Integrated Reconfigurable Modulator for Microwave Photonic Filtering

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***Abstract*—In recent years, extensive research has been conducted on integrated microwave photonic filters. Most of these studies have focused on achieving a a unversally programmable spectral filter profile, or at least a widely tunable passband, by employing single sideband modulation. However, this approach often results in a complecated system with single sideband modulation and ring-loaded Mach-Zehnder interfometers. In this report, we propose a reconfigurable modulator scheme that generates radio frequency (RF) sidebands with a tunable phase relationship. This allows for the utilization of simple optical filters, such as cascaded microring resonators, to form universal microwave photonic filters. Additionally, the modulator can be configured to function as a simple phase modulator or a Mach-Zehnder intensity modulator. Its specific performance can be optimized by considering trade-offs in other aspects to meet the application requirements. The effectiveness of the universal reconfigurable microwave photonic filter is verified through the use of two cascaded rings.**

***Keywords*—Silicon Photonics, Microwave photonics, Signal processing**

I. INTRODUCTION

Microwave photonic filters have been extensively investigated in recent years. These photonic filters possess several advantages, including low insertion loss and a large bandwidth in optical systems. Consequently, they support high frequencyies and offer a wide frequency tuning range [1], [2]. A typical microwave photonic filtering system comprises a laser, a high-speed modulator, a specially designed optical filter, and a high-speed photodetector (PD). However, if such a system is constructed using fiber devices, it becomes bulky and costly when compared to passive microwave components. Photonic integrated circuits offer a potential solution to this challenge. By leveraging mature CMOS technology, silicon photonic circuits can be fabricated with a small footprint, low cost, and high-volume production. Moreover, high-speed components such as PN junction-based modulators and germanium PDs are readily included in the process design kit (PDK) without additional costs. Nevertheless, unlike fiber-based optical systems, integrated photonic circuits are constrained by their initial connectivity and cannot be altered after fabrication, limiting the reconfigurability of integrated systems.

In optical filter design, a Mach-Zehnder interferometer (MZI) can be viewed as a moving average (MA) filter, characterized by its "zeros," while a microring resonator can be analyzed as an autoregressive (AR) filter, characterized by its "poles" [3]. By incorporating multiple phase shifters, a ring-loaded MZI structure can form a MAAR filter with independently tunable zero-pole pairs. This structure represents a limited but universal optical filter design. Several integrated microwave photonic filters have employed single-sideband modulation (SSB) schemes and ring-loaded MZIs to achieve universal microwave filtering. SSB modulation enables the complete mapping of optical filter responses in the optical domain to the radio frequency (RF) domain [4], [5]. However, SSB modulation necessitates complex modulator designs and driving schemes [4], or the use of additional optical filters [5]. Moreover, implementing a high-order rings-loaded MZI structure poses challenges in terms of tuning and scalability.

In this report, we present a reconfigurable modulator structure capable of achieving a universal microwave filter solely using simple ring resonators. The modulator is implemented by integrating a standard PN junction modulator into a tunable MZI comprising two tunable couplers (TCs) and a phase shifter. The PN junction modulator functions as a phase modulator, allowing for the imprinting of the RF signal onto the optical carrier. The other tunable components, namely the TCs and the phase shifter, are used to adjust the response of the entire circuit. By manipulating the coupling ratios of the TCs and the phase shifter, a double-sideband modulated signal with two RF sidebands (positive and negative frequencies) can be generated with a tunable phase relationship. The natural interference between these sidebands behaves as an interferometer when the signal is detected by a PD and converted back to the RF domain. As this interference supplies the MA filter component, only ring resonators (representing the AR filter) in the optical domain are necessary to form a MAAR filter in the RF domain, which can be easily scaled up to higher-order fiters. To validate the configuration of the filter, we utilized two cascaded rings. Moreover, this reconfigurable modulator can also achieve pure phase modulation, high extinction ratio intensity modulation, and other optimized responses using standard components available in the process design kit (PDK) [6]–[8].

