A MICROMACHINED THERMO-OPTIC TUNABLE LASER

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ABSTRACT

The paper presents a thermo-optic tunable laser that makes use of a micromachined etalon to form the external cavity. The wavelength tuning is obtained by the thermo-optic effect of the silicon material. In experiment, a wavelength tuning range of 14 nm is demonstrated by applying a heating current of 18.7 mA to a deep-etched silicon etalon of 206 μm wide. In the dynamic test, this laser measures a tuning speed of 3.2 μs, which is much faster than the typical speed of 1 ms as given by the previous MEMS tunable lasers that rely on the motion of mirrors or gratings. Since this laser is based on a different tuning mechanism of thermo-optic effect and requires no mechanical movement, it possesses many advantages such as fast speed, simple configuration and planar structure, and will broaden the applications of MEMS tunable lasers.

1. INTRODUCTION

Miniaturized and reliable tunable lasers have attracted increasing interests of research and development due to their simplicity, compatibility, and capability of spectral control. Meanwhile, tunable lasers have been intriguing because of its wide application range from sources for fiber-optic telecommunication systems to broad band sensors. In this vision, significant efforts have been devoted to the development of tunable lasers, resulting in various types of tunable lasers architectures. One of the prominent progresses is the miniaturized external-cavity tunable lasers that utilize the advanced fabrication and integration technologies of microelectromechanical systems (MEMS) [1-9]. Compared with the conventional mechanical tunable lasers, the MEMS lasers have demonstrated drastic improvements in the laser specifications such as wide tuning range, enhanced tuning speed, small size, batch fabrication, easy integration, low power consumption and so on. However, they are mostly based on mechanical movement of micromirrors and/or gratings, and thus suffer from the mechanics-related problems such as limited tuning speed (typically 1 ms), complicated movement control and unproven mechanical reliability and repeatability. To solve these problems, a fundamental solution is to utilize new mechanisms that require no mechanical movement.

It is well known that the silicon (Si) material has excellent electronic and mechanical properties. It is also a very good optical material and attractive for constructing various optical devices. Especially, it is transparent at λ > 1.2 μm, making it an exceptional waveguide medium for the 1.3- and 1.55-μm fiber-optic transmission wavelengths. Usually, silicon optoelectronic devices are based on the free carrier dispersion effect[10]. An alternative to this effect is the thermo-optic effect (TOE), namely the variation of the refractive index with the temperature of the material. The TOE of Si has a thermo-optic coefficient (dn/dT)S around 1.8×10⁻⁴ K⁻¹ at λ=1.5 μm [11], which is particular strong, about three times larger than those of the other transparent materials such as glasses. Moreover, the TOE requires only the heating (or cooling) and has no mechanical movement. Based on these understandings, this paper proposes to utilize the TOE of Si material for wavelength tuning of the micromachined tuning lasers and presents the experimental demonstration using the MEMS technology.

2. THEORY AND DESIGN

Design of tunable laser

The design of the micromachined thermo-optic tunable laser is illustrated in Fig. 1. The laser cavity consists of a Fabry-Pérot (FP) laser chip, a thermo-optic silicon etalon and a flat mirror. The Si etalon is positioned close to the FP chip as shown in Fig. 1. It has a curved shaped front surface for the collimation and coupling of the laser light. The mirror is intentionally attached on the end surface of the silicon etalon. This avoids the complication of extra cavities if there is a gap between the etalon and the mirror. Narrow serpentine wires on top of the silicon etalon are designed for resistive heating by running the electric current. As a result, a uniform temperature distribution can be obtained over the region of interest in the Si etalon during the heating. When the refractive index nS is changed, the effective external cavity length (Lext) and the effective reflectance (Rext) are changed accordingly. Consequently, the output wavelength of the FP chip can be tuned.

Figure 1: Schematic diagram of the MEMS tunable laser.

Optical phase of silicon etalon

When the Si etalon is heated up, it is subjected to a change of the refractive index. The corresponding optical path (ΔL) is varied as described by...
where δT is the change in the temperature and Lₜ is the heater length. As a result, the peak transmission wavelength λ is anticipated to vary as determined by

\[\Delta \lambda = \left( \frac{dn}{dT} \right)_{\lambda} L \Delta T \quad (1)\]

