Reconfigurable silicon photonic circuits for telecommunication applications

Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge MA, USA
*Current address: IBM T.J. Watson Research Center, Yorktown Heights NY, USA

ABSTRACT
Photonic circuits based on silicon wire waveguides have attracted significant interest in recent years. They allow strong confinement of light with moderately low propagation losses. Moreover, the high thermo-optical coefficient of silicon and the small device size in silicon photonics allow for micro-heaters induced trimming, tuning, and switching with relatively low power. In this paper, we review our recent progress towards telecom-grade reconfigurable optical add-drop multiplexers (ROADMs) based on silicon microring resonators. We discuss waveguide and micro-heater design and fabrication as well as the first demonstration of telecom-grade silicon-microring filters and the first demonstration of transparent wavelength switching. The reported devices can be employed in numerous optical interconnect schemes.

Keywords: Silicon photonics, optical switching, tunable filter, ROADM, microring resonator, microheaters, silicide, propagation loss, hydrogen silsesquioxane.

1. INTRODUCTION
Microphotonic devices employing strong confinement of light, such as photonic crystals and micron-sized resonators, have unique and desirable characteristics. In recent years, the use of silicon as a core waveguide material has attracted significant interest. Silicon wire waveguides allow strong confinement of light and moderately low propagation losses. Moreover, being the workhorse of the microelectronics industry, silicon is widely available and its properties well understood. In addition, the high thermo-optical coefficient of silicon and the small device size in strong confinement silicon photonics allow for micro-heaters induced trimming, tuning, and switching with relatively low power. Here, we review our recent progress towards telecom-grade reconfigurable optical add-drop multiplexers (ROADMs) based on silicon microring resonators. We discuss a comprehensive optimization of waveguide design and overcladding material, a novel loss mechanism observed in Si waveguides, and the design and fabrication of efficient micro-heaters showing largest single-resonator tuning reported in silicon photonics. We also discuss the first demonstration of tunable silicon-microring filters with sufficient performance for dense wavelength division multiplexing applications, and the first demonstration of transparent wavelength switching, which requires the disabling of both the amplitude and the phase response of resonant filters.

2. WAVEGUIDE DESIGN
Silicon wire waveguide devices most often rely on waveguide cross-sections about 450-nm-wide and 200-nm-high. Although this design provides single-mode operation and practical feature size, it is not necessarily the best option. In this section, we investigate optimal designs of silica-clad silicon-core waveguides in terms of waveguide cross-section and field polarization, with respect to an extensive set of practically relevant criteria: sufficiently large feature sizes; low sensitivity of resonance frequencies and waveguide-cavity couplings to dimensional variations; high quality factor (Q); large free-spectral range (FSR), small propagation loss due to sidewall roughness; and efficient thermo-optic tuning.

We parameterize our study by waveguide aspect ratio ($A_R$), for designs using TE and TM excitation. Fig. 1a maps the set of largest single-TE-mode (SM-TE) and single-TM-mode (SM-TM) rectangular Si waveguides for all $A_R$. Larger cross-section increases confinement and achievable FSR, for a given bending loss. For microring resonators excited by evanescent side-coupling single-mode waveguides are suited. Only one resonator mode must be excited to avoid spurious spectral resonances and to prevent coupler loss due to low-Q spurious modes. Mode effective indices specify
Fig. 1  a) The largest single-TE-mode and single-TM-mode rectangular silicon waveguide dimensions of all aspect ratios taken as the cutoff points for $\text{TE}_{21}$ and $\text{TM}_{21}$, respectively. (b) effective and group indices of a single-TM-mode waveguide for all aspect ratios and the allowed 3 modes: $\text{TE}_{11}$, $\text{TE}_{21}$ and $\text{TM}_{21}$. (c) Resonant frequency sensitivity to microring waveguide width for TE and TM designs (for thickness sensitivity $A_R \rightarrow 1/A_R$, TE ↔ TM).

