Tunable and Reconfigurable Bandpass Microwave Photonic Filters Utilizing Integrated Optical Processor on Silicon-on-Insulator Substrate

Dengke Zhang, Xue Feng, and Yidong Huang, *Member, IEEE*

***Abstract*— A tunable and reconfigurable bandpass microwave photonic filter based on an integrated optical processor is proposed and experimentally demonstrated on a silicon-on-insulator substrate. The optical processor based on microrings, Mach–Zehnder interferometer, and Y-branches is utilized to produce two bandpass responses for separately processing optical carrier and sideband. Moreover, the microwave responses can be varied by thermal tuning the resonance of microrings. According to the experimental results, the operating frequency and −3-dB bandwidth can be tuned from 18 to 40 GHz and from 5 to 15 GHz, respectively.**

***Index Terms*— Integrated optics, microwave photonic filters (MPFs), microrings, reconfigurable, tunable.**

I. Introduction

MICROWAVE photonic filters (MPFs) can be employed to process microwave (even millimeter wave) signal in the optical domain with attractive characters, such as low loss, wide bandwidth, and immunity to electromagnetic interference [1], [2]. The scope of the applications of MPFs is broad ranging from radar, satellite to wireless communications. These applications need tunable and reconfigurable MPFs for processing random and unpredictable signals. For this target, both the central operating frequency and bandwidth of MPFs are required to be tuned. Several approaches have been proposed and demonstrated based on fiber devices [3], [4]. However, high operating frequency with wide tuning range are difficult to be achieved using fiber devices based MPFs. Recently, As the development of photonic integrated circuit, MPFs based on integrated silicon optical processors, which are fabricated on Silicon-on-Insulator (SOI), attract much more attentions because of the compatibility with other integrated optoelectronic IC components, small footprints, and flexible tunings [5], [6]. B. Pile et al. have investigated the operation principle of MPFs based on optical microrings in theory firstly [7]. Then the tunable MPF, which consists of a notch microring, four microrings, and integrated optical delay line, were demonstrated by several groups [8]–[11]. But previous reports are mainly focused on tuning the operation frequency. To the best knowledge of authors, there are still no reports about integrated tunable and reconfigurable bandpass MPFs, in which both the operating frequency and bandwidth could be tuned.

In this letter, in order to pave the way for realizing integrated tunable and reconfigurable MPFs, an integrated optical processor consisting of microrings (MRs) and Mach–Zehnder interferometer (MZI) on SOI substrate is proposed and experimentally demonstrated for MPFs operating in millimeter wave domain. The proposed optical processor can produce two bandpass responses, which are used to separately process optical carrier and one of the sideband generated by intensity modulation [12]. The tunability and reconfigurability of MPF is achieved by tuning the resonance of MRs.

II. Proposed Structure and Operating Principle

Figure 1(a) depicts the typical scheme of a MPF with intensity modulation and direct detection. After the optical carrier is modulated, the optical spectrum includes two parts: carrier and two sidebands. If a proper optical processor with two bandpass responses is employed, carrier and one of sideband could be processed separately (another sideband out of the bandpass responses would be suppressed). Then after photodetection, the filtered signal in optical domain could be converted back to microwave signal. Based on this microwave processing in optical domain, bandpass MPFs can be obtained. For such MPFs, the operating frequency (OF) is determined by frequency interval of the two optical bandpass responses and the bandwidth is determined by the shape of bandpass response for sideband signal. Thus, tunability and reconfiguration of MPF can be achieved by tuning frequency interval and bandwidth of bandpass response for sideband independently.

Here, the optical processor with two bandpass responses is designed based on integrated MRs, which takes the advantage of high quality factor (narrow bandwidth). The proposed structure is shown in Fig. 1(b), which consists of a MZI and three MRs (MR1∼3). A Y-branch splitter is employed to split the input light into two separated copies that are

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The authors are with the State Key Laboratory of Integrated Optoelectronics, Department of Electronic Engineering, Tsinghua University, Beijing 100084, China (e-mail: zdk08@mails.tsinghua.edu.cn; x-feng@tsinghua.edu.cn; yidonghuang@tsinghua.edu.cn).

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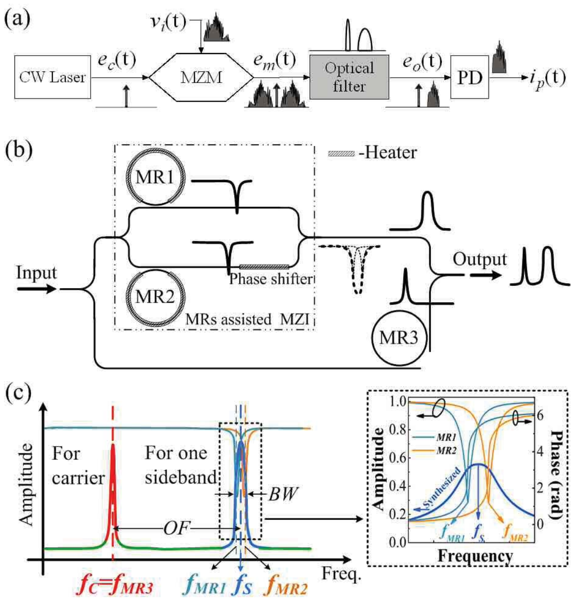