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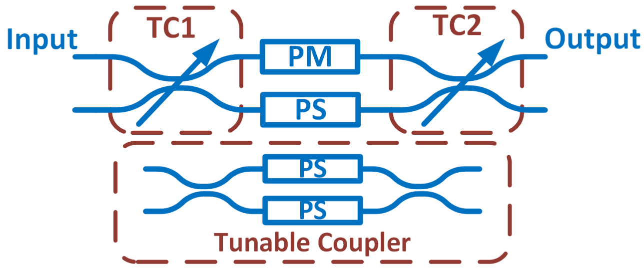

Fig. 1. Schematic of the reconfigurable modulator. TC: Tunable coupler. PS: phase shifter. PM: phase modulator.

II. Principle

The reconfigurable modulator is an MZI formed with two TCs, a PN junction based high speed modulator, two thermal phase shifters and two tap monitors. The scheme is shown in Fig. 1. Assuming that the modulator block works as bar state (from input to output in Fig. 1), the TC coupling ratios κ are set to be equal, to ensure the lowest insertion loss of the whole modulator [9]. Then, the transfer function of the modulator can be written as:

$$\begin{bmatrix} E_{\text{out1}} \\ E_{\text{out2}} \end{bmatrix} = \begin{bmatrix} \sqrt{(1-\kappa)} & j\sqrt{\kappa} \\ j\sqrt{\kappa} & \sqrt{(1-\kappa)} \end{bmatrix} \begin{bmatrix} \alpha e^{-j\phi_m} & 0 \\ 0 & e^{-j\phi_s} \end{bmatrix} \begin{bmatrix} \sqrt{(1-\kappa)} & j\sqrt{\kappa} \\ j\sqrt{\kappa} & \sqrt{(1-\kappa)} \end{bmatrix} \begin{bmatrix} E_{\text{in1}} \\ E_{\text{in2}} \end{bmatrix} \tag{1}$$

where α is the loss factor of the PN modulator (here we assume the loss is unrelated with the modulation signal, which means the modulator is a pure phase modulator) and ϕ_m is the modulator introduced phase shifts, which can be expressed as:

$$\phi_m = \pi \frac{V_{\text{rf}}}{V_\pi} \cos(\omega_{\text{rf}} t + \phi_{\text{rf}}) \tag{2}$$

In which the $V_\pi \cos(\omega_{\text{rf}} t + \phi_{\text{rf}})$ is the modulation RF signal.

Assuming the light signal $E_{\text{in1}} = e^{-j(\omega_c t)}$ is fed from the input, the modulated light signal at the output port can be expressed as:

$$E_{\text{out1}} = [(1-\kappa)\alpha e^{-j\phi_m} - \kappa e^{-j\phi_s}] E_{\text{in1}} \tag{3}$$

Using the Jacobi–Anger expansion,

$$\begin{aligned} e^{-j\phi_m} &= e^{-j[\pi \frac{V_{\text{rf}}}{V_\pi} \cos(\omega_{\text{rf}} t + \phi_{\text{rf}})]} \\ &= \sum_{n=-\infty}^{\infty} i^n J_n(\pi \frac{V_{\text{rf}}}{V_\pi}) e^{-jn(\omega_{\text{rf}} t + \phi_{\text{rf}})} \end{aligned} \tag{4}$$

where J_n is is the n-th Bessel function of the first kind, we can expend Eq.3 as:

