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Microwave photonic notch filter with integrated phase-to-intensity modulation transformation and optical carrier suppression

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We demonstrate for the first time, to the best of our knowledge, an on-chip microwave photonic (MWP) notch filter with high stopband rejection and integrated optical carrier suppression in a phase modulator-based system. The notch filter was achieved through phase modulation to intensity modulation (PM-to-IM) transformation and dual-sideband-processing using a network of three ring resonators (RRs) in a low-loss silicon nitride (Si_3N_4) platform. We show simultaneous PM-to-IM conversion and optical carrier processing for enhancing the filter performance using a single RR. We achieve filtering with a high stopband rejection of >55 dB, an optical carrier suppression up to 3 dB, a radio frequency link gain of 3 dB, a noise figure of 31 dB, and a spurious-free dynamic range of $100 \text{ dB} \cdot \text{Hz}^{2/3}$. These experiments point to the importance of vectorial spectral shaping of an MWP spectrum for advanced functionalities. © 2021 Optical Society of America

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High-frequency microwave signal processing based on an integrated microwave photonics (MWP) system has been evolving with an exceptional pace in the past decade and offers multiple advantages, such as integration and miniaturization of various advanced MWP signal processing systems [1,2]. In MWP signal processing, the combination of integrated spectral shaping capabilities, advanced functionalities, and performance enhancement technique become a powerful tool to make integrated MWP devices more comparable to conventional microwave electronics. To simultaneously achieve these multiple functionalities and high-performance metrics in an integrated MWP system, vectorial (phase and amplitude) shaping of a radio frequency (RF)-modulated spectrum becomes critical [3]. Such a spectral shaping can be implemented with various integrated optical components, including Bragg gratings [4,5], on-chip stimulated Brillouin scattering (SBS) [6,7], or a network of ring resonators (RRs) [8,9]. The RR, in particular, offers highly versatile, tunable, and scalable MWP spectral shaping.

Modulation transformation and MWP filtering are two key functions of integrated MWP that have been demonstrated through vectorial spectral shaping. Tailoring the phase and amplitude of MWP spectral components, in this case, the optical carrier and the first-order sidebands, allow one to transform modulation scheme from phase modulation to intensity modulation (PM-to-IM), or a more complex modulation format [3]. On the other hand, the same technique can be implemented to synthesize constructive and destructive interference patterns in the output microwave frequencies, thereby sculpting a complex microwave filter transfer function with high resolution and precision. Previous works show formation of notch or bandpass filters through the spectral shaping technique using RRs [10,11] or chip-based SBS [12,13].

In particular, shaping the amplitude ratio of the optical carrier and the sidebands is also beneficial for reducing the impact of noise to the microwave signal integrity. Suppressing only the optical carrier and then amplifying it back together with the RF sidebands can lead to dramatic reduction of the RF noise figure (NF). While implementing this in an IM-based system with a low-biased Mach-Zehnder modulator is rather straightforward, achieving the same effect in a PM-based system can be challenging [14]. On the other hand, PM-based systems are attractive due to the simplicity in their bias-free operation that can lead to higher system stability. In this view, it is thus important to explore the potential of vectorial spectral shaping in PM-based integrated MWP systems for simultaneous enhancement of functionality and noise performance.

In this Letter, we demonstrate vectorial spectral shaping of an optical carrier and RF sidebands generated from a phase modulator to achieve, for the first time, to the best of our knowledge, three simultaneous operations in the same circuit, namely PM-to-IM conversion, destructive-interference-based high-rejection notch filtering, and NF reduction through an emulation of low biasing. We implement these functions with a network of three silicon nitride RRs. With this approach, we experimentally demonstrate a notch filter with a high stopband rejection of >55 dB, an amplification in the RF passband with

Fig. 1. Principle and experimental setup of the proposed MWP notch filter with a high stopband rejection and improved filter performance. An RR was used to convert phase-to-intensity modulation and partially suppress the optical carrier, while two more RRs were used to form the high-rejection notch filter. RF, radio frequency; PM, phase modulator; EDFA, erbium-doped-fiber-amplifier; PC, polarization controller; OC, over-coupling; UC, under-coupling; PD, photodetector; CR, optical carrier; LSB, lower sideband; USB, upper sideband.

a link gain of 3 dB, a reduced NF of 31 dB, and a spurious-free dynamic range (SFDR) of $100 \text{ dB} \cdot \text{Hz}^{2/3}$.

