Athermal SOI ring resonators by overlaying a polymer cladding on narrowed waveguides

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Abstract—**Athermal silicon ring resonators are experimentally demonstrated by overlaying a polymer cladding on narrowed silicon wires. The wavelength temperature dependence of the silicon ring resonator is reduced from 54.2 pm/°C to -4.9 pm/°C.**

Keywords-athermal;wavelength temperature dependence; silicon waveguides

I. Introduction

With mature CMOS (Complementary Metal Oxide Semiconductor) fabrication technology, silicon based devices have the potential to provide highly compact circuits with low cost, multifunctionality and enhanced performance. However, the large temperature dependence of silicon material degrades the performance of silicon-based devices ($dn/dT=1.8 \times 10^{-4}$/°C), in particular by temperature induced spectral shifts in the behavior of interferometric components. To stabilize the chip temperature to a constant level, external heaters or coolers have to be employed. These elements takes extra space and reduce the power efficiency of the whole chip.

Athermal silica-based devices have been extensively studied in the past[1, 2]. One of the simplest ways to achieve athermal silica-based devices is to overlay a polymer cladding on the circuit and use the polymer's negative thermo-optic (TO) coefficient to counterbalance the waveguide core's positive TO coefficient. The biggest obstacle in using this method for silicon waveguides is that silicon has a quite large thermo-optic coefficient, of the same order of magnitude as for the polymer material (10^{-4}/°C), which requires almost half of the light to penetrate out of the silicon core into the polymer cladding to achieve the athermal condition.

Recently, some groups experimentally demonstrated the possibility of achieving athermal silicon waveguides by overlaying a polymer cladding on silicon circuits[3-5]. In order to have more light into the polymer cladding, the dimension of the silicon waveguides is highly reduced either by narrowing the core width [3] or by thinning the core height [5], or by using a slot waveguide structure[4]. Narrowed waveguides and slot waveguides impose big challenges for fabrication and typically have relativelylarge losses.

Winnie N. Ye et al fabricated thinner silicon waveguide (700nm × 100nm) by conventional lithography to avoid narrowing the waveguide width [5]. However, the thinned layer is not thinned enough to achieve complete athermal condition: the wavelength shift of ring resonators is only reduced to 11.2pm/°C (compared to a value of 84.7 pm/°C for normal silicon waveguides). For this thinned core structure, quite a large ring radius (100µm in [5]) has to be used to avoid extra bending loss.

In this paper, we successfully achieve athermal silicon ring resonators by overlaying a polymer PSQ-LH cladding on uniform narrowed silicon waveguides. The ideal width for athermal silicon waveguides (with a height of 220nm) is found to be around 350nm. The wavelength temperature shift of the silicon ring resonator is reduced to less than 5 pm/°C, almost 11 times lower than normal silicon waveguides.

II. Theoretical Analysis

In 1993, Y. Kokubun et al first proposed to achieve the athermal waveguides by overlaying a polymer cladding on silica waveguides [1]. Later an athermal optical filter was successfully achieved by this method [2, 6]. The principle of that technique is quite simple: the polymer's negative TO coefficient is used to compensate silica's positive TO coefficient. This method is applicable to most devices, not only to single path filters, like Fabry-Perot, ring resonator, DFB and DBR filters, but also to multipath interferometric devices, like Mach-Zehnder interferometers and arrayed waveguides gratings (AWG).

Taking the ring resonator as an example, the temperature dependence of the resonance wavelength can be expressed as follows [2, 6]. For silicon waveguides, the dispersion effect has to be taken into account,

$$\frac{d\lambda_m}{dT} = \left(\frac{1}{L}\cdot\frac{dS}{dT}\right)\frac{\lambda_m}{n_{eff}} = \left(n_{eff}\cdot\alpha_{sub} + \frac{dn_{eff}}{dT}\right)\frac{\lambda_m}{n_g} \quad (1)$$

where λ_m is the resonant wavelength; n_{eff} is effective index of the waveguide; S is the optical length defined as $S = n_{eff}\cdot L$; α_{sub} is the substrate expansion coefficient; n_g is the group index of the waveguide.

