On-chip Programmable Microwave Photonic Filter with an Integrated Optical Carrier Processor

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We demonstrate experimentally a programmable microwave photonic bandpass filter with a rectangular frequency response and a reconfigurable spectral resolution. We achieved these features through dual-sideband processing of a phase modulated signal using a network of four optical ring resonators in a low-loss silicon nitride (Si_3N_4) circuit. Furthermore, we integrate a pair of optical ring resonators in the same chip to precisely control the phase and amplitude of the optical carrier to enhance the modulation and noise performance of the filter.

1. Introduction

Microwave filters are important analog signal processing elements to remove unwanted signals or select desired information in the radio frequency (RF) spectrum for multiple practical applications, such as radar and next generation communication systems [1, 2]. In the past decades, microwave photonic filters have shown competitive performance to their electrical counterparts, with multiple advantages in term of flexibility, scalability, and electromagnetic interference (EMI) immunity. To be more competitive with state-of-the-art microwave filters, it is essential for microwave photonic filters to adopt integrated optics technology that gives integration and multiple functionalities in a single chip, owing to the complementary metal-oxide-semiconductor (CMOS) compatible fabrication technology.

Here, we focus on programmable microwave photonic bandpass filter. This filter is important for selecting desired information from interferers in radio communication systems. Programmable microwave photonic bandpass filters have been researched using various integrated photonic devices, such as fiber Bragg gratings [3], ring resonators [4, 5], and stimulated Brillouin scattering (SBS) [6, 7]. Among these photonic devices, integrated ring resonators are able to implement microwave photonic bandpass filter in a passive and compact form, that allows multiple ring resonators connected in series on a single bus waveguide.

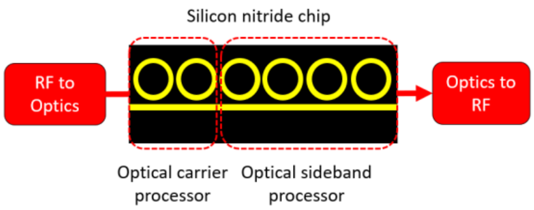

Fig. 1. Schematic of on-chip integrated microwave photonic filter proposed in this work

In this paper, we report and demonstrated experimentally a programmable microwave photonic bandpass filter with a rectangular frequency response and a reconfigurable spectral resolution. Such a filter based on a phase compensated cascaded four all pass ring resonators in a low-loss silicon nitride (Si_3N_4) [8]. Furthermore, we integrated a pair of ring resonators in the same chip (see Fig.1) to process the amplitude and phase of optical carrier for modulation and noise performance enhancement of the filter.

2. Principle of operation

Fig. 2 illustrates the operation principle of the proposed microwave photonic bandpass filter with integrated optical carrier filtering using six cascaded all-pass ring resonators. The input RF signal is converted into the optical domain with optical phase modulator (PM), generating two identical amplitude sidebands that are out-of-phase.

Here, we use the resonance of four ring resonators that operated at the over-coupling (OC) state and positioned asymmetrically with respect to the optical carrier ($f_1 \neq f_2 \neq f_3 \neq f_4$) to control the amplitude and phase of two sidebands (the resonance of two ring resonators for one sideband) to achieve phase-modulation to intensity-modulation (PM-IM) conversion. A π-phase shift is introduced at the desired notch frequency, creating constructive interference between mixing product of optical carrier and two sidebands, forming a strong RF passband at ω_{RF} with a box-like and a flat top filter response. By properly controlling the coupling coefficient and round-trip phase of the rings, we can subsequently tailor the bandwidth of the filter.

Additionally, two ring resonators operate at the under-coupling (UC) state are assigned as optical carrier filtering and used to reduce the optical carrier-to-sideband ratio, maintaining the input optical power to the photodetector. This operation, an equivalent of the low-biasing technique commonly employed intensity modulated microwave photonic links, can be exploited to improve the noise figure performance of the system. Low-biasing is a technique of moving the bias point away from quadrature point towards lower bias angle in Mach-Zehnder modulator (MZM) based intensity modulator. The purpose of low-biasing the MZM is to limit DC photocurrent, without significantly reduce the modulator link gain.

