STUDY OF INJECTION-LOCKING PHENOMENON USING MEMS TUNABLE LASER

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ABSTRACT

This paper reports our recent work that exploits the MEMS technology for the physical study of the laser injection-locking phenomenon, which is of great importance for atomic clock, all-optical networks and coherent communications. A MEMS injection locking laser (ILL) device has been developed to provide an experiment platform for physical and application studies. It employs a MEMS tunable laser as a master laser to lock a Fabry-Perot (FP) multimode laser; both are hybirdly integrated with the functional MEMS structures onto a single chip. Superior performance has been achieved in terms of wavelength tuning range, locking quality and optical response. As an example of the device capability, optically-controlled optical switching has been successfully demonstrated, up to 50 MHz (potentially 10 GHz). A general rate equation has also been developed to explain the phenomena of the wave mixing and the optical switching.

1. INTRODUCTION

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 [1], and was extended to the laser oscillators [2] after the invention of laser. 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 functions of the injection locking to the semiconductor lasers can be roughly categorized into two types: (1) improving the characteristics of the slave, and (2) 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, making it indispensable for many applications. For example, the high power lasers are commonly multiple longitudinal mode and have wide diverging angle. When locked by a low-power single-mode master laser, the high power lasers are able to obtain much higher power level but have single wavelength, high side-mode-suppression ratio (SMSR), narrow linewidth and diffraction-limited beam quality [3]. For high-speed modulation (i.e. time domain), the injection locking can be used to assure single-mode operation and to reduce the mode partition noise [4]. Additionally, it can significantly broaden the modulation bandwidth and flatten the modulation response. 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 [5].

Recently, considerable attentions have been attracted to the micromachined atomic wrist watches [6-8]. Commonly a ¹³⁷Cs 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) [9-10]. The lasers 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 [7] 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. A simple way is to form the injection-locked laser (ILL) by the microelectromechanical systems (MEMS) technology. In our recent works, on-chip tunable lasers have been developed by hybirdly integrating the necessary mechanical, optical and electrical parts of external cavity tunable lasers on a single silicon chip [11, 12].

Based on the MEMS tunable lasers, we further develop a hybridly integrated ILL and study the physical properties of the injection locking, such as the optical spectrum change, the locking depth and the drift of peak wavelength in the steady state. The dynamic response of the ILL is to be investigated by using an optical pulse train to turn on/off another optical train. To explain the phenomena observed in the experiment, which are not covered by the established theories, a general theory is also developed for multiple injections to a multimode laser based on the rate equations.

2. GENERAL RATE EQUATIONS

Injection locking of lasers has been extensively studied in literature; however, most of them deal with simple cases such as only one injection and single-mode slave laser [13, 14]. Some recent applications employ more than one external injection to lock a multimode laser. For example, in
optically-controlled optical switch to be discussed later, two optical injections are required, one for control signal and one for data signal. The rate equations for the injection locking can be generalized as
\[
\frac{dE}{dt} = \alpha E + \beta E^3 + E_{sp} + \kappa \sum_{k=1}^{3} E_{ext}^k
\]  
(1)
where \( t \) is the time, \( E \) is the slow varying amplitude of the complex electrical field, \( E_{sp} \) represents for the spontaneous emission, \( \kappa \) is the coupling efficiency, and \( E_{ext}^k \) stands for the electrical field of any of the multiple external injection. \( n \) is the carrier density, \( S_k \) represents the photon number of the \( k \)th laser mode, \( S \) is the total photon number of all the oscillation modes expressed as \( S = \sum S_k \), \( \alpha \) and \( \beta \) stand for the linear gain factor and the nonlinear gain factors, respectively, which are both dependent on \( S \) and \( n \). \( J \) is the injection current, \( e \) is the electron charge, \( V \) is the volume of the gain medium, \( \tau_{ph} \) is the photon lifetime, \( G(n,S) = g(n) v \tau_{ph} (1 - k_s S) \) is the normalized gain, \( g(n) = \frac{\partial G}{\partial n} (n - n_0) \) is the gain coefficient, \( v \) is the group velocity of light, \( k_s \) is the nonlinear gain coefficient, \( n_0 \) is the transparent carrier density, \( R_s \) is the spectral density of the white Gaussian noise, and \( \kappa_{tot} \) is the enhancement factor.

The physical processes of the injection locking includes (1) the external injections seed the modes to be oscillated, (2) the oscillation modes compete and deplete the free carriers, and (3) the oscillation modes interact with each other. Compared with the rate equations in Refs. [13] and [14], the key difference here is that the general equations take into account the 3rd order term in Eq. (1). This nonlinear term allows for the wave mixing of the laser modes and the injections, which results in the oscillation modes at new wavelengths. This cannot be predicted by the linear treatment in the previous theories.

3. DEVICE DESCRIPTION

The schematic diagram and the scanning electron micrograph (SEM) of the integrated MEMS ILL are shown in Fig. 2. 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 isolator is employed to guarantee unidirectional coupling for the master to the slave as shown in Fig. 2(a). For the convenience of measurement, an optical fiber can be used to couple the output. The master laser is a MEMS continuously tunable external-cavity laser using the Littrow configuration as shown in Fig. 2(b) [11]. The wavelength tuning is obtained by rotating the MEMS blazed grating about a pivot following the theory in Ref. [15]. A close-up of the grating is shown in Fig. 3(a). It is designed to work at the 3rd diffraction order with a blazed angle of 45 degree. The grating pitch is 3.3 \( \mu \)m. Its surface is coated with gold using a shadow mask. Since the blazed grating selects only one wavelength to oscillate, the output of the tunable laser is single longitudinal mode. The injection current of the master laser can be continuous wave (CW) or directly modulated, for static and dynamic performance studies, respectively. The isolator is a silicon prism placed in between the two lasers as shown in Fig. 3(b). The light from the master to the slave is incident at 45\(^\circ\) into the prism and at 90\(^\circ\) out of the prism. However, the light in the reverse path is totally reflected when entering the prism at 90\(^\circ\) and trying to leave at 45\(^\circ\) (angle of total internal reflection is 16.6\(^\circ\)). The prism also serves for active alignment between the lasers. By moving the prism back and forth, it can compensate the initial misalignment during the integration and packaging. In addition, it can control the coupling efficiency from the master and the slave, like a variable optical attenuator.
Figure 3: Close-up SEMs of MEMS components. (a) the grating; and (b) the silicon prism.

