Athermalizing and Trimming of Slotted Silicon Microring Resonators With UV-Sensitive PMMA Upper-Cladding

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***Abstract*—This letter experimentally demonstrates significant reduction in the resonance thermal sensitivity of the slotted silicon microring resonators by exploiting polymethyl methacrylate (PMMA) as upper-cladding. We investigate the resonance temperature dependence on the slot width with and without PMMA upper-cladding. The experimental results show that the temperature dependence is reduced from 91 pm/°C for a regular microring resonator to 27 pm/°C for the PMMA-clad slotted microring resonator. The ultraviolet (UV) sensitive PMMA upper-cladding also allows the resonance wavelengths of slotted microring resonators shift by 0.5 nm under UV light trimming. With the demonstrated schemes, each individual optical component can be athermalized and precisely registered to standard wavelengths for a future multiwavelength optically interconnected computing system-on-a-chip.**

***Index Terms*—Integrated photonic devices, microring resonators, silicon photonics, slotted waveguides, wavelength-division multiplexing.**

I. Introduction

OPTICAL interconnects can offer ultrahigh throughput, minimal access latency, and low-power dissipation that remains independent of capacity and distance [1]. Recent advances of the silicon photonics technologies [2], [3] indicate that optical interconnects based on submicrometer-scale silicon waveguides are a viable alternative to the conventional electrical interconnects in resolving the bandwidth and power bottleneck. The complementary metal–oxide–semiconductor compatibility of such photonic interconnects is also an exciting opportunity for realizing wavelength-division-multiplexing-based multicore computing system-on-a-chip where concurrency and parallelism are mapped onto multiwavelengths. However, the large thermo-optic (TO) coefficient of the silicon material dictates that even small ambient temperature variations will cause significant changes in its refractive index, resulting in significant deterioration of the performance of photonic devices and systems. In particular, high-Q microring resonators, one of the most attractive building blocks for optical interconnection, are extremely sensitive to the temperature variation. A 1 °C temperature change can shift the resonance wavelength of ~0.1 nm, which is in the same order as the resonance linewidth of the microring devices.

In order to control the resonance wavelengths, p-i-n diodes [4] and microthermal heaters [5] are introduced as tuning elements. Yet these active tunings are at the expense of extra power consumptions and additional control complexity that can couple to possibly induce chaotic thermal oscillation.

In this letter, we present slotted microring resonators upper-clad with polymethyl methacrylate (PMMA) to reduce the thermal sensitivity. With properly design, slotted waveguides have only one symmetrical mode and thus can be regarded as single-mode waveguides. The slotted waveguides have the unique feature that the electrical field is highly enhanced in the slot region for transverse-electric (TE) polarization (electric field parallel with the chip plane) and thus can interact more strongly with the PMMA filled inside the slot [6], [7]. PMMA has the opposite TO coefficient compared to the silicon material, and thus by proper design, the effective index of the slotted waveguides can be independent of temperature, such that the resonances can be maintained steady under temperature variations [8]–[10]. Another advantage of using PMMA cladding is that the resonant wavelengths can be trimmed by ultraviolet (UV) illumination on the PMMA layer, so that accurate wavelength registration of the athermal silicon microring resonator becomes possible.

II. Device Fabrication

The slotted microring resonator devices were fabricated using a silicon-on-insulator wafer with top silicon layer thickness of 0.26 μm and buried oxide layer thickness of 2 μm. The wafer was first coated with negative e-beam resist Microchem Corp. Ma-N 2403 with a thickness of ~0.35 μm and then exposed using Raith 150 e-beam lithography system with exposure dose of 80 $\mu C/cm^2$ at 20 kV acceleration voltage. The device pattern was transferred onto the silicon layer using HBr–Cl_2 gas-based reactive-ion-etching in a transformer coupled plasma lam etcher. The dry etched depth is ~0.24 μm and a 20-nm-thin silicon layer remains as the slab region.

Fig. 1(a) shows the scanning electron microscope (SEM) image of the fabricated slotted microring resonator. The microring resonator radius is 5 μm. The slotted waveguide width is 0.5 μm with a thin slot in the waveguide center. The gap between the mirroring resonator and straight waveguide is 0.15 μm. Note that slotted waveguides are used for both the

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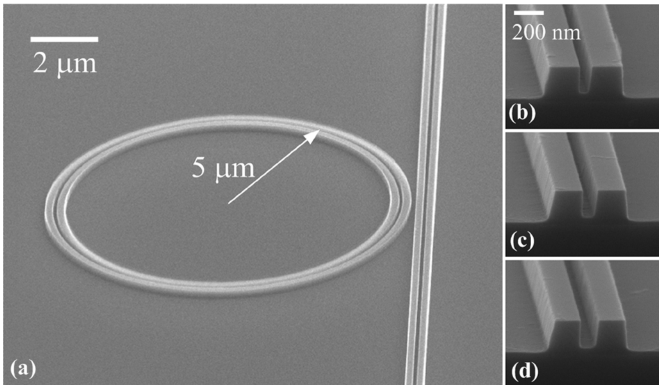

Fig. 1. (a) SEM image of a slotted microring resonator. Microring resonator radius is 5 μm. (b)–(d) Zoom-in SEM images of the slotted waveguide cross-section with various slot widths of (a) 100, (b) 120, and (c) 140 nm. Waveguide width is fixed at 0.5 μm.