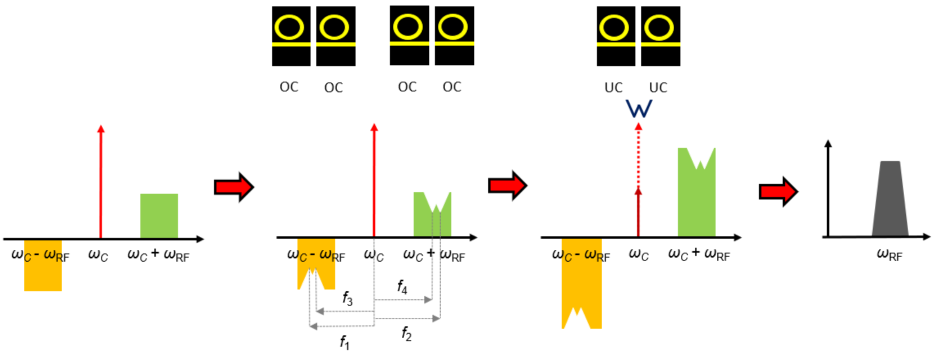

Fig. 2. Operation principle of on-chip programmable bandpass filter with integrated carrier filtering

3. Experimental setup

The experimental setup of on-chip programmable bandpass filter is depicted in Fig.3. An optical carrier from a low relative-intensity-noise (RIN) limited laser (Pure Photonics PPCL550) at 1550 nm is phase modulated using a phase modulator (Covega 10G Phase Modulator) with optical insertion losses of 3.5 dB. The PM is driven by an RF signal from a vector network analyzer (VNA, Keysight P9375A). The output of PM then sent to an erbium-doped amplifier (EDFA, KEOPSYS) with an output power of 21.5 dBm before being injected into a programmable silicon nitride chip (LioniX international) fabricated using the low-loss TriPleX (Si_3N_4/SiO_2) technology [8]. The utilized part of the chip consists of six optical ring resonators connected in series.

The chip has fiber-to-fiber insertion losses of 8.5 dB and the propagation loss of the optical waveguide is less than 0.2 dB/cm. Each ring resonator has a free spectral range

(FSR) of 25 GHz, and the coupling coefficient and resonance frequency are tunable through thermo-optic tuning and can be programmed via controller software in personal computer (PC). The processed optical signal is sent to a photodetector (APIC 40GHz Photodetector) and the converted RF signal is measured by the VNA.

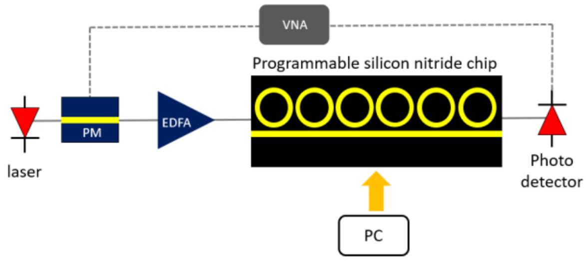

Fig. 3. Experimental setup of on-chip programmable bandpass filter with integrated carrier filtering

The tuning of four ring resonators to create bandpass filter can be explained as follows: by controlling the coupling coefficients (k) of each ring, we can tune the passband magnitude. Furthermore, by adjusting the round-trip phase of each ring resonator (φ), we are able to control the passband bandwidth. The resonance combinations of ring resonators obtained from the variation of coupling coefficients and round-trip phases of the rings define the total strength and the bandwidth of the bandpass filter.

