper position of a fixed pivot [42-46, 49]. McNicholl *et al.* developed a simple plane wavelength model to interpret the wavelength tuning in a mirror-grating Littrow oscillator, and concluded that the intersection of the mirror and the grating is the ideal pivot for mode-hopping-free tuning [42]. This result was later confirmed by another work [45]. Trutna *et al.* presented another model to predict the optimum pivot position [46]. In their work, the wavelength tuning in response to grating rotation is treated as the

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Doppler shift of the laser mode. One interesting point is that this theory predicted no wavelength change if the grating is moved perpendicular to the laser optical axis. It is counter-intuitive, but was observed experimentally [11, 46]. The theoretical model in this chapter should be able to explain this point.

Fig. 4.2 Superimposed output spectra of a MEMS tunable laser designed according to the conventional design theory. It has very limited tuning range of 5.9 nm. a.u. for arbitrary unit.

According to the analysis of Ref. [42], a Littrow external-cavity laser was once designed and fabricated using the DRIE process (the same to the MEMS laser to be discussed later). The microlens and the grating were also fabricated in the MEMS process. However, the maximum tuning range is very limited. As shown in Fig. 4.2, the wavelength can be tuned continuously only from 1503.2 nm to 1497.3 nm (tuning range 5.9 nm). Further tuning would result in mode hopping. After re-examination of the previous studies, we have found that in the Littrow lasers: (1) a mode-hop-free wavelength tuning requires a moving pivot; (2) more realistically, a fixed pivot has only

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limited tuning range; (3) the refractive index change of the gain medium, which has been neglected in the previous studies [42, 45, 46], significantly affects the obtainable tuning range; and (4) the chromatic aberration of the microlens also slightly affects the tuning range. Compared with the conventional ECTLs, the MEMS lasers have some different concerns. For example, the components in the MEMS structure are pre-aligned with high accuracy (limited by the resolution of photolithography), which cannot be readjusted. Therefore, in the laser design the position should be accurate. For this reason, the refractive index change may not be a serious problem in the conventional mechanical ECTLs since the fine adjustment in the laser calibration stage would be able to eliminate the position error. However, in the MEMS lasers it does not allow any further adjustment. Another concern is that MEMS integrated lasers have a short cavity length (typically ~ 1 mm) in comparison to the long cavity in the conventional lasers (typically ~ 1 cm to 1 m). For this reason, the cavity change owing to the refractive index change of the gain medium is negligible in the conventional lasers, but is significant in the MEMS lasers.

4.1.2.1 Ideal pivot position

The analytical diagram of the Littrow laser is shown in Fig. 4.3. It resembles the main parts of a Littrow laser, including a gain chip for optical amplification, a microlens for collimation and coupling, a blazed grating for wavelength selection, a pivot for grating rotation, and a dispersive element accounting for the wavelength dependence. In this configuration, the laser cavity resonance and the grating diffraction both place their requirements on the oscillating wavelengths as staged in Ref. [49] for Littman lasers. By adopting the same requirements to the Littrow lasers, they have

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Fig. 4.3 Analytical model of the Littrow external-cavity laser.

$$N_0 \lambda_m = 2[\mu_{e0} d_0 + L(\phi) + (\mu_{l0} - 1)t_0 + \delta(\phi)], \quad (4.1)$$

$$m_0 \lambda_g = 2p_0 \sin \theta, \quad (4.2)$$

where λ_m and λ_g represent the wavelengths determined by the laser cavity and the grating, respectively (subscript m for mode and g for grating); N_0 is the laser mode number, m_0 is the grating diffraction order, μ_{e0} is the refractive index of the gain chip, d_0 is the length of the gain chip, p_0 is the grating pitch, ϕ is the rotation angle of the pivot arm about the pivot point (clockwise direction is positive), $L(\phi)$ is the length of the external cavity in the free space (varies with ϕ), μ_{l0} is the refractive index of the lens (subscript l for lens), and t_0 is the effective thickness of the lens (different from the lens center thickness t_{l0} since it is a thick lens); θ stands for the diffraction angle that changes with ϕ by the relationship of $\theta = \phi - \beta_0$, where β_0 is the angle between the pivot arm and the grating surface. In most of the analyses and implementations of the ECTLs, the grating surface plane is chosen to pass the pivot point (i.e., $\theta \equiv \phi$) [28, 42, 103]. Here we

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intentionally make the difference between θ and ϕ in order to determine their different influence on the wavelength tuning range. Variables with the subscript 0 indicate that their values do not change with ϕ . The other variables are functions of ϕ , directly or indirectly.

The quantity $\delta(\phi)$ in Eq. (4.1) represents all the additional change of the cavity length due to the wavelength dependence of the gain chip, the lens and the other dispersive components (not including the grating). As the ECTL wavelength is dependent on ϕ , the additional cavity length change is eventually a function of ϕ , this is why it can be expressed in a form of $\delta(\phi)$. In the gain chip, the change of ϕ also influences the cavity length by altering the carrier density of the gain medium (to be discussed later). By introducing the term $\delta(\phi)$, the theoretical analysis become more general for the ECTLs, regardless of the types of the optics used for the laser beam coupling (e.g. lenses [17] or prisms [103]). From the definition it is easy to see $\delta(\phi_0) = 0$, where ϕ_0 is the initial value of ϕ . To the first order, it can be approximated by $\delta(\phi) = \eta_0 \Delta\phi$, where $\Delta\phi = \phi - \phi_0$ and

η_0 is the dispersion coefficient defined as $\eta_0 = \left. \frac{d\delta}{d\phi} \right|_{\phi=\phi_0}$.

In Fig. 4.3, the pivot point is chosen as the origin of the coordinate system (x, y) , and the end facet of the gain chip is located at (x_0, y_0) . From the geometry, it has

$$L(\phi) = y \tan(\phi) - x_0 - d_0. \quad (4.3)$$

To obtain an ideal mode-hop-free wavelength tuning, $\lambda_m = \lambda_g$ should be always satisfied for all ϕ . Therefore

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$$y = \cot(\phi) \left[\frac{N_0}{m_0} p_0 \sin(\theta) + x' \right]. \quad (4.4)$$

where $x' = x_0 - (\mu_{e0} - 1)d_0 - (\mu_{i0} - 1)t_0 - \delta(\phi)$. To better understand the pivot position affected by the grating angle as given by Eq. (4.4), we first study two simple and extreme cases before applying Eq. (4.4) to the more practical cases. In an extreme case of the normal incidence that $\theta = \phi \rightarrow 0$, y would be infinite if $x' \neq 0$, and keep constant at $N_0 p_0 / m_0$ if $x' = 0$. The normal incidence is not practical since it is difficult to maintain $x' = 0$ for all ϕ (the variation of $\delta(\phi)$ will be elaborated later). In addition, the 0th diffraction order is used to form the laser oscillation, but the 0th order is wavelength independent. Therefore, the grating is nothing other than a common mirror in the normal incidence. In another extreme case of the grazing incidence that $\theta = \phi \rightarrow 90$ deg, then it has $y \rightarrow 0$ and $x' \rightarrow -N_0 p_0 / m_0$, i.e., the ideal pivot can approach to a fixed position. However, the grazing incidence to the blazed grating has very low diffraction efficiency due to the large incident angle (nearly 90 deg).

To balance between the resolving power and the diffraction efficiency, in most applications the value of θ is chosen between 30 and 60 deg (e.g., 45 deg in [28, 30] and 51.81 deg in [103]). In such an angle range, it can be seen that y varies with ϕ (θ is also a function of ϕ), which implies that a moving pivot point is required for continuous tuning. An example of the relationship between y and ϕ is shown in Fig. 4.4. When the grating is rotated around its initial position from -1 deg to $+1$ deg (corresponding to about 53 nm wavelength tuning), y should be changed from 682.7 μm to 676.9 μm . A displacement of 5.8 μm should be applied to the pivot to maintain an ideal tracking of λ_m and λ_g . The parameters are shown in Table 4.1, which are for the MEMS laser to be discussed later.

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Fig. 4.4 Variation of the ideal pivot position with the grating rotation angle.

Table 4.1 Parameters of the MEMS Littrow tunable laser.

Pivot position y_0	680.3 μm
Pivot position x_0	50 μm
Grating period p_0	3.2 μm
Diffraction order m_0	3
Central wavelength λ_0	1.51 μm
Initial open angle ϕ_0	45 deg
Initial diffraction angle θ_0	45 deg
Length of gain chip d_0	250 μm
Initial refractive index of gain chip μ_{e0}	3.375
Initial length of external cavity $L(\phi_0)$	380.3 μm
Mode number N_0	1661
Center thickness of microlens t_{l0}	30 μm
Initial refractive index of microlens μ_{l0}	3.482
Focal length of microlens f_0	179 μm
Effective thickness of microlens t_0	12.1 μm
Dispersion coefficient η_0	-106.5 mm/rad
Grating rotation angle $\Delta\phi$	0 to 1.13 deg
Actuation voltage V	0 to 30.2 volts

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However, for mechanical convenience, a fixed pivot is preferable in the most of the tunable lasers [42, 45, 46, 49]. A fixed value y_0 should be chosen according to the criterion $y_0 = y(\phi_0)$ to make $\lambda_m(\phi_0) = \lambda_g(\phi_0)$ (ϕ_0 is the original pivot angle). When $\phi \neq \phi_0$, the wavelength difference $\Delta\lambda_{mg1}$ owing to the fixed pivot position is proportional to the first order of the rotation angle incremental $\Delta\phi$, i.e.,

$$\Delta\lambda_{mg1} = (\lambda_m - \lambda_g)_{y=y_0} \propto \Delta\phi \quad \text{when } \phi \neq \phi_0. \quad (4.5)$$

It should be noted that y is the ideal pivot position and is a function of ϕ , whereas y_0 is a fixed value that represents the optimized position for a fixed pivot. If the pivot takes its position as y according to Eq. (4.4), $\lambda_m - \lambda_g$ will be always 0. However, when the pivot is fixed to y_0 , $\lambda_m - \lambda_g$ is not equal to 0 except for $\phi = \phi_0$. To avoid confusion, the term “wavelength difference” hereinafter always bears a precondition that the pivot position is fixed. The physical meaning of $\Delta\lambda_{mg1}$ is the difference between the nominal wavelengths determined by the laser cavity and the grating. Since the actual output wavelength is affected by both the grating and the laser cavity, the laser can be continuously tuned only when λ_m is able to follow λ_g for all ϕ . Otherwise, λ_m may become the output wavelength when ϕ varies over a certain range, while λ_g rises to dominance over another range, or even worse, the laser output beats between λ_m and λ_g . To avoid such a mode hopping and competition associated with the choice of a fixed pivot, the value of $\Delta\phi$ must be limited, which in turn affects the tuning range. Therefore, a fixed pivot point has a limited tuning range.

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4.1.2.2 Optimization of pivot position for maximum tuning range

From Eqs. (4.1) and (4.2),

$$\begin{cases} \frac{d\lambda_m}{d\phi} = \frac{2}{N_0} \left[\frac{y}{\cos^2(\phi)} + \frac{d\delta}{d\phi} \right] \\ \frac{d\lambda_g}{d\phi} = \frac{2p_0}{m_0} \cos(\theta) \end{cases} \quad (4.6)$$

$$\begin{cases} \frac{d^2\lambda_m}{d\phi^2} = \frac{2}{N_0} \left[\frac{2y \sin(\phi)}{\cos^3(\phi)} + \frac{d^2\delta}{d\phi^2} \right] \\ \frac{d^2\lambda_g}{d\phi^2} = -\frac{2p_0}{m_0} \sin(\theta) \end{cases} \quad (4.7)$$

To maximize the continuous tuning range, we further let $\frac{d\lambda_m}{d\phi} = \frac{d\lambda_g}{d\phi}$ for all ϕ (or

equivalently, let $\frac{dy}{d\phi} = 0$). Under this condition, it yields

$$y = \frac{\cos^2(\phi) [x' + \eta_0 \tan(\theta)]}{\cos^2(\phi) \tan(\phi) - \tan(\theta)}. \quad (4.8)$$

Commonly in Eq. (4.7), $\frac{d^2\delta}{d\phi^2}$ is negligible since $\frac{d^2\delta}{d\phi^2} \ll \frac{2y \sin(\phi)}{\cos^3(\phi)}$. From Eq. (4.7),

$\frac{d^2\lambda_m}{d\phi^2} > 0$ but $\frac{d^2\lambda_g}{d\phi^2} < 0$. Therefore, there is no way to let $\frac{d^2\lambda_m}{d\phi^2} = \frac{d^2\lambda_g}{d\phi^2}$. It suggests that

if the pivot of the Littrow laser is fixed, the wavelengths given by the cavity mode and the grating can only be matched to the first order during the wavelength tuning. This is why the Littrow laser has limited continuous tuning range.

When the pivot position is chosen by $y_0 = y(\phi_0)$, the wavelength difference

$\Delta\lambda_{mg}$ can be expressed as

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$$\begin{aligned}\Delta\lambda_{mg} &= \lambda_m - \lambda_g \approx \frac{\Delta\phi^2}{2} \left(\frac{d^2\lambda_m}{d\phi^2} - \frac{d^2\lambda_g}{d\phi^2} \right) \bigg|_{\phi=\phi_0} = \Delta\phi^2 \left[\frac{2y_0 \sin(\phi_0)}{N_0 \cos^3(\phi_0)} + \frac{2p_0}{m_0} \sin(\theta_0) \right] \\ &= \lambda_0 \Delta\phi^2 [0.5 + \chi_0 \tan\phi_0 \cot(\theta_0)]\end{aligned}\quad (4.9)$$

where χ_0 is a coefficient standing for $\chi_0 = 1 + \eta_0/y_0$. From Eq. (4.9), $\Delta\lambda_{mg}$ is proportional to $\Delta\phi^2$ and therefore allows much larger rotation angle in comparison to that given by Eq. (4.5). It is noted that both $\Delta\lambda_{mg}$ and $\Delta\lambda_{mg1}$ stand for the wavelength differences when the pivot position is fixed to y_0 , and $\Delta\lambda_{mg}(\phi_0) = \Delta\lambda_{mg1}(\phi_0) = 0$. However, they differ in such a way that $\Delta\lambda_{mg}$ is the residual difference between λ_m and λ_g under the conditions that $\lambda_m(\phi_0) = \lambda_m(\phi_0)$ and $\frac{d\lambda_m}{d\phi} \bigg|_{\phi=\phi_0} = \frac{d\lambda_g}{d\phi} \bigg|_{\phi=\phi_0}$ whereas $\Delta\lambda_{mg1}$ is only under $\lambda_m(\phi_0) = \lambda_m(\phi_0)$.

