Athermal silicon optical add-drop multiplexers based on thermo-optic coefficient tuning of sol-gel material

SOHA NAMNABAT,1,* KYUNG-JO KIM,1 ADAM JONES,2 ROLAND HIMMELHUBER,1 CHRISTOPHER T. DEROSE,2 DOUGLAS C. TROTTER,2 ANDREW L. STARBUCK,2 ANDREW POMERENE,2 ANTHONY L. LENTINE,2 AND ROBERT A. NORWOOD1

1College of Optical Sciences, University of Arizona, Tucson, AZ 85721, USA
2Sandia National Labs, Albuquerque, NM, USA
*soha@optics.arizona.edu

Abstract: Silicon photonics has gained interest for its potential to provide higher efficiency, bandwidth and reduced power consumption compared to electrical interconnects in datacenters and high performance computing environments. However, it is well known that silicon photonic devices suffer from temperature fluctuations due to silicon’s high thermo-optic coefficient and therefore, temperature control in many applications is required. Here we present an athermal optical add-drop multiplexer fabricated from ring resonators. We used a sol-gel inorganic-organic hybrid material as an alternative to previously used materials such as polymers and titanium dioxide. In this work we studied the thermal curing parameters of the sol-gel and their effect on thermal wavelength shift of the rings. With this method, we were able to demonstrate a thermal shift down to -6.8 pm/°C for transverse electric (TE) polarization in ring resonators with waveguide widths of 325 nm when the sol-gel was cured at 130 °C for 10.5 hours. We also achieved thermal shifts below 1 pm/°C for transverse magnetic (TM) polarization in the C band under different curing conditions. Curing time compared to curing temperature shows to be the most important factor to control sol-gel’s thermo-optic value in order to obtain an athermal device in a wide temperature range.

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References and links
1. Introduction

The emergence of social media, video streaming, online gaming, and lately the Internet of things, has led to a significant increase in demand for data transfer and file sharing. As a result of this demand, datacenters and high performance computing (HPC) have gained a lot of attention for enhancing cloud computing and facilitating these high data demands. However, legacy datacenter and HPC architectures are struggling to keep up because of thermal management challenges [1] and limitations from electrical interconnects.

Electrical interconnects have turned into a bottleneck to more advanced integration due to their high power dissipation and poor performance in denser interconnects [2, 3]. On the other hand, photonic integrated circuits and interconnects have rapidly advanced and are expected to eventually replace electrical interconnects in many applications (chip-to-chip, on-chip, on-board, rack-to-rack, etc.). The transition to photonic devices would provide increased functionality, reliability, low cost and compact size, all of which are attractive for optical communications and bio-sensing, among other areas. Furthermore, they support higher bandwidth, denser interconnects, with higher efficiency in addition to reduced cross talk, latency, and specifically power consumption [3, 4]. In particular, the silicon photonics platform is becoming the preferred technology for photonic integrated circuits [5, 6], due to its high index contrast, low optical loss in the major telecommunications optical windows, and established CMOS fabrication technology. However, silicon's large thermo-optic coefficient ($1.8 \times 10^{-4}/\degree{C}$), can limit the application of these devices in applications where large temperature changes are experienced. This is especially a problem for WDM devices and narrowband optical filters where the wavelength shifts by an amount of 50-100 pm/°C.

There have been a number of efforts to achieve temperature independent silicon photonic devices by using both active and passive thermal compensation methods [7]. The active approach comprises the use of external—heaters or thermo-electric coolers—or integrated heaters and various monitoring mechanisms connected to feedback systems [8–11]. In addition to simple devices, e.g. ring resonators and Mach-Zehnder interferometers (MZI), many have demonstrated (de)multiplexers and switches with heaters [12]. Nevertheless, the extra power consumption and the required electronic interconnects for feedback systems eventually limit integration density, scalability and their size. Furthermore, the use of any external heating means or feedback circuit further increases the power consumption, which can be a non-starter for data center and HPC applications.