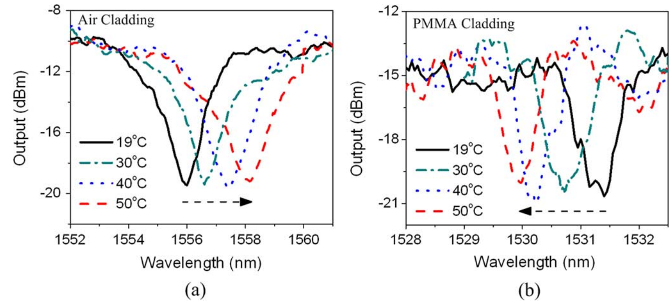

Fig. 2. Measured TE-polarized transmission spectra of the slotted microring resonator with (a) air-cladding and (b) PMMA-cladding at various temperatures. The slot width is 140 nm.

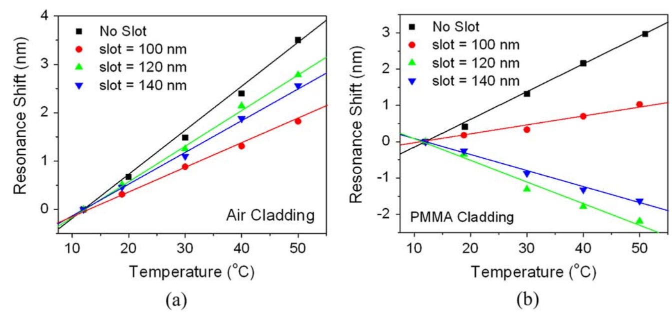

Fig. 3. Resonance shift varies as a function of substrate temperature for the slotted and regular (no slot) microring resonator devices with (a) air-cladding and (b) PMMA-cladding. Straight lines are the linear fitting.

straight waveguide and microring resonator waveguide for phase-matched coupling between them. Fig. 1(b)–(d) shows the zoom-in views of the slotted waveguide cross-sections with three different slot widths of 100, 120, and 140 nm. As the waveguide width is fixed at 0.5 μm, the two silicon strips composing the slotted waveguide are narrowed for the wider slot.

III. Experimental Results and Analysis

We used lensed fiber ($\sim$2.5-μm spot size) for the slotted waveguide input and output coupling. Coupling loss per facet is $\sim$15 dB, relatively high due to the mode mismatch between the fiber and slotted waveguide, which yet can be improved by using strip-to-slot waveguide transformers [11] and inverter tapers [12]. The waveguide propagation loss we measured is $\sim$5 dB/mm, mainly coming from sidewall roughness induced scattering loss.

To investigate the resonance temperature dependence, we used a thermo-electric cooler to set the device substrate temperature. We first characterized the resonance shift upon temperature change for the devices without any upper cladding (air cladding), and then coated the devices with a layer of PMMA and repeated the measurement for their temperature responses.

Figs. 2(a) and 4(b) show the resonance shift under various temperatures with air cladding and PMMA cladding for the slotted microring resonator with 140-nm slot. For air cladding, the slotted microring resonator has a resonance quality-factor (Q-factor) of $\sim$800 and extinction ratio of $\sim$9 dB, from which we deduce that the round trip loss is $\sim$0.3 dB, corresponding to 10-dB/mm propagation loss in the ring. When the temperature increases, the resonances experience redshift as expected, since the microring resonator composition materials silicon and silica both have positive thermal coefficients (1.84×10^{-4} for silicon and 1.0×10^{-5} for silica). With PMMA cladding, the Q-factor increases to $\sim$1700 and extinction ratio decreases to $\sim$6 dB. Lower refractive index contrast can essentially reduce the scattering loss. Lower internal loss and higher coupling also make the device work towards over-coupling regime, hence lowering the resonance extinction ratio. In contrast to the air-clad case, the resonance experiences a continuous blueshift because the negative thermal coefficient material PMMA (thermal coefficient -1.2×10^{-4}) over-compensates the device.

We compared the resonance shift temperature sensitivity for various slot widths. Fig. 3(a) and (b) shows the resonance shift as a function of substrate temperature with air cladding and PMMA cladding. The resonance shift curves for a regular microring resonator (no slot) are also included as a comparison. For the air cladding, the regular microring resonator has the highest thermal sensitivity of 92 pm/°C, and the slotted microring with 100-nm slot has the lowest thermal sensitivity of 48 pm/°C, nearly half of that of the regular microring resonator. The slotted microring resonators with wider slots (120 and 140 nm) have a slightly higher thermal sensitivity, implying that less optical field is concentrated in the air region compared with 100-nm slot device.