Let us choose half of the laser mode spacing $\delta\lambda_{FSR}$ as the tolerance for the wavelength mismatch, that is, $\Delta\lambda_{mg} \leq \frac{1}{2} \delta\lambda_{FSR} = \frac{\lambda_0^2}{4\mu_{e0}d_0}$. From Eq. (4.2), it has $\delta\lambda = \lambda_0 \cot(\theta_0) \Delta\phi$, where $\delta\lambda$ is the wavelength change. Substitute them into Eq. (4.9), the maximum tuning range $\delta\lambda_{max}$ can be expressed as

$$\delta\lambda_{max} = \lambda_0 \cot(\theta_0) \sqrt{\frac{2\lambda_0}{\mu_{e0}d_0 [1 + 2\chi_0 \tan(\phi_0) \cot(\theta_0)]}}. \quad (4.10)$$

Here $\delta\lambda_{max}$ includes the tuning in both the positive and negative direction rotations. It is worth noting that larger tuning range can be obtained by longer wavelength and shorter cavity. The reason is that the laser mode spacing would increase for the longer wavelength and shorter cavity. As a result, a larger tolerance is allowed for $\Delta\lambda_{mg}$. It also

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can be seen that the grating angle and the arm open angle affect the tuning range differently. The former is more significant.

In the laser design, once the parameters m_0 , p_0 , μ_{e0} , d_0 , ϕ_0 , $\theta(\phi_0)$, and $x'(\phi_0)$ are chosen, there are only 3 variables to be determined: x_0 , y_0 , and N_0 . As x_0 and y_0 are related by geometric relations and Eq. (4.3) links y_0 to N_0 , only one variable y_0 (or N_0) is left for choice. Physically, the design is just like giving the positions of the grating and the laser chip and giving the direction of the rotation arm, now it is to choose a point on the arm as the pivot. Larger y_0 (and N_0) means using a longer arm length for the grating rotation, and vice versa. However, there is one optimized value of y_0 that makes $\left. \frac{dy}{d\phi} \right|_{\phi=\phi_0} = 0$, which

can be proven to be identical to the condition $\left. \frac{d\lambda_m}{d\phi} \right|_{\phi=\phi_0} = \left. \frac{d\lambda_g}{d\phi} \right|_{\phi=\phi_0}$. Consequently, Eq.

(4.10) represents the optimized pivot position.

When the grating is rotated perpendicularly to the laser axis, it has $\phi_0 = 90$ deg. From Eq. (4.10), it yields $\delta\lambda_{\max} = 0$, that is, no wavelength change occurs. This agrees with the analysis of Trutna *et al.* [46] as discussed in subsection 4.1.2.

4.1.2.3 Variation of gain medium refractive index with grating rotation

This part is to calculate the value of $\delta(\phi)$. In many studies on the proper pivot position, the influence of the dispersion properties of the gain medium and the optical lens remains untouched [28, 30, 42, 45, 46, 49]. In a widely tunable external-cavity laser, the effective refractive index of the gain medium may vary significantly with the tuning of wavelength, which eventually shifts the effective length of the light path from its

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nominal value. The refractive index change mainly arises from two factors: (a) the variation of the effective reflectivity of the external reflector, and (b) the wavelength dependence of the refractive index of the gain medium $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$, as given by

$$\Delta\mu_e = \frac{\partial\mu_e}{\partial\rho}(\rho - \rho_0) + \frac{\partial\mu_e}{\partial\lambda}(\lambda - \lambda_0) = \Delta\mu_{e1} + \Delta\mu_{e2} \quad (4.11)$$

where n is the refractive index of the gain medium, and ρ and ρ_0 are the carrier density and the threshold carrier density, respectively. Here $\Delta\mu_{e1}$ and $\Delta\mu_{e2}$ stand for the index changes due to the carrier density and the dispersion property, respectively.

4.1.2.4 Influence of effective reflectivity of the external reflector

As explained above, commonly the microfabricated lens in a MEMS Littrow laser can collimate the light only in the plane parallel to the wafer surface. In the vertical plane, there is no collimation. The rotation of grating would change the distance between the grating and the gain chip, and thus varies the effective reflectivity of the grating, which in turn alters the photon density in the gain chip, and finally adjusts the refractive index of the gain medium.

The analysis here is based on the assumption that the scalar Gaussian beam optics is valid in dealing with the beam collimation by the lens, the diffraction by the blazed grating and the coupling of the diffracted beam into the internal cavity of the gain chip. Assuming the lens provides perfect coupling in the y direction as shown in Fig. 4.3, then the effective reflectivity of the grating can be estimated based on the coupling of Gaussian beams [99]

$$r_3 = T_0 \sqrt{\frac{2w_{z0}w_{z1}}{w_{z0}^2 + w_{z1}^2}} \quad (4.12)$$

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where T_0 is the transmittance of the lens, w_{z0} is the light beam size emitted from the gain chip in the z direction, and w_{z1} is that of the light beam returned from the grating. Both w_{z0} and w_{z1} represent the waist radii at the plane of the AR-coated facet, and have the relationship that

$$w_{z1} = w_{z0} \sqrt{1 + \frac{\lambda_0^2 z(\phi)^2}{\pi^2 w_{z0}^4}} \quad (4.13)$$

where $z(\phi)$ is the effective light path between the AR-coated facet and the grating as given by

$$z(\phi) = 2[y_0 \tan(\phi) - x_0 - d_0 + (n_{i0} - 1)t_0] \quad (4.14)$$

Based on Eqs. (4.12) – (4.14), one can obtain analytically

$$\Delta r_3 = \zeta \Delta \phi \quad (4.15)$$

where $\zeta = \frac{dr_3}{dw_{z1}} \cdot \frac{dw_{z1}}{dz} \cdot \frac{dz}{d\phi}$ represents the coefficient. For notation simplicity, ζ is not expressed in detail.

In a stationary laser oscillation, the amplitude condition should be met [8], yielding

$$r_1 r_3 \exp[(g_m - \gamma)d_0] = 1 \quad (4.16)$$

where r_1 and r_3 are the reflectivities of the uncoated gain chip facet and the grating, respectively (as shown in Fig. 4.3). The variables g_m and γ are the modal gain and loss of the gain medium. Therefore,

$$\Delta g_m = -\frac{1}{d_0 r_3} \Delta r_3 \quad (4.17)$$

The carrier density variation induces the change of gain Δg as given by [8]

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$$\frac{\partial \mu_e}{\partial \rho} (\rho - \rho_0) = \alpha_0 \frac{\partial \mu_e''}{\partial \rho} (\rho - \rho_0) = -\frac{\partial g}{\partial \rho} \frac{\alpha_0 \lambda}{4\pi} (\rho - \rho_0) = -\frac{\alpha_0 \lambda}{4\pi} \Delta g = -\frac{\alpha_0 \lambda}{4\pi \Gamma_0} \Delta g_m \quad (4.18)$$

where α_0 is the linewidth enhancement factor, g is the material gain, and Γ_0 is the optical confinement factor. It should be noted that in Eq. (4.16) the gain Δg_m is a modal gain while in Eq. (4.18) the gain Δg is a material gain. This difference significantly alters the value since Γ_0 is generally quite small (e.g. 0.1) [97], but it has long been neglected in the previous studies that dealt with the similar cases [8, 19, 95].

Substituting Eq. (4.15) and (4.17) into (4.18), and taking the values at $\phi \rightarrow \phi_0$, it yields

$$\Delta \mu_{e1} = \frac{\alpha_0 \zeta_0 \lambda_0}{4\pi d_0 r_{30} \Gamma_0} \Delta \phi \quad (4.19)$$

where $\zeta_0 = \zeta|_{\phi=\phi_0}$ represents the initial grating reflectivity coefficient, $r_{30} = r_3|_{\phi=\phi_0}$ is the initial reflectivity of the grating. In the experiment, the parameters are as listed in Table 4.1. The calculated value of $\zeta_0 = -0.32$ and $r_{30} = 0.10$. When the grating is rotated by 1.13 deg, the effective grating reflectivity is reduced to 0.09. Taking typical parameters of the gain medium that $\alpha_0 = 3$ and $\Gamma_0 = 0.05$, then

$$\Delta \mu_{e1} = -0.092 \Delta \phi. \quad (4.20)$$

4.1.2.5 Wavelength dependence of gain medium refractive index

The gain medium is also a dispersive material whose refractive index varies slightly with the wavelength. When $x = 0.28$ and $y = 0.6$ (the parameter of the gain chip used in the experiment), the refractive index of $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ is given as [104, 105]

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$$\mu_e = \left[10.452 + \frac{2.009}{\lambda^2} + \frac{0.245}{\lambda^4} \cdot \ln \left(\frac{\lambda^2 - 0.114}{\lambda^2 - 1.664} \right) \right]^{\frac{1}{2}} \quad (4.21)$$

where λ is the wavelength. At $\lambda = \lambda_0 = 1.51 \mu\text{m}$, $\mu_{e0} = 3.375$. After Taylor expansion at $\lambda_0 = 1.51 \mu\text{m}$, it yields

$$\Delta\mu_{e2} \approx -0.334\Delta\lambda/\lambda_0. \quad (4.22)$$

From Eq. (4.2), $\Delta\lambda/\lambda = \Delta\phi \cot(\theta_0)$, thus

$$\Delta\mu_{e2} = -0.334\Delta\phi. \quad (4.23)$$

In total,

$$\Delta\mu_e = -0.426\Delta\phi \quad (4.24)$$

Eventually, the additional cavity variation can be expressed as

$$\delta(\phi) = d_0 \Delta\mu_e = -106.5\Delta\phi \text{ (in } \mu\text{m)} \quad (4.25)$$

therefore, $\eta_0 = -106.5$.

Fig. 4.5 Change of the refractive index of $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ with the wavelength.

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The relationship between the refractive index and the wavelength is shown in Fig. 4.5. The linear approximation of Eq. (4.22) matches the theoretical curve with marginal discrepancy over the wavelength range of 1.48 μm to 1.54 μm . With the increase of the wavelength, the refractive index decreases gradually. A wavelength change of 30.3 nm would result in a refractive index change of -0.008. Using the same laser parameters in Table 4.1, the effective light path length of the gain chip will be changed by -2.0 μm . According to Eq. (4.1), the cavity mode would be shifted from its expected position by a value of -2.46 nm, which is about two times of the cavity mode spacing $\delta\lambda_{\text{FSR}} = 1.36$ nm. Here the expected position refers to the wavelength value when the refractive index is considered to be independent of the wavelength (i.e., taking $\eta_0 = 0$ in Eq. (4.8)). In a Littrow laser, such a wavelength shift would cause unwanted mode hopping. Therefore, the refractive index change during the wavelength tuning should be taken into account in the design of Littrow lasers.

Fig. 4.6 Comparison of the wavelength tuning ranges predicted by the conventional design and the improved design.

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Fig. 4.7 Overview of the MEMS Littrow laser.

4.1.2.6 Comparison of the optimized design and the conventional design

To further illustrate the influence of the refractive index change to the Littrow laser design, the variation of $\delta(\phi) + \Delta\lambda_{\text{mg}}$ and $\Delta\lambda_{\text{mg}}$ with the wavelength tuning are compared in Fig. 4.6. If the pivot position is designed according to Eq. (4.8) (in which the gain chip refractive index is considered dependent on the wavelength and the grating angle), the mismatch of λ_{m} and λ_{g} is only $\Delta\lambda_{\text{mg}}$ since $\delta(\phi)$ is counterbalanced (named as Case 1). In contrast, if the refractive index is regarded as a fixed value, the mismatch is $\delta(\phi) + \Delta\lambda_{\text{mg}}$ (named as Case 2) since $\delta(\phi)$ cannot be eliminated. It can be seen from Fig. 4.6 that within the limit of half-mode spacing, the continuous wavelength tuning is between ab for Case 1, and between cd for Case 2 (a , b , c and d are points on the horizontal axis, $a = -27.5$ nm, $b = 27.5$ nm, $c = -8.5$ nm, and $d = 11.1$ nm). It shows that by taking into account the refractive index change, the continuous tuning range can be improved from $\delta\lambda_{\text{max}2} = 19.6$ nm to $\delta\lambda_{\text{max}1} = 55.0$ nm (see Fig. 4.6). It is noted that the

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value $c = -8.5 \text{ nm}$ is close to the tuning range value of 5.9 nm in our first design; this may explain why the tuning range cannot be further improved in that MEMS laser. The difference of the tuning ranges showcases the advantage of the new theoretical analyses.

(a)

(b)

Fig. 4.8 SEM micrographs of the close-ups of the MEMS rotary grating. (a) Side view of the grating surface; and (b) top view of the grating tooth profile.