confinement (bend loss) while, in strong confinement waveguides, mode group indices affect tunability, FSR, and Q. The larger the group index is, the smaller the tunability, the smaller the FSR, and the larger the Q due to propagation losses are. Fig. 1b shows effective and group indices of SM-TM designs. Three modes are allowed in this case: $\text{TE}_{11}$, the used $\text{TM}_{11}$, and $\text{TE}_{21}$. By symmetry, TE and TM modes will not couple. This somewhat unconventional “overmoded” SM-TM design, where the employed TM mode is not the fundamental (best confined) mode, is justified by the analysis of propagation loss $^2$ that shows that TM modes in wide, thin waveguides can radiate less than TE. Then, the TM-polarized case is a viable option if the sidewall roughness quenches the Q of the TE resonances sufficiently to prevent spurious resonant responses due to perturbative excitations.

The sensitivity of resonance frequencies to dimensional errors impacts the feasibility of producing multiple resonators with similar, or prescribed relative, resonance frequencies. Frequency-matched HIC filters showed that a sensitivity of $40\text{GHz/\text{nm}}$ is manageable with high-fidelity nanofabrication.$^3$ Fig. 1c shows that near-square waveguides have $\sim 200\text{GHz/\text{nm}}$ sensitivity to width (and thickness) error while typical TE guides with $A_R = 2$ show $\sim 100\text{GHz/\text{nm}}$ sensitivity to width errors. On the other hand, TE guides with $A_R > 6$ and TM guides with $A_R > 1.8$ have less than...
Fig. 2. Loss induced by a metallic heater expressed as the microring loss $Q$ due to a 100-nm-thick chromium slab at various distances above the microring. A loss $Q$ of 250k or more is desired for 40-GHz-wide filters.

40GHz/nm sensitivity. This provides lower bounds on the aspect ratio and assures a low sensitivity to sidewall roughness. Upper bounds on the aspect ratio are imposed by confinement related issues, such as bend loss ($Q$), FSR, coupling to the Si substrate, and thermal tunability. For thermally tunable Si add-drop filters optical loss due to optical field overlap with metallic heaters is the most critical parameter. Fig. 2 shows that for TM guides with $A_R > 2$, a 100 nm Cr slab placed above the waveguides must be displaced more than 1 µm above a ring resonator to avoid spoiling a loss $Q$ of 250k, suitable for a 40GHz-wide filter. TE waveguides are better confined, so $A_R \leq 7$ can be used with a 1 µm waveguide-to-heater gap. To keep the heater power and electromigration within limits, the metal must be placed as close to the resonator as possible and preferably no more than a micron away.

In this first global optimization of Si waveguides, we have found that Si filter microring resonator waveguide designs are constrained primarily by dimensional sensitivity and tuning requirements. The results give two very different optimal designs for the choice of TE or TM device operation: about 700x120nm ($A_R = 6$) and 480x260nm ($A_R = 2$), respectively. In comparison, the Si waveguides typically employed for TE excitation (~450x200nm) are much more sensitive to dimensional error and sidewall roughness, rendering high-order filters difficult to realize.

3. OPTICAL LOSS DUE TO METALLIC CONTAMINATION

Low propagation loss is key for most microphotonic devices. However, propagation losses in silicon wire waveguides are not fully understood. For instance, by applying the fabrication process reported in Ref. 3 to silicon waveguides, we have observed a loss mechanism that, to our knowledge, has not yet been reported in the literature.

We have observed loss reaching 70 dB/cm in single-crystal silicon waveguides that were patterned in the proximity of metals that have a low temperature of silicide formation. The experimental data points toward formation of a dilute silicide at the waveguide sidewalls during reactive-ion etching (RIE). As shown on Fig. 3, the silicide forms without intimate contact between the metal and the silicon and without anneal. The temperature of the sample does not exceed 90°C in the fabrication process. However, the metal atoms sputtered by the reactive ions have more than sufficient energy to react with silicon on contact and are blamed for the observed silicide.

