High Efficiency Ring-Resonator Filter With NiSi Heater

Qing Fang, Junfeng Song, Xianshu Luo, Lianxi Jia, Mingbin Yu, Guoqiang Lo, and Yuliang Liu

***Abstract*— We demonstrate a high efficiency tunable ring-resonator filter on the silicon-on-insulator platform. The fabricated device shows the characteristics of a low power consumption and an ultrafast temperature-rise response. The ring-resonator is based on ridge-type silicon waveguide with NiSi heater formed on the silicon slab region surrounding the ring. The heat generated from the NiSi heater is directly transferred to the ring resonator through the silicon slab layer. Meanwhile, the ring-resonator is suspended by removing the adjacent SiO_2 layer and the underlying silicon substrate. The measured temperature-rise response time is only 1.25 μs. The power consumption for 1-nm wavelength shift is only 0.38 mW, corresponding to 4.9 mW/free spectral range. The power consumption reduces 92% as compared to a similar structure without the air-isolation trench.**

***Index Terms*— NiSi heater, ring-resonator, silicon-on-insulator platform, suspended structure, temperature-rise response.**

I. Introduction

RECENTLY, dramatically active research and development activities have been devoted in the field of silicon photonics due to the excellent silicon performances including low cost, high reliability, and mature process which is compatible with complementary metal oxide semiconductor (CMOS) technology [1], [2]. Ring-resonator is an ultra-compact filter structure [3], [4] which can selectively transmit light signal and would be potentially used in the wavelength division multiplexing (WDM) system. Other than WDM systems, it also finds the application in optical switches. However, ring-resonators are sensitive to the fabrication imperfection which makes resonance wavelengths different from the desired values, especially in the multi-ring filter systems [5]. Fortunately, such deviation caused by fabrication imperfection can be compensated by the thermo-optic effect [6]. In general, the thermal heater in tunable ring-resonator is isolated from the silicon waveguide using a SiO_2 layer sandwiched between the waveguide and the thermal heater. In order to minimize the optical loss caused by the absorption of thermal heaters, the SiO_2 layer cannot be too thin, e.g., a typical value is 2 μm. However, the thermal conductivity of the SiO_2 material is $\sim$ 0.014 W/cm·K at room temperature, only 1% of the thermal conductivity ($\sim$1.35 W/cm·K) of the silicon material. The temperature-rise time of such kind of tunable ring-resonator is usually long ($>$10 μs) due to the low thermal conductivity of the SiO_2 layer. Besides the slow response, the power consumption of such design is also high, which is more than 20 mW per free spectral range (FSR). A low power 1.10 mW/nm) tunable ring-resonator was reported in Ref. [6]. However, the temperature-rise time is as long as 6 μs.

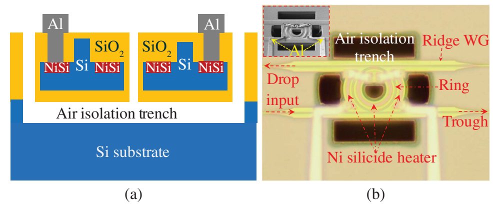

Fig. 1. (a) Cross-sectional schematic of the suspended tunable ring-resonator filter (not to scale). (b) Optical microscope image of the suspended tunable ring-resonator filter with bus waveguides, NiSi heater, and Al electrodes. SEM image of suspended tunable ring-resonator filter is shown in the inset.

Nickel silicide (NiSi) is usually used to reduce the contact resistance to enhance the high speed performance of integrated optical devices, especially for high speed modulator and photo-detector. NiSi can also be used as the heater material [7]. The NiSi heater is formed on the silicon slab region, so the heat generated can be directly transferred to the ring resonator through silicon slab layer, which makes the temperature of Si waveguide rise very fast.

