Programmable Silicon Photonic RF Filters with Symmetric Out-of-Band Rejection

Bijoy Krishna Das

IIT Madras

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Abstract

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Ashitosh Velamuri and Bijoy Krishna Das

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Index Terms—Microwave photonics, silicon photonics, programmable photonics, RF filter, microring resonator, optical signal processor

I. INTRODUCTION

The bandpass filter is an important block of radio frequency (RF) receiver architectures to suppress the noise and to eliminate cross-talks [1]. Passive electrical filters are commonly used because of their robustness and cost-effectiveness. However, filter design for the RF receivers operating at higher frequencies (mm-Wave) is not so trivial [2]. Moreover, these filters are typically designed to operate at a desired frequency band and not possible to tune in general. Therefore as an alternative, RF photonic filters are being explored in recent times [3]–[21]. In theory, the RF photonic filters are very promising in terms of size, weight and power (SWaP), wide-band tunability, scalability, immunity to electromagnetic interference and programmable filter functions. In practice, there are plenty of scopes for improvement in filter characteristics such as shape factor, out-of-band rejection, link gain, noise figure and spurious free dynamic range to replace its electronic counterparts for mass manufacturing and deployment. Nevertheless, the research progress in integrated RF photonic filters are phenomenal. For example, RF photonic filters demonstrated based on stimulated Brillouin scattering (SBS) [3], [4], comb sources [5], photonic crystal cavity (PhC) [6], distributed Bragg gratings (DBR) [7], micro disk resonators [8], [9], microring resonators (MRR) [10]–[18], coupled resonator optical waveguides (CROWs) [19], [20] and ring-assisted Mach-Zehnder interferometers (RAMZIs) [21] are found to be very promising. Especially, the MRR based photonic filters are attractive owing to its lower footprint, higher tunability through electro-optic and/or thermo-optic phase shifters and thereby better bandwidth control.

The silicon nitride (SiN) on insulator (SNOI) and silicon-on-insulator (SOI) are two widely used CMOS compatible technology platforms for the demonstration of MRR based RF photonic filters. The SiN waveguides in SNOI platform offers low waveguide loss in order to achieve high Q-value of the MRR and to realize filter response with sub-GHz bandwidth [10]–[13]. Zhu et al [11] and Yang et al [13] has reported a tunable filter response with a bandwidth of 260 MHz and 100 MHz respectively. However, the thermo-optic/electro-optic tuning for SiN microring resonators are either inefficient or extremely difficult to fabricate; need hybrid integration [22]. Though the silicon waveguides are relatively lossier, they offer a compact design of microring resonators, and losses can be optimized by a better design of waveguide geometry. Moreover, both thermo-optic and electro-optic detuning can be achieved to reconfigure the MRR response. In addition to that, high-speed modulators and detectors (up to 50 GHz) can be integrated for the development of fully integrated reconfigurable RF photonic filters [23]. To achieve the sub-GHz bandwidth in SOI platform Qiu et al [15] and Tao et al [16] have used adiabatically tapered low-loss waveguide sections in the ring to improve the Q-factor (∼ 10^6). They have reported a RF filter bandwidth of 170 MHz and 100 MHz, respectively. These filters could be detuned to a frequency range upto 18 GHz. The out-of-band rejections are reported as 27 dB. These designs are relatively higher footprints and bandwidth detuning options are not included, which is essential for high-speed data transmission at higher operating frequency range. Also, the filter response exhibits asymmetric out-of-band rejection in reported literatures, which is attributed to the phase change in carrier frequency along with the modulated sidebands [10]. This in turn effects the shape factor of the RF photonic bandpass filter limiting its applications. The issue of
shape factor degradation due to asymmetric rejection has been addressed recently by considering certain design aspects and operating conditions. Li, et al [10] has used wavelength division multiplexing of two optical carriers before launching into the phase modulator and positioned their wavelengths on the lower and upper sides of the two resonances (with frequency separation greater than the photodetector bandwidth). Song, S., et al [17] has designed a non-identical cascaded ring structure on two different chips, whereas Yang, Wenjian, et al [14] has used an external phase compensator after the microring resonator. However, all the mentioned methods involve the introduction of additional components into the setup, with no scope for on-chip integration or altering the fabrication process altogether.

In this paper, we propose a novel design of an integrated optical signal processor in silicon-on-insulator platform for a tunable RF bandpass filter with symmetrical out-of-band rejection. It has been shown that the design helps to improve the filter shape factor. In Section. II, we have discussed about the design and the working principle of the proposed optical signal processor chip. In Section. III, we have presented the fabrication details using in-house facilities and the passive/active characterization of the chip. In Section. IV, we discuss RF filter experimental results. Finally, in Section. V we conclude by summarising the results and future scopes of improvements.

