Thermally-tuned Silicon Double Ring Resonator for External Cavity Tunable Laser

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Abstract— We designed and fabricated a thermo-optic tunable filter based on silicon double ring resonator for external cavity laser. The footprint of the device is $\sim 700\,\mu m \times 400\,\mu m$. The tuning range is about 16 nm and the tuning efficiency of the device is estimated to be about 0.56 nm/mW, owing to the Vernier effect.

1. INTRODUCTION

Silicon photonics has been considered a promising technology for 21st century [1]. To date, silicon photonic devices can be wafer scale produced on a silicon-on-insulator (SOI) platform, which are compatible with standard complementary metal oxide semiconductor (CMOS) technology [1–6]. SOI materials system has the inherent high-index contrast between the Si-SiO_2 ($\Delta n = 2.03$) with strong light confinement in the Si core [1, 2]. The high Δn permits to sharp bends and small sizes, thus, allowing the miniaturization of passive optical devices and leading to high-density photonic integrated circuits. The SOI optical devices offer the potential for integration with CMOS electronics in order to achieve monolithically integrated optoelectronic systems [3].

For the past decade, many research groups have demonstrated many silicon devices to process optical signals, such as coupling systems from optical fibers to optical waveguides, tunable filters and high-speed modulators [4]. These devices have been mainly focused on two major physical effects, namely, electro-optic and thermo-optic effects [5]. The electro-optic effect has the advantage of low-loss and low-power with relatively fast response time, but it required large drive voltages and tuning range is small. On the other hand, the thermo-optic effect is inherently lossless, which can be utilized to efficiently tune devices with negligible insertion loss. In addition, silicon has a relatively high thermo-optic coefficient (1.86×10^{-4}/K) [6], which allows for wavelength tuning and switching with relatively low power. The only shortcoming of these devices is slow response time [7]. Heating of photonic devices for the utilization of the thermo-optic effect has been widely used with integration of micro-heater close to the silicon device, which can reduce the optical absorption by the metal [5].

In this paper, we present a thermally-tuned silicon double ring resonator (DRR) based on Vernier effect for hybridly integrated external cavity tunable laser. It contains cascaded double rings on SOI with micro-heaters on the top, as schematically depicted in Figure 1. The Vernier effect is an effective approach to realizing a wide tuning range.

This paper is organized as follows. In the second section, the thermal tuning of the device is mathematically analyzed. In the Section 3, the fabrication of the device is discussed. In the Section 4, the external cavity tunable laser employing the double-ring filter is presented. Finally, some conclusions are drawn in Section 5.

2. THERMAL-TUNING DESIGN

In our design, we used the thermo-optic effect in silicon, which has a relatively high thermo-optic coefficient, causing a large shift of the resonant wavelength. A change of the effective index Δn_{eff} results in a shift of the resonant wavelength $\Delta\lambda = \lambda \cdot n_{eff}/n_g$ [8]. Here, n_{eff}, n_g are the effective refractive index and the group index, respectively. The height and width of the waveguide are designed to be 250 nm and 500 nm, respectively, which was chosen for TE single-mode operation at wavelength = 1550 nm. For one ring resonator, the variation of effective refractive index of about 0.02 is achieved when the temperature changes by 100 K, corresponding to a wavelength shift in the order of 8.4 nm, which is shown in Figure 2.

To achieve thermo-optic effect, we used micro-heater. The structure of the micro-heater is shown before in Figure 1. Here, the micro-heater is placed on top of the waveguide and is separated from the waveguide by a SiO_2 upper-cladding layer, which can reduce the optical loss. The micro-heater

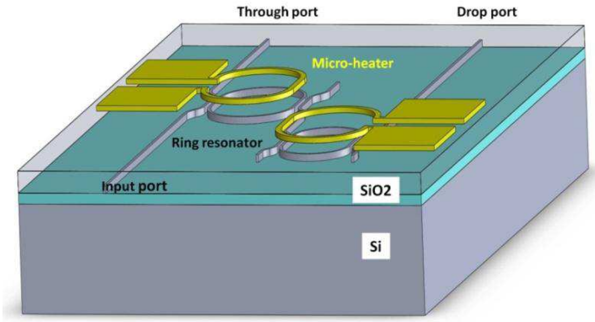


Figure 1: Schematic demonstration of the device.