$$\begin{aligned} E_{\text{out1}} &= [(1-\kappa)\alpha \sum_{n=-\infty}^{\infty} j^n J_n(\pi \frac{V_{\text{rf}}}{V_\pi}) e^{-jn(\omega_{\text{rf}} t + \phi_{\text{rf}})} - \kappa e^{-j\phi_s}] e^{-j(\omega_c t)} \\ &\simeq [(1-\kappa)\alpha J_0(\pi \frac{V_{\text{rf}}}{V_\pi}) - \kappa e^{-j\phi_s}] e^{-j(\omega_c t)} + \\ &\quad j(1-\kappa)\alpha J_1(\pi \frac{V_{\text{rf}}}{V_\pi})(e^{-j((\omega_c - \omega_{\text{rf}})t - \phi_{\text{rf}})} + e^{-j((\omega_c + \omega_{\text{rf}})t)\phi_{\text{rf}})}) \\ &= A_0 e^{-j\phi_{A_0}} e^{-j(\omega_c t)} + jA_1(e^{-j((\omega_c - \omega_{\text{rf}})t - \phi_{\text{rf}})} \\ &\quad + e^{-j((\omega_c + \omega_{\text{rf}})t + \phi_{\text{rf}})}) \end{aligned} \tag{5}$$

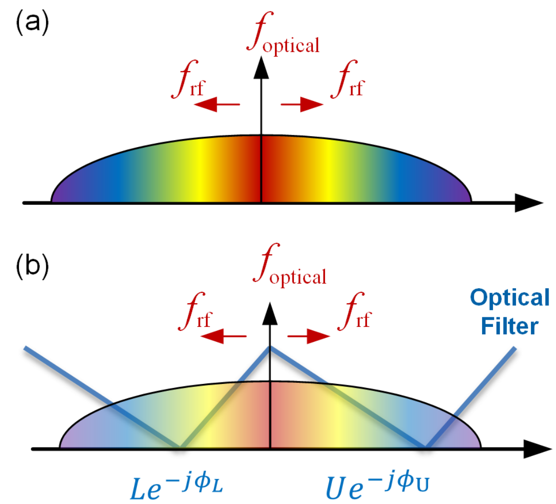

Fig. 2. (a) Broadband RF modulated optical signal. (b) Modulated optical signal with optical filter.

where just the ± 1 sidelobes are kept. The coefficients are:

$$\begin{aligned} A_0 e^{-j\phi_{A_0}} &= (1-\kappa)\alpha J_0(\pi \frac{V_{\text{rf}}}{V_\pi}) - \kappa e^{-j\phi_s} \\ A_1 &= (1-\kappa)\alpha J_1(\pi \frac{V_{\text{rf}}}{V_\pi}) \end{aligned} \tag{6}$$

When the modulated light signal is received by a PD, we can get the photocurrent with the square law detection, which can be expressed as:

$$\begin{aligned} I_{\text{PD}} &= E_{\text{out1}} \times E_{\text{out1}}^* \\ &= [A_0 e^{-j\phi_{A_0}} e^{-j(\omega_c t)} + jA_1(e^{-j((\omega_c - \omega_{\text{rf}})t - \phi_{\text{rf}})} \\ &\quad + e^{-j((\omega_c + \omega_{\text{rf}})t + \phi_{\text{rf}})})] \\ &\quad \times [A_0 e^{j\phi_{A_0}} e^{j(\omega_c t)} - jA_1(e^{j((\omega_c - \omega_{\text{rf}})t - \phi_{\text{rf}})} + e^{j((\omega_c + \omega_{\text{rf}})t + \phi_{\text{rf}})})] \\ &= A_0^2 + 2A_1^2 - 4A_0 A_1 \sin(A_0) \cos(\omega_{\text{rf}} t + \phi_{\text{rf}}) \\ &\quad + 2A_1^2 \cos(2\omega_{\text{rf}} t + 2\phi_{\text{rf}}) \end{aligned} \tag{7}$$

Then we can know that the field amplitude of the recovered RF signal at the original frequency is (with Eq.6):

$$-4A_0 A_1 \sin(A_0) = 4\kappa(1-\kappa)\alpha J_1(\pi \frac{V_{\text{rf}}}{V_\pi}) \sin(\phi_s) \tag{8}$$

which is determined by the coupling ratio of the TCs κ and the phase shifter's phase delay ϕ_s.