II. DESIGN AND WORKING PRINCIPLE

As discussed in the introduction section, the MRR based RF photonic filters in SOI platform are attractive in terms of compactness, broadband tunability, CMOS compatibility and scalability. [10]. To overcome this limitation and to achieve a RF photonic bandpass filter with symmetric out-of-band rejection, we propose a novel design of optical signal processor chip comprised of two cascaded microring resonators (MRR1, MRR2) in an all-pass configuration. It has been integrated with four phase shifters to reconfigure the ring characteristics, as shown schematically in Fig. 1a along with its operational scheme. A representative RF band with centre frequency at \( f_m \) is upconverted into optical frequency range centering around \( f_0 \) via a phase modulator and subsequently launched into the proposed OSP chip. The phase modulation of the optical carrier results in a passband and lower outband (USB) and lower sideband (LSB) with \( \pi \) phase difference, as shown in top-left section of Fig. 1b. The two cascaded MRRs are configured with identical coupling conditions as well as identical Q-values. Since both the MRRs are identical they resonate at same wavelengths. A desired order of their resonant wavelength (\( \lambda_r \sim 1550 \text{ nm} \)) can be made non-degenerate by detuning one of the microring resonators. However, the degeneracy can be easily broken in any fabricated device due to process induced variations in waveguide dimensions. The optical carrier frequency \( f_0 \) needs to be positioned between these two non-degenerate resonances such that two resonance frequencies are at \( f_0 - f_1 \) and \( f_0 + f_2 \), respectively. To achieve a symmetric out-of-band rejection the condition for the resonance offsets with the carrier is \( 0 < |f_1 - f_2| \leq \Delta \lambda_{FWHM} \), where FWHM stands for the full-width at half maxima of the MRR resonances. The RF photonic bandpass filter response at the photodetector output is achieved by the phase readjustment in the USB and LSB induced by the microring resonators, as depicted in Fig. 1b. The resultant photocurrent at the detector output is the sum of two components: (i) beat current of carrier with the LSB \( (i_-) \) and (ii) beat current of carrier with the USB \( (i_+) \). Because of the asymmetric spacing of the resonances from the carrier, the resultant phase \( \Delta \phi = \phi_+ - \phi_- \) results in a non-\( \pi \) from \( f_1 \) to \( f_2 \) and therefore, a passband is obtained with a central frequency \( f_c,RF \) around \( \frac{1}{2}(f_1 + f_2) \) with a symmetric out-of-band rejection.

![Fig. 1: (a) The schematic of the proposed OSP chip along with its operational scheme for the RF photonic bandpass filter functions with symmetric out-of-band rejection; (b) top-left: schematic representation of the phase modulated optical spectrum with RF frequency band centering around \( f_m \). Top-right: optical transmission characteristics of the modulated laser light along with the transmission and phase spectrum of the OSP, \( f_1, f_2 \) correspond to the resonance spacings with respect to the laser carrier frequency \( f_0 \). Bottom-left: the phase spectrum of the beat signal corresponding to carrier and USB (top), and carrier and LSB (bottom). Bottom-right: schematic representation of the phase deviation \( \Delta \phi \) (from \( \pi \)) between beat photocurrents \( i_+ \) and \( i_- \) at the photodetector as a function of RF frequency (top), and the RF filter response corresponding to the superposition of \( i_+ \) and \( i_- \) at the photodetector output.](image)

The time-dependent transmitted field amplitude of the laser light phase modulated with a RF angular frequency of \( \omega_m(= 2\pi f_m) \) and received by the photodetector can be mathematically expressed for small RF signal approximation as:

\[
e(t) \propto \sqrt{P_{RF}} e^{j\omega_m t} \left[ T_1(\omega_0)T_2(\omega_0)J_0(\delta) + T_1(\omega_0 - \omega_m)T_2(\omega_0 - \omega_m)J_1(\delta)e^{-j\omega_m t} - T_1(\omega_0 + \omega_m)T_2(\omega_0 + \omega_m)J_1(\delta)e^{j\omega_m t}\right]
\] (1)
where \( p_{m} \) is the optical power launched into the modulator, \( \omega_{0} = 2\pi f_{0} \) is the angular frequency of the laser light, \( \delta \) is the modulation index (\( = \frac{V_{m}}{V_{r}} \)). \( J_{n} \) is the Bessel function of \( n^{th} \) order, \( T_{1}, T_{2} \) are the transfer function of the MRR1 and MRR2, respectively. The RF photocurrent dominates at \( \omega_{m} \) and is given by:

\[
i(t) \propto R_{d}|e(t)|^{2}
\]

where \( R_{d} \) is the responsivity of the photodetector. From equations (1) and (2), the photocurrent can be expanded into:

\[
i(t) \propto A[i_{+}(t) + i_{-}(t)]
\]

