Athermal silicon microring resonators with titanium oxide cladding

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Abstract: We describe a novel approach for CMOS-compatible passively temperature insensitive silicon based optical devices using titanium oxide cladding which has a negative thermo-optic (TO) effect. We engineer the mode confinement in Si and TiO2 such that positive TO of Si is exactly cancelled out by negative TO of TiO2. We demonstrate robust operation of the resulting device over 35 degrees.

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References and links
1. Introduction

Integrated photonic devices are extremely sensitive to ambient temperature fluctuations which 
limit their integration in wavelength sensitive applications. This problem is especially severe in 
silicon photonics where high index contrast, large thermo-optic coefficient of Si \(^1\) and high 
quality factors make the microring resonators extremely susceptible to thermal fluctuations. For 
example, a Si ring resonator with a quality factor of 10,000 will tune out of resonance with only 
1°C change in temperature.

Solutions to overcome the temperature sensitivity have been proposed using polymers, exter-
nal temperature compensating devices or active control of device temperature. Table 1 summa-
rizes previously reported temperature stabilization schemes and their corresponding advantages 
and disadvantages.

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Here we describe a novel approach for passive and CMOS-compatible temperature insensitive 
integrated optical devices using a metal-oxide cladding having negative thermo-optic effect. 
Metals oxides like TiO\(_2\) and SrTiO\(_3\) have been investigated in semiconductor industry as a gate 
dielectric \cite{15}. These metal oxides also have negative thermo-optic coefficient due to presence 
of a soft electronic band \cite{16} \((TO_{\text{TiO}_2} \sim -1 \times 10^{-4} K^{-1}, TO_{\text{SrTiO}_3} \sim -1 \times 10^{-5} K^{-1})\). This is 
in contrast to commonly available dielectrics and semiconductors which have positive thermo-
optic coefficients \((TO_{\text{Si}} = 1.8 \times 10^{-4} K^{-1}, TO_{\text{SiN}} \sim 2 \times 10^{-5} K^{-1}, TO_{\text{SiO}_2} \sim 1 \times 10^{-5} K^{-1})\).

There has been some limited effort in reducing temperature sensitivity of optical devices using 
TiO\(_2\) overcladding \cite{17–19}. Ref \cite{18} has done a thorough analysis of TiO\(_2\) deposition and 
showed close to athermal performance. Here we show that completely athermal optical devices 
can be realized by engineering the mode-overlap between Si based materials (Si / SiN/ SiO\(_2\))
and TiO$_2$. This scheme of temperature compensation is CMOS-compatible, lossless, does not require any extra footprint and can lead to very large temperature operating range.

2. Athermal design

In order to ensure that the positive TO effect of the Si core is exactly cancelled out by negative TO effect of the cladding, we engineer the optical mode confinement in TiO$_2$ cladding layer by tailoring the waveguide dimension and the cladding thickness. We consider both transverse electric (TE) and transverse magnetic (TM) like optical modes in a 220nm thick Si guiding layer with varying waveguide widths and TiO$_2$ cladding thicknesses. Figure 1(a) shows the Poynting vector of the TE mode of a 250nm wide hybrid TiO$_2$ - Si waveguide and temperature sensitivity of the resonance wavelength, when the TE mode is in resonance. Figure 1(b) shows the same for the TM mode. Optical modes are simulated using a Finite Element Method based solver (COMSOL), assuming the thermo-optic coefficients mentioned previously. The refractive indices of TiO$_2$ was assumed to be 2.35 (measured using ellipsometry). Temperature sensitivity is characterized in terms of resonance wavelength change with temperature ($\frac{\partial \lambda_0}{\partial T} = \frac{\lambda_0}{n_e} \frac{\partial n_{eff}}{\partial T}$). It is important to note that this sensitivity is independent of device structure (ring resonators or photonic crystal cavitites) and depends only on modal confinement in Si. For both TE and TM polarizations, the resonance wavelength sensitivity is $\sim$ 0.1nm/K for modes strongly confined in Si, and without any TiO$_2$ cladding. This sensitivity decreases as the mode is delocalized into
the TiO$_2$ cladding and the thickness of the TiO$_2$ cladding is increased. For achieving true athermal operation, the exact geometry of the Si waveguide and TiO$_2$ cladding thickness needs to be chosen very carefully. For TM mode of a 220nm thick silicon waveguide, any waveguide width will have a corresponding TiO$_2$ cladding thickness that would allow athermal operation. On the other hand, for the TE mode, if the waveguide is too wide such that the optical mode is strongly confined in Si, athermal operation will not be possible irrespective of TiO$_2$ cladding thickness.