4.2 Fabrication and integration

Based on the above analysis, a tunable laser has been designed and fabricated as shown in Fig. 4.7. The parameters of the MEMS laser are listed in Table 4.1. The MEMS components, including a blazed grating, a rotary comb drive for actuating the grating, a microlens and some trenches for containing the gain chip and coupling fiber, are fabricated simultaneously on a SOI wafer using the DRIE process. The SOI wafer has a structural silicon layer of 75 μm thick, an insulator silicon oxide layer of 2 μm thick and a substrate. After being patterned and etched, the MEMS structure is dry-released by the notching effect. The process flow is the same with that in Section 3.3. In the final process step, the MEMS structure is selectively coated with a gold layer of 0.5 μm thick. The gold coating improves the reflectivity of the grating and provides the electrical connections. However, the microlens should not be coated, this is to allow the laser light to pass through. This selective coating is implemented by a shadow mask, which protects the microlens from coating while exposing the other areas. The microlens has a focus length $f_0 = 179 \mu\text{m}$, which expands the laser beam in the horizontal direction from a beam diameter of about 3 μm to 211 μm . After this expansion, the laser beam covers about 96 grating teeth. The grating is etched on the sidewall of a rotary comb drive structure as shown in Fig. 4.8 (a) and (b). The tooth profile is uniform and the grating surface is smooth and clean, which guarantees good diffraction efficiency of the grating.

Once fabricated, the MEMS structure is then assembled with the gain chip and the optical fiber. The MEMS Littrow laser has dimensions of 2.0 mm $\times$ 1.5 mm $\times$ 0.6 mm (not including the full length of the optical fiber). The gain chip having a contact on the

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top surface is placed face down into a trench in the silicon wafer (Fig. 4.7). A layer of indium foil about 45 μm thick is sandwiched between the gain chip and the trench bottom. The bonding is not self-aligned, the chip and the fiber are manually aligned to the markers that are made in the fabrication. This foil serves two purposes. It bonds the gain chip to the trench, therefore providing better ohmic contact and heat transfer. It also raises the optical axis of laser emission to align to the MEMS grating and the optical fiber. Since in the MEMS fabrication the upper part of the etched grating (between 20 μm to 75 μm high) has good profile fidelity and surface quality, the optical axis is chosen at 45 μm height. The fiber is etched by the 49% hydrofluoric acid to reduce the radius to 45 μm (etching rate 3.5 $\mu\text{m/s}$). The coupling loss is typically 2 – 4 dB for the cleaved fibers and 0.5 – 0.8 dB for the lensed/tapered fibers. In the experiment, two probes are employed to apply the injection current. The negative contacts with the exposed surface of gain chip, while the positive touches a square sink on the wafer. The bottom of the square sink is connected to the gain chip trench through gold wires.

The experiment setups include mainly a laser driver and some stages. For bare MEMS laser samples without the fixation of laser chips and the optical fibers, in the experiment one sample is placed on a 5-axis stage for positioning, and an optical fiber is aligned by another 5-axis stage for coupling of the output light. Two probes positioned by 3-axis stages are employed to apply injection current to the laser chip, and one more probe is for fine alignment of the laser chip to the MEMS lens/grating. A microscope is used to visualize the operation of the MEMS laser sample. Other equipment include an oscilloscope for monitoring the junction voltage of the laser chip, an optical power meter and an optical spectrum analyzer. All the equipment are fixed to an isolation table. If the

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MEMS laser samples have laser chips and fibers packaged and wires bonded, the adjustment stages are not necessary.

Fig. 4.9 Close-up of the double clamped beam for virtual pivot.

Fig. 4.10 Rotation angle of the grating versus the driving voltage.

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When a potential is applied to the comb drive, the comb fingers produce electrostatic force between the moving fingers and the fixed ones, and thus generates an electrostatic torque to rotate the grating. The rotary comb drive follows the standard structure of the in-plane rotary actuators [106] except for an improved design of the pivot. Through a stiff frame structure that supports the movable comb, the comb drive is connected to the middle point of a clamped beam, whose two ends are anchored to the substrate. Under the pure torque from the frame, the center of the clamped beam generates a pure rotation, providing an ideal virtual pivot as shown in Fig. 4.9. The beam has dimensions of $218\ \mu\text{m} \times 75\ \mu\text{m} \times 2\ \mu\text{m}$ and a stiffness of $5.6 \times 10^{-7}\ \text{N}\cdot\text{m}$ (the Young's modulus of the silicon is taken as 190 GPa). The rotary comb drive has 40 pairs of fingers spaced by a gap of $2\ \mu\text{m}$, producing a torque of $1.2 \times 10^{-11} V^2\ \text{N}\cdot\text{m}$ (V is the actuation voltage in volts). The comb drive provides a unidirectional pure rotation as measured to be $\Delta\phi = 1.24 \times 10^{-3} V^2$ (designed $\Delta\phi = 1.19 \times 10^{-3} V^2$), where $\Delta\phi$ is in units of degrees. From Fig. 4.10, the grating rotations in the “forward” stage (i.e. the angle increases from small to large) and in the “backward” stage (i.e. the angle decreases from large to small) have small hysteresis, and both of them matches the designed value with marginal discrepancy.

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(a)

(b)

Fig. 4.11 Characteristics of the grating and the microlens. (a) The relative diffraction intensity and the far-field patterns of the grating; (b) the filtering spectra of the microlens-grating set in comparison to that of a normal fiber.

4.3 Experimental results and discussions

4.3.1 Characteristics of blazed grating and microlens

As the grating is the key component, its performance is first studied. Then, the microlens-grating set formed by the combination of the grating and the micro-lens is characterized. The grating has a period of $3.2\ \mu\text{m}$ and is designed to work at a blazed angle of 45 degrees (corresponding to the 3rd diffraction order) as shown in Fig. 4.8. The grating sample is prepared by isolating it and taking it out from a spare MEMS die. The far-field diffraction pattern is measured using a collimated laser beam illuminated at the designed angle. The diffracted power and pattern vary with the change of the input wavelength as shown in Fig. 4.11 (a). The diffraction efficiency reaches its maximum at about 1511 nm. The full-width-half-maximum (FWHM) bandwidth is about 5 nm.

The performance of the microlens-grating set is measured using another spare die as shown in Fig. 4.11 (b). An anti-reflection coated lensed single mode fiber (SMF, from Nanonics, Israel) is placed to the designed position of the gain chip to simulate the optical input/output of a laser chip. The lensed fiber has a nominal focus diameter of $3.5\ \mu\text{m}$, which is close to the emitting spot size of the laser chip. In comparison to the normal single mode optical fiber whose diameter is $10.4\ \mu\text{m}$, the lensed fiber can simulate the laser chip better in providing a Gaussian light beam to the microlens/grating and in coupling the diffracted light back into the cavity/fiber core. In the experiment, a tunable laser provides the light source while a synchronized optical spectrum analyzer measures the reflection. When no voltage is applied to the comb drive, the spectrum is centered at 1511.2 nm with a FWHM bandwidth of 3.8 nm. The peak is at least 15 dB higher than

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the side lobes. As the voltage increases to 3.5 V, the center shifts to a longer wavelength by about 0.5 nm. As a reference, the reflection of a normally-cleaved SMF under the same condition is also shown in Fig. 4.11 (b). The peak reflectivity of the microlens-grating set is 5.3 dB higher than that of the SMF, corresponding to a value of 13.6% if the SMF reflectivity is taken as 4%. It shows the microlens-grating set functions well. The 13.6% reflectivity is comparable to the estimated value of $r_{30} = 0.1$ in Section 4.2.3. The discrepancy of the bandwidth 3.8 nm from the value of 5 nm may be attributed to the fact that the spot size of the lensed fiber is different from the designed value for the gain chip. The light is not well collimated, and thus the diffracted intensity decays rapidly when the light wavelength leaves the peak position, yielding a narrower bandwidth.

Fig. 4.12 Gain curve of the laser chip.

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(a)

(b)

Fig. 4.13 Far-field beam profile of the laser output. (a) Intensity; (b) 3D view.

4.3.2 Characteristics of laser gain chip

As the gain chip determines the laser tuning performance, it is also characterized in details. The gain chip is a stripe-guide multiple-quantum-well InGaAsP/InP device

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having dimensions of $250\text{ }\mu\text{m} \times 300\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ (length $\times$ width $\times$ height). The gain curve of the laser gain chip is shown in Fig. 4.12, which was obtained by measuring the amplified spontaneous emission (ASE) spectrum. It has a broad wavelength range; the 3 dB bandwidth is $\sim 100\text{ nm}$ (1490 – 1590 nm). It is observed that there is a certain oscillation in the curve. It is likely due to the interference of the parasitic reflections. The beam quality is measured by a beam profiler after driving the MEMS laser over the threshold. The far-field beam profile is shown in Fig. 4.13. It has a nearly circular cross section with far-field divergence angles of 30.4 deg and 31.3 deg in the planes parallel

Fig. 4.14 The ASE spectra of the gain chip at (a) $I = 10\text{ mA}$, $m = 0.17$; (b) $I = 15\text{ mA}$, $m = 0.27$; and (c) $I = 25\text{ mA}$, $m = 0.63$. For the original laser chip before AR coating, the threshold current is 15 mA.

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and vertical to the contact surface, respectively (thus, the spot size is $1.63 \mu\text{m} \times 1.58 \mu\text{m}$). The beam has single transverse mode, and the intensity distribution is nearly in a Gaussian form.

The gain chip facet that faces the microlens is anti-reflection (AR) coated. The reflectivity is measured by monitoring the modulation index of the ASE spectra as shown in Fig. 4.14. The modulation index m is defined as $m = (P_{\max} - P_{\min}) / (P_{\max} + P_{\min})$, where $P_{\max}$ and $P_{\min}$ are taken at the peak of the spectrum [107]. The modulation depth varies at different injection current levels. At a low level of $I = 10 \text{ mA}$, m is only 0.17. At $I = I_t = 15 \text{ mA}$, $m = 0.27$. As I increases to 25 mA , m reaches 0.63. The wavelength spacing of the maxima and minima of the modulation index corresponds to a roundtrip phase shift. The roundtrip amplification factor a of the gain chip has a relationship with m as given by $m = 2|a| / (1 + |a|^2)$. The amplification factor a is also dependent on the injection current I as expressed by

$$\ln(|a|) = (\gamma L) \frac{I}{I_t} - \left(\gamma L - \frac{\sqrt{R_1 R_2}}{R_l} \right) \quad (4.26)$$

where γ is the gain coefficient, L is the internal cavity length, and I_t and R_l are the threshold current and the facet intensity reflectivity of the original laser chip (before AR coating). R_1 and R_2 are the intensity reflectivity of the AR-coated facet and the other facet of the gain chip. Eq. (4.26) suggests that $\ln|a|$ changes linear with the normalized injection current I/I_t . In the curve of $\ln(|a|)$ versus I/I_t , the slope gives the gain coefficient γ while the interception at $I/I_t = 0$ gives R_l .

The ASE spectra measured at various currents are used to obtain the curve of the roundtrip amplification versus the normalized current as indicated in Fig. 4.15. At the

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high current level, the curve tends to saturate. However, at the low current level, the amplification $\ln(|a|)$ increases nearly linear with the injection current I/I_t as suggested by Eq. (4.26). The trend line is $\ln(|a|) = 1.45 I/I_t - 3.44$. With a Fresnel reflectivity $R_l = 0.31$, $R_2 \approx 0.9$ and $L = 250 \mu\text{m}$, it gives $\gamma = 58 \text{ cm}^{-1}$ and the facet reflectivity $R_1 = 0.19\%$.

Fig. 4.15 Roundtrip amplification factor versus the normalized injection current.

Fig. 4.16 Superimposed spectra of the MEMS laser at different wavelengths.

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Fig. 4.17 Variation of the output wavelength and power with the grating rotation angle.

4.3.3 Experimental results

The various output spectra at different actuation voltages is shown in Fig. 4.16 at an injection current of 80 mA. The output maintains a single longitudinal mode over a wide range. The side-mode suppression ratio (SMSR) decreases with the increase of the wavelength. Further wavelength tuning will result in a multi-mode output arising from the other diffraction orders. The variations of the output wavelength and power are shown in Fig. 4.17. The wavelength shifts linearly from 1510.9 nm to 1541.2 nm when the actuation voltage rises from 0 to 30.2 volts to rotate the grating by 1.13 deg. A tuning range of 30.3 nm is obtained. The tuning accuracy is about 0.03 nm/V^2 . High tuning resolution can be obtained by fine adjustment of the actuation voltage. The wavelength repeatability and stability are measured to be about $\pm 0.06 \text{ nm}$. The linewidth is below 0.01 nm and does not change noticeably. The power has initially a maximum of 0.4 dBm and drops to -11.8 dBm at the end. Its values fluctuate noticeably at the first half of the

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wavelength tuning range, which suggests that there is strong energy redistribution among the desired 3rd order and the other diffraction orders during the grating rotation. In the second half, the power drops monotonically due to the decrease of the diffraction efficiency with higher diffraction angle.

Fig. 4.18 Light-current curve of the laser under different actuation voltages.

It is noted that the obtained tuning range of 30.3 nm is somewhat larger than $b = 27.5$ nm (since the grating of the MEMS laser is rotated to only one direction, the measured tuning range 30.3 nm should be compared with the predicted range $b = 27.5$ nm rather than the whole range 55 nm). It can be attributed to the neglected dispersion of the lens. At 1541.2 nm, according to Eq. (4.9), $\Delta\lambda_{\text{mg}} = +0.80$ nm, which is larger than half of the mode spacing 1.36 nm of the gain chip. However, the effective refractive index of the silicon lens decreases slightly with the increase of the wavelength [108]. It can be approximated by $n(\lambda) = -0.0760\lambda + 3.5939$ within the wavelength range of 1.4 μm to 1.8 μm . According to this relation, a wavelength change from 1510.9 nm to 1541.2 nm

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would reduce the refractive index by 2.28×10^{-3} , and in turn shortens the light path by $0.069 \mu\text{m}$ when the wavelength changes from 1510.9 nm to 1541.2 nm . Equivalently, the wavelength difference is compensated by -0.08 nm to be $\Delta\lambda_{\text{mg}} = +0.72 \text{ nm}$, which is quite close to half of the mode spacing. The remained discrepancy may be due to the omitted higher order term of $\delta(\phi)$. The 30.3 nm tuning range of this MEMS Littrow laser is smaller than the value of 40 nm obtained in Ref. [17], which was in a Littman configuration. As the Littman laser has longer optical path, it tends to be less sensitive to the dispersion issue. However, since the laser in Ref. [17] is not a miniaturized laser, it is not appropriate to directly compare the tuning range. Besides, as stated above, the Littman configuration is not suitable for the deep etched MEMS lasers due to low grating diffraction efficiency. If ignoring the technical issues originated from the deep etching, under the same condition, the MEMS Littman lasers should have larger tuning range than the Littrow ones but to have smaller output power.