To understand the origin of the loss, 360- and 450-nm-wide waveguides were fabricated with various metal hardmasks. A 50-nm layer of metal was evaporated on the patterned e-beam resist and lifted off. The metal was then used as a hardmask for RIE before being thoroughly stripped via wet processing. This approach is commonly used for circumventing the weak etching resistance of most e-beam resists. Fig. 3 illustrates the material stack during RIE. A Plasmatherm 790, a conventional RIE system, was used at a pressure of 10 mT and a bias of 500 V. A gas flow of
17 sccm of CHF₃ was used for etching the top layer of SiO₂ and 60 nm into the thick SiO₂ on the bottom of the stack. A gas flow of 13.5 sccm of CF₄ and 1.5 sccm of O₂ was used to etch the Si.

The waveguide transparency was assessed by measuring the transmitted optical power through 2- to 4-mm-long straight waveguides at wavelengths ranging from 1430 to 1610 nm. Table 1 summarizes the experimental results and shows the silicide formation temperatures for the metals investigated. The attenuation of the fundamental mode was at least 50 dB/cm larger in waveguides considered non-transparent than in waveguides considered transparent. The waveguide roughness was qualitatively assessed by scanning-electron microscopy. The waveguide transparency correlates well to a low silicide formation temperature of the metal. On the other hand, the waveguide transparency shows an inverse correlation with the observed sidewall roughness indicating that roughness does not play a significant role in this experiment. To further test the silicide formation hypothesis, the waveguides fabricated with a Pd hardmask were inspected with a scanning transmission electron microscope (STEM) equipped with an energy dispersive x-ray spectrometer (EDS). Pd was detected in the silicon waveguide at 1-2 nm from the sidewall but not at 8-9 nm from the sidewall. The Pd signal corresponded to about 5% atomic concentration of Pd in Si, indicating that a dilute silicide was present. Such a dilute silicide was found difficult to remove. It did not respond to HF based solutions, which are commonly used for removing stoichiometric silicides. Moreover, the silicides of interest are not consumed but only displaced by oxidation so they cannot be removed by sacrificial oxidation of the outer silicon layer.

Silicide formation at RIE can, in principle, appear without metal on the surface of the wafer being etched. Metal chambers and electrodes are commonly used in RIE and give rise to metallic contamination. To estimate the impact such common contamination can have on loss, we compare the observed metal content in the above experiment to Ni contamination on bare silicon wafers resulting from the stainless-steel electrode of a RIE chamber. We find that loss in excess of 1 dB/cm could be expected. This indicates that typical RIE contamination levels can be of sufficient order to produce measurable optical loss without the presence of a metal hardmask on the wafer. In contrast, the metal contamination levels in state-of-the-art front-end of the line microelectronic processing are sufficiently low for the reported loss mechanism not to be observable.
4. OVERCLADDING OPTIMIZATION

Overcladding materials need to show low refractive index, high optical transparency, and acceptable thermal conductivity. On the processing side, the overcladding deposition process must fill in high-aspect-ratio gaps and provide sufficient material thickness for acceptable optical isolation. Once deposited, the overcladding must show acceptable temperature and environmental stability. The above qualities were previously simultaneously achieved mostly through TEOS (tetraethyloxysilicate)-based deposition of SiO₂. In this section, we demonstrate how hydrogen silsesquioxane (HSQ) can be used as a lower-cost alternative to TEOS with superior gap-filling and self-planarization properties. HSQ is a spin-on dielectric designed for low-k applications. The standard curing process for HSQ results in a low-k porous film that is not adequate for photonic applications. It shows very low thermal conductivity, some potential optical absorption due to Si-H bonds, and high intrinsic tensile stress limiting the achievable layer thickness to below a micron. By optimizing the HSQ curing process, we eliminate these shortcomings while maintaining HSQ’s excellent gap-filling and self-planarization properties. We demonstrate that HSQ layers can be made almost arbitrary thick, with no detectable Si-H bonds while easily filling high-aspect ratio sub-100nm gaps and providing planar top surfaces without polishing.

Blanket HSQ films of various thicknesses were prepared by spin-coating and the standard consecutive hotplate anneals (150, 200, and 350°C for 1 minute each) specified by the manufacturer. Then, the effect of various annealing conditions was explored. A set of samples was used for each annealing condition. The bonding structure of the HSQ was then investigated by Fourier transform infrared spectrometry (FTIR) and the thickness and optical properties were investigated by spectroscopic ellipsometry. Results are shown in Fig. 4 and Table 2. The samples labeled as hotplate annealed are the reference set as they did not withstand any additional anneal beyond the consecutive three hotplates. For low-k applications, HSQ is usually annealed at 400 C for 1 hour in a nitrogen ambient. Higher temperature anneals densify the HSQ raising its dielectric constant and thermal conductivity. After annealing in oxygen ambient at the highest temperatures tried in this study, the HSQ’s bonding structure and optical properties resemble closely to SiO₂.