The athermal condition is achieved when Eq. (1) equals zero. Normally silicon is used as substrate and the thermal

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expansion coefficient of Si is on the order of 10^{-6} [2, 6] (α_{sub}= 2.6×10^{-6}/°C); dn_{eff}/dT depends on the thermo-optic coefficient of the core material and cladding material. For highly confined waveguides, dn_{eff}/dT is of the same order as the TO coefficient of the core's material. As silicon has a large TO coefficient ($dn/dT=1.8\times10^{-4}$/°C [7, 8]), of the same order as polymer material ($dn/dT=-(1\sim3)\times10^{-4}$/°C), athermal silicon waveguides require almost half of the light out of the core.

To obtain athermal silicon waveguides, the dimension of the silicon waveguide should be highly reduced to allow more light extending out of the core waveguides. In this paper, a standard SOI (silicon on insulator) structure with a height of 220nm is used to design the athermal waveguides. Polymer PSQ-LH with a large TO coefficient of -2.4×10^{-4}/°C and low loss at 1550nm is chosen as the cladding material [9, 10]. By using Eq.(2), $d\lambda_m/dT$ of the TE mode for different widths of the SOI straight waveguide has been calculated (Fig.1). dn_{eff}/dT and n_g are calculated by FIMMWAVE (©PhotonDesign Ltd). The index and TO coefficient of silicon is set as 3.4757 (20°C) and 1.8×10^{-4}/°C. The index of silica and polymer PSQ-LH is set as 1.444 (20°C) and 1.515 (20°C). As shown in Fig.1, the $d\lambda_m/dT$ of standard 500nm width SOI waveguides (with polymer overlay) is near to +60pm/°C; by narrowing the width of SOI waveguides, $d\lambda_m/dT$ is reduced to zero and then becomes negative. From the theoretical calculation results, the ideal width for athermal silicon waveguide is around 306nm (Fig.1).

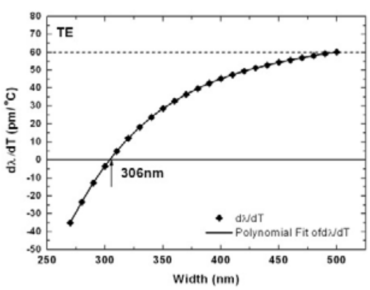


Fig.1 Calculated wavelength temperature dependence of TE mode for SOI waveguide with polymer overlay as a function of waveguide width

III. Fabrication & Measurement Results

A. Waveguides Fabrication

As shown in Fig.1, athermal SOI waveguides are achieved when a relatively small waveguide core width is used. And the temperature dependence of the resonance wavelength becomes more sensitive to the waveguide core width as the core width decreases. Therefore, high quality, high resolution fabrication technologies are required for these narrow silicon waveguides. The narrow SOI waveguides in this paper are fabricated by deep UV lithography with standard CMOS fabrication technology [11, 12]. This technology offers both the required resolution and the throughput for commercial application.

The SOI wafer with a silicon thickness of 220nm and an oxide layer of 2μm is used for this work. Simple racetrack ring resonators with different waveguide widths are designed and fabricated. Referring to the theoretical calculation results mentioned above, the ideal width for the athermal waveguides is around 306nm. So ring resonators with a narrow width of 300nm and 350nm are designed on the mask. The waveguide width can be adjusted a little by varying the exposure dose when doing deep UV lithography[11, 12]. The racetrack ring resonators are designed with different radius, a coupling length of 2μm, and a gap of 180nm.