Fig. 4.19 Variation of the threshold current and the differential quantum efficiency with the grating actuation voltage.

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The light-current (LI) curves of the laser under different actuation voltages are shown in Fig. 4.18. For comparison, the original LI curve of the gain chip in the free space is also illustrated, which is very close to the axis of the injection current. That is to say, the laser output is very small when there is no grating to form the resonant cavity. It also indicates that the AR coating of the gain chip facet is quite successful. Otherwise, the residual reflectivity would let it emit laser light when the injection current becomes quite high. With the presence of the grating, which acts as the reflector, obvious laser oscillation can be observed when the injection current goes beyond certain threshold. However, the LI curves shift to the right-bottom corner with the increase of the voltage. The threshold current rises from 21.9 mA to 24.7 mA while the differential quantum efficiency (slope of the LI curve) drops from 0.019 mW/mA to 0.009 mW/mA as shown in Fig. 4.19. This is due to the reduction of the effective diffraction efficiency when the grating rotation angle increases. A clear inflection can be observed in the external efficiency curve at about 3 volts, which coincides with the light power change in Fig. 10 (b). Theoretically, the efficiency would decline monotonically. Since the laser structure is the same during the LI test, the inflection is unlikely related to the gain chip. It must be from the grating side. The inflection could be due to the energy redistribution among the other diffraction orders, or due to the slight misalignment of the gain chip to the grating.

4.4 Summary

In conclusion, theories and experiment of the continuously tunable lasers have been studied in this chapter. To maximize the wavelength range of continuous tuning, a new theory for choosing the ideal pivot is developed. The physical improvement of this

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theory in comparison to the previous analyses is that it takes into account the wavelength dependent change of the refractive index, whose influence is negligible in the conventional long-cavity-length lasers but is significant in the MEMS lasers. According to the new theory, a MEMS laser is fabricated by the DRIE process on a SOI wafer. It has dimensions as small as $2.0 \text{ mm} \times 1.5 \text{ mm} \times 0.6 \text{ mm}$, and can be tuned continuously over 30.3 nm at a resolution of 0.03 nm/V^2 . As a comparison, another MEMS laser designed according to the conventional theory has only a tuning range of 5.9 nm. It proves that the new model can produce large continuous tuning range compared with the conventional models.

Similar to the MEMS discretely tunable laser, this tunable laser shows again that the MEMS technology is able to realize very short cavity, large tuning range and superior performance. It also shows that in the MEMS field, the tunable lasers have some difference in physical aspects.

CHAPTER 5

MEMS INJECTION-LOCKED LASERS

The objective of this chapter is to present a theoretical study of the injection locking based on a new concept of injection seeding, and to prototype a MEMS injection-locked laser (ILL) device, which employs a MEMS tunable laser as the master laser to lock the state of a FP multi-mode slave laser. The works in the previous two chapters provide a technological base for the ILL device in the MEMS fabrication/integration and wavelength tuning technology. From the engineering point of view, the two types of tunable lasers developed in previous chapters are standalone devices, each uses only one laser chip. In contrast, the ILL device has a sense of subsystem since it consists of two lasers. From the physical point of view, the ILL device is more complicated as it has to taken into account many laser modes and their interaction, which are not necessary in the previous lasers.

The theoretical study is inspired by the emerging applications of injection-locked-based all optical switching and wavelength conversion, which employ multiple injections to lock multi-longitudinal mode lasers. The experiments of switching and conversion have been successfully demonstrated [34, 35] but the theoretical analysis is not available since the previous small signal models (SSMs) in literature [58-73] are mostly for simple conditions such as weak injection power, single injection and single mode slave. Therefore, the new model (named as the generalized model, i.e., GM) in this chapter will

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be generalized to extend its validation to broader conditions, including single and multiple injections, weak and strong injection power, and single mode and multi-mode slave. The validation of the GM should be verified in two aspects: it should agree with the previous SSMs in case of weak single injection; and it should match the experiment.

Based on these considerations, this chapter is organized as follows. Section 5.1 will focus on theoretical studies by deriving the GM and then applying it to the cases of single injection and multiple injections. The GM will be compared with the SSM in both weak injection and strong injection conditions. Section 5.2 will brief the fabrication and integration of the MEMS ILL. Finally, Section 5.3 will elaborate the experiment issues, such as the locking characteristics under single and multiple injections, and the comparison between the experiment data and the GM.

5.1 Theoretical study of injection locking

The theoretical analyses of the injection locking have been extensively developed in literature [58-73, 109]. Especially the small signal analysis presented by Lang in 1982 [61] and later extended by Li using simple mathematics [109]. Their model has been extensively used and proven in many theoretical and experimental studies [63-66, 69-71]. In this chapter, this SSM will be used as the standard to verify our proposed model under the condition of weak injection power. However, most of the previous analyses are simplified based on the assumptions that: (i) *quasi-locking condition*, that is, the slave laser is tuned within a small wavelength range near to the locking state [59-61, 64, 68-73, 109]; (ii) *single mode slave condition*, i.e., the slave laser is single longitudinal mode [60, 64, 68-73]; (iii) *single injection condition*, i.e., there is only one external

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injection, which is injected at one wavelength position [59-61, 64, 68-73, 109], and (iv) *small signal condition*, i.e., the injection current of the slave is just over the threshold and the optical injection is weak [33, 58- 61, 68-73, 109-114]. Although the previous analyses are capable of explaining some observed phenomena such as threshold injection power [59-61, 68-73,109], asymmetric locking range [61, 67, 69, 109-113] and locking instability [61, 63, 109, 111-113], their applicability is limited. For example, the quasi-locking limits the validation of the analyses to a very narrow wavelength range near to the fully locked state (FLS, i.e. only one locked mode exists while all the others are suppressed to minimum). Therefore it cannot be used to study the locking property far from the FLS, especially the progression from the unlocked state (ULS) to the FLS. The conditions of single mode slave and single injection make the previous analyses valid only for the case of single injection to a single-mode laser (SISL). However, it has become more common to use multiple injections to lock a multi-mode laser in some emerging applications, for example, all optical switches and wavelength converters [34, 35, 81, 115]. For the case of multiple injections to multimode lasers (MIML), the theoretical study remains open. In addition, in practices it is more common to drive the slave at large injection current and strong optical injection for better performance (for example, high optical powers, better stability and narrow linewidth). The validity of the previous small signal models remains uncertain. Although there are some attempts on large signal analysis, they rely more on numerical simulation [63, 67] rather than analytical form. To tackle these problems, the GM targets at broad conditions such as either weak or strong injection power, single injection or multiple injections, single mode or multiple mode slave, near to the FLS or in the ULS.

Fig. 5.1 Definition of the terms of laser modes for the injection-locked multimode lasers. (a) External optical injections; (b) laser modes of the slave in the free running state; and (c) laser modes of the slave under external injections.

5.1.1 Generalized model based on the concept of injection seeding

To simplify further discussion, here several terms related to the laser modes in the injection locking are defined as shown in Fig. 5.1. The external injections at different wavelengths are named as the “injected modes” as shown in Fig. 5.1 (a). Of all the multiple longitudinal modes of the slave in the free running state (i.e., no external injections), those close to the injected modes are named as the “targeted modes” (i.e., the targets for locking) while the others are named the “side modes” as shown in Fig. 5.1 (b).

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In the presence of the external injections, the injected modes would appear in the optical spectrum of the slave as shown in Fig. 5.1 (c). As these modes are seeded by the injections, they are named as the “seeded modes”. The wavelengths of the seeded modes are exactly the same with those of the injected modes. Under the injection, the slave may also present some secondary modes owing to the interaction between the modes (e.g., the wave mixing effect [80]). These modes are named as the “secondary modes”. Since the targeted modes and sides modes are determined by the phase condition of the FP resonant cavity in the slave laser, they altogether are called the “cavity modes”. All the modes that are in oscillation under the external injections are named as “oscillation modes”, including the cavity modes, the seeded modes, and the secondary modes. It is worth noting that the injected modes are from the master laser while the oscillation modes are generated inside the slave laser.

The key point of the SSMs is the concept of linear superimposition of electromagnetic (EM) fields, i.e., the external injection is treated as an EM field to be linearly superimposed onto the original EM field inside the slave cavity [61, 64, 69, 109]. More specifically, the amplitude of the injected mode is considered to contribute to the amplitude of the target mode, while the wavelength difference between the injected mode and the targeted mode contributes to the phase of the targeted mode, like a vector summation. This linear superimposition method has become a standard treatment for both the rate equation method and the propagation method since Adler developed the so-called “Adler equation” for the electrical injection in 1946 [52] and later Lang adopted it for the semiconductor lasers in 1982 [61]. This method is based on an implicit presumption that the injected mode transfers all its power to the target mode and it would disappear from

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the final optical output spectrum of the slave (i.e., not seeded modes exist). It might be true in the FLS state. But, it is well observed that out of the FLS state the seeded mode would exist, and it could be the dominant mode of the slave output [59, 69, 72, 113]. The linear method also implies that the locking properties (power, wavelength drift and linewidth etc) are influenced by the initial phase of the injected mode, for example, the injected mode would have no contribution if it has a phase difference of $\pi/2$ from the initial electrical field in the FP cavity of the slave. This prediction is opposite to the experimental observation. Moreover, in the MIML case, the inclusion of phase would complicate the analysis due to the multiple injections.

The key point of the GM is the concept of seeding. The idea originates from the understanding that in a free running laser the spontaneous emission actually provides the seed photons, which are amplified and then selected by the FP cavity condition to form the intrinsic laser modes. In the other words, the laser modes are seeded by the spontaneous emission photons. Similarly, it can be considered that in the ILLs the external injections provide the seed photons, which are then amplified to form the seeded modes. It is noted that the term “injection seeding” was once suggested by Siegman to describe the approach that a weak external injection is use to establish the initial condition for a pulsed oscillator during the turn-on period [116]. In this chapter, the term “injection seeding” means that the external injections seed the new oscillation modes in the slave. As the concept of injection seeding leaves out the phase term, the propagation method cannot be used any longer since the phase is essential for the electrical field interference. Consequently, the GM is based on the rate equation method.

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The analytical model of the ILL is schemed in Fig. 5.2 . The external injections provide seed photons U_j to be injected into the resonant cavity of the slave, in which all the oscillation modes S_i are amplified/suppressed and then form the final output (S_i and U_j are the photon numbers, and i and j are integer referring to the i^{th} and j^{th} mode, respectively). Therefore, the laser output has all the cavity modes and seeded modes. In addition to the seeding effect, there are some other physical processes inside the laser cavity: (i) the oscillation modes interact with each other to produce secondary modes through nonlinear effects (e.g. wave mixing [80]); and (ii) all the oscillation modes compete with each other and deplete the carriers. Based on the multi-mode laser rate equation of Eq. (3.1) in Ref. [8], a generalized mode for the injection locking is conceived by including the injections and the interactions, as given by

Fig. 5.2 Analytical model of the injection-locked laser.

$$\frac{dS_i}{dt} = S_i \left(R_{st,i} - \frac{1}{\tau_{ph,i}} - \sum_j \theta_{i,j} S_j \right) + R_{sp,i} \kappa_{tot0} + \sum_j \xi_{i,j} S_j + \sum_j \Xi_{ij} U_j \quad (5.1)$$

where t is the time, $R_{st,i}$ is the stimulated emission coefficient of the i^{th} mode, $\tau_{ph,i}$ is the photon lifetime, $\theta_{i,j}$ is the cross-mode gain saturation coefficient of the j^{th} to the i^{th} mode, $R_{sp,i}$ is the spontaneous emission coefficient, κ_{tot0} is the total enhancement factor of spontaneous emission, $\xi_{i,j}$ is the cross-mode optical pumping coefficient of the j^{th} to the i^{th}

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mode, and Ξ_{ij} is the seeding coefficient. The rate equation in Eq. (5.1) takes into account the factors such as the photon amplification and saturation (the 1st term on the right side of Eq. (5.1)), the seeding of spontaneous emission (the 2nd term), the cross-mode pumping (the 3rd term) and the seeding of the external injections (the 4th term). Eq. (5.1) can also be used to describe the case of single injection by ignoring some coefficients. In dealing with the secondary generated modes, the coefficients $\xi_{i,j}$ and Ξ_{ij} may not be constant but depends on the photon numbers of the other modes. As Eq. (5.1) treats the laser modes individually, it is easy to deal with the case of multiple injections and multimode slave. Therefore, the model represented by Eq. (5.1) is generalized. With respect to the polarization, it is assumed that seeded mode is identical to the targeted mode. Otherwise, the seeded mode will be divided into TE and TM components, each is considered as a separate injection to lock a targeted mode with corresponding polarization state.

As the external injections cause the power redistribution among all the modes, the carrier density and the frequency positions of the cavity modes are changed as given by

$$\frac{dn}{dt} = \frac{I_0 - I_{th0}}{e_0 V_0} - \frac{n - n_{th0}}{\tau_{s0}} - \frac{1}{V_0} \sum_i S_i R_{st,i} \quad (5.2)$$

$$\frac{d\phi}{dt} = 2\pi(f - f_0) = \frac{1}{2} \alpha_0 v_{g0} \frac{\partial g}{\partial n} (n - n_{th0}) \quad (5.3)$$

where, n and n_{th0} are the carrier density and the threshold carrier density, respectively. Similarly, I_0 and I_{th0} are the injection current and the threshold current, respective. e_0 is the electron charge, V_0 is the volume of active medium (optical confinement factor Γ_0 should be taken into consideration), and τ_{s0} is the carrier lifetime. In Eq. (5.3), ϕ is the phase of the slowly-varying complex field (following the definition in Eq. (2.77) of Ref.