The recovered RF signal at the original frequency can also be expressed as:

$$\begin{aligned} I_{1^{st}} &= -4A_0 A_1 \sin(A_0) \cos(\omega_{\text{rf}} t + \phi_{\text{rf}}) \\ &= -2A_0 A_1 (\sin(\omega_{\text{rf}} t + \phi_{\text{rf}} + \phi_{A_0}) + \sin(-\omega_{\text{rf}} t - \phi_{\text{rf}} + \phi_{A_0})) \end{aligned} \tag{9}$$

Then it can be regarded as two sidelobes ($\sin(\omega_{\text{rf}} t + \phi_{\text{rf}})$ and $\sin(-\omega_{\text{rf}} t - \phi_{\text{rf}})$) interference with a phase difference of $2\phi_{A_0}$. The ϕ_{A_0} is determined in Eq. 6.

As a conclusion, the modulator block as showed in Fig. 1. can load the RF signal on the optical carrier signal, and the phase relation of the recovered RF sidelobes can be tuned with the modulators configuration. This property builds up the fundamental of reconfigurable microwave photonic filter with double sideband modulation scheme.

From Fig 1, it can be found that if $\kappa = 0$, all light would go through the PN modulator, then the modulator block works as a phase

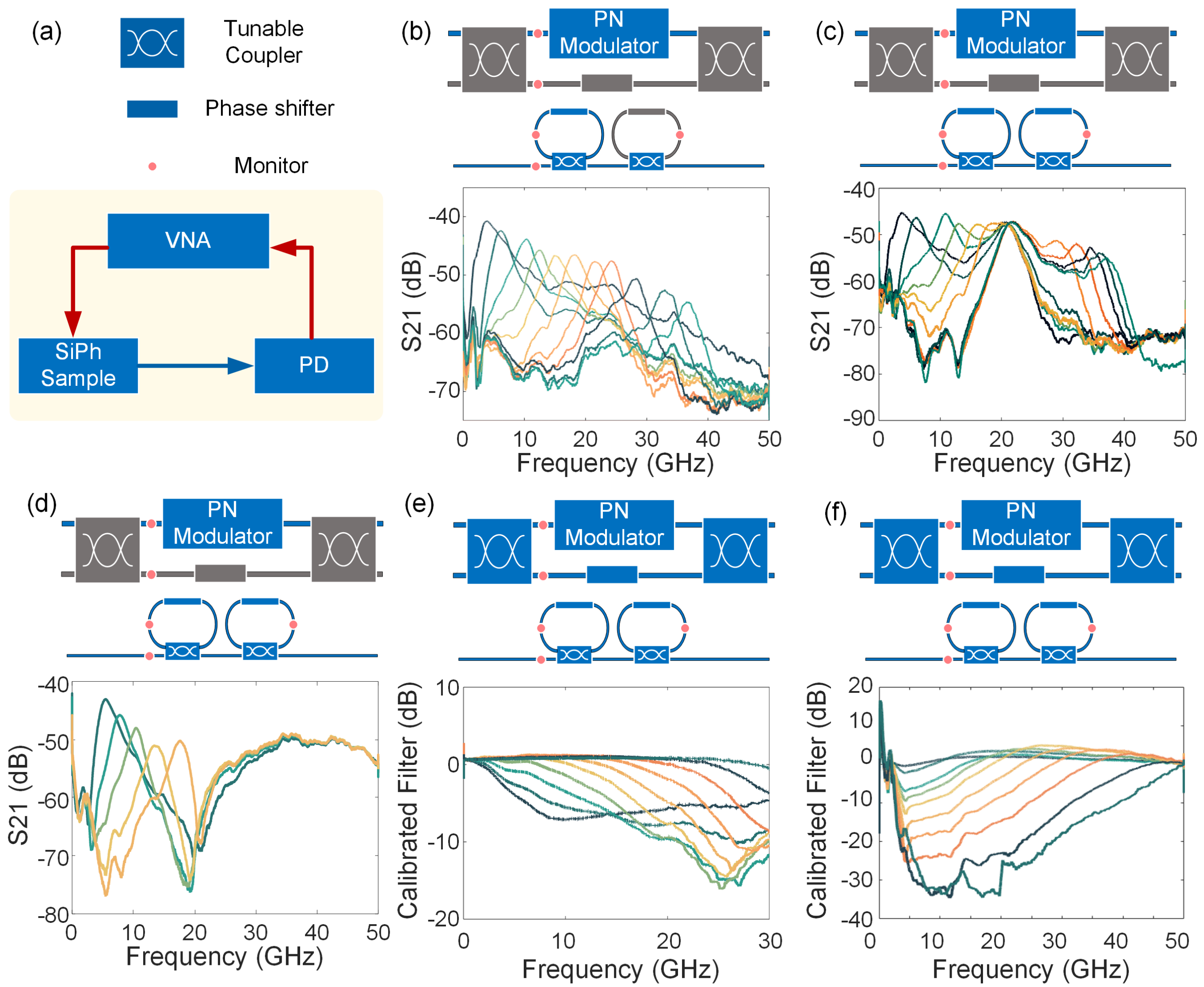

Fig. 3. (a) Measurement setup of the microwave photonic filter. (b) Microwave filter: single-tunable bandpass filter. (c) Microwave filter: double-tunable bandpass filter; (d) Microwave filter: tunable one-pass one-stop band filter; (e) Microwave filter: tunable low pass filter; (f) Microwave filter: tunable high pass filter. VNA: Vector network analyzer; SiPh sample: silicon photonic sample. PD: photo detector.

modulator. And if $\kappa = 0.5$, the modulator block is set as a common intensity modulator, which can be verified with Eq. 8 when $\kappa(1-\kappa)$ and $\sin\phi_s$ are maximized.