4. Bandpass filter results

Fig. 4 (a) shows the measured microwave photonic bandpass filter responses at central frequency of 5 GHz. The bandwidth tuning range is around 4 GHz (2 to 6 GHz) obtained from precise control of coupling coefficient and round-trip phase of four over coupled ring resonators operated at two sidebands. It should be noted that the passband loss of the filter measured at around -16 dB due to the losses introduced at RF-to-optical and optical-to-RF conversion.

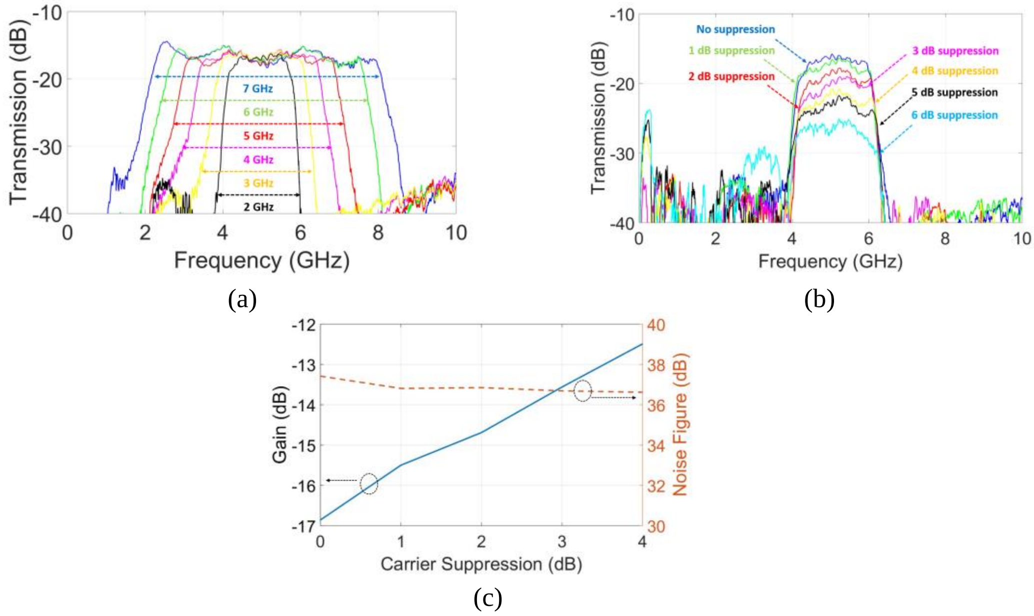

Fig. 4. Measured RF responses with (a) multiple bandwidths (b) multiple suppressions; (c) measured gain and noise figure of microwave photonics bandpass filter

Fig. 4 (b) shows the measured filter responses with additional carrier filtering by a pair of under-coupled ring resonators. The suppression of optical carrier can be varied from 1 to 5 dB by controlling both phase and amplitude of two under-coupled ring resonators. This carrier suppression was then compensated by increasing the gain from the EDFA. As a result, for each case the optical carrier power is kept at 13 dBm at the photodetector, but the filter link can be improved approximately by the amount of the carrier suppression (Fig. 4(c)).

We further measure the noise performance of the filter with and without carrier filtering. As shown in Fig. 4 (c), the noise figure of the filter remains virtually the same for all cases of carrier suppression. This hinted that the system noise is not limited by the relative intensity noise (RIN) of the laser source, but rather by the amplified spontaneous emission (ASE) noise from the EDFA. Further investigations are ongoing to explore possible noise figure improvement using the technique we report here.

5. Conclusions

We have demonstrated on-chip programmable microwave photonic filter with an integrated optical carrier processing. The programmable microwave photonic filter is achieved using cascaded four ring resonators operated at over-coupling state for dual-sidebands processing. The bandwidth tunability (2 to 6 GHz) can be obtained by properly control the coupling coefficient and round-trip phase of the rings. An auxiliary two ring resonators operated at under-coupling state are added for optical carrier filtering, leading to enhancement of the passband gain while maintaining input optical power to the photodetector. Investigation on the noise and linearity performance of the filter is ongoing.

Acknowledgments

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