where

\[
A = 2R_{d}p_{m}J_{0}(\delta)J_{1}(\delta)|T_{1}(\omega_{0})T_{2}(\omega_{0})|
\]

\[
i_{+}(t) = |T_{1}(\omega_{0} + \omega_{m})T_{2}(\omega_{0} + \omega_{m})|\cos(\omega_{m}t + \phi_{USB})
\]

\[
i_{-}(t) = |T_{1}(\omega_{0} - \omega_{m})T_{2}(\omega_{0} - \omega_{m})|\cos(\omega_{m}t + \phi_{LSB} - \pi)
\]

here \( i_{+} \) and \( i_{-} \) are the photocurrents corresponding to the carrier beat with USB and LSB, respectively, and \( \phi_{USB}, \phi_{LSB} \) are phases of \( i_{+}, i_{-} \), respectively, given by:

\[
\phi_{USB} = \phi(\omega_{0} + \omega_{m}) - \phi(\omega_{0})
\]

\[
\phi_{LSB} = \phi(\omega_{0}) - \phi(\omega_{0} - \omega_{m})
\]

where \( \phi \) at any given frequency is equal to sum of the individual phase response of MRR1, MRR2 \((\phi_{1} + \phi_{2})\). The total photocurrent \( i(t) \) is dependent on the phase difference \( \Delta \phi \) between \( i_{+} \) and \( i_{-} \), which is given by:

\[
\Delta \phi = \phi_{+} - \phi_{-} = \phi(\omega_{0} + \omega_{m}) + \phi(\omega_{0} - \omega_{m}) - 2\phi(\omega_{0}) + \pi.
\]

It is obvious that, in the absence of the OSP \( (|T_{1}| = |T_{2}| = 1 \) and \( \phi_{1} = \phi_{2} = 0) \), \( i_{+} \) and \( i_{-} \) have equal amplitude with phase difference \( \Delta \phi = \pi \) and hence cancel each other i.e., \( i(t) = 0 \) and no RF signal is detected at the output. Now, in presence of the OSP the said phase deviates from \( \pi \), as given by Eq. (8), which is again is a function of RF frequency dependent on the relative position of the laser carrier wavelength and the resonance spectrum. The frequency dependent filter response can be obtained by performing the Fourier transform on the detected photocurrent \( i(t) \). The average power at a given RF frequency can be expressed by:

\[
P_{RF,\text{out}} = \frac{1}{2} < i(t) >^2 R_{L}
\]

where \( R_{L} \) is the matched load of the detector.

Thus the relative phase of the optical carrier frequency due to the resonance responses corresponding MRR1 and MRR2 are affecting the identical out-of-band rejections on the either sides of the RF passband (also see Fig. 1). The performance figure of merits (FOMs) e.g., bandwidth, out-of-band rejection, central frequency, link gain, etc. of the RF filters depend on the resonant wavelength, extinctions and the Q-values of microring resonators (MRR1 and MRR2). Therefore, we need to design our OSP such that Q-values and extinctions of each MRRs could be tuned independently via thermo-optic/electro-optic effect. The Q-value and extinction of a microring resonator in all-pass configuration is given by [24]:

\[
Q = \frac{\pi n_{g}L_{r}\sqrt{ra}}{\lambda_{r}(1-ra)} \quad (10)
\]

\[
\text{Extinction} = \left[\frac{(r + a)(1-ra)}{(1+ra)(r-a)}\right]^{2} \quad (11)
\]

where \( n_{g} \) is the group index of guided mode, \( L_{r} \) is the perimeter length, \( \lambda_{r} \) is the resonance wavelength, \( r \) is the self-coupling coefficient and \( a \) is round trip loss factor \( (e^{-\alpha L_{r}}; \alpha \) is the waveguide loss coefficient) of the MRR. From Eq. (10), (11), it is evident that both the FOMs are dependent on the coupling coefficient \( r \) of the coupler and the loss factor \( a \) inside the ring. Usually, the waveguide loss in a silicon waveguide is mainly attributed to the sidewall roughness, and the value is fixed for a given waveguide dimension; we have assumed the coupler itself is lossless. Nevertheless, designing a nearly lossless tunable coupler is critical to controlling the MRR extinction and its Q-value. In practice, the Mach-Zehnder interferometer (MZI) is the popular choice for a tunable coupler. However, the MZI-based design increases the device footprint and the perimeter of the ring \( L_{r} \). The increase in perimeter eventually results in: (i) the drop of the Q-factor [24], which increases the resultant bandwidth of the filter, and (ii) the decrease in FSR, which affects the tuning range of the filter response \((\sim \text{FSR}/2) [10]\).