The stress in HSQ films is due mostly to the removal of hydrogen through pyrolysis and oxidative reactions. In theory it should be possible to relax the stress as it is formed if the anneal is performed at temperatures above 1000°C to allow for viscous reflow of the oxide. The problem is that HSQ films with any substantial thickness crack by pyrolysis and oxidation-induced stress in the ramp-up before reaching the viscous reflow temperature. By increasing the heating rate from ~10°C/min in quartz furnace to ~50°C/s using rapid thermal processing (RTP), we found that it was possible to

![FTIR spectra for HSQ films annealed under various conditions. All data is normalized to a film thickness of 1 μm and the scans are vertically offset for ease of comparison. For anneals above 650°C in O₂, the spectrum resembles that of thermally grown SiO₂.](image)

Fig. 4  FTIR spectra for HSQ films annealed under various conditions. All data is normalized to a film thickness of 1 μm and the scans are vertically offset for ease of comparison. For anneals above 650°C in O₂, the spectrum resembles that of thermally grown SiO₂.
bypass the intermediate regime and obtain thicker films without cracking. Due to the low residual stress of the HSQ film annealed at these high temperatures, it is possible to spin and anneal multiple layers of HSQ without cracking. This has allowed us to fabricate multilayered films with thickness in excess of 2.5 µm.

We confirmed that the excellent planarization and gap-filling properties of HSQ were retained in the high temperature anneals. This was accomplished by overcladding silicon-rich silicon nitride (SiN) structures with HSQ and annealing with the RTP process in oxygen ambient. As shown on Fig 5a and 5b, the surface of the 2 µm-thick HSQ is completely planar above the 450-nm-high patterned structures. Fig. 5a shows that gaps with an aspect ratio greater than 6:1 were fully filled in. To test the HSQ uniformity, a decorative etch in a 0.12% HF solution was performed on the exposed cross-section. The result is shown in Fig. 5b. Uncured HSQ is etched much faster in dilute HF solutions than cured HSQ or SiO2. The HSQ in the gaps and at the outside vertical edges of the patterned structure was attacked much more rapidly by diluted HF than the rest of the annealed HSQ overcladding and the thermal oxide undercladding. This indicates that HSQ in close proximity to vertical edges of the SiN structure has not fully converted to SiO2 and further suggests that lateral confinement prevents the process of oxidation and densification from reaching completion in the provided annealing time. This is, however, not a significant issue for photonic structures. A detailed presentation of the HSQ optimization is presented in Ref. 6.

![Fig. 5](image_url)

Table 2  Measured refractive index and film shrinkage

<table>
<thead>
<tr>
<th>Temperature (ºC)</th>
<th>Ambient</th>
<th>Anneal Type</th>
<th>Shrinkage (%)</th>
<th>First Thicknesses Observed to Crack (µm)</th>
<th>Refractive Index b)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Single layer</td>
<td></td>
</tr>
<tr>
<td>350</td>
<td>Air</td>
<td>Hotplate (1 min)</td>
<td>0.0</td>
<td>1.20</td>
<td>1.362</td>
</tr>
<tr>
<td>400</td>
<td>N2</td>
<td>Tube (1 hr)</td>
<td>3.6</td>
<td>1.15</td>
<td>1.370</td>
</tr>
<tr>
<td>400</td>
<td>N2</td>
<td>Tube (12 hr)</td>
<td>11.3</td>
<td>0.93</td>
<td>1.16</td>
</tr>
<tr>
<td>400</td>
<td>O2</td>
<td>Tube (1 hr)</td>
<td>7.9</td>
<td>1.10</td>
<td>1.24</td>
</tr>
<tr>
<td>650</td>
<td>N2</td>
<td>Tube (1 hr)</td>
<td>19.4</td>
<td>0.85</td>
<td>1.06</td>
</tr>
<tr>
<td>800</td>
<td>O2</td>
<td>Tube (1 hr)</td>
<td>21.7</td>
<td>0.82</td>
<td>0.99</td>
</tr>
<tr>
<td>1150</td>
<td>N2</td>
<td>RTP (1 min)</td>
<td>37.9</td>
<td>0.74</td>
<td>2.0 (No Cracks)</td>
</tr>
<tr>
<td>1150</td>
<td>O2</td>
<td>RTP (1min)</td>
<td>23.7</td>
<td>0.92</td>
<td>&gt;2.5 (No Cracks)</td>
</tr>
</tbody>
</table>