The light intensity I, transmitted across the Si etalon can be expressed by

\[I = I_{\text{inc}} \left( 1 - R_{\lambda} \right) \left( 1 - R_{\lambda} \right) \left[ 1 + \frac{4F_{g}^{2} \cos^{2} \theta}{\pi \sin^{2} \phi} \right] \quad (3)\]

where \(I_{\text{inc}}\) is the incident light intensity; \(\phi = 2n_{\text{eff}} l_{\lambda} \cos \theta / \lambda\) is the phase coefficient, whose variation takes into account the tuning of the cavity; \(l_{\lambda}\) is the etalon length; \(\theta\) is the incidence angle (here \(\theta = 0\)); and \(n_{\text{eff}}\) is the refractive index of Si (at room temperature and 1550 nm wavelength, \(n_{\text{Si}} = 3.42\) [12]). \(F_{g}\) is the reflecting finesse of the etalon as defined by the relationship \(F_{g} = \pi \left[ 1 - (R_{\lambda} R_{\lambda} \lambda) \right] \left[ 1 - (R_{\lambda} R_{\lambda} \lambda) \right] \), here \(R_{\lambda}\) and \(R_{\lambda}\) are the reflectance of the two facets of the Si etalon, respectively. In Eq. (3), the absorption losses in silicon and the scattering losses induced by the roughness of the facets are neglected. With this assumption, the maximum of \(I\) is obtained when the resonance condition \(\phi = m \pi\) is satisfied, here \(m\) is integer.

On the other hand, the phase coefficient is a function of the temperature \(T\) through \(n_{\text{eff}}\) and \(l_{\lambda}\), thus its variation is given by

\[\Delta \phi = \frac{2n_{\text{eff}} l_{\lambda} \cos \theta}{\lambda} \Delta n + \frac{2n_{\text{eff}} l_{\lambda} \cos \theta}{\lambda} \Delta l \quad (4)\]

where \(\Delta n\) is the variation of \(n_{\text{eff}}\) due to TOE, and \(\Delta l\) is the thermal expansion of the cavity as given by \(\Delta l = k \Delta T\), with \(k\) being the thermal expansion coefficient \((k = 2.6 \times 10^{-6} \text{ K}^{-1} \text{ for Si})\). Therefore, a heating of the etalon structure induces a variation of the phase coefficient, which results in a shift of the transmission comb of the Si etalon.

The TOE of the silicon material is characterized by the empirical expression based on single oscillator model [11], which is expressed as

\[dn_{\text{eff}}dT = 1.8 \times 10^{-4} + 3.47 \times 10^{-7} T - 1.98 \times 10^{-2} T^{2} \quad \text{(K}^{-1}) \quad (5)\]

### Wavelength tuning of FP chip

The concept of wavelength tuning is illustrated in Fig. 2, where the tunable laser system is modeled by an effective cavity with two mirrors \((R_{FP}\) and \(R_{\text{eff}}\) \((n_{\lambda})\)), which are corresponding to \(R_{1}\) and \(R_{2}\) in Eq (1), respectively). The effective reflectance \(R_{\text{eff}}\) can be expressed as

\[R_{\text{eff}} = \frac{R_{FP} - g_{\lambda} R_{\lambda} n_{\lambda}}{1 - R_{FP} n_{\lambda} g_{\lambda}} \quad (6)\]

The roundtrip gain within the Si etalon \(g_{\lambda}\) is given by

\[g_{\lambda}(l_{\lambda}, n_{\lambda}, \lambda) = \exp(-2n_{\lambda} \alpha_{\lambda} l_{\lambda} - j4\pi n_{\lambda} l_{\lambda} / \lambda) \quad (7)\]

where \(\alpha_{\lambda}\) denotes the optical loss coefficient. Through the effective reflectance \((R_{\text{eff}})\), the FP chip of the MEMS laser is modulated as a function of refractive index of the Si etalon. Therefore, the lasing mode of the proposed MEMS tunable laser is determined by the coincidence of the resonant mode of the FP chip and the transmission mode of the Si etalon. In this tuning scheme, the effective cavity could initially have many possible modes for lasing (Fig. 2a). However, at a specific reflectivity \(R_{\text{eff}}\) (e.g. \(R_{3,\text{eff}}\)), only the mode of \(\lambda_{3}\) can be amplified by the cavity for lasing, the rest modes are filtered (Fig. 2b). Once the Si etalon is heated up by the metal heater, \(R_{\text{eff}}\) is changed (e.g. \(R_{2,\text{eff}}\)). Consequently, the mode of \(\lambda_{2}\) (instead of \(\lambda_{2}\)) is supported for lasing. In the other word, the mode selectivity of the laser cavity is dependent on the refractive index change of the Si etalon, which is in turn determined by the temperature of the etalon.

![Figure 2. Mechanism of the wavelength tuning based on TOE, with different lasing modes corresponding to the different reflectivity controlled by the Si etalon.](Image 340x627 to 419x667)

![Figure 3. Calculated wavelength shift and reflectivity as a function of the wavelength for a Si etalon at two different temperatures, with the temperature difference \(\Delta T = 6.5\) K.](Image 353x531 to 365x543)

Figure 3 gives the simulation results of the etalon reflectivity and the shift of the transmission peaks in response to the temperature change. When the temperature is increased by 6.5 K, the peaks of the reflectivity are shifted by 0.8 nm. In such case, the thermal expansion effect is neglected since its contribution to the tuning of the cavity is very small.