Fig. 2: Left: schematic top view of an MRR design in SOI platform for which the ring waveguide is relatively wider than the bus waveguide; the design is to facilitate desired value of \( r \) and resonance wavelength setting using thermo-optic phase-shifters \( PS_{R} \) and \( PS_{DC} \); \( L_{dc} \) is the length of the parallel section of the directional coupler, \( R \) is the bend radius of the ring waveguide. Right: schematic cross-sectional view of the coupler annotated with important design parameters.

To overcome the challenges due to the MZI-based tunable coupler, we have designed an asymmetric directional coupler with a width \( W_{1} = 0.5 \mu m \) for the bus waveguide and width \( W_{2} = 1 \mu m \) for the ring waveguide, as shown in Fig. 2. The phase shifts \( PS_{DC} \) and \( PS_{R} \) tune the ring coupling coefficient and the resonant wavelength, respectively. However, we must note that for the slab height \( h = 150 \) nm, the waveguide with width 1 \( \mu m \) supports two TE-like modes (TE0 and TE1). Hence, there is a high chance that near the directional coupler, the input power from the bus waveguides gets coupled into the fundamental and first-order mode of the ring waveguide. In the case of higher order modes getting coupled into the ring, the conventional transfer function of the
microring resonator given in [24] is not valid. The modified transfer function can be derived as:

\[ T_R = r - \sum_{n=0}^{\infty} \frac{t_m^2 a_m e^{-j\beta_m}}{1 - a_m t_m e^{-j\delta_m}} = |T_R|e^{j\phi_R} \]  

(12)

where, \( m \) is the mode number, \( n \) is the number of modes coupled into the ring (= 2, in our case), \( r \) is the self coupling coefficient, \( t_m \), \( a_m \), \( \delta_m \) are the cross coupling coefficient, loss factor and phase accumulated inside the ring for \( m^{th} \)-order mode, respectively, and \( t_m = \sqrt{1 - t_m^2} \), \( \phi_R \) is the phase response of the MRR. For the lossless directional coupler, \( r^2 + \sum_{m=0}^{\infty} t_m^2 = 1 \). It must be noted that the transfer functions corresponding to MRR1 and MRR2 are expressed as \( T_1 \) and \( T_2 \) in Eq. (1), after incorporating the respective design parameters in Eq. (12).

From the coupled mode theory, the expression for the cross coupling coefficient \( t_m \) for a \( m^{th} \)-order mode, is given by [25]:

\[ t_m = e^{i(\Delta \beta_m/2)L} \left[ -i\kappa_m \frac{\sin (s_m L)}{s_m} \right] \]  

(13)

where

\[ s_m = \frac{1}{2} \sqrt{4|\kappa_m|^2 + (\Delta \beta_m)^2} \]  

(14)

\( \Delta \beta_m, \kappa_m \) are the effective phase mismatch and the coupling exchange between the fundamental mode of bus waveguide and the \( m^{th} \)-order mode of the ring waveguide, and \( L \) is the effective directional coupler length, which is not equal to the \( L_{dc} \), due to the bend induced coupling [26]. Fig. 3 shows the simulated MRR response with two modes coupled into the ring with the parameter values given in Table I. The values \( \kappa_0, \kappa_1 \) were calculated from the super-mode theory as discussed in [25] and the values \( a_0, a_1 \) are chosen based on our prior experimental observations. As the higher order modes tend to leak more due to the longer evanescent tail, the resonance of the TE\(_1\) mode in Fig. 3 is broader than the resonance of the TE\(_0\) mode.

The design parameters of the MRR has been chosen carefully such that the Q-value and extinction can be tuned efficiently using a thermo-optic phase shifter \( (PS_{DC}) \). Fig. 4a

Fig. 3: Transmission characteristics of the MRR exhibiting resonances corresponding to fundamental (TE\(_0\)) and first-order (TE\(_1\)) guided modes at \( \lambda_{r0} \sim 1549.792 \) nm and \( \lambda_{r1} \sim 1549.3 \) nm, for the parameter values given in Table I.
shows the $r_0$ as a function of $\Delta \beta_0$, for the given length of the directional coupler and the gap between coupled waveguides as given in Table. I. For our chosen waveguide dimensions the value of $\Delta \beta_0 \approx 0.43 [1/\mu m]$ and the corresponding $r_0 = 0.995 (> a_0 = 0.99)$, which is the undercoupled condition of the MRR resonance. Now, with the differential increment in temperature of the bus waveguide the values of $\Delta \beta_m$ and $\kappa_m$ will be changed and hence the values of $r_m$ too. That means, the integrated thermo-optic phase shifter ($PS_{DC}$) will be able to tune the value of $r_0$ such that the resonance can be tuned from undercoupled toward critically coupled condition ($r_0 = a_0$), and thus the Q-value can also be tuned. Higher Q-value is desired for a narrowband RF filter. It is important to note that in our proposed OSP design the best performance can be achieved when Q-value and the extinctions are matched for both the resonances.