The operation principle of the proposed integrated MWP notch filter is depicted in Fig. 1. The RF input signal was converted to the optical domain using a phase modulator, creating a spectrum consisting of an optical carrier and two identical amplitude sidebands that are out-of-phase. Photodetection of such a spectrum will lead to destructive interference between the beating products of the optical carrier and the two optical sidebands at ω_{RF} , resulting in no RF signal at the output. For this reason, we implement an RR as a complex optical filter that alters the phase of the optical carrier and converts the PM input into IM. Specifically, we set the coupling of light to the resonator in the over-coupling (OC) state to achieve $\pi/2$ -phase shift for a slightly detuned frequency from the center of the ring resonance [Fig. 1(b)].

In practice, we control the amplitude and phase response of an OC and under-coupling (UC) ring by varying the two tuning properties of the RR, namely the coupling coefficient from the bus waveguide to the ring (k) and the round-trip phase ($\emptyset$). Figures 2(a) and 2(b) depict the simulated RR notch depths, and the phase responses correspond for varying k , set at OC and UC state, respectively. In Fig. 2(c), the variation of the RR phase response with $\emptyset$ is shown. Here we assume that the optical carrier is aligned to the resonance frequency of RR ($\emptyset = 0$), and the round-trip phase of RR was used to shift the resonance frequency of RR relative to the optical carrier to achieve $\pi/2$ -phase shift at optical carrier frequency for PM-to-IM transformation [Fig. 2(d)]. Because the RR gives simultaneous shaping of both the phase and amplitude of the optical carrier, the same RR for PM-to-IM conversion is also used for carrier suppression necessary to obtain filter performance enhancement. More details of this will be discussed shortly.

In addition to the processing of the optical carrier, we align the resonance frequencies for two additional RRs to the upper and lower RF-modulated sidebands for creating a high-rejection notch filter. Following the approach in [15], we use resonances from two RRs operating at OC and UC states. These resonances have identical amplitudes and were positioned symmetrically

Fig. 2. Simulated transmission and phase responses of the RR with different k -value sets at the (a) OC and (b) UC state. (c) OC ring phase response with different $\emptyset$ -values for the frequency shift. (d) Illustration of phase and amplitude response configurations to implement modulation transformation in this Letter. CR, optical carrier; LSB, lower sideband; and USB, upper sideband.

with respect to the optical carrier ($f_1 = f_2$) to control the amplitude and phase of the two sidebands, as shown in Fig. 1(c). Due to the phase difference between the OC and UC state of the rings, a π -phase shift is introduced at the desired notch frequency, creating destructive interference between mixing products of the optical carrier and two sidebands, forming a strong notch response at ω_{RF} with a high stopband rejection filter response. This high-rejection notch filter can be achieved only when we can precisely spectrally shape the phase and amplitude relation of a PM spectrum and impose a $\pi/2$ -phase rotation of the optical carrier for PM-to-IM transformation simultaneously.

Figure 3(a) shows the simulation results of the filtering response obtained from the optical carrier processing (rotation) in the PM-to-IM transformation process in combination with the notch filtering. In a PM-based MWP system, the combination of OC and UC rings introduced a π -phase shift at

Fig. 3. (a) Illustration of the optical carrier processing in the PM-to-IM transformation process. Simulated OC and UC ring combination (b) before optical carrier processing ($\theta_c = 0$), (c) when half optical carrier processing ($\theta_c = \pi/4$), and (d) when full optical carrier processing ($\theta_c = \pi/2$). RR, ring resonator; θ_c , optical carrier rotation angle.

dedicated notch frequency, creating a passband response, as shown in Fig. 3(b). Later, when an OC ring rotates the optical carrier for modulation transformation, a transition from passband to stopband/notch can be observed. Figure 3(c) shows simulated transmission of the transition when the OC ring rotated the optical carrier halfway through the modulation transformation process ($\theta_c = \pi/4$). We can see that there is a stopband/notch at previous passband frequency and an imbalance level in passband. Later, when we rotate the optical carrier further until we have full modulation transformation ($\theta_c = \pi/2$), we can see a strong stopband/notch response with high stopband rejection at dedicated frequency (in this case at 5 GHz), as shown in Fig. 3(d).