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[8]), and f_0 and f are the initial frequency and the frequency after injection, respectively. The variables f_0 and f refer to any of the FP cavity modes. It is assumed that all the cavity modes are shifted by nearly the same amount of frequency. α_0 is the linewidth enhancement factor, v_{g0} is the group velocity in the active medium, and $\partial g/\partial n$ is the gain coefficient.

5.1.2 Locking property under single external injection

To prove the validation of the GM, it is first used to deal with a simple case of single external injection. When an external signal is injected into a multi-mode slave laser, the study can be focused on three separate laser modes: the seeded mode T , the targeted mode S_1 , and the side mode S_2 that is nearest to the seeded mode. The governing equations will be first presented, followed by the derivation of the threshold injection power and the critical detuning, and finally, the numerical comparison between the GM and the SSM in cases of strong and weak injections.

5.1.2.1 Governing equations

In case of single injection, the rate equations for the photon numbers, carrier density and frequency shift can be simplified from Eqs. (5.1) – (5.3) to be

$$\frac{dS_1}{dt} = S_1 \left(R_{st1} - \frac{1}{\tau_{ph0}} \right) + R_{sp1} \kappa_{tot0} - \xi_1 S_1 + \xi_2 U_0 \quad (5.4)$$

$$\frac{dS_2}{dt} = S_2 \left(R_{st2} - \frac{1}{\tau_{ph0}} \right) + R_{sp2} \kappa_{tot0} \quad (5.5)$$

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$$\frac{dT}{dt} = T \left(R_{stT} - \frac{1}{\tau_{phT}} \right) + \xi_1 S_1 + (1 - \xi_2) U_0 \quad (5.6)$$

$$\frac{dn_e}{dt} = \frac{J_0}{e_0 V_0} - \frac{n_e}{\tau_{s0}} - \frac{S_1 R_{st1} + S_2 R_{st2} + T R_{stT}}{V_0} \quad (5.7)$$

$$\Delta f_{drift} = \frac{1}{4\pi} \alpha_0 v_{g0} a_{10} \chi \Delta n_e \quad (5.8)$$

where n_e is the net carrier density defined by $n_e = n - n_{th0}$, Δn_e is the change of the net carrier density, J_0 is the net injection current $J_0 = I_0 - I_{th0}$, and Δf_{shift} is the frequency drift of the FP cavity comb due to the injection. As the external injection consumes more carrier, therefore $\Delta n_e \leq 0$. As a result, $\Delta f_{shift} \leq 0$, that is, the external injection always leads to a red shift. U_0 is the photons number of the injected mode given by $U_0 = P_{in0} / (h_0 \nu_T)$, where P_{in0} is the injected power, h_0 is the Planck's constant and ν_T is the frequency of the seeded mode, which is always identical to that of the injection. R_{st1} , R_{st2} and R_{stT} are the stimulated emission coefficients given by $R_{st1} = g_1 v_{g0}$, $R_{st2} = g_2 v_{g0}$ and $R_{stT} = g_T v_{g0}$, where g_1 , g_2 and g_T are the mode gains further related to the net carrier density by $g_1 = a_{10} n_e \chi$, $g_2 = a_{20} n_e \chi$ and $g_T = a_{T0} n_e \chi$. a_{10} , a_{20} and a_{T0} are the linear gain coefficients, which are determined by the gain curve of the slave and remain nearly constant during the injection locking [8]. Since in most cases the seeded mode is close to the targeted mode, therefore it is assumed that $a_{T0} \approx a_{10}$. χ is the gain suppression factor given by

$$\chi = \frac{1}{1 + \frac{S_\Sigma}{S_{sat0}}} \quad (5.9)$$

where S_Σ represent for the total photon number as expressed by

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$$S_{\Sigma} = S_1 + M_0 S_2 + \frac{\tau_{ph0}}{\tau_{phT}} T \quad (5.10)$$

$$S_{sat0} = \frac{w_0 t_0}{\tau_{s0} v_{g0} \alpha_{m0}} \frac{\partial g}{\partial n} \quad (5.11)$$

where M_0 is the number of side modes that should be taken into account. S_{sat0} is the saturation photon number, which can be derived based on Eq. (19) of Ref. [117] and Eq. (3.9) of Ref. [8]. α_{m0} the modal facet loss given by $\alpha_{m0} = -\ln(r_1 r_2)/L_0$, r_1 and r_2 are the amplitude reflectivities of the two laser facets, and w_0 , t_0 and L_0 are the width, depth and length of the active medium of the slave, respectively. As the lifetime of the seeded mode could be much smaller than that of the cavity mode at the presence of certain detuning (for example, when $\Delta\nu = 0.3 \delta_{FSR}$, $\tau_{phT} \approx 0.5 \tau_{ph0}$), the ratio τ_{ph0}/τ_{phT} in Eq. (5.10) is to normalize the photon number of the seeded mode to the same time scale of the cavity modes. Otherwise, the energy conservation will be breached since the output power P_i of the i^{th} individual mode is related to the photon number S_i and the photon lifetime $\tau_{ph,i}$ by $P_i \propto S_i/\tau_{ph,i}$. This treatment makes it feasible to analyze the slave not in the FLS, especially under the strong injections.

In Eqs. (5.4) – (5.7), R_{sp1} and R_{sp2} are the effective spontaneous emission coefficients of the targeted mode and the side mode, respectively. They are related to the stimulated emission coefficients by $R_{sp1} = n_{sp0} R_{st1}$ and $R_{sp2} = n_{sp0} R_{st2}$ with n_{sp0} being the inversion factor [8]. The variable ξ_1 is the cross-mode pumping coefficient of the targeted mode to the seeded mode, while ξ_2 is that of the seeded mode to the targeted mode. Since the optical pumping requires high energy photons to pump out low energy photons, $\xi_1 = 0$ and $\xi_2 > 0$ when ν_T is greater than that of the targeted mode ν_1 , and $\xi_1 > 0$ and $\xi_2 = 0$

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when $\nu_T < \nu_1$. It is noted that only the cross-mode pumping between the targeted mode and the seeded mode is considered since they are very close in the frequency (or wavelength) domain. The side modes are quite far from the seeded mode and thus the interaction is weak.

The variables τ_{ph0} and τ_{phT} are the photon lifetimes for the cavity modes and the seeded mode, respectively. τ_{ph0} is defined by $1/\tau_{ph0} = \alpha_{s0} + \alpha_{m0}$, with α_{s0} being the modal scattering loss of the FP cavity. For the seeded mode, in addition to the scattering loss and the facet loss, it suffers one more loss since its frequency may not match the FP cavity resonant condition. Therefore,

$$\frac{1}{\tau_{phT}} = \alpha_{s0} + \alpha_{m0} + \alpha_{\psi} \approx \frac{1}{\tau_{ph0}} (1 + \beta_0 \Delta \nu^2) \quad \text{for } \Delta \nu \ll \delta \nu_{FSR} \quad (5.12)$$

$$\beta_0 = \frac{2\pi^2}{L_0 (\alpha_{s0} + \alpha_{m0}) \delta \nu_{FSR}^2} \quad (5.13)$$

where the phase mismatch loss α_{ψ} is given by $\alpha_{\psi} = -\ln[\cos(\psi)]/L_0$, ψ is the phase mismatch $\psi = 2\pi\Delta\nu/\delta\nu_{FSR}$, $\Delta\nu = \nu_T - \nu_1$ is the actual frequency detuning (i.e. the real frequency difference between the seeded mode and the targeted mode), $\delta\nu_{FSR} = c_0/2\bar{\mu}_e L_0$ is the spacing of the FP laser modes, c_0 is the light velocity in vacuum, and $\bar{\mu}_e$ is the effective group refractive index. β_0 is a phase mismatch factor that directly associates the photon lifetime with the frequency detuning.

In a steady state, all the terms $d/dt = 0$ in Eqs. (5.4) – (5.7). After certain derivation, the governing equations for the static locking properties can be expressed as

$$S_1 = \frac{n_{sp0} \kappa_{tot0} + \xi_2 \tau_{ph0} U_0}{1 - G_1 + \xi_1 \tau_{ph0}} \quad (5.14)$$

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$$S_2 = \frac{n_{sp0} \kappa_{tot0}}{1 - G_2} \quad (5.15)$$

$$T \approx \frac{U_0 \tau_{ph0}}{1 + \beta_0 \Delta \nu^2 - G_1} \quad (5.16)$$

$$n_e = \frac{\tau_{s0} J_0}{e_0 V_0} - \frac{\tau_{s0}}{V_0 \tau_{ph0}} (S_1 G_1 + M_0 S_2 G_2 + T G_T) = \frac{\tau_{s0}}{V_0} \left(\frac{J_0}{e_0} - \frac{S_\Sigma}{\tau_{ph0}} \right) \quad (5.17)$$

$$\Delta f_{shift} = -\rho_0 (S_\Sigma - S_{\Sigma 0}) \quad (5.18)$$

where G_1 , G_2 and G_T are the normalized roundtrip gains of the targeted mode, the side mode and the seeded mode as given by $G_1 = v_{g0} \tau_{ph0} g_1$, $G_2 = v_{g0} \tau_{ph0} g_2$ and $G_T = v_{g0} \tau_{ph0} g_T$, respectively. ρ_0 is the frequency shift coefficient given by $\rho_0 = \tau_{s0} \alpha_0 v_{g0} a_{10} \chi / (4\pi \tau_{ph0} V_0)$. Here it is assumed that the main side modes have the same property, which comes from the experiment observation that all the main side modes are decreased in the same trend. This treatment is not accurate, but is not far from the reality as compared to the simplification in the SSM [61, 109], which sums up all the side modes into one mode. When the slave is driven far over the threshold current, the sum-up of the side modes could be much higher than the targeted mode (though any single side mode may be small), which in turn requires a very high gain and thus invalidates the predicted data. Therefore, the SSM is limited to the slaves driven slightly over the threshold. In contrast, our treatment allows for strong injection current.

5.1.2.2 Threshold injection power and critical detuning

The threshold injection power for the FLS can be determined from Eqs. (5.14) – (5.18). To lock the slave with a minimum injection power, the injection should be well

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aligned to one of the FP cavity modes, that is, $\Delta\nu = 0$. Commonly the threshold power of the injection is weak compared with the original output power of the slave. It is observed in experiment that under the weak injection the total output power S_Σ does not have large change in comparison to the drastic increase or drop of T, S_1 and S_2 (for example, T is 0 in the free running state but can be $> 10^4$ after locking, while S_1 and S_2 change from large values to nearly 0). Therefore, the changes of photon numbers ΔS_1 , ΔS_2 and ΔT , the change of carrier density Δn_e and the frequency shift can be related solely to the change of the total photon number ΔS_Σ , as expressed by

$$\Delta S_1 = \frac{n_{sp0} \kappa_{tot0} + \xi_2 \tau_{ph0} U_0}{(1 - G_{10} + \xi_1 \tau_{ph0})^2} \Delta G_1 = -\zeta_1 \Delta S_\Sigma \quad (5.19)$$

$$\Delta S_2 = \frac{n_{sp0} \kappa_{tot0}}{(1 - G_{20})^2} \Delta G_2 = -\zeta_2 \Delta S_\Sigma \quad (5.20)$$

$$\Delta T = -\zeta_T \Delta S_\Sigma \quad (5.21)$$

where the changes of the normalized gains ΔG_1 and ΔG_2 are given by $\Delta G_1 = -a_{10} \gamma \Delta S_\Sigma$

and $\Delta G_2 = -a_{20} \gamma \Delta S_\Sigma$, and γ is the gain slope $\gamma = v_{g0} \tau_{ph0} \chi \left[\frac{\tau_{s0}}{\tau_{ph0} V_0} + \frac{n_{e0} \chi}{S_{sat0}} \right]$, where n_{e0} is the

initial net carrier density in the active gain medium. ζ_1 , ζ_2 and ζ_T are the gain suppression

factors as given by $\zeta_1 = \frac{a_{10} \gamma (n_{sp0} \kappa_{tot0} + \xi_2 \tau_{ph0} U_0)}{(1 - G_{10} + \xi_1 \tau_{ph0})^2}$, $\zeta_2 = \frac{a_{20} \gamma n_{sp0} \kappa_{tot0}}{(1 - G_{20})^2}$ and

$\zeta_T = \frac{a_{10} \gamma U_0 \tau_{ph0}}{(1 - G_{10})^2}$. G_{10} and G_{20} are the initial values of G_1 and G_2 in the free running state,

respectively. It is noted that ΔT is the change of the seeded photon from its nominal value

$$T_0 = U_0 \tau_{ph0} / (1 - G_{10}).$$

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In fact, the change of total photon number before and after the locking is due to the decrease of the side and target modes and the increase of the seeded mode, that is,

$$\Delta S_{\Sigma} = \Delta S_1 + M_0 \Delta S_2 + T_0 + \Delta T \quad (5.22)$$

As $\Delta \nu = 0$, the ratio of $\tau_{ph0}/\tau_{phT} = 1$ and thus does not appear in Eq. (5.22).

By substituting Eqs. (5.19) – (5.21) into Eq. (5.22), it can be determined that the incremental of the total photon number $\Delta S_{\Sigma th}$ at the threshold of locking state is given by

$$\Delta S_{\Sigma th} = \frac{S_{\Sigma 0}}{1 + \zeta_1 + M_0 \zeta_2} \quad (5.23)$$

Let set the condition $T \geq k_0 S_{\Sigma 0}$ as the criterion for the fully locked state, where k_0 is the decision level (for example, 0.8). From Eq. (5.21), the threshold injection power U_{0th} can be expressed as

$$U_{0th} = \frac{b_1 S_{\Sigma 0}}{1 - b_2 S_{\Sigma 0}} \quad (5.24)$$

where b_1 and b_2 stands for $b_1 = \frac{k_0(1 - G_{10})}{\tau_{ph0}}$ and $b_2 = \frac{k_0 a_{10} \gamma}{(1 - G_{10})(1 + \zeta_1 + M_0 \zeta_2)}$,

respectively. The threshold injected power P_{0th} can be expressed as $P_{0th} = h_0 \nu_1 U_{0th}$.