TABLE I: The calculated values for the directional coupler of effective length $L = 9.75 \mu m$ used in MRR design of waveguide bend radius $R = 100 \mu m$, $W_1 = 0.5 \mu m$, $W_2 = 1 \mu m$, $g = 250$ nm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \beta_0$</td>
<td>0.43 [1/\mu m]</td>
</tr>
<tr>
<td>$\kappa_0$</td>
<td>0.26 [1/\mu m]</td>
</tr>
<tr>
<td>$a_0$</td>
<td>0.99</td>
</tr>
</tbody>
</table>

TABLE II: Simulation parameter values for calculating RF filter output of the proposed OSP described in Fig. 1a.

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulator</td>
<td>Half-wave voltage $V_n$</td>
<td>6 V</td>
</tr>
<tr>
<td></td>
<td>Insertion loss</td>
<td>2.7 dB</td>
</tr>
<tr>
<td></td>
<td>Input RF power</td>
<td>$-10$ dBm</td>
</tr>
<tr>
<td></td>
<td>Matched load $R_M$</td>
<td>50 $\Omega$</td>
</tr>
<tr>
<td></td>
<td>Input voltage $V_{in}$</td>
<td>0.1 V</td>
</tr>
<tr>
<td></td>
<td>Laser input power $P_{in}$</td>
<td>13 dBm</td>
</tr>
<tr>
<td></td>
<td>Laser wavelength $\lambda_0$</td>
<td>$\sim 1550$ nm</td>
</tr>
</tbody>
</table>

| Optical signal processor | Waveguide loss | 1 dB/cm |
| | Coupling loss $|\gamma|^2$ | 3 dB/facet |
| | Estimated Q-value | $3 \times 10^5$ |
| Photodetector | Responsivity $R_d$ | 0.75 A/W |
| | Matched load $R_L$ | 50 $\Omega$ |

Fig. 4b and Fig. 4c shows the comparison of the self-coupling coefficients ($|r_0|$) and the corresponding extinction ratio (Eq. (11)) between the symmetrical directional coupler ($W_1 = W_2 = 0.5 \mu m$) and the asymmetrical directional coupler ($W_1 = 0.5 \mu m$, $W_2 = 1 \mu m$) with the differential temperature $\Delta T$ (between the bus and ring waveguide in the coupler region). From the calculated results shown in the figures it is evident that the proposed waveguide design ($W_1 = 0.5 \mu m$, $W_2 = 1 \mu m$) is more efficient for the thermo-optic tuning of the Q-value and the extinction ratio, than those for standard design with symmetric coupler ($W_1 = W_2 = 0.5 \mu m$). In addition to the improved tuning efficiency of the coupling coefficient, the proposed design also provides an additional advantage of the reduced mode interaction with sidewall roughness inside the ring (higher waveguide width), and thus improving the Q-value of the MRRs to be fabricated. We have restricted our ring waveguide width to $1 \mu m$ supporting two guided modes; to avoid additional resonances which would limit the tuning range of RF bandpass filter operation.

Fig. 5: Phase and amplitude spectrum for single MRR and cascaded double MRRs: (a) Calculated phase difference (deviation from $\pi$) between the LSB and USB beat signals at the photodetector as function of frequency; and (b) the simulated RF filter response for single ring and cascaded ring configuration. Calculations are carried out for $f = 10$ GHz (laser wavelength position with respect to a resonant frequency of the MRR) for the single ring and $f_1 = 9.75$ GHz, $f_2 = 10.25$ GHz for cascaded ring.

The RF filter response was simulated using the Eq.(9) and the simulation parameter values listed in Table. I and Table II for the proposed link given in Fig. 1a. The calculated phase and amplitude spectra are shown in Fig. 5, for single MRR and the proposed cascaded two MRRs OSP chip. In case of single MRR we have positioned the laser wavelength with 10 GHz offset from the resonant wavelength of interest, whereas for the proposed OSP chip we have used $f_1 = 9.75$ GHz, $f_2 = 10.25$ GHz. Thus we obtained bandpass filter response centering around 10 GHz with a 3-dB bandwidth of 500 MHz. As expected, in case of single MRR the filter response (Fig. 5b) exhibits asymmetric out-of-band rejection, which is directly related to the asymmetric phase spectrum obtained in Fig. 5a. However, our proposed design architecture of the OSP chip comprised of two cascaded MRRs exhibits well-defined symmetric out-of-band rejections. The shape factor, defined as the ratio of 20–dB bandwidth to the 3–dB bandwidth, has reduced from 9.67 (single MRR) to 2.76 (cascaded MRRs).
The maximum RF output power of -40 dBm implying the RF-to-RF insertion loss of -30 dB which can be improved by increasing input laser power and decreasing optical losses. The detector responsivity $R_d$ and modulator half-wave voltage $V_{\pi}$ also play roles for the RF insertion loss. The centre frequency of the RF bandpass filter can be tuned by detuning the MRR resonances using thermo-optic phase shifters. In our design, the tuning range is limited by half of the free spectral range of the MRRs, which is $\sim 60$ GHz. The bandwidth can be tuned by detuning one of the MRR resonant wavelength.