a) Thickest sample that showed no cracks typically ~20% thinner
b) Refractive indices were measured with a Sopra spectroscopic ellipsometer and are quoted at 1550 nm (SiO₂ = 1.445)
5. MICRO-HEATERS

Thermo-optic tuning has been widely used on microring filters because it can induce large refractive index changes without optical loss. A large tuning range is necessary to enable microring filters to operate over the whole C-band. For this reason, we have chosen to employ thermo-optical tuning in our work towards microphotonic silicon ROADMs. We designed novel heater structures to maximize the tuning range by minimizing the temperature difference between the resonator and the heater at a distance that avoids optical loss. We argue that the heater temperature is the tuning limiting parameter. Metal heaters cannot be made arbitrarily thick because of fabrication constrains. Hence, the current density cannot be decreased arbitrarily and the electromigration sets a limit on the operating temperature of the heater.

The heaters were designed to cover the full resonator FSR, which is chosen to span half of the C-band. With an FSR doubling geometry, the filter’s operating wavelength range can span the entire C-band. A wide tuning range is achieved by making the heat injection surface (heaters) produce an approximately 1D heat flow in the vertical through-the-ring direction. As shown in Fig.6(a-b), a narrow heater provides a more “diffracting” heat flow than a wide heater. In Fig.6(c), we note that the quasi-1D heat flow of a 6 µm-wide heater enables a larger temperature at the waveguide for a given heater temperature than a narrow heater. A hydrogen silsequioxane (HSQ) uppercladding was chosen in our devices for its excellent gap-filling and self-planarization capabilities. An SiO2 uppercladding, however, can further enhance the tuning efficiency due to the higher thermal conductivity of SiO2 with respect to HSQ.

A multi-wire-structure heater was designed as shown in Fig.7a. The wire height was chosen to be 0.1 µm, the width to be 0.8-1 µm, and the gap between wires to be 0.8 µm to allow fabrication with contact photolithography. Ti was chosen as the heater material because its resistivity leads to a relatively low current density and no serious electromigration happens at the elevated heater temperatures (~500°C) required for full 16-nm FSR tuning.

Tunable silicon microring filters were fabricated on a Unibond silicon-on-insulator (SOI) wafer with 3 µm buried-oxide undercladding and a 220 nm silicon layer, thinned to 106 nm by calibrated steam oxidation and HF stripping. The waveguides were defined by e-beam lithography using 60-nm-thick hydrogen silsesquioxane (HSQ) as e-beam resist and mask for reactive-ion etching in pure HBr. The e-beam exposed HSQ was removed and the structure was spin-coated with a 1 µm layer of HSQ annealed at 400 C in oxygen ambient for 1 hour. The RTP oxidation was not used here as the overcladding thickness was achievable without it and the possibility of thinning of the silicon waveguides via oxidation at high annealing temperatures could be avoided. Next, 100-nm-thick Ti heaters were formed on top of the HSQ by
aligned contact photolithography, e-beam evaporation and liftoff. A second photolithography and liftoff step defined 100-nm-thick gold contact pads. Finally, a 100-nm-thick layer of SiO2 was sputtered to hinder the heater oxidation at the operating temperatures (up to ~500°C).