The range for the frequency detuning can be derived from Eq. (5.16) as

$$0 \leq \Delta \nu \leq \Delta \nu_{up} = \sqrt{\frac{U_0 S_{10} \tau_{ph0} - n_{sp0} \kappa_{tot0} S_{\Sigma 0}}{\beta_0 S_{10} S_{\Sigma 0}}} \quad (5.25)$$

where $\Delta \nu_{up}$ is the upper limit of frequency detuning (named as the critical detuning), and S_{10} is the initial value of S_1 in the free running state. The lower limit of the detuning is set to 0 rather than $-\Delta \nu_{up}$ according to the experiment observation (to be discussed later). It is also noted that $\Delta \nu$ refers to the actual detuning since the frequency of the targeted mode is shifted by Δf_{shift} under the external injection as given by Eq. (5.18). In

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experiment, it is more convenient to use the nominal detuning $\Delta\nu_{nom}$ (i.e., the difference between the current injection frequency and the initial frequency of the targeted mode). Therefore, $-\Delta f_{shift} \leq \Delta\nu_{nom} \leq \Delta\nu_{up} - \Delta f_{shift}$. However, as Δf_{shift} is also dependent on $\Delta\nu$, the closed-form expression is complicated.

Table 5.1 Parameters of the MEMS injection-locked laser for theoretical analysis and experiment.

Peak wavelength of the slave λ_0	1533.890 nm
Length of the active gain medium L_0	267.5 μm
Width of the active gain medium w_0	1.30 μm
Thickness of the active gain medium t_0	0.5 μm
Optical confinement factor Γ_0	0.1
Group refractive index of InGaAsP $\bar{\mu}_e$	3.375
Amplitude reflectivities of the slave r_1, r_2	0.54
Mode spacing of the slave $\delta\nu_{FSR}$ ($\delta\lambda_{FSR}$)	166 GHz (1.30 nm)
Linewidth enhancement factor α_0	3
Scattering loss inside the cavity α_{s0}	36 cm^{-1}
Photon lifetime τ_{ph0}	1.38 ps
Total enhancement factor of the spontaneous emission κ_{tot0}	1.3
Inversion factor n_{sp0}	2
Carrier lifetime τ_{s0}	2 ns
Saturation photon number of slave S_{sat0}	1.0×10^6
Initial gain suppression factor χ_0	0.80
Phase mismatch factor β_0	$3.27 \times 10^{-22} \text{ Hz}^{-2}$
Frequency drift coefficient ρ_0	$1.20 \times 10^6 \text{ Hz}$
Threshold current of the slave I_{th0}	15 mA
Injection current of the slave I_0	30 mA

Fig. 5.3 (a)

Fig. 5.3 (b)

(c)

Fig. 5.3 Comparison of the photon numbers predicted by the generalized mode (GM) and the conventional small signal model (SSM) at strong and weak injection power levels. (a) Total output photon numbers S_{Σ} (normalized by $S_{\Sigma 0}$); (b) the seeded mode T (normalized by $S_{\Sigma 0}$); and (c) the side mode S_2 (normalized by S_{10}). The nominal detuning frequency $\Delta \nu_0$ is normalized by $\delta \nu_{FSR}$.

5.1.2.3 Comparison of the generalized model with the small signal model

The relationships between the photon numbers and the frequency detuning predicted by the GM are shown in Fig. 5.3 at two different injection power levels of -10 dBm and -4 dBm, which represent for the cases of weak and strong injections, respectively. For comparison, the data predicted by the SSM developed by Li (Eqs. (5.16) - (5.18) of Ref. [109]) are also shown as a reference since Li's work has been widely accepted and proven [63-66, 69-71]. The parameters of the ILL are listed in Table 5.1. Other data are: $S_{10} = 8,955$, $S_{20} = 2,997$, $S_{\Sigma 0} = 2.69 \times 10^4$, $M_0 = 6$, $n_{e0} = 2.62 \times 10^{24}$, $1 -$

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$G_{10} = 2.9 \times 10^{-4}$, and $1 - G_{20} = 8.7 \times 10^{-4}$, where S_{20} is the initial value of S_2 in the free running state. These data are measured from the experiment in Section 5.3. For simplicity, the axes S_Σ , T , S_2 and $\Delta\nu_0$ in Fig. 5.3 are normalized with respect to $S_{\Sigma 0}$, $S_{\Sigma 0}$, S_{10} and $\delta\nu_{FSR}$, respectively. In Fig. 5.3 (a), the total photon number does not change obviously when the frequency detuning is larger than $0.18\delta\nu_{FSR}$ for -4 dBm (or $0.06\delta\nu_{FSR}$ for -10 dBm), and then increases gradually with the decrease of the frequency detuning. Further reduction of the detuning to a certain value (about $-0.16\delta\nu_{FSR}$ and $-0.02\delta\nu_{FSR}$ for -4 dBm and -10 dBm, respectively) would cause the photon number drops abruptly to its initial value of $S_{\Sigma 0}$. This detuning corresponding to the critical detuning defined in Eq. (5.25). The curves given by the two models are quite close at a weak injection of -10 dBm. At a strong injection of -4 dBm, the critical detunings predicted by the two models are nearly identical; however, the SSM predicts larger total photon number than the GM. From Fig. 5.3 (a), the output power would be increased by 38% and 60% as predicted by the GM and the SSM, respectively. Similarly, in Fig. 5.3 (b) the photon numbers of the seeded modes calculated by the two models match well at the weak injection, but larger value is predicted by the SSM at the strong injection. When the detuning is larger than the critical detuning, the photon number of the seeded mode predicted by the GM decreases slower than that given by the SSM, especially under the strong injection. This might be due to that the SSM takes into account the phase (directly related to the detuning), and the increase of detuning rapidly makes the injection field and the laser cavity field out of phase. In contrast, the phase is omitted in the GM. In Fig. 5.3 (c), clear difference can be seen in the photon numbers of the side models predicted by the two models. Out of the locking range, the side model given by the SSM is close to S_{10} . This is

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not realistic as the side mode should be comparatively weak in comparison to the targeted mode ($S_{20} \approx 0.33 S_{10}$). In contrast, the GM handles the side model properly. It can be seen from Fig. 5.3 that the SSM is valid only on the conditions of weak injection power, close to the FLS and nearly single mode slave while the GM works well for both weak and strong injection power, single and multi-mode slave, the FLS and ULS. The reason behind is that the SSM involves linearization process while the GM does not.

5.1.3 Locking property under multiple external injections

The GM in Eq. (5.1) can be used to describe the laser property under multiple injections. Here a simple case of two external injections a and b will be analyzed since in many applications only two injections are employed [34, 35]. Similar to Eq. (5.16), the two seeded modes can be expressed as

Fig. 5.4 Changes of the photon numbers (normalized by $S_{\Sigma 0}$) with the normalized injection power difference under two external injections.

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$$T_a = \frac{U_a \tau_{ph0}}{1 + \beta_0 \Delta \nu_a^2 - G_a} \quad (5.26)$$

$$T_b = \frac{U_b \tau_{ph0}}{1 + \beta_0 \Delta \nu_b^2 - G_b} \quad (5.27)$$

where T_a and T_b are the photon numbers of the two seeded modes, respectively; U_a and U_b are the photon numbers of the injections; $\Delta \nu_a$ and $\Delta \nu_b$ stand for the detunings; and G_a and G_b represent the normalized gain of the corresponding seeded modes.

Assume the laser is initially locked by only the injection b (with a power of P_{bin}) at the position of one side mode. When another injection a is present at the position of the peak side mode, the power will be redistributed among the oscillation modes. Fig. 5.4 shows the relationship between the photon numbers and the seeded photon U_a when the other injection b is kept constant. In Fig. 5.4 all the photon numbers are normalized by $S_{\Sigma 0}$, in the horizontal axis the seeded photon U_a is also normalized by U_b . The parameters are the same with those for Fig. 5.3 by letting the injection a target at the peak mode and b at the side mode. When $P_{bin} = -10$ dBm (i.e., $U_b = 7.72 \times 10^{14}$), T_a rises gradually with the increase of U_a/U_b while T_b keeps on decreasing, and the total photon numbers S_{Σ} is close to $S_{\Sigma 0}$. At $P_{bin} = -4$ dBm (i.e., $U_b = 3.07 \times 10^{15}$), T_a increases rapidly over $S_{\Sigma 0}$, and S_{Σ} rises nearly linearly. At the same time, T_b is dropped. When $U_a/U_b = 1.68$ (i.e., 2.3 dB), T_a reaches $S_{\Sigma 0}$ and becomes dominant (this power difference is named as the gating threshold). This relation implies one of important applications of the multiple injections, i.e., all optical switching. In Fig. 5.4, T_b is dominant at the absence of U_a , but is well suppressed at the presence of a strong U_a . Let U_a be the control signal and U_b be the data signal; the optical pulse of U_a would be able to turn on/off the optical pulse train of U_b .

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This phenomenon has been used in recent applications [34], but has not been analyzed theoretically.

Fig. 5.5 Configuration of the injection-locked laser. (a) Schematic diagram; and (b) SEM micrograph of a single-chip integrated device.

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(a)

(b)

Fig. 5.6 Close-ups of the key components of the MEMS injection-locked laser.
(a) Blazed grating; and (b) tunable laser.

5.2 Fabrication and integration

The MEMS structure is fabricated on a 6" SOI wafer using the DRIE process. The structure layer is silicon material of 35 μm thick, the oxide layer is 1 μm and the handling wafer is 400 μm thick. The structure layer is deeply etched to form the gratings, actuators, microlenses and trenches for the laser chips and the optical fibers. The floating structure is released by patterning and etching from the bottom side of the handling wafer. A gold coating process is used by a shadow mask to provide bond pads, electrical routing and grating reflection surfaces while keeping the microlenses uncoated. After fabrication, the wafer is diced into small pieces of dies to expose the fiber grooves to the edge. During the laser packaging, the laser chips is put into the MEMS trenches with its top surface facing down. A layer of indium foil about 10 μm thick is sandwiched between the laser chips and the trenches on the dies. The foil lifts up the optical axis, and also provides good electrical and heat transfer. The alignment of the laser chips to the MEMS gratings is done coarsely by the marks on the dies and finely by driving the laser to oscillate and monitoring the output. Fixation of the laser chips is realized by applying thermal-conductive epoxy. After that, the single mode optical fibers are aligned into the fiber grooves on the dies, and then fixed by the UV-curable epoxy.

The diagram and SEM micrograph of an integrated MEMS injection-locked laser are shown in Fig. 5.5. A tunable laser is used as the master laser to provide the external locking light for a FP laser, which acts as the slave laser. In between, an optical coupling component is used for unidirectional coupling for the master to the slave as shown in Fig. 5.5 (a). An optical fiber can be used to couple the output and to inject external lasers in

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case of multiple injections (for example, the all optical switching experiment later). After fabrication and integration, the injection-locked laser has a dimension of $3\text{ mm} \times 2\text{ mm} \times 0.6\text{ mm}$.

In the real prototype as shown in Fig. 5.5 (b), the master laser is a continuously tunable laser in the Littrow external-cavity configuration (similar to the one developed in Chapter 4). The wavelength tuning is obtained by rotating the blazed grating using the MEMS rotary comb actuator. A close-up of the grating is shown in Fig. 5.6 (a). It is etched on the sidewall of the structure layer and is then coated with a gold layer of $0.2\text{ }\mu\text{m}$. The grating has 60 teeth at a period of $3.3\text{ }\mu\text{m}$. The diffraction angle is 45 degrees at the 3rd order. The actuator can rotate the grating by 1.0 degree with a voltage of 30 V. A prism is used as the optical coupling component. It maintains the mutual coupling of oscillating mode between the master and slave while preventing the other modes of the slave from entering the master. In this sense, it acts as an isolator.

The gain chip of the master is a stripe-guided multi-quantum-well InGaAsP/InP laser chip having a dimension of $250\text{ }\mu\text{m} \times 300\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ (length $\times$ width $\times$ height). One facet of the gain chip is AR-coated (intensity reflectivity $< 0.1\%$) while the other is high-reflection (HR) coated (intensity reflectivity $\approx 85\%$). The output wavelength can be tuned continuously from about 1510 nm to 1540 nm at a resolution of 0.001 nm. The slave is a FP laser chip coming from the same wafer with the gain chip, but its facets are just normally cleaved. The internal cavity length is $267.5\text{ }\mu\text{m}$. The threshold current is 15 mA. In the test below, the slave laser is driven at 30 mA DC current and gives out an output optical power of about 1.5 mW.

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Fig. 5.7 Experimental setup for characterizing the MEMS injection-locked laser.

The experimental setup is illustrated in Fig. 5.7. The MEMS ILL is placed under a microscope, on which a charge coupled device (CCD) camera is mounted and connected to a monitor. This is to visualize the integration, assembly and operation of the MEMS components, the laser chips and the optical fiber. The master and slave lasers are driven by the laser drivers (SDL-820 Laser Diode Driver from SDL, and 236 Source Measure Unit from Kaithley, respectively). The output of the slave laser is connected to a 50/50 2×2 optical coupler through an optical isolator. The isolator is to avoid the backreflection into the slave laser, which would deteriorate the laser characteristics and complicate the analysis. If multiple injections are needed, the external injections may be injected from the fiber. In this case, the isolator needs to be removed. The coupler has one output branch connected to an optical spectrum analyzer (Q8384 Optical Spectrum Analyzer from Advantest) for the spectrum measurement, and the other one to a photodetector (2832-C Dual-Channel Power Meter + 818-IR detector head, all from Newport) for the

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optical power measurement. The electrical signals of the injection current from the laser drivers and the optical power from the photodetector are both served to a digit oscilloscope (TDS 360 from Tektronix) to measure the waveforms. At the same time, the output of the master laser is also monitored.