In passive athermal approaches, the main idea is to minimize the changes in optical path length difference induced by temperature variations. In Si Photonic devices this can be done either by special MZI or microring assisted MZI designs [12–16], or through utilizing a hybrid material approach by incorporating negative thermo-optic coefficient (TOC) materials as cladding layers. In the latter, the first athermal silica photonic devices were demonstrated using polymers in the O and C band [17–19]. This hybrid polymer/silica approach inspired others to extend this work to silicon photonics platform. Many have used polymer claddings with silicon and amorphous silicon [20–25] as the core material in a variety of waveguide geometries (channel, slot, ridge, and etc.). They successfully have shown the possibility for achieving athermal ring resonators within 20-70°C. The downside for polymers is that they can only reduce thermal sensitivity for waveguides with a narrowed width. Moreover, they have fixed TOCs (for a given polymer) which may limit material selection for specific waveguide geometries. Polymers frequently have issues such as thermal stability, chemical stability, photo-degradation, and mechanical integrity.

Titania (titanium dioxide, TiO$_2$) has been demonstrated as an alternative cladding material
to achieve athermal ring resonators [26]. Athermality for these rings were achieved over a very limited temperature range, 6 pm/°C for 20°C at 1310 nm [27] and 1.7 pm/°C for 7°C at 1550 nm [28]. The tight tolerance in cladding thickness variation which is needed to reach athermal conditions limits this strategy. In addition, large waveguide mode asymmetry, relatively high loss of titania, and high cost arising from vacuum deposition are potential drawbacks to this approach.

In this work, we demonstrate the first athermal multichannel optical add-drop multiplexer (OADM) device based on silicon microring resonators. Reduction in temperature dependent wavelength shifts were established through using a sol-gel derived inorganic-organic hybrid material as the cladding. The sol-gel we used here is composed of 95% to 5% mole ratio of methacryloxypropyltrimethoxysilane (MAPTMS) to zirconium(IV)-n-propoxide (ZPO) [29,30].

Moreover, we have studied the effects of sol-gel material’s processing conditions which enables us to control the TOC of sol-gel material to reduce the OADM ring resonator’s thermal wavelength shifts. This study can provide the route to achieve athermal conditions for various waveguide structures without greatly altering the cladding material. By changing the curing condition of the sol-gel, we have achieved thermal shifts as low as -6 pm/°C for rings as wide as 325 nm and 310 nm wide in TE polarization. Although these rings were ideally designed for TE, we obtained significant thermal shift reductions in TM which were less than 1 pm/°C from 5°C to 90°C.

2. Device design and modeling

2.1. Athermal theory

The resonant wavelength shift of a microring resonator due to temperature change is given by [17,21]:

$$\frac{d\lambda}{dT} = \lambda \left( n_{eff} \alpha_{Si} + \frac{\partial n_{eff}}{\partial T} \right)$$

(1)

where $\lambda$ is the resonance wavelength and $n_{eff}$ is the effective index of the ring waveguide. $\alpha_{Si}$ and $n_g$ are the linear thermal expansion coefficient for silicon ($\alpha_{Si} = 1.8 \times 10^{-6}/{°C}$) and the waveguide’s group index, respectively, where the latter accounts for chromatic dispersion [21,31]. Athermality is achieved when $\frac{\partial n_{eff}}{\partial T} = -n_{eff} \alpha_{Si}$, thus $\frac{\partial n_{eff}}{\partial T}$ needs to be negative; this is in contrast to a number of previous reports that have ignored the effects of thermal expansion [24,25]. A simple calculation shows that thermal expansion induces an approximately 5 pm/°C wavelength shift at 1550 nm, which is significant if full athermality is required.

Fig. 1. Waveguide cross section of the chip.

The effective TOC of the waveguide depends on the refractive index change of the core and the cladding due to the temperature change. For an asymmetric channel waveguide with different upper and lower cladding materials, the effective TOC of the waveguide can be expressed [26] as

$$\frac{\partial n_{eff}}{\partial T} \approx \Gamma_{clad} \frac{\partial n_{clad}}{\partial T} + \Gamma_{Si} \frac{\partial n_{Si}}{\partial T} + \Gamma_{SiO_2} \frac{\partial n_{SiO_2}}{\partial T}$$