3. Fabrication

The athermal ring resonators were fabricated on a 220nm thick silicon-on-insulator (SOI) device layer. The waveguides were patterned using electron beam lithography and etched in chlorine chemistry in an inductively coupled reactive ion etcher. Titanium oxide was deposited on top of the waveguides using reactive sputtering of a titanium target in O$_2$. The sputtering was performed at a pressure of $2 \times 10^{-6}$ Torr and 26 W power. Sputtered TiO$_2$ films were characterized using a visible-near IR ellipsometer and Raman spectroscopy. Refractive index of $\sim 2.35$ was measured at near IR wavelengths. Raman spectrum of the sputtered sample shows no visible peaks, indicating the amorphous nature of the deposited TiO$_2$ film. AFM scan of the surface (Fig. 2(b)) indicates surfaces roughness below 2 nm RMS. Figure 2(a) shows a microscope image of a fabricated Si ring resonators with TiO$_2$ cladding. Si waveguide width in the fabricated ring resonators was varied from 450nm to 150nm to observe the effect of mode delocalization on thermal sensitivity. Inset of Fig. 2(a) shows cross section of a waveguide with 150nm width and 200nm thick TiO$_2$ cladding.

4. Experimental results

We demonstrate temperature insensitive operation of a Si microring resonator with TiO$_2$ overcladding. Figure 3(a) shows the temperature sensitivity of resonance wavelength of the fab-
Fig. 3. (a) Measured resonance sensitivity to temperature as a function of waveguide width, for TE and TM modes. Resonance sensitivity decreases significantly as mode is delocalized into TiO₂ cladding. Theoretical curves are obtained assuming 200nm thick TiO₂ layer. (b) Temperature dependence of the resonance for hybrid Si-TiO₂ resonator (athermal TM mode, right) compared to that of a conventional Si resonator (left).

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ricated microring resonators, for different waveguide widths and polarizations. All of these resonators were fabricated on the same chip. The temperature sensitivity was measured by collecting spectra over 10 degrees, at intervals of 2 degrees, followed by a linear fit to resonance wavelengths. Error bar corresponds to uncertainty in the linear fit. Each waveguide width corresponds to a different confinement in the Si core. Measured data is compared against numerically calculated sensitivity assuming TiO₂ thickness of 200nm and λ₀ = 1550nm. For the case of TE polarization (Fig. 3(a) blue line), the temperature sensitivity is around 0.09nm/K when the mode is strongly confined in Si (450nm wide waveguide). However as the optical mode is delocalized more into TiO₂, temperature sensitivity decreases and becomes negative (−0.03nm/K) for 150nm wide waveguide. For the case of TM polarization (Fig. 3(a) red line), the sensitivity is around 0.04nm/K for a strongly confined mode in Si and very close to zero for 150nm wide waveguide. Figure 3(b) shows the corresponding athermal transmission spectrum compared to that of a resonator without any thermal compensation. Losses in the deposited TiO₂ was estimated to be around 16 dB/cm, by comparing change in quality factor of the resonances as a function of mode confinement in Si and TiO₂. This loss can be reduced significantly by improving the deposition and reducing scattering at Si – TiO₂ interface. Optical losses in similar material has been reported to be less than 3 dB/cm [20, 21].
We demonstrate error free operation of hybrid TiO$_2$ – Si microring resonator based optical filter over 35 degrees. The device used was similar to the one shown in Fig. 2(a) with an extra drop waveguide coupled to the ring. We transmitted $2^{31}-1$ PRBS (pseudo random binary sequence) data at 5 Gbps through the device, centered at resonance wavelength, and varied the stage temperature (using a thermoelectric stage and temperature controller). The data was then sent to a commercial receiver (Picometrix PT15) and a bit error rate detector. Figure 4(a) shows the bit error rate (BER) and corresponding eye diagrams for both the athermal ring resonator and a conventional Si resonator with similar quality factor (where the temperature sensitivity is around 0.09 nm/K). For the conventional uncompensated device, BER becomes greater than 1E-9 after only 2 degrees (Fig. 4(a) blue line). For our athermal device, data transmission is close to error free over 35 degrees (Fig. 4(a) red line). This operating range should extend even further. Slight variations in BER is due to fluctuation in fiber to waveguide coupling with temperature. We also characterized the power penalty of the athermal optical filter for a 1°C fluctuation in temperature, and compared it to an uncompensated Si resonator based filter [7]. The 1°C temperature fluctuation was introduced by placing the sample on a temperature controlled stage and modulating the stage temperature at a rate of 1 Hz. This amount of temperature fluctuation is small enough such that the waveguide to fiber coupling is minimally perturbed, while modeling a realistic operating condition. The conventional resonator has a power penalty $> 1dB$, while the hybrid Si – TiO$_2$ resonator has power penalty $< 0.1dB$ (Fig. 4(b)).

5. Conclusion

In conclusion, we demonstrated a new technique for realizing athermal Si photonic devices using a TiO$_2$ over cladding. This approach is CMOS compatible, low loss and yields large temperature operating range. Simulations show that athermal operation is relatively insensitive to slight variations in TiO$_2$ thickness. Engineering the mode confinement is extremely critical for achieving athermal operation. It should be noted that this method is mainly applicable for resonators with radius $> 10\mu$m radius due to the need for a slightly delocalized mode. This method of passive athermalization can lead to practical monolithic integration of silicon photonic devices.
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