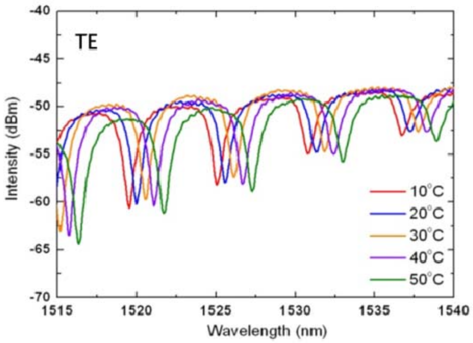
B. Measurement Results

To couple light in and out of the silicon wires from a single mode fiber, shallow etched (70nm) gratings are fabricated near the edge of each waveguide[11-14]. This kind of grating has polarization selectivity and therefore the transmission spectra measured below are all for TE mode polarization. A broadband infrared light source (SLED) and spectrum analyzer (Agilent 86140B) are used for the characterization of the transmission spectrum of the ring resonator. To measure the transmission spectrum at different temperatures, the sample is mounted on a heating system to accurately control the chip temperature. Fig.2 shows the measured transmission spectrum of a ring resonator (Width=350nm, Gap=180nm, L=2μm, R=15μm) for temperatures from 10°C to 50°C with an interval of 10°C. By linear fitting of one resonance wavelength at different temperatures, the wavelength temperature dependence $d\lambda/dT$ is extracted (Fig.3). As shown in Fig.3, the wavelength temperature dependence of the 350nm-width ring resonator is reduced from 54.2pm/°C to -4.9pm/°C after overlaying a polymer PSQ-LH cladding. The ideal width for the athermal ring resonator is found to be around 350nm, a little different from the theoretically calculated value of 306nm.

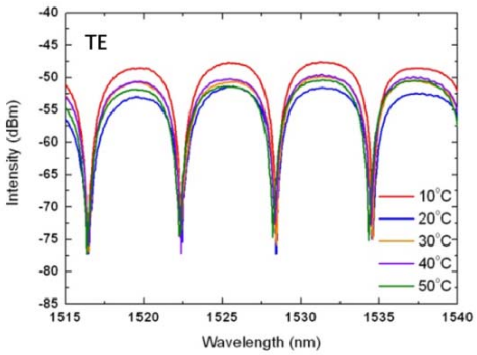
It has to be pointed out that the value $d\lambda/dT$, which is calculated from the linear fitting of the data, is not an absolute value. The spectrum analyzer resolution, temperature measurement range, the number of the data taking into account for linear fitting all have some influence on the value of $d\lambda/dT$, especially when the waveguide width is near the athermal condition and the $d\lambda/dT$ slope is quite small. Taking into account the above uncertainties, a conclusion can be drawn that the wavelength temperature dependence of silicon ring resonator can be reduced to less than 5 pm/°C after deposition of a polymer cladding, almost eleven times less than normal silicon waveguides. [10]

IV. Conclusion

Athermal silicon ring resonators are experimentally demonstrated in this paper. Standard deep UV lithography and dry etching are used for fabricating such silicon wires. By overlaying a polymer layer on narrowed silicon wires, the wavelength temperature dependence of a silicon ring resonator is reduced to less than 5 pm/°C, almost eleven times less than normal silicon waveguides. The ideal width to achieve athermal condition for the TE mode of 220nm-height SOI waveguides is found to be around 350nm.



(a)



(b)

Fig.2 Transmission spectrum of a ring resonator with width of 350nm at different temperatures (a) before overlaying a polymer cladding (b) after overlaying a polymer cladding
(Width=350nm, Gap=180nm, L=2μm, R=15μm)

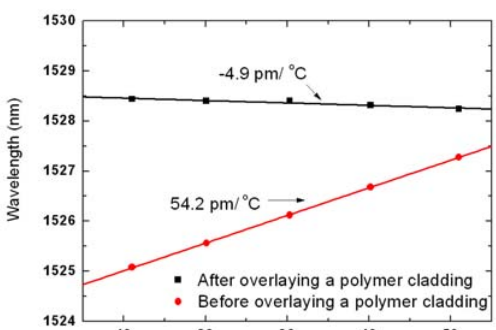


Fig.3 Linear fit of the wavelength versus temperatures

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