(2)
where $\frac{\partial n_{eff}}{\partial T}$ is the effective TOC of the waveguide at a given wavelength, while $\frac{\partial n_{clad}}{\partial T}$, $\frac{\partial n_{Si}}{\partial T}$, and $\frac{\partial n_{SiO_2}}{\partial T}$ represent the TOCs of the upper cladding, silicon core, and silica lower cladding, respectively. $\Gamma_{clad}$, $\Gamma_{Si}$, and $\Gamma_{SiO_2}$ in Equ. (2) are the confinement factors for the upper cladding, silicon core and silica lower cladding, respectively. Silica and silicon have positive TOCs, $1 \times 10^{-5}/\degree C$ and $1.8 \times 10^{-4}/\degree C$ [32] respectively. Therefore, a material with a negative TOC is needed to achieve athermal operation.

2.2. Suitable thermo-optic material

The thermo-optic coefficient of materials is determined from a balance of the electronic polarizability and the thermal expansion coefficient (CTE) of the materials [33]. Inorganic-organic hybrid materials prepared through sol-gel processing are another class of materials can address this problem. They have high CTEs with low polarizabilities due to their organic functional groups. Thus, it makes them good candidates for athermal applications, since they possess a wide range of negative TOCs (from $-0.9 \times 10^{-4}/\degree C$ up to $-3 \times 10^{-4}/\degree C$) [33–36] with low optical losses and tunable refractive indices. Furthermore, their organic-inorganic hybrid nature enables one to adjust their optical and mechanical properties from glassy to polymeric, providing additional degree of freedom in the waveguide design, which is often limited by material properties. Another benefit of sol-gel material is the ease of deposition through spin coating that provides a low-cost solution. All of these considerations have brought sol-gel’s attention for use in athermal silicon devices [37,38].

As previously mentioned, polymers are suitable candidates to be applied as claddings. However, selecting a polymer with the right refractive index and TOC is not trivial as for each waveguide geometry one must use a particular combination. On the other hand, it is possible to control the TOC of sol-gel materials by changing and controlling the degree of polymerization, organic modifier, hetero-metallic oxide network, or inorganic condensation degree [33–36,39,40]. Once the material composition is chosen and synthesized, another means to further raise the magnitude of the TOC is either through the increase of polymerization or an increase in inorganic condensation. This can be done after the material has been deposited on the chip and the degree of crosslinking in a sol-gel material would increase with longer curing time.

![Fig. 2. OADM layout and filter response: (a) layout of the optical add-drop multiplexer, (b) Simulated filter response of the OADM device.](image)

2.3. OADM design

The design goal of the OADM as shown in Fig. 2(a) was to add and drop wavelengths with 200 GHz channel spacing on the ITU grid. Each ring was designed in order to provide an
800 GHz free spectral range (FSR) as shown in Fig. 2(b). We designed a number of OADMs with a variety of ring widths and gaps to study the effect of the width on resonance wavelength temperature dependence. The input straight waveguide is 450 nm wide and tapers down to the ring width at the coupling point with widths of 300 nm, 310 nm, and 325 nm. The bus and drop waveguide coupling were symmetric and equal for all rings within a device. Though these gaps were also varied from 280 nm to 500 nm with 20 nm increments. The rings were designed to have a resonance at 1.5501 nm, 1.5505 nm, 1.5509 nm, and 1.5513 nm respectively. Thus, the diameters were determined according to the desired ring waveguide width, their effective indices and FSR. Finally, the add-drop ports were all separated by 127 µm to allow convenient optical fiber connections to fiber arrays.

2.4. Simulation

As it is possible to tune the optical properties of sol-gel materials, it is important to study the parameter space of ring waveguide geometry (width and thickness) and required TOCs of sol-gel materials to achieve athermal condition. The effective index and effective thermo-optic coefficient of the eigenmode was calculated with a commercial mode solver, Fimmwave (Photon Design Ltd.) from 0°C to 100°C. These values were then used to calculate the temperature dependent resonant wavelength shifts for ring resonators through Equ. 1. Silicon-on-insulator (SOI) platform waveguides are mainly used and designed to operate in TE polarization. Thus, we studied waveguide widths from 280 nm to 500 nm and changed thickness from 220 nm to 260 nm for 1550 nm wavelength with TE polarization. The cross-section of the simulated channel waveguide illustrated in Fig. 1, is located between the silica lower cladding and silica/sol-gel upper cladding. The corresponding refractive index and TOC values used for 95/5 sol-gel —cured at 150°C at 12 hours— in the simulation were 1.485 and -1.52×10^{-4}/°C which was measured with a Metricon(M2010) prism coupler.