In this letter, we demonstrate a suspended ring-resonator filter on silicon-on-insulator (SOI) platform by removing the adjacent SiO_2 layer and the underlying silicon substrate. The filter shows ultra-fast temperature-rise response (1.25 μs), low power consumption (0.38 mW/nm), and low optical transmission loss ($<$0.8 dB). The temperature change in the ring waveguide for one FSR shift (12.5 nm) is $\sim$168 °C.

II. Design and Fabrication

As mentioned above, silicon has an excellent thermal conductivity, so the heat can be transmitted very fast in silicon. NiSi is an alloy made of nickel and silicon, which can be used as the heater material [7] in silicon waveguide circuits. This kind of heater allows for fast heat transfer from heat source to the waveguide, since it can be formed directly

Manuscript received June 21, 2011; revised October 10, 2011; accepted November 16, 2011. Date of publication November 30, 2011; date of current version February 10, 2012. This work was supported in part by the National Natural Science Foundation of China under Grant 61177064.

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Digital Object Identifier 10.1109/LPT.2011.2177816

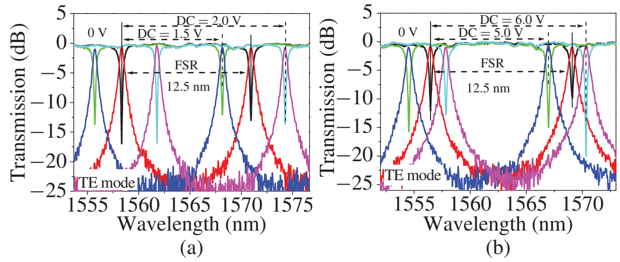

Fig. 2. (a) Optical power spectra of tunable ring-resonator filter with air isolation trench upon DC biases. (b) Optical power spectra of tunable ring-resonator filter without air isolation trench upon DC biases.

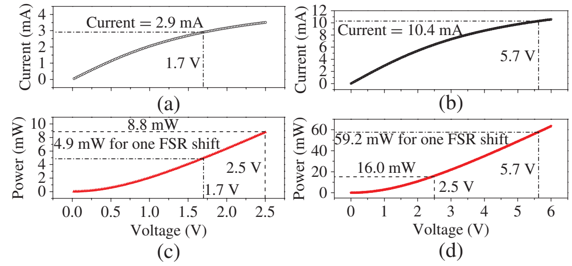

Fig. 3. (a) IV curve of tunable filter with isolation trench. (b) IV curve of tunable filter without isolation trench. (c) Power consumption of tunable filter with isolation trench. (d) Power consumption of tunable filter without trench.

on the silicon slab region. In the ring resonator filter reported in this work, NiSi alloy was used as thermal heater to enhance the temperature-rise response and a suspended micro-ring structure was fabricated by using air isolation trenches to prevent the heat from spreading into the adjacent SiO_2 layers. By employing both NiSi heater scheme and suspended ring structure, the reported devices show not only a fast temperature-rise response but also a very low power consumption.

The device was fabricated on an 8-inch SOI wafer with a 220-nm-thick top Si layer and a 2-μm-thick buried oxide layer. The fabrication of ring waveguide was previously reported in Ref. [5]. At first, the ridge waveguide was etched to have a height of 110 nm, remaining Si slab with the height of 110 nm also. After a 400-nm-thick SiO_2 layer was deposited, the window for NiSi heater formation was opened. Then, a 20-nm-thick Ni layer was deposited on Si slab and annealed to form NiSi alloy at 280 °C for 200 seconds. The nonreactive Ni was removed using H_2SO_4 solution. The sheet resistance of the NiSi was measured to be $\sim 9.7 \pm 0.2$ Ω/sq at the room temperature. Afterwards, a 1.5-μm-thick SiO_2 layer was deposited and electrical contact was formed with aluminum. Finally, the isolation trench was patterned with photo-resist, and the suspended structure was formed by removing the adjacent SiO_2 layer and the underlying Si substrate. This process is similar to Ref. 8.