If the modulated signal is not a single frequency signal (ω_{rf}) as discussed above, but a broadband signal, the two sidelobe signals will become two sidebands, as shown in Fig. 2(a). To fuction as a microwave photonic filter, an optical filter will be needed, which can be described as shown in Fig. 2(b), with a different filter profile in the upper and lower sideband:

- Lower sideband: $Le^{-j\phi_L}$
- Upper sideband: $Ue^{-j\phi_U}$
- Central frequency: 1

Then, at the output, all the frequency components will be added up with this filter profile, and the Eq. 5 will be as:

$$E_{\text{filtered}} = A_0 e^{-j\phi_{A_0}} e^{-j(\omega_c t)} + jA_1\big(Le^{-j((\omega_c-\omega_{\text{rf}})t-\phi_{\text{rf}})+\phi_L} + Ue^{-j((\omega_c+\omega_{\text{rf}})t+\phi_{\text{rf}}+\phi_U)}\big) \tag{10}$$

and the output RF signal from PD at its original frequency will be:

$$\begin{aligned} I_{1^{st}} = & -2A_0A_1[U\sin(\omega_{\text{rf}}t+\phi_{\text{rf}}+\phi_{A_0}+\phi_U) \\ & + L\sin(-\omega_{\text{rf}}t-\phi_{\text{rf}}+\phi_{A_0}+\phi_L)] \end{aligned} \tag{11}$$

Then the field transformation function can be calculated as:

$$|H_{\omega_s}| = 2A_1A_0\sqrt{U^2+L^2-2UL\cos(\phi_U+\phi_L-2\phi_{A_0})} \tag{12}$$

Based on this, we can calculate the transfer function of the microwave photonic filter for a generic optical filter, where the coefficients A_0, A_1, ϕ_{A_0} can be found in Eq. 6 and $Le^{-j\phi_L}$, $Ue^{-j\phi_U}$ are the optical filters optical response for the lower and upper sideband, respectively.