![Simulated results](image)

(a)

(b)

Fig. 3. Simulation results for designing: (a) thermal wavelength shifts for silicon waveguides with silica and 95/5 sol-gel cladding at TE polarization; (b) plot of thermo-optic coefficients required to achieve athermality for waveguide widths from 260 nm-325 nm with 220 nm core thickness.

The dependence of the thermally induced resonance wavelength shifts for silica and 95/5 sol-gel cladding with respect to waveguide geometry are shown in Fig. 3(a). Regardless of the cladding material, the thermal dependence decreases as the waveguide ring width reduce. Waveguides with silica cladding, show positive thermal wavelength shifts that decrease down to 25 pm/°C.
Alternatively, with the 95/5 sol-gel cladding the thermal wavelength shift changes from 75 pm/°C down to -80 pm/°C as we narrow the ring’s waveguide width. The thermal wavelength shift passes the zero line which shows that there is an optimal waveguide width that is considered athermal. On the other hand, the temperature dependence is more tolerant to waveguide thickness changes, consideration of which only becomes critical for achieving very high athermality.

We also studied a range of possible TOC values based on the values mentioned in section 2.2 the available for sol-gel materials and matching geometrical conditions that would athermalize the waveguides. For this purpose, we used the refractive index of the measured 95/5 sol-gel. We have found that as the waveguide widths increase from 260 nm to 325 nm we need claddings that have larger magnitude TOCs to achieve athermal rings. These results, plotted in Fig. 3(b), are in line with our expectations as the increase of waveguide width, increases amount of light confined in the silicon core. Thus a larger cladding TOC magnitude is needed in order to obtain a negative effective TOC to cancel the thermal expansion effect.

3. Device fabrication

![Fabrication process of the chip](image)

Fig. 4. (a) Fabrication process of the chip: the chip comes with SiO₂ cladding, the silica over the rings is etched, and then this exposed region is coated with sol-gel; (b) microscope image of the fabricated device; (c) SEM image after etching the top cladding; (d) the actual chip before etching (left); the chip deposited with sol-gel (right).

Figure 4(b) shows a microscope image of the fabricated OADM silicon waveguides. The silicon photonics fabrication process was done at Sandia National Labs on an SOI wafer with a 3 µm bottom oxide layer. Silicon waveguides were patterned by photolithography and dry etching. The
waveguide thicknesses were nominally 230 nm. Subsequently, silicon dioxide was deposited on the structures through a plasma enhanced chemical vapor deposition (PECVD) up to 1.5 $\mu$m.

The sol-gel materials were prepared as follows. In a glass vial with 10 g of methacryloxypropyltrimethoxysilane (MAPTMS, Gelest) and 0.64 g of 0.1 M HCl a mixture of 0.96 g of zirconium propoxide (60% in 1-propanol, Aldrich) and 0.16 g of methacrylic acid (99% Aldrich) are added while stirring. The reaction mixture is stirred for 5 days before spin coating [30].

After the primary OADM silicon waveguide chip fabrication, the silica material of the top cladding is replaced with the sol-gel material to achieve athermal operation. The fabrication process for replacing the top cladding layer is shown in Fig. 4(a). First, we removed the silica top layer in a wet etching process using buffered oxide etchant (Transene, 6:1 H2O: BOE). To preserve the coupling end faces of the chips and to avoid damage caused by wet etching, we covered the end faces with Kapton tape as a mask. Next, we verified the intended oxide opening by imaging the chips through a scanning electron microscope (SEM). As shown in Fig. 4(c), the silicon ring waveguide structures on the bottom silica layer are clearly evident. After this opening process, the 95/5 sol-gel was spin-coated on the trench at 3000 rpm for 40 s after a 2 min oxygen plasma surface treatment. The trench was completely covered which indicated the sol-gel layer was more than 1.5 $\mu$m thick. Later, the chips were thermally cured to complete the fabrication. In order to study the effect of 95/5 sol-gel’s thermal curing time and curing temperature on the microring temperature dependence, the curing was performed at 130 $^\circ$C and 150 $^\circ$C for 10.5 h, 11 h, and 12 h. Figure 4(d) shows an OADM chip (left) before and (right) after depositing 95/5 sol-gel upper cladding layer.