As the third function in our integrated circuit, we implemented optical carrier suppression using the same ring for PM-to-IM transformation to emulate low biasing in a PM-based integrated MWP system. In this scheme, we compensate for the losses due to the optical carrier suppression by re-amplification using the gain from an erbium-doped fiber amplifier (EDFA). This re-amplification was done such that, at various carrier suppression levels, the detected direct current (DC) optical power on the photodetector (PD) remains constant. The performance enhancement is achieved, because the optical carrier suppression is only reducing the DC optical power, whereas the broadband gain of the EDFA leads to amplification of all signal components, including the two sidebands. As a result, the combination of re-amplification and optical carrier suppression give RF link gain enhancement with increasing optical carrier suppression levels to the system. Then, by tuning the ring's phase and amplitude simultaneously, the central frequency of the notch filter can be modified.

An experimental setup, such as the one illustrated in Fig. 1, was established to characterize the on-chip MWP notch filter with its noise performance. A low relative intensity noise (RIN) continuous-wave laser (Pure Photonics PPCL550) set at 1550 nm generated an optical carrier that was phase modulated using a phase modulator (EOSpace 20 GHz) with optical insertion losses of 3 dB. A vector network analyzer (VNA, Keysight P9375A) with RF power of -3 dBm was used to drive the PM

Fig. 4. Measured (a) PM-to-IM transformation. A MWP notch filter (b) using one RR and two RRs, (c) with central frequency variations, and (d) with optical carrier suppression. CS, carrier suppression.

where the output was then sent to a 2 W EDFA (Amonics) before being injected into a programmable silicon nitride chip (LioniX International) fabricated using the low-loss TriPleX ($\text{Si}_3\text{N}_4/\text{SiO}_2$) technology. The photonic chip has propagation loss of the optical waveguide of 0.15 dB/cm with fiber-to-fiber insertion losses of 8.5 dB. The chip contains three all-pass RRs, where each ring has a free spectral range of 25 GHz and can be tuned through thermo-optic tuning using chromium heaters controlled with custom-made controller software. Later, the processed optical signal was sent to a matched PD (APIC 40 GHz), and the retrieved RF signal was measured in the VNA and RF spectrum analyzer (RFSAs, Keysight N9000B). For all measurements, the detected optical power was set to a constant value of 16 dBm.

Figure 4(a) shows the measurement results of PM-to-IM transformation using $\pi/2$ -phase shift of OC ring placed at optical carrier frequency. In this figure, when PM-to-IM transformation was implemented, we can see the RF link gain improvement up to 30 dB, showing a strong passband at 0 dB as the highest point. Then we used another OC RR aligned in central frequency to one of the sidebands to create a MWP notch filter with 8 dB of rejection [red line in Fig. 4(b)]. When we aligned another RR set at UC state with an identical amplitude, but at the opposite sideband, we created a MWP notch filter with a high stopband rejection of >55 dB [black line in Fig. 4(b)] and a 3 dB bandwidth of 390 MHz. Here an optical quality factor (Q-factor) of the RR was 5.1×10^5 , while the Q-factor of the notch filter at central frequency of 5 GHz was 12. The Q-factor of the notch filter refers to the ratio of the central frequency of the notch filter to the filter 3 dB bandwidth. Further, by adjusting the rings' central frequencies relative to the optical carrier, the MWP notch filter central frequency can be tuned as shown in Fig. 4(c). We then implement the optical carrier suppression using the same RR that we used for PM-to-IM transformation. The maximum suppression we get from the ring is 3 dB, as depicted in Fig. 4(d). As expected, a 3 dB suppression of the optical carrier leads to 3 dB reduction of the RF link gain [red line in Fig. 4(d)]. If we implement re-amplification to compensate for the reduction of RF link gain using a broadband EDFA, we obtain an enhancement of RF link gain of 3 dB [blue line in Fig. 4(d)] compared to the case with no

Fig. 5. Simulated and measured filter's (a) gain enhancement, NF reduction, and (b) SFDR.

carrier suppression [black line in Fig. 4(d)] without increasing the DC photocurrent.