Figure 1(a) shows the cross-sectional schematic of the suspended tunable ring-resonator filter. The whole ring-resonator is isolated with air isolation trench. The heat generated from NiSi alloy is transferred to the ring-resonator through the Si slab. The width of waveguide is 500 nm and the gap between ring and bus waveguide is 200 nm wide. In order to reduce the ring loss, its diameter is ~ 16 μm long. The space between NiSi and ring waveguide is 1 μm wide, which was carefully designed to minimize the NiSi absorption loss as well as ensure fast heat-transference. A reference device without isolation trench was also fabricated for comparison.

III. Measured Results and Analysis

Agilent optical measurement system (Photonic Dispersion and Loss Analyzer) was used to characterize the optical performances of the tunable filter. Other than this, the measurement setup also included a polarization controller, rotatable fiber holders, an optical polarizer, and a 6-axis auto-alignment system. The measurements were performed after selecting the transverse-electric (TE) polarization. An external temperature controller was used to keep the testing environmental temperature. In order to reduce the insertion loss, we used a tapered lensed fiber to couple the light into Si waveguide with a nano-tip. Figure 2 shows the measured optical spectra of the tunable filters with and without air isolation trenches under different direct-current (DC) biases. The power spectra were normalized by the transmission power spectrum of a short waveguide test structure, so as to decouple the coupling losses. The on-chip transmission loss is less than 0.8 dB, suggesting the space of 1 μm between the NiSi heater and ring is enough to avoid the absorption loss. The measured free spectral range (FSR) is 12.5 nm. For the wavelength shift of one FSR, the DC biases for the ring-resonator filters with and without air isolation trench were 1.7 V and 5.7 V, respectively.

In order to obtain the power consumption, the current-voltage (IV) characteristics of the two filters were measured as presented in Fig. 3. As can be seen, both the devices with and without isolation trenches show non-linear IV characteristics. With the increase of voltage, the consumed power and the temperature increase, making the resistance rise. Figure 3 shows that the resistance increasing rate of the filter with isolation trench is larger than that of the filter without isolation trench. We attribute the faster resistance increasing rate of the filter with isolation trench to the better heat confinement which induces faster temperature rise. Thus, as shown in Fig. 3, the power consumption of filter with isolation trench is lower under the same voltage. In order to evaluate the operating temperature in the ring-resonator filter, we first measured the power consumption with different wavelength shifts. Figure 4 shows the power consumption of the suspended filter, suggesting only 0.38 mW for one nanometer wavelength shift, which is $\sim$12 times lower than that of filter without isolation trench (4.60 mW). Based on the FSR shown in Fig. 2, we can calculate the power consumptions of both filters for one FSR wavelength shift, which are 4.9 mW and 59.2 mW, respectively. With the suspended structure, the power consumption reduces 92% as compared to the filter without isolation trench.

In consideration of the temperature factor, we can get the following expression based on the differentiation principle.

$$\frac{\Delta\lambda}{\lambda} = \frac{\partial n_{eff}}{\partial\lambda} \cdot \frac{\Delta\lambda}{n_{eff}} + \frac{\partial n_{eff}}{\partial T} \cdot \frac{\Delta T}{\partial n_{eff}} \tag{1}$$

where, λ and T are the wavelength and temperature. $\Delta\lambda$ and ΔT are the increments of wavelength and temperature. n_{eff} is

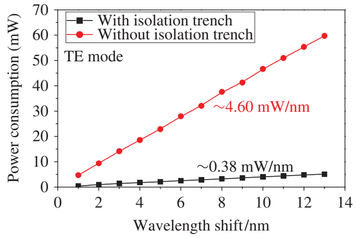

Fig. 4. Power consumption of both tunable filters for different wavelength shifts.