### 3. FABRICATION PROCESS

The overview of the fabricated MEMS tunable laser is shown in Fig. 4 by the scanning electron micrograph. All the MEMS structures, including the Si etalon, are fabricated on a silicon-on-insulator (SOI) wafer by
deep-reactive-ion-etching (DRIE). The structure layer is 75 µm and the oxide buffer layer is 2 µm thick. Before the etching process, an aluminum layer of 0.5-µm is deposited and patterned for Si etalon heating and electrical connections. After the etching process, the device is undercut with buffered oxide etch (BOE) in order to fully electrically isolate the FP chip bottom contacts and the Si etalon. After that, another layer of 0.2-µm thick aluminum is coated on the end flat facet of the etalon by thermal evaporation. Following that, the FP chip with the size of 250 µm long by 250 µm wide is assembled. Finally, the output fiber is inserted and fixed to the MEMS substrate through the self alignment to the etched tapered fiber trench.

The Si etalon is designed with a curvature profile of front surface, while the rear surface is flat. To further reduce the coupling loss between the FP chip and the Si etalon, the curved front surface of the etalon has been optimized, with a curvature radius of 175.08 µm. On the other hand, to improve the reflectivity of the rear surface, an aluminum metal coating is applied. As a result, the flat facet acts as a mirror. The long narrow heating elements are formed by serpentine aluminum wires of 2 µm wide on the top of the Si etalon.

4. EXPERIMENTAL RESULTS

Before evaluating the optical performance of the micromachined laser, the FP chip is characterized before assembly. The original spectrum output of the FP chip is shown in Fig. 5(a), with an injection current of 14.1 mA (its threshold is 12 mA). It is observed that the single chip operates in a multimode regime. After the chip is assembled onto the MEMS substrate to build the micromachined laser, the output spectrum is then characterized. During the experiment, the output spectrum is changed to single longitudinal mode as shown in Fig. 5(b) thanks to the wavelength selection property of the Si etalon. The inset exemplifies a close-up of the measured output spectrum of the device, showing a narrow linewidth of ~ 0.1 nm.

The static and dynamic performances of wavelength tuning are both important. In the former case, the Si etalons with different cavity lengths \( l_{\text{Si}} \) are fabricated for different tuning characteristics. Fig. 6 plots the wavelength shift versus the tuning current for two laser devices in which the Si etalons have the lengths of 206 µm and 106 µm, respectively. Experimental results show that both devices can obtain the same wavelength tuning range of 1542.5 to 1556.5 nm. However, the etalon with the length of 206 µm requires 18.7 mA while the other needs 22.7 mA. It shows that the laser with shorter Si etalon requires more current variation to achieve same wavelength tuning. The theoretical results are also plotted in Fig. 6. The discrepancy between theoretical and experimental modulation patterns is mainly due to those effects inherent in the experiments such as the nonideal characteristic of the output (which is not a plane wave) from the FP chip, coupling loss within the external cavity, diffraction effects and the roughness of the semi-reflective Si-air interfaces [13]. Additionally, the output power level observed for cavity length of 106 µm experiences a decrease as compared to that of the length 206 µm. It might be because that higher current induces more temperature increment but it causes a decay of the performance of the FP chip. In the dynamic response experiment, the tuning speed measures approximately 3.2
µs, which is comparable with the thermo-optic switching speed demonstrated in our previous work [12]. It is about 1000 times faster than the typical tuning speed of 1 ms in the other micromechanical tunable lasers [2-6].

Figure 7 shows the superimposed output spectra and the wavelength tuning relationship. In Fig. 7 (a), the laser output maintains a single longitudinal mode with the increase of the tuning current, but the wavelength peak moves to longer wavelength. According to Fig. 7 (b), the laser wavelength increases almost linearly when the tuning current applied to the Si etalon is increased from 0 to 18.7 mA. At the same time, the side-mode-suppression-ratio (SMSR) is also improved, with an average value of 22 dB.

Figure 7. Measured wavelength tuning. (a) Superimposed spectra of the laser output, and (b) wavelength shift as a function of the heating current.

5. CONCLUSIONS

In conclusion, this work demonstrates a MEMS tunable laser that utilizes the thermo-optic effect rather than the mechanical movement for wavelength tuning. The external cavity is constructed by a deep-etched silicon etalon, whose far end is coated with aluminum to serve as a flat mirror, and aluminum wires are patterned on top of the etalon as the microheater. Two devices are fabricated and tested; one has an etalon width of 106 µm while the other is of 206 µm. Both of them demonstrate the wave tuning range of 14 nm, but the longer etalon requires only 18.7 mA as compared to the 22.7 mA of the shorter etalon. The laser devices measure a fast response speed of 3.2 µs. This type of TOE-based MEMS tunable laser requires no mechanical movement for wavelength tuning and thus solves the fundamental problems in the previous demonstrated micromechanical tunable lasers such as limited tuning speed (typically 1 ms), complicated movement control and mechanical stability and reliability issues. In addition, this laser has simple configuration and planar structure, making it suitable for the integration with other semiconductor electronics and high-density photonic integrated systems.

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