

MEMS INJECTION-LOCKED LASER

X. M. Zhang, A. Q. Liu[†], H. Cai, C. Lu and D. Y. TangSchool of Electrical & Electronic Engineering
Nanyang Technological University, Singapore[†] Tel.: (65) 6790-4336, Fax: (65) 6792-0415, E-mail: eaqliu@ntu.edu.sg

ABSTRACT

This paper reports an injection-locked laser (ILL) device constructed by the MEMS technology to provide a wavelength-stabilized laser source for the atomic watches. The device mainly consists of a MEMS tunable laser and a FP laser chip by a scheme of external injection. The combination of the injection locking and the MEMS technology brings about stabilized wavelength ($\leq \pm 0.002$ nm) at a small size (3 mm \times 2 mm \times 0.6 mm); both are crucial for the atomic watches.

Keywords: Atomic clocks, Injection locking, Tunable lasers, MEMS

INTRODUCTION

Precise timekeeping is of great importance to various applications such as electronic computers, optical/wireless communications, satellites, and global positioning systems etc. It is also a trend to miniaturize the timepieces for portable applications. This paper is trying to pinpoint the niche applications of miniaturized laser systems to compact atomic clocks.

Up to now, the most accurate time is measured by atomic clocks, which extracts the time information from the transition of discrete quantum states of the electrons [1, 2]. As shown in Fig. 1 (a), the ^{133}Cs atom has a spin quantum number $I = 7/2$ for the nucleus and $s = \pm 1/2$ for the electron. As a result, there are two hyperfine multiplets with total spins of $f = 4$ and $f = 3$, respectively. Under a magnetic field \vec{B} , the spin is projected along the magnetic field. The projected spin quantum number is $m = -4, -3, \dots, +3, +4$ for $f = 4$ and $m = -3, -2, \dots, +2, +3$ for $f = 3$. As the 0-0 transition is insensitive to the external magnetic field, its resonance frequency is commonly used for timing. The current international standard for a second was defined in 1967 as the time it takes for 9,192,631,770 oscillations of the microwave radiation corresponding to the 0-0 transition of the ground state of an atom of ^{133}Cs [3].

Figure 1(b) illustrates the configuration of the atomic clocks [2-5]. A gas cell contains the ^{133}Cs atoms in the gaseous state. A laser source is modulated by a local oscillator and is then projected to the gas cell. When the laser wavelength and the modulation frequency are properly adjusted, the absorption of the gas cell is

population trapping (CPT). The photodetector measures the laser power and then feedback to the oscillator to maintain the minimum absorption. As the modulation frequency is directly related to the transition between the hyperfine energy states, it is used as the timing signal. In the atomic clocks, a key issue is to maintain a fixed laser wavelength, i.e., it should be stabilized to avoid modulation chirp and time/temperature drift. Conventional lasers can be stabilized using bulky systems, but is not realistic for portable applications such as atomic watches.

Microelectromechanical systems (MEMS) technology has been successfully demonstrated to downscale the conventional bulky tunable lasers to a size as small as millimeters [6-10]. Based on the previous

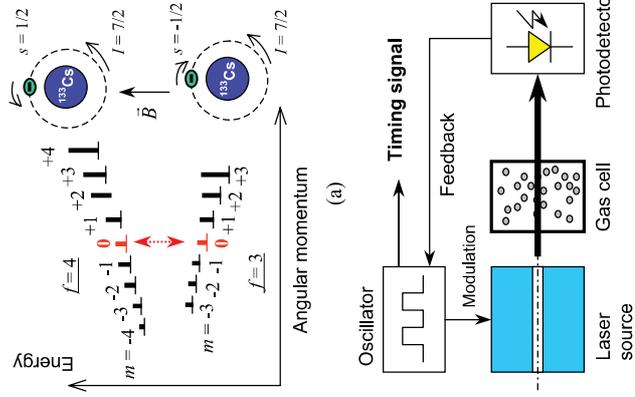


Fig. 1. Working principle of atomic clocks. (a) The hyperfine energy levels of the ground state of ^{133}Cs , and (b) configuration of an atomic clock using a laser source to excite and detect the 0-0 transition through feed-back control.