4. Measurement setup

The spectral temperature dependence of the fabricated OADM device was characterized using the setup shown in Fig. 5. We used the broadband amplified spontaneous emission of an erbium doped fiber amplifier (EDFA) source (PriTel, FA-18) with a spectrum spanning from 1520 nm to 1570 nm. The EDFA is connected to an inline fiber polarizer and a polarization controller. Light from the fiber is coupled into the input waveguide and collected from the drop ports which are shown in Fig 2(a).

![Fig. 5. Schematic of the measurement setup for characterizing the athermal microrings.](image)

We used ultra-high NA fibers (UHNA-7, Nufern Inc., NA =0.410 with mode field diameter 3.2±0.3 $\mu$m at 1550 nm) that were spliced to SMF-28 in order to increase fiber-waveguide coupling efficiency. The device under test is located on a temperature controlled stage put together using a thermo-electric cooler (TEC) and a semiconductor temperature sensor. Finally, the light enters an optical spectrum analyzer (OSA) (Yokogawa Electric Co., AQ6730B) in order to observe the spectrum at a 0.05 nm resolution. The measurement procedure described was
automated in LabVIEW to control the instruments for collecting spectral data at a wide range of temperatures for the individual drop ports of the chips.

5. Experimental results

After the chips were prepared, we measured the transmission of the OADM devices. A typical transmission spectrum from the first drop of a sol-gel cladded chip with 325 nm waveguide width and 500 nm gap is shown in Fig. 6(a). The resonances have a 6 nm FSR with 3 dB bandwidths that vary from 0.3 nm to 0.6 nm throughout the C band. The measured total $Q$ factor of the sol-gel cladded rings yielded 2000-3700 for 300 nm width rings and varied from 3000-4700 for the wider 325 nm rings—as in Fig. 6(a) inset. The increase in $Q$ factor is because of the lower losses of wider 325 nm compared to 300 nm silicon waveguides.

Fig. 6. (a) Transmission spectra from Drop 1 ring with 325 nm width, 500 nm gap. The inset is a close-up look at a resonance with 0.32 nm 3-dB bandwidth and a $Q$ of 4700. (b) Temperature dependent wavelength shifts for different drops of a sol-gel coated OADM cured at 12 hours for a 300 nm ring waveguide.

In order to study the thermal performance of the OADM device, we looked at the thermal...
dependent behavior at the output port and the different drop ports. The thermal dependence of all different drops shown in Fig. 6(b), indicate similar trends and very small differences in the thermal shift. The results shown are for an OADM with 300 nm wide ring waveguides. The temperature dependent wavelength shift shows a nonlinear behavior especially for temperatures below 35°C. Theoretically, the thermal shifts shouldn't be different, as the ring diameters are different by less than a micrometer. Nevertheless, the wavelength dependence of the thermal shift can account for minor differences.

The temperature dependent behavior of sol-gel cladded rings was improved compared to their original silica cladded ones. The thermal shifts obtained in all sol-gel devices—geometrical and curing parameters—showed lower values compared to silica. To learn the effect of sol-gel curing time on thermal dependent wavelength shifts, we plotted the relative shifts for the resonance wavelengths with respect to temperature changes for ring waveguide widths of 310 nm and 325 nm cured at 130°C in Fig. 7(a) and (b). The thermal shift for a similar ring covered with silica are also plotted to compare the sol-gel’s performance. For the 325 nm wide ring, slopes for 10.5 h, 11 h and 12 h cure time were -6.8 pm/°C, 37.6 pm/°C and 38.6 pm/°C, respectively, as shown in Fig. 7(b). We observe that as the curing time increases, the thermal shift increases as well; particularly the slope changes sign while the sol-gel is cured between 10.5 h (negative slope) to 11 h (positive slope). When the sol-gel is cured beyond 11 h, the slope doesn’t change as rapidly as before and for the 12 h cured sol-gel the slope values agree well with our simulation results.