Figure 4: Wavelength tuning of the MEMS tunable laser.

Figure 5: The slave spectra at different locking states. (a) Free running state; (b) detuning = 0.375 nm, far from locking; (c) detuning = 0.095 nm, wave mixing; and (d) detuning = 0, fully locked.

4. RESULTS AND DISCUSSIONS

The wavelength tuning is first studies since the MEMS tunable laser acts as the master and determines the locking property of the ILL. Fig. 4 shows the superimposed spectra in various output states. Benefited from the short cavity length of the MEMS laser, the output can be tuned over a wide range from 1510.9 nm to 1541.2 nm (tuning range 30.3 nm). Due to the fine tuning capability and high stability of the MEMS structure, the laser obtains a tuning accuracy of 0.03 nm/V² and a wavelength repeatability of ±0.06 nm.

The detune, i.e. the wavelength difference between the master and the targeted mode of the slave, influences the locking state considerably. To study this effect, the wavelength of the master laser is swept within a range covering the targeted mode of the slave while all the other parameters are kept constant. Figure 5 illustrates the progress of the locking state by the output spectra of the MEMS ILL. In the free running state (Fig. 5(a)), the slave laser has 4 longitudinal modes in the observation window, with a peak wavelength at 1534.575 nm and a SMSR of only 6.81 dB. When the wavelength of the external injection is at 1534.26 nm, which is far from the target mode at 1534.635 nm, the power of the modes does not change obviously, and the mode spacing also keeps constant (Fig. 5(b)). However, the mode comb is translated by a small drift of 0.06 nm. Further reduction of the detune to 0.095 nm leads to more obvious interference between the injection and the target as shown in Fig. 5(c). As evidence, strong side lobes can be observed. The injection becomes dominant and concentrates most of the total power while the other FP modes becomes ever weaker though the total power is increased by about 30%. The mode comb also drifts further to 0.20 nm. When the detuning becomes 0, that is, the wavelengths of the injection and the target are identical at 1534.68 nm, the slave is locked to its best. As shown in Fig. 5(d), the slave is well locked to single mode with a SMSR of 44 dB, much larger than the typical value 20 dB obtained by other methods [3].

In Fig. 5 (a) and (b) the original laser cavity modes and the injected mode get oscillated, which can be explained qualitatively using Eq. (1). The interaction of the oscillation modes is negligible since the detune is large, that is, the 3rd term in Eq. (1) is small. The mode comb exhibits a small drift, which can be attributed to the change of the carrier density in the internal cavity of the slave. Under the external injection, the photon density would increase and consume more carriers as shown in Eqs. (2) and (3). Thus, the excess carrier density would decrease and shift the phase term. As a result, the mode comb is drifted [13]. The refractive index would also be increased and thus the effective length of the resonant cavity would be elongated. However, the change is too small to cause noticeable change in the mode spacing. In Fig. 5(c), it is clearly observed that new wavelength modes emerge as a result of the wave mixing, as predicted by the 3rd term in Eq. (1). In Fig. 5(d), the locking mode is fully amplified and deplete the gain, thus the other modes become very weak, resulting in the high SMSR.

Figure 6: Influence of the wavelength detune on the locking depth and the wavelength drift.

To quantitate the quality of injection locking, let us define a term locking depth $\zeta$ as

$$\zeta = \frac{\eta - \eta_0}{\eta_{\text{max}} - \eta_0} \times 100\%$$  \hspace{1cm} (4)
where $\eta$ is the current SMSR, and $\eta_0$ is the initial SMSR in the free running state. $\eta_{\text{max}}$ is the maximum SMSR given in the perfect locking state. All the power values are in unit of dBm. With this definition, $\zeta$ always falls into 0 to 100%, 0 for the free running state and 100% for the locked state.

The variation of the locking depth and the wavelength drift with the wavelength detune is shown in Fig. 6. It can be seen that the locking depth reaches its maximum at 0 detune, and then decreases nearly linearly but rapidly till detune $= 0.25$ nm. Later it decreases slowly to lower levels. The drift of the FP mode comb of the slave laser reaches its maximum of $0.23$ nm at the perfect locking state, and then it drops rapidly down to about 0.1 nm within a small detuning range of $0.15$ nm. It then decreases slowly to 0 at larger detuning value. The wavelength drift is like a “red shift” of the slave laser. It can be quite large, especially when the slave is well locked.

**CONCLUSIONS**

This paper presents the theoretical and experimental studies of the injection locking using an injection-locked laser system realized by MEMS fabrication and integration. Phenomena such as the wave mixing and the optical controlled optical switching have been observed, and a general rate equation has been developed to explain the phenomena. The inclusion of MEMS into the injection-locked laser, on one hand, reduces the device size to only 3 mm × 3 mm, making it possible for portable applications such as the atomic wrist-watches. On the other hand, it brings in significant performance improvement, which is indispensable for further study.

**REFERENCES**