We further analyze the performance metrics improvement of our notch filter in the system, including the RF link gain enhancement and the NF reduction of the filter using the optical carrier suppression technique. We plot the measured RF link gain with EDFA re-amplification together with the calculated link gain. From the measured values of RF link gain and noise power, we calculated the RF NF with RIN of -155 dB/Hz. The simulated and measured RF link gain and NF are shown in Fig. 5(a). In this figure, we plot the calculated RF link gain and NF with EDFA re-amplification to compensate for the losses created by optical carrier suppression, showing RF link gain improvement to 3 dB and NF reduction to 31 dB.

Furthermore, we also measured the filter linearity in our system using a two-tone test with a tone spacing of 10 MHz and measured the third-order intermodulation distortion (IMD3) using an RFSA. The measured third-order intermodulation powers as a function of input RF power at the two-tone center frequency of 3 GHz are shown in Fig. 5(b). It can be seen that the third-order input intercept points (IIP3) can be estimated at $+7$ dBm with measured third-order SFDR to be $100 \text{ dB} \cdot \text{Hz}^{2/3}$ with the measured noise power spectral density of -139 dBm/Hz. For all these measurements, the notch filter frequency was set at 5 GHz, and the optical power was maintained at 16 dBm. It is important to stress that these results are achieved without using any custom-made high-power handling PD and RF amplifier in the system.

In our experiments, high input optical power to the ring generates resonance shift due to the nonlinearity and thermal effects. In the thermal effect, the heat is generated from the part of the high power in the resonator that is absorbed by the RR. The temperature shift translates to a resonance frequency shift via both the thermo-optic effect and thermal expansion of the resonator. Here the temperature is stabilized by a thermoelectric cooler (TEC) controller.

Further, the notch filter's central frequency in this experiment depends on the laser source's frequency stability and the drift in the resonance frequency of the RRs operating at the sidebands. Thus, the most viable way to stabilize the central frequency is through the wavelength locking of the laser to the rings via a feedback loop consisting of a lock-in amplifier [16]. Then the notch depth of the filter critically depends on the shifts in the resonance frequencies of the three RRs and their coupling states. Ultra-high notch depth can be achieved through perfect destructive interference in the notch frequencies that is dictated by the phase and amplitude responses of the rings in the sidebands as well as the phase response of the ring at the carrier. It was reported in [17] that the long-term stability of such a cancellation notch filter varies with time due to the loss in the balance of amplitude and phase. One way to mitigate this

effect is through monitoring the notch depth and implementing a feedback loop to control the phase amplitude response of the rings.

Regarding the filter noise performance, the lowest NF measured in our experiments was 31 dB. This result was achieved because of the limitation of optical carrier suppression and added noise power introduced to the system in PM-to-IM transformation. In a PM-based MWP link (without modulation transformation and filtering functionalities), we measured total noise power spectral density at -149 dBm/Hz. This noise power level increased to -139 dBm/Hz when we implemented PM-to-IM transformation, meaning that there was a 10 dB added noises to the system. This added noise came from the combination of amplified spontaneous emission from the EDFA, and the phase noise from laser converted to intensity noise by RR during PM-to-IM transformation. To avoid this added noise, an alternative for RR-based PM-to-IM transformation can be considered, such as modulation transformation device [3].

In conclusion, we have demonstrated an integrated MWP signal processor using a network of three RRs in a single photonic chip that spectrally shape the PM spectrum, for the first time, to the best of our knowledge, to create a MWP notch filter with a high stopband rejection and enhanced filter performance.

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