III. FABRICATION AND CHARACTERIZATION

TABLE III: Design parameters chosen for the fabrication of the OSP.

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device layer thickness</td>
<td>$H$</td>
<td>220 nm</td>
</tr>
<tr>
<td>Slab height</td>
<td>$h$</td>
<td>150 nm</td>
</tr>
<tr>
<td>Ring radius</td>
<td>$R$</td>
<td>100 $\mu$m</td>
</tr>
<tr>
<td>Directional coupler gap</td>
<td>$g$</td>
<td>250 nm</td>
</tr>
<tr>
<td>Bus waveguide width</td>
<td>$W_1$</td>
<td>0.5 $\mu$m</td>
</tr>
<tr>
<td>Ring waveguide width</td>
<td>$W_2$</td>
<td>1 $\mu$m</td>
</tr>
<tr>
<td>Directional coupler length</td>
<td>$L_{dc}$</td>
<td>10 $\mu$m</td>
</tr>
<tr>
<td>Heater width</td>
<td>$W_H$</td>
<td>2 $\mu$m</td>
</tr>
<tr>
<td>Heater thickness</td>
<td>$t_H$</td>
<td>100 nm</td>
</tr>
<tr>
<td>Waveguide to heater gap</td>
<td>$g_H$</td>
<td>2 $\mu$m</td>
</tr>
</tbody>
</table>

We have fabricated the proposed design of cascaded MRR based optical signal processor in a SOI substrate with 220 nm device layer thickness using our in-house facilities available at the Centre for NEMS and Nanophotonics (CNNP), IIT Madras. The various design parameter values chosen for fabrication are based on the theoretical discussion in the previous section and they are listed in Table III. The microscope image of the fabricated chip is shown in Fig. 6, in which a reference directional coupler and a reference MRR design have been included. The input/output waveguides are terminated with grating couplers for fiber-chip-fiber coupling. The Titanium micro-heaters are integrated on the silicon slab within a close proximity of the rib waveguide structures as per requirements of the thermo-optic phase detuning. The micro-heater design parameters were chosen based on the previously studied experimental results [27]. Since all the microheaters may need to be functional simultaneously, we have routed the heater connections using Aluminium interconnects to the contact pads (100 $\mu$m $\times$ 100 $\mu$m) in a row with a pitch of 150 $\mu$m such that they can be probed simultaneously using a DC probe card. The fabrication process steps are followed same as described in [27].

The passive transmission characteristics and thermo-optic detuning of the resonance wavelengths as well the coupling coefficients were experimentally investigated using the setup as shown schematically in Fig. 7. The in-built tunable laser source (TLS) of the optical source/spectrum analyzer (APEX 2043B) was used to sweep the laser wavelength and the transmitted output was measured in the optical spectrum analyzer (OSA). For thermo-optic tuning a 8-channel programmable DC power supply (nicslab XDAC-8MUB-R4G8) was used by means of DC probe card. Both fiber-optic coupling and electrical probing were facilitated using a FormFactor silicon photonic probe station (MPS-150). The experimental results are discussed below.

A. Passive Transmission Characteristics

The devices were characterized for $1520 \text{ nm} \leq \lambda \leq 1620$ nm. The transmission characteristics of the single MRR and cascaded MRR are given in Fig. 8a and Fig. 8b, respectively; the results are shown only around $\lambda \sim 1540$ nm, as the grating coupler efficiency (loss $\sim 8 \text{ dB/facet}$) is found to be maximum around this wavelength range. As expected, resonances corresponding to the fundamental (TE$_0$) and first-order (TE$_1$) guided modes are present in both the devices. The resonances corresponding to the TE$_0$ are found to have higher Q-values ($\sim 10^5$) than those for TE$_1$ ($\sim 10^4$). The extinction ratio (ER), free spectral range (FSR) and the corresponding group indices ($n_g$) could be directly estimated from the transmission characteristics (FSR = $c/n_gL_r$). The other parameters such as self-coupling coefficient $r$, round trip loss factor $a$, waveguide loss $\alpha$ and Q-values were extracted by modeling individual
resonance and are listed in Table. IV. The group index of the TE1 mode is found to be slightly higher (~3.87) than that of the TE0 mode (~3.81). Similarly, the minimum losses corresponding to the TE0 guided mode is extracted to be lower (~1.4 dB/cm) than that of the TE1 mode (~8 dB/cm). These results are in accordance with the theoretical prediction as discussed in the previous section. It must be noted that the extracted waveguide loss for an equivalent MRR designed with a single mode waveguide (TE0) reported earlier in our lab was three times higher (5 dB/cm) and the corresponding Q-value was about 3.8 times lower (~6.5 × 10^4) [28]. Therefore, the proposed OSP chip designed with multi-mode waveguide ring resonator is expected to perform better in terms of RF photonic bandpass filter function, which would be discussed in the following section.