5.3 Experimental results and discussions

5.3.1 Locking property under single external injection

From the engineering point of view, the quality of the injection locking is dependent on many parameters of the master laser such as the injection power, the wavelength detuning, the polarization direction, and even the misalignment relative to the slave. The locking property under weak injection has been extensively studied, both theoretically and experimentally. Therefore, this study focuses on the strong injection (i.e., the injection power is comparable to the output power of the slave in the free running state). The parameters of the slave are as listed in Table 5.1 and in the Subsection 5.1.2. In the free running state, the slave output has more than 30 modes with a total output power of -2 dBm as shown in Fig. 5.8 (a). In the window of observation, there are 4 modes. The peak mode at 1533.890 nm is 4.8 dB stronger than the second highest mode, and is chosen as the targeted mode. According to Eq. (5.24), the injection power should be ≥ -23.1 dBm (the SSM predicts ≥ -74 dBm). The actual threshold injection power for locking is -21.9 dBm. The GM gives a close estimation in comparison to the SSM. Table 5.2 compares some key parameters predicted by the GM with the experimental data.

Fig. 5.8 The output spectra of the slave at different locking states. (a) Free running state; (b) $\Delta\lambda_0 = -0.19$ nm, far from locking; (c) $\Delta\lambda_0 = 0.065$ nm, close to the locked state, but have strong wave mixing; and (d) $\Delta\lambda_0 = 0.255$ nm, fully locked state.

Table 5.2 Comparison of the predicted parameters by the generalized model with the experimental data.

Laser characteristics	Generalized model	Experiment
Critical detuning	0.310 nm	0.295 nm
Increase of total output power	38%	30%
Maximum red shift	0.27 nm	0.29 nm
Threshold injection power	-23.1 dBm	-21.9 dBm
Gating threshold	2.3 dB	2.0 dB

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The external injection is from the master laser with an estimated power of -4 dBm. Therefore, it is a strong injection. The output spectra of the slave are illustrated in Fig. 5.8 (b) – (d) when the detuning is varied. In Fig. 5.8 (b), the external injection is far from the targeted mode (the nominal detuning $\Delta\lambda_0 = -0.085$ nm and the actual detuning $\Delta\lambda = -0.19$ nm), and it is simply added up to the spectrum of the free running state. However, the cavity modes are red shifted by 0.105 nm. In addition, secondary modes are excited on both sides of every cavity mode. In Fig. 5.8 (c), as the seeded mode moves close to the targeted mode ($\Delta\lambda_0 = 0.065$ nm and $\Delta\lambda = -0.16$ nm), the red shift is increased to 0.225 nm, and most of the output power is concentrated on the seeded mode and the targeted mode while the side modes become suppressed. At the same time, the secondary modes become more obvious. These secondary modes may be due to the wave mixing effect between the seeded mode and the cavity modes [118]. In the previous studies, the mechanism for generating of new wavelength components is not taken into account, and thus has no way to simulate. However, this kind of new modes could be important in some applications such as coherent communications and chaos synchronizations [36, 119, 120]. In contrast, the GM of Eq. (1) allows producing new modes by treating them as separate modes and then includes them in the nonlinear interactions inside the laser cavity following Eqs. (5.2) and (5.3). For example, wave mixing and bifurcation are able to generate new modes, which are not F-P modes. However, in this experiment the influence of the secondary modes is neglected as they are relatively weak (> 20 dB power difference) and not among our focus. In Fig. 5.8 (d), as the seeded mode becomes very close to the targeted mode ($\Delta\lambda_0 = 0.255$ nm and $\Delta\lambda = -0.03$ nm), the laser is fully locked. The seeded mode dominates over the other modes by a side mode suppression ratio

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(SMSR) of 53.4 dB. At this time, the cavity mode is shifted by 0.285 nm. It is observed that the total output power in the locking state is increased by 30%, which is comparable to the 38% estimated by the GM (see Table 5.2) but significantly smaller than the 60% given by the SSM (refer to Fig. 5.3 (a)). Further increase of $\Delta\lambda_0$ up to 0.295 nm would push the cavity mode to longer wavelength but the actual detuning is always close to but smaller than 0. Once the actual wavelength detuning becomes larger than 0, the slave suddenly loses the locking state. This is why the boundary condition $\Delta\nu \geq 0$ (i.e., $\Delta\lambda \leq 0$) should be applied to the GM.

Fig. 5.9 The relationship between the red shift and the nominal detuning.

The relationship between the red shift $\Delta\lambda_{shift}$ and the nominal wavelength detuning $\Delta\lambda_0$ is measured and compared with the simulation of the GM as shown in Fig. 5.9. It can be seen from the test data that the cavity mode has a red shift of 0.065 nm even when the amount of detuning is large (< -0.3 nm). This phenomenon is named as the red shift baseline. It may be due to that the injected photons consume the carrier and thus reduce

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the carrier density even they do not satisfy the FP cavity condition. In the case of weak injection, this baseline of red shift is negligible. As the GM does not take into account this type of red shift, a value of 0.065 nm is added to the simulation result. After compensation, the GM curve has a reasonable agreement with the experiment data. The critical detuning predicted by the GM is 0.31 nm while the measured value is 0.295 nm. According to Eq. (5.25), the critical detuning is 0.255 nm, and becomes 0.32 nm after the compensation of the baseline. The maximum red shift is 0.27 nm by the GM and 0.29 nm by the experiment (see Table 5.2).

5.3.2 Locking property under multiple external injections

The locking property under multiple external injections is also investigated. For simplicity and the need of most applications, two injections are used, one from the master (named as the control signal) while the other from another laser source injected through the optical fiber (named as the data signal). The injection wavelength positions of the control and the data are shown in Fig. 5.10 (a) when the DC injection current of the slave is not turned on. The control is at the wavelength of 1535.39 nm while the data at 1534.06 nm. The data signal is fixed at -4 dBm. It is able to lock the slave to a SMSR of 51.4 dB when there is no control injection as shown in Fig. 5.10 (b). When the control signal is increased, the seeded control mode rises gradually while the seeded data mode decreases, following the same trend as shown by Fig. 5.4. When the control is -2.0 dBm, the slave is locked by the control to a SMSR of > 50 dB even at the presence of the data signal as shown in Fig. 5.10 (c). The gating threshold is 2.0 dB (i.e., the injection power of the control is 1.58 times of that of the data). From Fig. 5.4, the GM predicts a value of

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2.3 dB (i.e., 1.68 times). Reasonable agreement has been obtained (refer to Table 5.2). Such a power difference is relatively small compared with the values used in literature, but the obtained SMSR is much higher than the typical value of 20 dB [34, 121].

Fig. 5.10 Output spectra of all optical switching. (a) The injected modes of the control and the data; (b) locked solely by the data; and (c) locked by the control at the present of the data.

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(a)

(b)

Fig. 5.11 Waveforms of the slave output under the pulsed injection signal. The injection wavelength is pre-adjusted for the locking under static injection. (a) The slave can follow the injection modulated at 9.99 KHz; and (b) the locking becomes unstable when the injection is modulated at 10.2 KHz.

Fig. 5.12 Waveforms of all optical switching.

To demonstrate the switching between the control and the data, the response of the slave laser to a modulated injection is measured as shown in Fig. 5.11. In experiment, the injection wavelength is determined by obtaining the FLS in the static state (i.e., the injection is DC). With the wavelength kept unchanged, the master laser is modulated and injected to the slave. At a low modulation rate of 9.9 kHz, the slave can follow the power change of the injection signal as shown in Fig. 5.11 (a). The waveform of the slave output comes from the fact that the power of the slave in the locked state is about 30% higher than that in the free running state as discussed in Subsection 5.2.1. With the increase of the modulation rate to 10.2 kHz, the locking becomes unstable as shown in Fig. 5.11 (b). The slave cannot follow the injection change and therefore miss some pulses. This instability has been mentioned by Lang [61]; but in his study, the slave power should vary periodically. However, in the experiment, the loss of pulse is non-periodic.

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From Fig. 5.11, the modulation limit is about 10 KHz, which is too low compared with the reported values such as 5 Gbs and 10 Gbs in literature [34, 122]. The problem is solved by further adjustment of the injection wavelength. After that, the slave can easily respond to the injection modulation rate up to 100 MHz (limited by the available equipment) while maintaining high quality waveform. The influence of the detuning on the maximum response speed might be attributed to that the pulsated injection makes the slave parameters slightly different from those under the static injections. As the theoretical study in this chapter focuses mainly on the static state, the dynamic property is not analyzed in detail. However, the generalized model in Eq. (5.1) should also be valid as it is actually a dynamic model.

When the control is pulsated at 1 MHz and the data is at 50 MHz, the waveforms are shown in Fig. 5.12. It can be seen that the data is turned off once the control is on and vice versa. As the control and the data are all in their original optical form, Fig. 5.12 demonstrates the function of all optical switching as implied by Fig. 5.4. Such a switching speed of 50 MHz is much higher than the conventional micromechanical switches (~ 1 KHz) and makes it potential for packet optical switching.

5.3.3 Locking property under weak injection

The locking properties discussed above are measured under the strong injection power of -4 dBm. The MEMS ILL is also characterized under a weak injection of -10 dBm ($>$ the threshold injection power -21.9 dBm, but much smaller than the initial total output power of the slave -2 dBm). Various locking properties are investigated, including

the lockable spectrum range, influence of injection power, tolerance for misalignment and polarization dependence.

5.3.3.1 Lockable spectrum range

The experimental result of the lockable spectrum range is shown in Fig. 5.13. In the free running state, i.e., no external injection, the output spectrum is multimode as shown in Fig. 5.13 (a). It is noted that the power reading in the spectrum does not reflect the actual value since it is found that in this OSA the reading changes with the sweep mode, the wavelength resolution and the sampling point number. However, it reflects the relative relation. Fig. 5.13 (b) shows the lockable mode at the minimum wavelength of 1520.08 nm (named as the minimum mode) when the power of the single injection is fixed at -15 dBm. Any mode with shorter wavelength cannot be locked. Fig. 5.13 (c) illustrates the locking of the mode at 1521.41 nm, which is just next to the minimum mode. All the longitudinal modes on the right side of the minimum wavelength are lockable up to a maximum wavelength 1570.13 nm as shown in Fig. 5.13 (d) (named as the maximum mode). Any modes with longer wavelength cannot be locked. As shown in Fig. 5.13 (e), the mode at 1571.44 nm, which is adjacent to the maximum mode, loses the locking if the external injection power keeps constant. A lockable spectrum range of 50.05 nm is obtained, covering 39 longitudinal modes. In the locking states in Fig. 5.13 (b)-(d), the SMSR is > 30 dB, that is, most of the optical power is concentrated on the locked modes. The peak power after locking is about 10 dB higher than that of the free running state, but the total power does not increase significantly, unlike the case of strong injection in which the total power is increased by 30%. It can be seen from Fig. 5.13 (e) that even after the amplification in the laser cavity, the injected light in the unlocked state

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is still about 10 dB lower than the peak power of the free running state. Therefore, the red shift baseline does not exist under the weak injection, which is opposite to the case of the strong injection. It is also noted that the lockable spectrum range is shorter on the left side than on the right side. This may be due to the asymmetry of the gain curve.

Fig. 5.13 Lockable spectrum range. (a) Free-running spectrum; (b) the minimum lockable wavelength 1520.08 nm; (c) locking at 1521.41 nm; (d) the maximum lockable wavelength 1570.13 nm, and (e) loss of locking at 1571.44 nm.

Fig. 5.14 Theoretical and experimental data of the lockable spectrum range with change of the injection power.

Fig. 5.15 Change of the spectrum with the effective injection power. (a) Locking state at -10 dBm; and (b) loss of locking at -21.9 dBm.

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If the injection power decreases, the lockable range becomes smaller as shown in Fig. 5.14. At the critical value of -21.9 dBm, only the peak wavelength of the multi-longitudinal FP spectrum can be locked; in the other word, the lockable spectrum range becomes zero. Further reducing of the injection power makes none of the modes lockable. The theoretical prediction is also shown in Fig. 5.8. The theoretical curve follows the trend of the experiment one.

5.3.3.2 Influence of injection power

To study the influence of the injection power on the mode locking, a mode next to the peak mode of the free running state is locked with an injection power of -10 dBm. The mode is well locked as shown in Fig. 5.15 (a). The SMSR reaches as high as 42 dB in contrast to the original 4.8 dB of the free running state. To obtain the FLS, the wavelength is adjusted by a step of 0.001 nm to maximize the SMSR. With the decrease of the injection power, the locking remains stable until the injection drops to -21.9 dBm. The slave laser loses the locking, and the spectrum becomes multimode as shown in Fig. 5.15 (b). In lower injection power, the locking cannot be seen. When the injection power increases from very low to high, the locking does not emerge until -21.7 dBm. There is a hysteresis of 0.2 dB. The relationship of the locking quality and the injection power is shown in Fig. 5.16. Here a term “locking depth” is introduced to quantitate the locking quality as defined by

$$\zeta = \frac{\text{SMSR} - \text{SMSR}_0}{\text{SMSR}_{\max} - \text{SMSR}_0} \times 100\% \quad (5.28)$$

where ζ is the locking quality in percentage, SMSR is the current side mode suppression ratio determined by (the power of the mode of interest minus the maximum power of all

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the other modes), SMSR_0 is the initial ratio in the free running state, and $\text{SMSR}_{\max}$ is the maximum ratio given in the perfect locking state. All the power values are in unit of dBm. Noted that the variables of SMSR and SMSR_0 can be negative if the mode of interest is not the peak mode of the free running state. ζ is valid only for any longitudinal mode of the slave laser, not for the master laser. According to the definition, ζ always falls into 0 to 100%, 0 for the free running state and 100% for the FLS. The hysteresis can be seen clearly in Fig. 5.16. Either in the up or down state, the locking depth keeps flat initially, and changes abruptly when reaches the critical values. After the abrupt change, the increase of the injection power makes the locking depth closer to 100%.