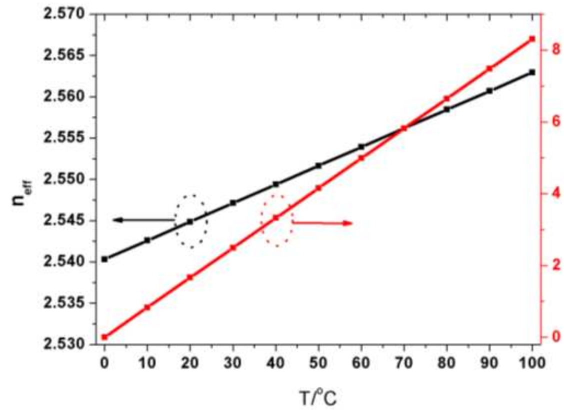
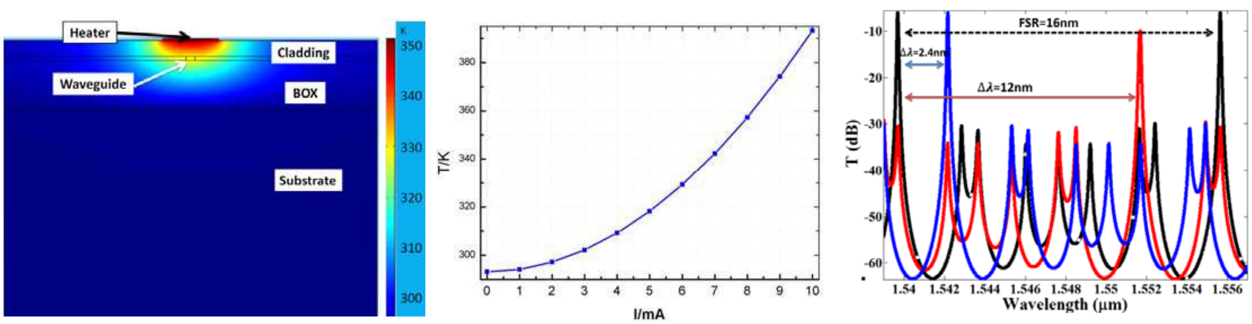


Figure 2: Variation of effective refractive index and resonant wavelength shift when the temperature changes.



(a) (b) (c)

Figure 3: (a) Temperature distribution at the cross-section of the waveguide when an electrical current of 6 mA is applied on the micro-heater. (b) Temperature variation of the waveguide when applying current in the micro-heater. (c) The resonant wavelength shift when different currents are applied on the micro-heaters.

has Ω shape, which conducts most of the heat along with the ring waveguide and confines the heat to reduce thermal crosstalk. Heat transport in the device is numerically simulated based on the heat-transport equation, as follows [5]:

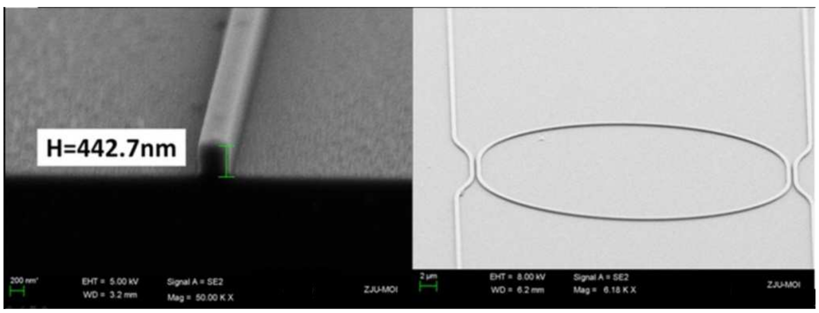
$$\nabla(-k\nabla T) + \rho c \frac{\partial T}{\partial t} = q_s \tag{1}$$

Here, k, c and ρ are the thermal conductivity, heat capacity and density of the material, respectively; q_s and T are the density of the heat power generation and the temperature, respectively. Using the finite-element method, the temperature distribution in the waveguide is calculated with applying 6 mA current as shown in Figure 3(a). When applying different current in the micro-heaters, a temperature variation is induced in the waveguide as shown in Figure 3(b). The free spectral ranges (FSRs) of the two racetrack ring resonators are designed to be 400 GHz and 500 GHz, respectively. In Figure 3(c), the black line is the transmission spectrum under room temperature when no electrical current is applied. The FSR of the double-ring filter is 16 nm. When 6 mA current is applied in the micro-heaters of the two resonators simultaneously, the resonant wavelength shifts by 2.4 nm, as shown by the blue line. When 6 mA current is applied in the micro-heater of the larger resonator alone, the resonant wavelength shift is 12 nm, as shown in the red line. The wavelength tuning is amplified five times by the Vernier effect. The tuning range is limited by the FSR, which is about 16 nm.