An optical micrograph of a tunable microring resonator filter is shown in Fig. 7a. The microrings have a 7µm radius and the ring waveguide have a 600 nm x 106 nm cross-section. The heater is about 900 nm above the top surface of the waveguides. The microring filters were designed with a 16 nm free spectral range (FSR) to cover half of the C-band. The loss Q’s were measured to be, as designed, ~250k and ~130k without and with a Ti heater present, respectively. This corresponds to a propagation loss in the rings of ~2-2.5 dB/cm and ~4.5 dB/cm, respectively. The wide tuning range and FSR are shown in the drop-port transmissions of the fabricated single-ring filters (Fig. 7b). A direct tuning of 20 nm is shown, which is the largest single-resonator tuning reported in silicon. The tuned wavelength shifts by 10 nm with an
average tuning efficiency of ~28 µW/GHz and shifts by 20 nm with an average efficiency of ~17 µW/GHz. The slope of the resonance wavelength shift in terms of electrical power becomes larger at higher electrical power. This is a consequence of the increase in the Si thermo-optic coefficient with temperature.8

As shown in Fig. 8, the time response was measured by applying a square-wave voltage on a heater placed on the arm of the Mach-Zehnder interferometer (MZI). The heater changes the temperature at one arm and induces a phase difference between the two arms of the MZI. This MZI heater has the same cross-section as the microring heater discussed above. As there is no significant delay between the current and the input voltage in Fig. 8b, the driving circuits don’t contribute notably to the switching speed and the measured time response is mainly from the heat flow process in the devices. The rise and fall times are 7us and 14us, respectively. This response time enables applications to ROADM.

6. TELECOM-GRADE TUNABLE FILTER

Telecom applications require add-drop filters with a large through-port extinction, large FSR (THz), and wide tunability. In this section, we present the first Si tunable high-order add-drop filter 9 with suitable drop- and through-port characteristics for telecom applications. The filter is compatible with a dense wavelength-division multiplexed (DWDM) optical network with 40 GHz-wide channels and 100 GHz channel spacing. It is designed for full tunability over its 16-nm FSR. With an FSR doubling scheme, full C-band FSR and tunability can be achieved. The filter can route channels on a 0.8/1.6 Tbps (20/40 channel x 40 Gbps) aggregate ROADM.

The tunable add-drop filter was designed for a 40GHz clear channel with a flat drop-port, >24 dB through-port extinction and <30ps/nm in-band dispersion (leading to a ~70 GHz-wide passband), and >30 dB extinction at 100 GHz spaced adjacent channel edges. The filter employs a fourth-order series-coupled design10 in a folded, compact geometry.

![Schematic cross-section of the filter structure](image)

Fig. 9  (a) Schematic cross-section of the filter structure near the ring-to-bus coupling region. (b) Optical micrograph of the first fabricated tunable 4th-order Si-microring-resonator add-drop filter. The microrings are outlined as masked by the Ti heaters. The Si microrings have an outer radius of 7 um. (c) Tuning spectra show high-quality responses, matching design and experiment, efficient thermal tuning. Two 16-nm-FSR spectral bands are shown on the right.
A schematic of the filter cross-section at the ring-to-bus coupling region is shown in Fig. 9a. A top view of the add-drop filter showing the bus waveguides, an outline of the microring resonators, and the four Ti micro-heaters (one heater per ring) is presented in Fig. 9b. The filter was fabricated with the same fabrication process as reported in Sec. 5. The waveguide design is based on the analysis of Sec. 2. An efficient electromagnetic filter design was achieved by designing resonators and asymmetric couplers to suppress spurious mode coupling losses, arriving at device dimensions by 3D finite-difference modesolver and time-domain (FDTD) simulations. The Ti micro-heater design is similar to the one presented in Sec. 5.

Drop- and through-port responses are presented in Fig. 9c. The spectral response shows a ~1-dB drop loss, ~20-dB through-port extinction, >32-dB out-of-band rejection, 66-GHz 1-dB-bandwidth, and 2050-GHz FSR. In-band dispersion was estimated to be <45 ps/nm by taking the Hilbert transform of the measured amplitude response. A 40-dB through-port extinction can be achieved by incoherently cascading two filters as demonstrated in Ref. 10. From the experimental data, we estimate that tuning over the full 16-nm FSR can be achieved with only <50mW per ring. This high efficiency is due to the high Si thermo-optic coefficient and a thermo-optically efficient heater-waveguide system design. Structural defects at the heater and passivation layer have limited the tuning of this particular filter to about 40% of its FSR. Based on the 20-nm tuning demonstration of Sec. 5, this can be easily remedied for the observed tuning range to exceed 16 nm.