Fig. 5.16 Hysteresis of the locking state with the change of injection power.

The hysteresis of threshold injection can be regarded as a history dependent property of the injection locking, that is, the current locking property is influenced by the previous state, like a Markov chain. It can be explained qualitatively using the GM. From Eq. (5.14) – (5.18), it can be seen that the final locking property is influenced by the initial parameters S_{10} , S_{20} , T_0 , and n_{e0} . When the injection changes from strong to weak to

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pass the threshold point, the slave is initially locked and tends to maintain this locking state. Therefore it requires the injection power to go to lower value. Oppositely, when the injection increases from the unlocked state, it requires higher injection.

An interesting observation in Fig. 5.15 (b) is that when the locking state gets lost, the power of the side modes return to near the original values, while the power of the targeted mode is reduced. One possible reason is that the targeted mode transfers part of its power to the seeded mode through a process similar to the optical pumping since the wavelength difference is small (0.06 nm). As the wavelength of the targeted mode is longer than that of the seeded mode, the seeded mode does not reversely pump the targeted mode. This is an experimental evidence of the optical pumping coefficients $\xi_{i,j}$ in Eq. (5.1) and ξ_1 and ξ_2 in Eq. (5.4). The pumping coefficients are quite small and dependent on the wavelength difference. It can be neglected in most cases.

Fig. 5.17 Influence of the lateral misalignment on the locking depth.

5.3.3.3 Tolerance for misalignment

The alignment between the master and slave lasers is very important when the lasers are assembled with the MEMS structure. Since the lateral misalignment would reduce the coupling from the master laser to the slave, it should be within a tolerance. The misalignment tolerance at different injection power levels are also studied as shown in Fig. 5.17. When the effective injection power is -10 dBm, the slave has a locking depth close to 100% within the misalignment range of -2.1 μm to 2.5 μm . Out of this range, the locking depth drops sharply to very low level. When the injection power decreases to -13 dBm, the tolerance shrinks to a range from -1.8 μm to 1.4 μm . At -20 dBm, it is from -0.7 μm to 1 μm . At the critical value of -21.9 dBm, the depth rate is close to 100% only when the lateral misalignment is negligibly small. In the other word, the alignment tolerance is very small. From Fig. 5.17, the curves of locking depth are not very symmetrical to the line of misalignment = 0. It can also be observed in Fig. 5.17 that the locking quality experiences sharp changes in all the curves. It suggests that the transition is abrupt once the injection power drops to the threshold level.

The misalignment tolerance can be explained by the influence of injection power. At the critical injection, it allows no misalignment. This explains the sharp drop of the curve for the injection of -21.9 dBm in Fig. 5.17. At high injection, the actual injection can be maintained over the threshold even at the presence of misalignment. The higher the injection, the larger the tolerance. As the coupling efficiency drops rapidly with the increase of misalignment, this may explain why the tolerance does not increase linearly with the injection power as illustrated in Fig. 5.17.

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Fig. 5.18 Degrading of the locking quality with the change of polarization direction. (a) The fully locked state; (b) polarization angle at 30° ; (c) polarization angle at 45° ; and (e) polarization angle at 60° .

5.3.3.4 Influence of polarization

Since the stripe waveguide of the active layer in the slave laser has high modal gain for the transverse electric (TE) mode than that for transverse magnetic (TM) mode, the polarization of the external injection should affect the locking quality. In the analyses and experimental results stated above, the polarization of the injection locking is always identical to the slave. In all the above experiments that optical outputs of the master and slave are always linearly polarized in TE mode. The section will study the influence of the injection polarization. The experimental observation is shown in Fig. 5.18. In the experiment, the polarization of the injection from an external laser is adjusted by a polarization controller.

When the polarization direction of the injection light is well aligned, the slave laser is fully locked at 1534.92 nm with a maximized SMSR of 42 dB as shown in Fig. 5.18 (a). The peak is high and narrow, the linewidth is only about 0.02 nm (limited by the resolution of the OSA). When the polarization angle changes to about 30°, the locking state is deteriorated as shown in Fig. 5.18 (b). The output becomes multimode with a SMSR of only 14 dB. The power level of the peak drops by 8.7 dB. The spectral shape of the modes is rounded and broadened. The linewidth increases to 0.1 nm. At the same time, the total output power reduces by 20%. As the polarization direction is rotated to 45°, the slave output is further degraded (see Fig. 5.18 (c)). The SMSR becomes as low as 1.7 dB while the peak power drops by another 4 dB. When the polarization angle is changed by 60° or larger, the slave loses the locking entirely as shown in Fig. 5.18 (d). The slave output spectrum is just like that of its free running state. It is also measured that the FP mode comb shifts by -0.005 nm in every increase of the polarization angle. This

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“blue shift” during the degrading of the locking state agrees with the “red shift” observed in Fig. 5.14, in which the locking quality (or locking depth) is gradually improved.

Based on the GM, the degrading of the locking state due to the polarization change can be attributed to the combination of the reduced effective injection power and increased noise. The injection can be decomposed into the TE mode and the TM mode. In the FLS, the polarization of the injection is aligned to the TE direction. With the deviation of the polarization angle, it decreases the effective injection power in the TE mode, therefore the locking state is gradually degraded (i.e., the side modes rise up) as shown in Fig. 5.18 (a) – (d). At the same time, the effective injection power in the TM mode is increased. Just out of the FLS, the TM mode is too weak to oscillate, and therefore it acts as a noise source to the TE mode. As a result, the linewidth is broadened obviously as shown in Fig. 5.18 (b). Further increase of the TM mode will make it strong enough to oscillate, thus the linewidth returns to be narrow as shown in Fig. 5.18 (c) and (d).

5.4 Summary

In conclusion, theoretical and experimental studies of injection-locked lasers have been carried out, yielding a new generalized model and a working device of MEMS single-chip integrated injection-locked laser. The generalized model is based on the concept of injection seeding, which treats the external injections as the seed photons and leaves out the phase. Compared with the previous small signal models of injection locking that treats the injections as linear superimposition of electromagnetic fields, the

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generalized model has many advantages, for example, it can handle the cases of multiple injections to a multi-mode slave laser and strong injection power. The prototype of the MEMS injection-locked laser mainly consists of a MEMS Littrow tunable laser as the master, a FP laser chip as the slave, and an optical fiber for optical coupling; all are integrated onto a SOI wafer within a volume of $3\text{ mm} \times 2\text{ mm} \times 0.6\text{ mm}$. The locking properties are measured under strong injection power with single and multiple external injections. Locking states with a side mode suppression ratio $> 50\text{ dB}$ have been obtained, and all optical switching up to 50 MHz has also been demonstrated. Other static properties such as the influence of the injection power, the polarization and misalignment tolerance have also been investigated. The generalized model predicts the laser characteristics such as critical detuning, increase of total output power, maximum red shift, threshold injection power and gating threshold to be 0.31 nm , 38% , 0.27 nm , -23.1 dBm and 2.3 dB , respectively, as compared to the measured data of 0.295 nm , 30% , 0.29 nm , -21.9 dBm and 2.0 dB , respectively. The reasonable agreement has been obtained. The generalized model would provide a useful tool for some emerging applications such as the all optical switching and wavelength conversion, which employ strong injection power, multiple injections and multi-mode slave lasers.

CHAPTER 6

CONCLUSIONS

6.1 Conclusions

Three schemes of MEMS tunable laser devices have been developed. The contents cover mainly the theoretical analyses for discrete/continuous wavelength tunings and injection locking, and the experiments of the tunable lasers and the injection-locked lasers. The major conclusions are listed below.

- (i) In the theoretical study of the mirror-configuration tunable lasers, an extended feedback model and a theoretical explanation for the discrete wavelength tuning have been developed. Compared to the conventional theories valid only for the weak feedback, the extended feedback model covers both the weak and medium feedback regions, and is suitable for most of the MEMS tunable lasers that have extremely short cavity and medium feedback strength. The mechanism of the transition between the continuous tuning and the mode hopping during the change of the external cavity length has been elucidated theoretically. Such transition has long been observed in the experiment but does not have ready interpretation. The condition has also been derived for purely discrete tuning.
- (ii) In the experimental study of the mirror-configuration tunable lasers, a MEMS discretely tunable laser has been fabricated by deep reactive ion etching on a

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silicon-on-insulator wafer. Optical fibers and bare laser chips have been packaged with the MEMS structure to form an integrated device on a single silicon substrate. The overall dimension is as small as $1.5 \text{ mm} \times 1 \text{ mm}$. The laser yields a sweeping speed of 1 ms, and a wavelength range of 13.5 nm by stepwise tuning. This discrete tuning is well maintained to such a degree that the continuous wavelength shift is suppressed to be $< 0.04 \text{ nm}$. The experiment has also verified the discrete tuning theory in various aspects such as tuning range, mode spacing and mode stability.

- (iii) In the theoretical investigation of the Littrow-configuration tunable lasers, the design theory of the pivot position has been revised for maximizing the continuous tuning range. It is proven that a fixed pivot allows for only a limited range of continuous wavelength tuning, unlike the unlimited range predicted by some previous theories. It has been newly found that the refractive index change of the gain medium significantly affects the wavelength tuning range, which is commonly neglected in previous works.
- (iv) In the experimental investigation of the Littrow-configuration tunable lasers, a MEMS laser has been formed by integration of the deep-etched MEMS structure with the optical fibers and the bare laser chip onto a single chip. It has a dimension of $2.0 \text{ mm} \times 1.5 \text{ mm} \times 0.6 \text{ mm}$, and can be tuned continuously within 30.3 nm at a resolution of 0.05 nm/V^2 . As a comparison, another MEMS laser designed by the conventional theory has only a tuning range of 5.9 nm.
- (v) In the theoretical study of the injection locking mechanism, a new model based on the concept of injection seeding is developed. The model treats the external

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injections as the seeding source for laser oscillation, and takes into account the effect of gain suppression and the interaction of the laser modes. Compared with the available small-signal theories, the model of injection seeding has more capabilities, for example, it is applicable to the case of multiple injections to a multi-mode laser, it is valid for a large power range of injections, and it can be used to analyze the evolution of the locking from the unlocking state to the best locking state. The model also takes into account the newly-observed phenomena such as cross-mode optical pumping and the wave mixing.

- (vi) In the experimental study, a working device of the MEMS injection-locked laser has been fabricated and integrated. It has a dimension of $3\text{ mm} \times 2\text{ mm} \times 0.6\text{ mm}$. Locking states with a side mode suppression ratio $> 50\text{ dB}$ have been obtained under strong injection power with single and multiple external injections. All optical switching up to 50 MHz has also been demonstrated. Other static properties such as the influence of the injection power, the polarization and misalignment tolerance have been investigated as well. The new model predicts the laser characteristics such as critical detuning, increase of total output power, maximum red shift, threshold injection power and gating threshold to be 0.31 nm , 38% , 0.27 nm , -23.1 dBm and 2.3 dB , respectively, as compared to the measured data of 0.295 nm , 30% , 0.29 nm , -21.9 dBm and 2.0 dB , respectively. The reasonable agreement has proven the effectiveness of the new model.

The experimental results of the MEMS lasers have shown that the MEMS is able to improve the laser specifications such as fast tuning speed, large tuning range, compact size, high tuning accuracy and high mechanical stability. In addition, it introduces batch

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fabrication and easy IC integration to the tunable lasers, which would cut the cost and broaden the applications. Moreover, the miniaturization makes it possible to construct very short external cavity, which brings in the improvement in the level of physics.

6.2 Recommendations

The recommendations for future research are summarized as below.

- (i) It is significant to develop on-chip MEMS optics to further improve the specifications of the MEMS lasers. Since the deep etching results in a vertical sidewall, the lenses, mirrors and gratings 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 the MEMS tunable laser. A possible solution is to fabricate the MEMS optics separately, and then to package it with the main part by bonding. For example, using thermal reflow to fabricate 3D lenses. Another option is to exploit the waveguide for the transmission of the laser beam between the different components. The waveguide would be able to confine the light in the vertical direction. However, it may make it difficult to obtain large tuning.
- (ii) It would save many technical problems if the laser source, the MEMS tuning part and the micro-optics are fabricated in the same process. In this way, all the components are pre-aligned and no later integration/assembly is necessary. However, other material groups may have to be used since the silicon and silicon compound material group is not very mature for the laser source.

Chapter 6 Conclusions and recommendations

- (iii) A simple way to solve the problem of focusing/collimation in the vertical direction for the tunable laser systems is to use an optical fiber as the cylindrical lens. The optical fiber is cheap, easily available, and have good cylindrical shape. The small refractive index difference between the core and cladding is negligible, thus the fiber can be treated as a homogenous medium. In addition, fiber alignment and packaging are convenient and mature. The diameter of the fiber can be thinned by HF etching (typical etching rate $3.5 \mu\text{m}/\text{min}$ in 49% HF).
- (iv) For sake of all optical switching in the DWDM networks, it would be meaningful to develop a tunable laser that has only two longitudinal modes, one is always fixed while the other is tunable. The two modes provide two locking wavelength positions for the control and the data signal, respectively. The fixed is for the locking of the control and the tunable for the data signal. By aligning the signal wavelength to the different DWDM channels, it allows to use a fixed-wavelength master as the control to turn on/off the signal channels one at a time. Such dual-mode MEMS tunable laser can be implemented by making two decoupled resonant cavities, or using two diffraction orders of a grating. The length of one cavity is fixed while the other can be tuned by MEMS structures.
- (v) There are many uncompleted works in the theoretical study and applications of the injection locking. The dynamics for the model of injection seeding is worth further analysis, for example, beating of modes, chaos synchronization, turn-on process etc. The MEMS injection lasers have various potential applications, for example, all optical packet/burst switches, and optical signal regenerators etc, and thus require further development.

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