The resistance of micro-heaters of the double rings are 500 Ω, 590 Ω, respectively. When 6 mA is applied on each of the two micro-heaters, the total power consumption is about 39.2 mW and the tuning range is the same as the case with one ring resonator. The tuning efficiency in this case is about 0.06 nm/mW. With 6 mA is applied on the larger ring alone, the total power consumption is only 21.3 mW and the tuning efficiency increases to about 0.56 nm/mW, owing to the Vernier effect.

3. FABRICATION

The device in this work was fabricated on SOI wafer with a 250 nm silicon top layer and a 3 μm buried oxide (BOX) layer. The fabrication process comprises three steps with three different photolithographic mask layers: a waveguide layer and two metal layers. The waveguide layer was fabricated by means of electron-beam lithography using ma-N 2405 photoresist to pattern the samples on the SiO_2 mask, followed by dry etching of SiO_2 and Si. Figure 4(a) shows the cross-section of the etched waveguide. The total height includes the waveguide height and the thickness of the SiO_2 mask. The ring structure and the coupler section are shown in Figure 4(b). After etching and photoresist cleaning, a one-micron-thick layer of silicon dioxide is deposited as an upper-cladding layer by plasma enhanced chemical vapor deposition (PECVD).



(a) (b)

Figure 4: SEM images of (a) the waveguide cross-section and (b) the ring structure and the coupler section.

The metal was deposited in two steps using contact photolithography. The first step was photolithography of the micro-heaters and 100 nm Nichrome metal deposition, followed by lift-off. The second step consisted of photolithography of contact pads and Ti/Pt/Au (20 nm/20 nm/400 nm) deposition, followed by second lift-off. Table 1 shows the design parameters used in the fabrication of the device. The footprint of the device is $\sim 700\,\mu m \times 400\,\mu m$.

Table 1: Designed parameters for the fabricated device.

<table>
<tr><td rowspan="2">Waveguide cross-section</td><td colspan="2">Width</td><td colspan="2">Height</td></tr>
<tr><td colspan="2">500 nm</td><td colspan="2">250 nm</td></tr>
<tr><td rowspan="2">Coupling regions</td><td colspan="2">Gap</td><td colspan="2">Coupling length</td></tr>
<tr><td colspan="2">300 nm</td><td colspan="2">16 μm</td></tr>
<tr><td rowspan="2">Radii</td><td colspan="2">R_1</td><td colspan="2">R_2</td></tr>
<tr><td colspan="2">17.5 μm</td><td colspan="2">23.2 μm</td></tr>
<tr><td rowspan="2">Micro-heaters</td><td>Material</td><td colspan="2">Thickness</td><td>Width</td></tr>
<tr><td>Nichrome</td><td colspan="2">100 nm</td><td>3 μm</td></tr>
<tr><td rowspan="2">Contact pads</td><td>Material</td><td colspan="2">Thickness</td><td>Width</td></tr>
<tr><td>Ti/Pt/Au</td><td colspan="2">20 nm/20 nm/400 nm</td><td>150 μm</td></tr>
</table>

4. EXTERNAL CAVITY LASER

Using this double ring resonator as a wavelength-tunable filter, a III-V/SOI external cavity tunable laser with narrow emission linewidth is designed, which is schematically shown in Figure 5. The laser consists of an InP based gain chip, the DRR and a free-space transmission section. The latter uses graded-index lenses to couple the gain chip with the DRR, constructing a long external cavity. The double ring resonator is used for laser mode selection. And the laser emits from the front facet of the gain chip. The fabrication of the device is currently in progress and the results will be reported later.

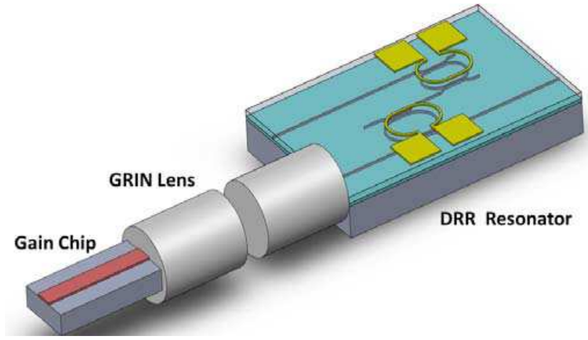


Figure 5: Schematic diagram of external cavity tunable laser.

5. CONCLUSION

In this work, numerical simulation of heat transport in micro-heater is presented for the study of thermal tuning of the silicon double ring resonator. The tuning efficiency of the device is estimated to be about 0.56 nm/mW, owing to the Vernier effect. The fabrication process of the device is discussed, and a design concept of external cavity tunable laser is presented.

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