If we make an assumption for high quality factor ring resonators, namely that the ring only filters within one sideband and has no effects on the other sideband, the optical filter can be simplified as (say, on lower side):

- Lower sideband: $L_r e^{-j\phi_{L_r}}$

- Upper sideband: 1
- Central frequency: 1

Then the Eq. 11 becomes:

$$\begin{aligned} I_{1^{st}} = &-2A_0A_1[\sin(\omega_{\mathrm{rf}}t + \phi_{\mathrm{rf}} + \phi_{A_0}) \\ &+ L_r \sin(-\omega_{\mathrm{rf}}t - \phi_{\mathrm{rf}} + \phi_{A_0} + \phi_{L_r})] \end{aligned} \tag{13}$$

which can be regarded as the interference of two RF signals (normal frequency and reversed frequency), and the lower sideband signal (reversed frequency) is filtered by an optical ring. Note that the phase relation between the RF signals can be individually tuned. The end-to-end RF frequency response is now equivalent to that of a ring-loaded MZI in the optical domain. This makes the microwave photonic filter a universal MAAR filter in the RF domain, while the filter order is determined by the number of ring resonators in the optical path.

III. Experimental results

A sample was fabricated in imec's iSiPP50G silicon photonic platform confirmed the filter design algorithm described above. The measurement setup is shown in Fig. 3(a), where the vector network analyzer used was Keysight E8364B ($50\,\mathrm{GHz}$) and the PD used was Discovery LabBuddy DSC10H ($43\,\mathrm{GHz}$). On the silicon photonic chip, we implemented the proposed reconfigurable modulator, and two cascaded tunable ring resonators, as shown in Fig. 3(b)-(f). Built-in tap PDs were added in the circuits to monitor the configuration of the photonic system.

The quality (Q) factor of the rings depend on their round trip loss, which includes the propagation loss and coupling loss [10]. In our implementation we used a TC as the ring coupler, so the coupling loss in the ring can be tuned, which leads to a tunable Q factor of the ring. The rings were measured with a $3\,\mathrm{dB}$ bandwidth of around $30\,\mathrm{pm}$ when in the critical coupling state, corresponding to a Q factor of 50k. The Q was limited by the extra loss introduced by a tap PD inside the ring.

Fig. 3(b) shows that, if the reconfigurable modulator is set as a phase modulator and a single ring is used, we can achieve a single bandpass filter in the RF domain. If two rings are used, a double bandpass filter or one-pass one-stop band filter can be realized,where the difference is that the second ring is either under/critically coupled (shown in Fig. 3(c)), or overcoupled (shown in Fig. 3(d)). This filter configuration is set for the $\kappa = 0$, thus $\phi_{A_0} = 0$ in Eq. 6, and these filtering results fully match the optical filtering response of a double-ring-loaded MZI with zero offset phase.

Fig. 3(e-f) shows a tunable high-pass filter and a low-pass filter response, respectively. Here the modulator is set as an intensity modulator, and the rings are all overcoupled, which maps onto a Chebyshev type II filter. With the phase tuning of one ring, the filter bandwidth can be tuned. The roll-off speed of these filters depends on the filter order in both upper and lower sideband, which can be easily scaled up with additional rings.

What to be noticed is that the ring filters are not always configured with high Q factors, which breaks the high Q assumption discussed for Eq. 13. Especially, the phase shift introduced by the ring show effects on both of the lower sideband and upper sideband, which can be noticed in Fig. 3(d) where the notch position drifts with the peak position. So the final results may need extra tuning to reach a target filtering response, and this tuning can be fully predicted with Eq. 12.

IV. Conclusion

In this report, we proposed a reconfigurable modulator design which can implement a universal microwave photonic filter just with cascaded ring resonators. The modulator can generate a double-sideband modulated light signal, which will results in two RF sidebands (plus frequency and negative frequency) in PD with a tunable phase relationship. The natural interference of RF signal release the optical filter design complexity. Compared to previous SSB + ring-loaded MZI schemes, this double sideband modulation + cascaded rings simply the optical design as well as the driving calibration/control systems, also with a lower RF loss in principle. An analytical expression of mapping the optical filter response into RF domain was also provided, both in amplitude and phase. This can also guide the optical filter design if a target RF transfer function is needed.

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