![Transmission characteristics of the fabricated single MRR and cascaded MRR devices around λ ~ 1540 nm.](image)

Fig. 8: Transmission characteristics of the fabricated (a) single MRR; and (b) cascaded MRR devices around λ ~ 1540 nm.

### B. Thermo-Optic Tuning Characteristics

To realize an efficient RF photonic bandpass filter functions with symmetric out-of-band rejection, the resonances of MRR1 and MRR2 corresponding to the TE0 mode should be positioned with a desired spacing (decides the central frequency of the RF passband) and the identical extinction ratio; and also the resonances corresponding to TE1 modes do not intrude within the RF frequency band of interest. Therefore, the thermo-optic tuning of four integrated phase-shifters (see Fig. 6) play crucial roles; they need to be individually reconfigured or programmed. Fig. 9a and Fig. 9b present the thermo-optic detuning of resonance wavelengths and coupling coefficient for the MRR2 by using the phase-shifters PS_{R2} and PS_{DC2}, respectively. By tuning PS_{R2}, we observed the tuning efficiency of ~ 8 pm/mW for both TE0 mode and TE1 mode resonances. It must be noted that this tuning efficiency is directly related to the FSR of the MRR; higher the FSR, higher is the tuning efficiency. In the process, there is a thermal crosstalk observed in MRR1 while the active tuning of MRR2 using PS_{R2}; we noted thermal crosstalk induced tuning of MRR1 resonances is nearly about 8 times lower (~1 pm/mW) than that of active MRR2 resonance tuning. This thermal crosstalk can be mitigated by suitable programming of all the phase shifters simultaneously. As we intend to have identical extinction for TE0 resonances for both the MRRs, we carried out thermo-optic tuning of the PS_{DC2} and the results are shown in Fig. 9b. We could achieve change in extinction from 9.3 dB to 13.2 dB for a thermal power consumption of 83.7 mW. However, we also observed wavelength tuning with a slope of ~ 2.32 pm/mW. Again, the desired extinction and resonance wavelength settings can be obtained by configuring the four phase shifters simultaneously. For example, we achieved one set of desired operating condition (see Fig. 10) by following set of thermal power consumption at the phase shifters: PS_{DC1} - 83.7 mW, PS_{R1} - 10.8 mW, PS_{DC2} - 0 mW, PS_{R2} - 0 mW.

### IV. RF Filter Experiments

To demonstrate the RF photonic bandpass filter function with the symmetric rejection, we have modified the experimental setup shown in Fig. 7 by connecting Lightwave Component Analyzer (Keysight N4735E), carrier laser light source

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>λ_{R0}</td>
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</tr>
<tr>
<td>λ_{R1}</td>
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</tr>
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</tr>
<tr>
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</tr>
<tr>
<td>Q_1</td>
<td>3 × 10^4</td>
</tr>
<tr>
<td>a_3</td>
<td>0.978</td>
</tr>
<tr>
<td>α_0</td>
<td>1.4 dB/cm</td>
</tr>
<tr>
<td>α_1</td>
<td>8 dB/cm</td>
</tr>
<tr>
<td>α_2</td>
<td>8 dB/cm</td>
</tr>
<tr>
<td>α_3</td>
<td>8 dB/cm</td>
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</table>

**TABLE IV:** Extracted coefficients of the fabricated devices. FSR: free spectral range, λ_r: resonant wavelength, n_g: group index, r: self-coupling coefficient, a: round trip loss factor, Q: quality factor α: waveguide loss and ER: extinction ratio.
Fig. 9: The thermo-optic tuning characteristics of: (a) resonance wavelength; and (b) extinction ratio of MRR2 using the phase shifters $PS_{R2}$ and $PS_{DC2}$, respectively. Inset: different settings of the thermal power level $P_{th}$.

Fig. 10: The transmission characteristics of the fabricated OSP for a programmed setting of thermo-optic phase shifters, along with the launched optical carrier ($\lambda_0 = 1540.032$ nm) for a RF photonic bandpass filter (central frequency $\sim 8$ GHz) with symmetric out-of-band rejection.