For the PMMA cladding, the regular microring resonator still has the highest thermal sensitivity of 76 pm/°C and the slotted microring resonator with 100-nm slot also has the lowest thermal sensitivity of 27 pm/°C. Both the slotted microring resonators with 120 and 140 nm have negative TO coefficients, which indicate that their thermal coefficients for the waveguides are over-compensated by PMMA upper cladding in both cases.

In order to further explore the waveguide thermal sensitivity, we also used a finite difference method to numerically calculate the effective index and get its temperature variation $\Delta n_{\rm eff}/\Delta T$ as a function of slot width and slab thickness, as shown in Fig. 4(a). Fig. 4(b) and (c) shows the waveguide mode profile for various slot widths and slab thicknesses. Waveguides with smaller bending radii had their waveguide optical

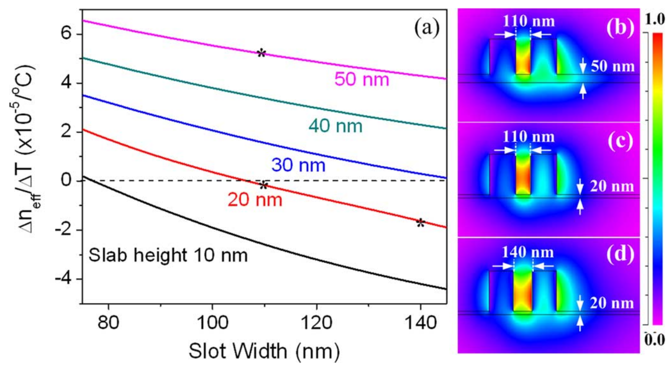

Fig. 4. (a) Numerical calculated 5-μm radius slotted waveguide effective index changes as a function of slot width and slab thickness. Waveguides are clad with PMMA. (b)–(d) Electrical filed intensity patterns for various slotted waveguides: (b) slot 100 nm and slab 50 nm; (c) slot 120 nm and slab 20 nm; and (d) slot 140 nm and slab 20 nm.

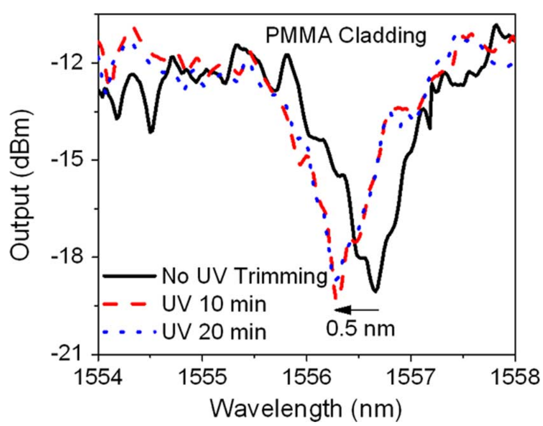

Fig. 5. Resonance shift upon UV trimming of the slotted microring resonator with PMMA cladding.

modes leaning towards the outer sidewall, implying that the materials filled in the slot and surrounding both significantly affect the effective index of the curved slotted waveguide. A thin slab and wide slot tends to push the optical field to the upper cladding, making the waveguide thermal sensitivity more dependent on the upper cladding material. From the simulation, the zero thermal sensitivity condition can be obtained: slot width 105 nm and slab thickness 20 nm is one of the optimum combinations. In contrary to the simulation, we found that the thermal sensitivity in our experiment does not monotonically decrease with slot width. We attribute this complication to the nonuniform silicon etch and PMMA coating.

PMMA cladding of the slotted microring resonators not only compensates for the resonance thermal shift, but also provides a convenient way to accurately control the resonance wavelength with UV trimming. Illuminating UV light onto the PMMA layer can change its refractive index, and as a result, the resonance wavelengths can be changed accordingly. Fig. 5 shows the resonance spectra before and after UV trimming for the slotted microring resonator with 100-nm slot. The employed UV light intensity is $\sim$700 mW/cm^2 with its central wavelength at 365 nm. After 10-min trimming, the resonance blueshift is saturated at $\sim$0.5 nm. The trimmed PMMA is quite stable and even after one week, the resonance is still remains at the shifted position.

IV. Conclusion

We demonstrated that PMMA upper cladding on slotted microring resonators can greatly reduce the temperature dependence of the resonance wavelengths and that UV-trimming can offer an effectively way to achieve wavelength registration. The experimental results showed the lowest temperature dependent wavelength shift is 27 pm/°C, less than one third of that in a regular air-clad microring resonator. It is possible to attain nearly athermal response with properly designing the slotted waveguides. The UV-trimming of the PMMA layer resulted in the shift of the resonance wavelength by 0.5 nm. The athermalization and the trimming capability of the slotted silicon waveguide devices imply future optically interconnected computing systems with stable, low power, and high-performance applications.

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