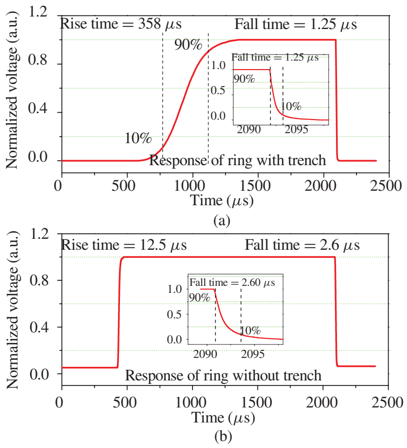

Fig. 5. Temperature-rise response of both tunable filters. (a) Temperature-rise time of tunable filter with isolation trench. (b) Temperature-rise time of tunable filter without isolation trench.

the effective refractive index of the waveguide. The waveguide group refractive index n_g can be defined as

$$n_g = n_{eff} - \lambda \cdot \frac{\partial n_{eff}}{\partial \lambda}. \tag{2}$$

From (1) and (2), we can get

$$\frac{\Delta\lambda}{\Delta T} = \frac{\lambda}{n_g} \cdot \frac{\partial n_{eff}}{\partial T} = \frac{\lambda}{n_g} \cdot \frac{\partial n_{eff}}{\partial n_{si}} \cdot \frac{\partial n_{si}}{\partial T}. \tag{3}$$

The operating wavelength is $\sim$1.55 μm and group index is 3.8 calculated from the measured FSR from $n_g = \lambda^2/(2\pi R \times FSR)$. The value of $\partial n_{eff}/\partial n_{si}$ can be calculated to be $\sim$ 1.01 based on the waveguide geometry and the optical properties of Si. When Si thermo-optic coefficient is $1.84 \times 10^{-4}\text{K}^{-1}$, the value of $\Delta\lambda/\Delta T$ for both tunable ring-resonator filters is 7.66×10^{-2} nm/K. Moreover, the relation between power consumption and the temperature change can be expressed as

$$\frac{\Delta W}{\Delta T} = \frac{\Delta W}{\Delta\lambda} \cdot \frac{\Delta\lambda}{\Delta T}. \tag{4}$$

Based on the result shown in Fig. 4, the power consumptions of 1K temperature change for the filters with and without isolation trenches are 2.91×10^{-2} mW and 3.52×10^{-1} mW, respectively. According to the power consumption results in Fig. 3 and the above calculated results, the temperature change of both tunable filters for one FSR shift are the same, $\sim$168 °C. This same temperature change suggests that the above calculation is reliable. The temperature change of 168 °C produces the Si refractive index change of 0.031 for one FSR shift.

Temperature-rise response of the tunable ring-resonator filters was measured using a square signal generator and an oscilloscope. The response time of the input square signal is less than 100 ns. The peak wavelength is used for characterization. For the filters with/without isolation trench, the peak wavelengths are 1558.4 nm and 1556.8 nm, respectively. The powers of applied signals with 300 Hz frequency for both filters are the same. For the filter with isolation trench, 1.7 V_{pp} square signal with +0.85 V offset is applied while for the filter with isolation trench, 1.3 V_{pp} square signal with + 0.65 V offset is applied. Figure 5 shows the optical responses for both filters. The 10%-90% temperature-rise time, corresponding to the fall time of the response in Fig. 5, is 1.25 μs and 2.60 μs, respectively. The response of filter without isolation trench is close to the result reported by IBM in Ref. [7]. The isolation trench contributes to the temperature-rise response because it can confine the heat in the ring waveguide region and interact effectively with the ring waveguide. To the best of our knowledge, this is the fastest temperature-rise response for thermally tunable microring filters reported so far. However, the temperature-fall time (rise time of response) of the filter with isolation trench is long of $\sim$358 μs, which is due to the isolation trench preventing the heat to spread out.

In conclusion, we have reported a high efficiency tunable ring-resonator filter on SOI platform. NiSi heater on Si slabs is employed to enhance the temperature-rise response, while a suspended structure with air trench is designed and fabricated to reduce the power consumption. The measured temperature-rise response time is only 1.25 μs. The power consumption for 1 nm wavelength shift is only 0.38 mW, corresponding to 4.9 mW/FSR. By employing air-isolation trench, the power consumption reduces as much as 92% as compared to the device without air trench.

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