CONFIGURATION AND FABRICATION

The key feature of the ILL is that when the slave is fully locked by the master, its laser properties (e.g., wavelength, phase and chaos state etc.) become identical to those of the master. A microfabricated and integrated ILL is shown in Fig. 2, which has a size of $3 \text{ mm} \times 2 \text{ mm} \times 0.6 \text{ mm}$. In Fig. 2, a AMEMS tunable laser is used as the master laser to provide a single longitudinal mode light. The wavelength tunability makes it easy to adjust to the fully-locked state. The slave laser is a common multimode FP laser. In between, a movable prism is employed to guarantee unidirectional coupling for the master to the slave (i.e. optical isolation). For the convenience of measurement, an optical fiber is integrated for output coupling. The injection current of the master laser can be continuous wave (CW) or directly modulated, for static and dynamic performance studies, respectively. The master laser has a Littrow configuration developed in the previous work [9]. A MEMS blazed grating is used to form an external cavity; the rotation of grating provides a continuous wavelength tuning over 30.3 nm and a tuning accuracy of 0.03 nm/V^2 , which are well suitable for the injection locking. A close-up of the grating is shown in Fig. 3(a). It is designed to work at the 3rd diffraction order at a blazed angle of 45° . The grating period is $3.3 \mu\text{m}$. The prism isolator has a cross-sectional shape of right-angled triangle with an acute angle of 20° as shown in Fig. 3(b). The light from the master to the slave can enter the prism, then be deflected and finally leave out of the prism. However, the light in the reverse path is totally reflected when entering the prism at 90° and trying to leave at 20° (angle of total internal reflection is 17.0°). To guarantee a unidirectional light propagation, the prism angle α should satisfy the conditions that

$$\alpha \geq \arcsin(1/n) \quad (1)$$

and

$$\alpha - \arcsin[\sin(\alpha)/n] \leq \arcsin(1/n), \quad (2)$$

where n is the optical refractive index of the bulky silicon material. In this case, $n = 3.42$, and therefore

$$17^\circ \leq \alpha \leq 23.8^\circ. \quad (3)$$

As the prism can be translated by the comb drive actuator, it also serves as active alignment between the lasers. By moving the prism back and forth, it can compensate the initial misalignment of the lasers during the integration and packaging. In addition, it can control the coupling efficiency from the master and the slave, like a variable optical attenuator. The output powers of the master and the slave are 0.4 dBm and 8.8 dBm , respectively. The power of the targeted mode of the slave is 2.1 dBm . The prism isolator induces an insertion loss about -15 dB , however, it well avoids the phenomenon of mutual locking owing to the reverse light coupling from the slave to the master.

works [9, 10], this paper will develop a miniaturized wavelength-stabilized laser through a scheme of external injection locking while using the MEMS technology for on-chip adjustment/tuning and integration. From the configuration point of view, a tunable laser has only one laser chip while an injection locked laser (ILL) has two laser chips, one as the master while the other as the slave.

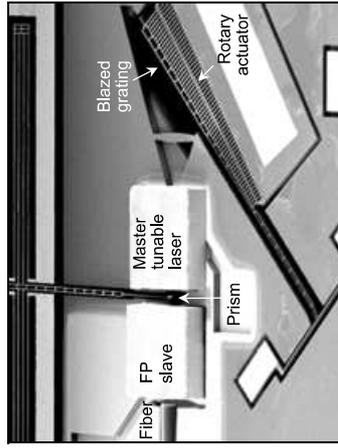


Fig. 2. Scanning electron micrograph (SEM) of the MEMS injection-locked laser.

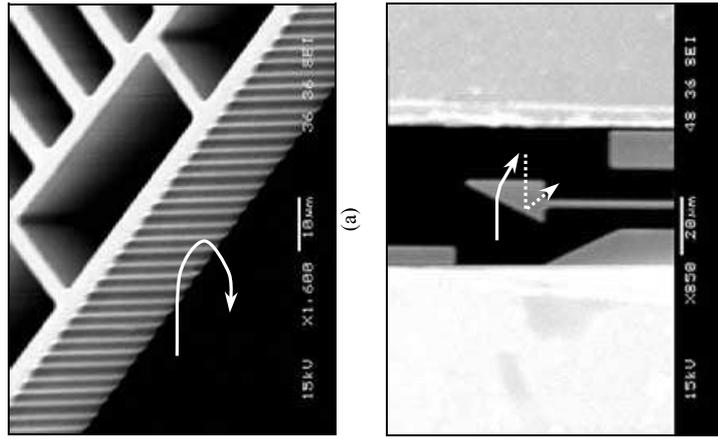


Fig. 3. Close-ups of the MEMS components. (a)

The fabrication process of the MEMS structure (including the actuators, grating, prism, microlens, laser trenches and fiber groove etc.) is based on the deep reactive ion etching of the silicon layer (35 μm thick) on a silicon-on-insulator (SOI) wafer. The movable structures are released by backside wet etching of the silicon

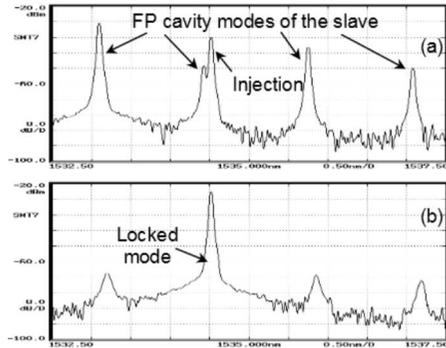


Fig. 4. Spectra of the injection-locked laser. (a) out of the locked state, and (b) in the fully locked state.