7. TRANSPARENT SWITCHING

Hitless tuning is a prerequisite for ROADMs. It requires that channel add-drop filters switch from one target wavelength to another without causing bit errors in other wavelength channels. Hitless tuning of microring resonators has been claimed but not achieved because suppression of the phase response was ignored, whereas it is critical for tuning without introducing signal degradation and bit errors. Hence, the cavity detuning approach is not truly hitless. In this section, we discuss the demonstration of the first general approach to the tuning of a microphotonic resonant circuit response from one resonant wavelength band to another in a manner that is fully transparent to signals laying at all other wavelengths. This means that no substantial attenuation or dispersion is seen in the rest of the spectrum before, during and after tuning.

This novel fully-hitless disabling of filters is based on interferometric input couplers that provide a controllable waveguide-resonator coupling coefficient, and operating so that switching takes resonances into an undercoupled (minimum-phase) regime of operation. A practical design of the simplest case of such a hitless filter is shown in Fig. 10a, where a Mach-Zehnder (MZ) input coupler has an arm length difference $\Delta L = 2\pi R$ (any integer multiple

Fig. 10  Fully (amplitude- and phase-) transparent tuning of a filter based on a Si-core microring resonator. (a) Top-view optical micrograph showing waveguides and the Ti micro-heaters performing the tuning and switching operation. (b)-(c) Hitless tuning in action in the drop- and through-port responses. The filter is disabled at a 1546 nm wavelength channel, tuned by two channel spacings to a 1550 nm channel, and re-enabled. This fabricated demonstrator shows a 40 GHz bandwidth, <2 dB drop loss, >35 dB through-port extinction, and 16-nm FSR.
thereof), with $R$ the ring radius. When the MZ coupler and the ring have coincident FSRs, the input ring-bus coupling coefficient is strictly zero only at one frequency per FSR in the off-state. Full switching from on to off state requires a 180° phase shift applied to the MZ switching arm.

To demonstrate hitless switching and tuning in silicon microring resonators, a 40GHz, single-ring hitless demonstrator filter (Fig. 10a) was designed and fabricated with the process described in Sec. 5. The material stack was similar to the one presented in Fig. 9a and the heater design was similar to the one discussed in Sec. 5.

In Figs. 10b-c, the fabricated hitless filter is shown performing a hitless tuning operation. The demonstration filter shows extinction levels suitable for operating on a notional 8-channel grid with 250GHz channel spacing, covering the 2-THz FSR. By first actuating the MZ coupler heater, the filter is turned off and the drop-port resonance is extinguished by 25-dB, while the initial through-port extinction of >35dB is replaced by a flat spectrum with no signature of a resonance. Next, by actuating both heaters, the filter (in the off state) is tuned to align with another channel. Reducing the power on the coupler heater (Fig. 10c, legend) returns the filter to operation at the new wavelength. The key aspect of this operation is that the switching action suppresses both the amplitude and phase response in the through port, in contrast to previously used cavity detuning approaches where a dispersive “all-pass” response remains at all times. We believe this is the first demonstration of truly hitless tuning in microphotonic. The implementation of this approach to high-order microring filters is discussed in Ref. 17.

8. CONCLUSION

We have demonstrated the building blocks of fully-hitless silicon microphotonic ROADMs. We have shown efficient micro-heaters that provide a 20 nm tuning range with only 19 mW/THz power consumption per resonator, fourth-order microring tunable filters with high-quality, telecom-grade spectral responses, and the first demonstration of transparent switching. These building blocks are fully compatible with one another and can be brought together, with FSR-doubling and a multistage filter configuration, to form the first telecom-grade fully-hitless silicon microphotonic ROADM. Such device would be an important advance for dynamically reconfigurable networks applications and optical interconnect schemes.

REFERENCES