These observations were also found for OADM devices with smaller ring waveguide widths (300 nm and 310 nm) cured at 130°C and also for devices cured at 150°C. The results for a 310 nm ring waveguide width in Fig. 7(a), shows that the resonance peak shifts varied from -14.7 pm/°C to 40 pm/°C. Comparing the geometrical factors, we see that an increase in waveguide width raises the thermal shift for the same curing parameters. This follows our expectation from our model, simulations results, and previous reports.

Sol-gel devices cured with equal curing time but at higher temperature, shows an increase in thermal dependence for similar rings as shown in Fig. 8. Even though we were able to obtain -6 pm/°C for a 325 nm ring cured at 130°C, we achieved a thermal shift of -7 pm/°C for rings with 310 nm width cured at 150°C.
Even though, these devices were designed to operate only at TE polarization, as shown in Fig. 9 we found that when sol-gel was cured for 11 h, the thermal shifts for TM polarization were lower than -0.9 pm/°C reaching the ultimate desired athermal condition. The reason for this huge difference in thermal shifts is since Si waveguides are birefringent due to their rectangular shape, the effective indices and their optical confinement in the sol-gel cladding is different. TM modes have more optical confinement in the sol-gel cladding compared to TE modes, therefore it’s easier to achieve a lower thermal wavelength shift.

The polarization dependence in the data comes from the fact that the waveguides are not polarization independent. Silicon photonic waveguides typically have widths between 300 nm to 500 nm and thicknesses between 220 nm up to 260 nm. This rectangular waveguide shape causes an effective index difference between the two polarizations which results in polarization dependent effects.

The nonlinearity was a phenomena which, the cause for the nonlinearity at temperature below 25°C was later found to be due to the water condensation on the sol-gel layer after the chip was cooled down. It is well known that silica based sol-gel materials to adsorb water and humidity which eventually raises their refractive index [41,42]. Therefore the wavelength shift in those temperatures were not due to negative TOC.

The explanations for the influence of curing parameters on the thermal wavelength shift results are related to the degree of condensation and crosslinking density of the sol-gel material. The amount of condensation and cross-linking is controlled through curing time and curing temperature. This structural change in the material has an effect on the thermal expansion coefficient, which eventually correlates with its TOC [34]. Therefore, this can manifest in a change in the thermal shift for the ring resonators.

To confirm this hypothesis, we studied the IR spectrum of 95/5 sol-gel films cured at the same conditions as with our experimental devices using an FTIR (Fourier transform infrared) spectrometer. Our findings showed that longer curing time or a higher curing temperature resulted in a reduction of the amount of C=C which indicates an increase in degree of polymerization of the organic groups. Such similar structural modifications of the sol-gel material were also confirmed with previous reports conducted to study the effect of thermal [43] and UV curing on organically modified silicates [34,35]. Hence, an increase in polymerization reduces the CTE together with the TOC magnitude and the athermalizaty which agrees with our experimental results above.
6. Conclusion

We designed and demonstrated an athermal ring resonator based OADM through the use of organically modified sol-gel claddings. Hereby, we studied sol-gel curing conditions—time and temperature—in order to obtain athermal waveguides by modifying the thermo-optic coefficients. We found that curing time was a major factor compared to curing temperature in order to obtain the desired thermal shifts. By controlling 95/5 sol-gel’s curing time, the thermal wavelength shift for devices with 325-nm wide rings were significantly reduced down to -6.8 pm/°C in comparison with silica with 61.9 pm/°C. Curing sol-gel at 150°C with 10.5 h curing time, reduced the thermal shifts of OADMs with 310-nm rings to -7 pm/°C. Even though, these devices were not designed for TM operation, the temperature dependence at this polarization showed less change, with -0.9 pm/°C achieved when the sol-gel was cured for 11 h at 130°C. Our FTIR results proves sol-gel TOC can be adjusted by varying thermal curing conditions. Moreover, the tunable TOC of the sol-gel provides a key lever for achieving athermality for various waveguide structures without changing the cladding material. All features mentioned above make sol-gel a viable material for manufacturing of athermal devices in silicon photonics.

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