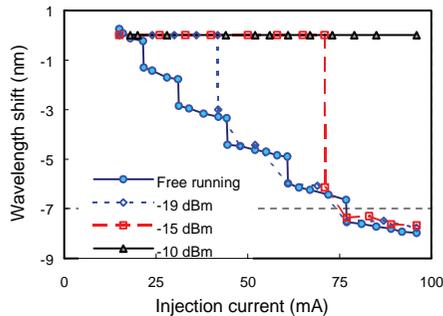


Fig. 5. Wavelength stability of the injection-locked laser with the increase of injection current of the slave laser.

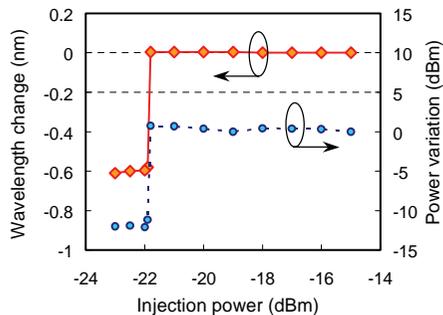


Fig. 6. Satiability of the wavelength and power of the injection-locked laser under different injection

substrate (475 μm thick). A shadow-masked deposition of gold (0.2 μm thick) is used to coat the grating surface and to provide electrical connection for the lasers, while the prism and the microlens are protected. After fabrication, the wafer is diced into small pieces 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. After that, the single mode optical fibers are put into the fiber grooves on the dies, and then fixed by the UV-curable epoxy.

EXPERIMENT RESULTS

The MEMSILL is investigated mainly in two aspects: the locking quality of the slave, and the wavelength stability after the slave is fully locked. The locking is obtained by gradually tuning the wavelength of the master while monitoring the output spectrum of the slave. This is to make sure that the slave is fully locked before characterization. As shown in Fig. 4(a), the slave has multiple longitudinal modes at 1533.095 nm, 1534.42 nm, 1535.75 nm and 1537.1 nm, respectively (mode spacing 1.325 nm) when the wavelength/power of the master is not well adjusted to lock the slave. Although the injected laser from the master also presents at 1534.52 nm and absorbs part of the power of the nearby slave mode, it does not suppress the other slave modes. In the locking state as shown in Fig. 4(b), the external injection is amplified while all the other FP modes of the slave are suppressed. The spectrum becomes a pure single mode with a side mode suppression ratio (SMSR) of 42 dB (Figure 4(b)), much better than the value of 7.5 dB in the unlocked state. By carefully adjusting the power and wavelength of the external injection, a SMSR as high as 55 dB can be obtained, much higher than the typical value of 20-30 dB in the reported works [11-16].

For a common FP laser, the output wavelength would vary with the increase of injection current. However, in the fully locked state, the output wavelength of the slave is locked to that of the external injection and therefore becomes insensitive to the injection current. The wavelength stability of the ILL at different injection current of the slave is shown in Fig. 5. In the free running state, the wavelength of slave is shifted by about 9 nm when the injection current varies from 15 mA to 96 mA. This shift is probably due to the increases of carrier density and temperature in the laser chip. However, once the slave is locked, the wavelength of the slave can be stabilized (variation $< \pm 0.002$ nm). When the injection power P_{in} is -19 dBm, the locking can be maintained up to $I = 41.9$ mA; for $P_{in} = -15$ dBm, $I = 71$ mA; and for $P_{in} = -10$ dBm, $I = 96$ mA. It can be inferred that higher injection power leads to larger stable range.

external injection is too weak, the slave is not locked. Once the slave is fully locked, the optical power is rapidly saturated and therefore becomes insensitive to the increase of the external injection power. This wavelength and power stabilities of the slave relative to the injection power is shown in Fig. 6. It can be seen that once $P_{in} > 21.9$ dBm, the wavelength and output power of the slave are stabilized over a large range. The variations of the wavelength and the power of the slave are ± 0.002 nm and ± 0.3 dB, respectively.

Combined with the data in Fig. 5, it proves that the ILL has stabilized wavelength and power in resistance of the changes of the injection current and temperature of slave and the injected power of the master. However, as the wavelength of the slave is fully determined by the master, the wavelength of the master should be pre-stabilized by controlling the temperature and current. The idea behind pre-stabilizing the master rather than directly stabilizing the slave is due to that a weak external injection can be used to lock a strong slave. In this sense, it is easy to stabilize the low-power master. As the atomic watches place a strict limit to the volume of the laser source, various wavelength stabilization approaches are disqualified. Although the MEMS ILL may not provide the best wavelength stability, its small size makes it very competitive. Further study will focus on achieving higher stability and self wavelength stabilization so as to eliminate the requirement of pre-stabilizing the master laser.

CONCLUSIONS

In conclusion, a miniaturized laser device has been developed by MEMS fabrication and integration to obtain stabilized wavelength regardless of the changes of temperature, injection current and injection optical power etc. Compared with the macroscale ILLs, the MEMS injection-locked laser has the advantages of stabilized wavelength and small size, making it competitive for the applications in the atomic watches. In addition, it brings in significant improvement and convenience in terms of locking quality, active alignment and optical isolation.

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