The OSP was configured to its operating condition, as shown in Fig. 11, such that $f_1 = 7.78$ GHz, $f_2 = 8.22$ GHz and subsequently the observed RF filter function in LCA has been shown in Fig. 12a. To distinguish the performance of our proposed OSP with double ring configuration, we have also shown the performance of a RF filter function with single MRR design. It is clearly evident that the asymmetric out-of-band rejection is observed in case of single MRR and symmetric out-of-band rejection in case of cascaded MRRs, as predicted in our theoretical simulations shown earlier in Fig. 5b. The observed 3-dB bandwidth of the OSP RF filter function is 0.84 GHz and the out-of-band rejection is greater than 20 dB. As expected, the shape factor of the filter response has improved from 12.34 (in case of single MRR) to 3.31 (for cascaded MRRs). The centre frequency of the RF photonic bandpass filter is 8 GHz, which is matching to the expected value of $f_{c,RF} = \frac{1}{2}(f_1 + f_2)$. For a fixed optical carrier wavelength ($\lambda_0 = 1540.032$ nm) and the fixed $f_{c,RF} = 8$ GHz, the values of $f_1$ and $f_2$ were adjusted by thermo-optically detuning the resonance wavelengths (MRR1-TE$_0$ and MRR2-TE$_0$), to obtain the bandwidth detuning from 0.84 GHz to 1.8 GHz of RF photonic bandpass filter function, as shown in Fig. 12b.

Fig. 13a shows the tuning characteristics of the RF photonic bandpass filter function by tuning the value of $f_{c,RF}$ (2
GHz to 8 GHz) through thermo-optic detuning of $f_1$ and $f_2$, maintaining the value of $|f_1 - f_2|$ constant. Our tuning characteristics was limited upto 8 GHz, due to the limitation of microheater operation. An improved design of microheater would facilitate the RF photonic filter function upto 60 GHz ($\sim$ FSR$_0$/2). For each value of $f_{c,RF} = 2$ GHz, 4 GHz, 6 GHz and 8 GHz, the bandwidth of the RF photonic filter function could be detuned and there values are shown in Fig. 13b. The bandwidth detuning was obtained without maintaining the overall operating temperature of the OSP chip and therefore we observed a bit of randomness in the observed bandwidth values.

V. CONCLUSION

A novel integrated optical signal processor (OSP) design concept has been proposed to realize an RF photonic bandpass filter with symmetric rejection. The design concept has been implemented in CMOS-compatible silicon photonics platform along with theoretical modeling and experimental demonstration. The OSP is comprised of two identical microring resonators (MRRs) cascaded in series through a single bus waveguide in all-pass configuration, in silicon-on-insulator (SOI) substrate with the device layer thickness of 220 nm. The design parameters for the ring and bus waveguides were chosen such that the Q-values could be maximized even using standard fabrication process available in our labs. Moreover, the proposed OSP could be reconfigured using suitably integrated four thermo-optic phase shifters such that the RF photonic filter functions could be programmed to a desired central frequency and bandwidth. It has been shown theoretically that the proposed OSP design can be programmed to tune the central frequency of the RF photonic bandpass filter response up to 60 GHz and the bandwidth could be detuned from 0.5 GHz (FWHM of the resonance) to 1 GHz (two times FWHM). We have also shown theoretically that the proposed OSP can offer a symmetric out-of-band rejection with a shape factor of 2.76 (ratio of 20-dB bandwidth and 3-dB bandwidth).

We have shown experimentally that the MRRs of the fabricated OSP have Q-values $\sim 3 \times 10^5$ and FWHM $\sim 5$ pm ($\sim 0.6$ GHz). The OSP could be programmed to experimentally demonstrate the RF photonic filter functions to be tuned from 2 GHz to 8 GHz with the 3-dB bandwidth tunability from 0.84 GHz to 1.8 GHz. The experimentally observed symmetric out-of-band rejection was found to be $> 20$ dB and the shape factor is $\sim 3.3$, which are in accordance with our theoretical prediction. The tuning range of the RF photonic filter in experiments was limited by the phase modulator bandwidth available to us and partly due to the limited performance of thermo-optic phase shifter; the optimized design of the phase shifters has not been considered for this experimental
demonstration. Nevertheless, we have shown the proof-of-concept of a novel design of the OSP for widely tunable RF photonic filter functions, the performance of which can be improved further.

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Ashishvel Velamuri received the B.Tech. degree in Electronics and Instrumentation Engineering from Vallurupalli Sadaswaram Rao Vignana Jyothi Institute of Engineering and Technology, Hyderabad, India, in 2014 and the Master of Science (Research) degree from Centre for Lasers and Photonics, Indian Institute of Technology (IIT) Kanpur, India, in 2019. He joined as PhD scholar at IIT Madras in Jan 2019. His current research interest is in the design, fabrication and testing of CMOS compatible silicon photonics devices for integrated microwave photonics applications.

Bijoy Krishna Das Biography text here.