Fig. 1. (a) Schematic setup of a typical MPF. (b) Structure of proposed optical processor. (c) Schematic response composition of optical processor.

guided in the each arm. Then the carrier light is selected by a drop-output MR (MR3) inserted in the lower arm and one sideband is selected and processed by an MZI with two thru-output MRs (MR1 and MR2) inserted in the upper arm. In the lower arm, a bandpass response achieved by designing the center frequency of MR3 (f_{MR3}) according to carrier light (f_C) due to the nature of drop-output MR. In the upper arm, a synthesized bandpass response for processing sideband is generated utilizing MRs assisted MZI. According to the center frequency and bandwidth of sideband signal, the resonances of two thru-output MRs (MR1 and MR2) are designed carefully, and their typical amplitude and phase responses are depicted in Fig. 1(c). Since the response of direct combining the outputs of two thru-output MRs with MZI would be band-stop as depicted in dotted line in Fig. 1(b), an additional phase shift ϕ_S of about π is introduced in one arm of the MZI to achieve a bandpass response (see Fig. 1(c)). Specifically, the median point and interval of the resonant frequencies of MR1 and MR2 (f_{MR1} and f_{MR2}) should correspond to the center frequency f_S and bandwidth (BW) of synthesized response for sideband, respectively. At last, the processed carrier light and signal sideband are combined by a Y-branch combiner. The optical response of the whole optical processor can be deduced as:

$$H_O(\omega) = \frac{1}{4}(T_{MR1} + e^{j\phi_S} T_{MR2})e^{j\phi_{L1}} + \frac{1}{2} D_{MR3} \cdot e^{j\phi_{L2}} \quad (1)$$

where T_{MR} and D_{MR} are thru-output and drop-output amplitude transmissions of MR respectively, and $\phi_{L1(2)}$ is the phase shift of upper (lower) arm waveguide of the outer loop. In principle, the output of MPF would be affected by the phase difference of $\phi_{L1(2)}$. However, in our designed MPF, the interference between the processed carrier light and signal sideband is weak due to their quite different wavelength so that $\phi_{L1(2)}$ would not affect the optical and microwave responses significantly. Moreover, such phase difference would be keeping constant for a fabricated device so that such weak impact would also be unchanged.

The phase shifter for ϕ_S of about π is realized by the micro-heaters covered on one arm of MZI to vary the refractive index of silicon. To tune the central frequency and bandwidth of the synthesized response for sideband signal, the resonance of MR1 and MR2 is required to be tuned, which is achieved by the micro-heaters covered on MR1 and MR2. Then the operating frequency of MPF can be varied by tuning median frequency of the resonances of MR1 and MR2, while the bandwidth can be adjusted by tuning the interval of such two resonances.

III. Fabrication and Experimental Results

The proposed optical processor was fabricated on a SOI wafer (3-μm buried oxide layer) with electron-beam lithography, inductively coupled plasma etching, and depositing a 600-nm-thick SiO_2 cladding layer by plasma-enhanced chemical-vapor deposition. The width and height of the shallow-ridge waveguide are 1 μm and 0.22 μm, respectively, while the etch depth is 60 nm. The radius of all these three MRs is 100 μm and the gaps between the MR1 (2) and arms of MZI are 400 nm while that is 500 nm for MR3. The heaters and electrical contact pads, which consist of 100-nm-thick Ti and 200-nm-thick Al, were sequentially patterned with lithography, evaporation, and lift-off processes. Only part of the MRs and one arm of the MZI are covered by micro heaters with the resistance of 910 and 520 Ω, respectively. An optical micrograph of fabricated sample is shown in Fig. 2 and a scanning electron microscope (SEM) image of MR1 is shown in the inset.

The employed measurement system is shown in Fig. 3(a), which consists of a tunable laser source (TLS, 1350 nm∼1620 nm), two polarization controllers (PCs), a 40-Gbps $LiNbO_3$ Mach-Zehnder modulator (MZM, Codeon, Mach-40TM 005), two erbium-doped fiber amplifiers (EDFAs), and a high-precision auto-align optical testing system (SURUGA SEIKI, C7214-9015) with two tapered fibers. At the output terminals, a power meter (PM, Agilent, 81624A) and a 50-GHz photodetector (PD, U2T, XPDV2120R) with a 40-GHz vector network analyzer (VNA, Agilent, N5247A) were used to measure the spectra.

By carefully tuning the heaters, proper phase shift and resonances of MR1 and MR2 can be achieved. Inset of Fig. 3(b) shows a measured optical spectrum (dotted line) with two bandpass responses, which is well consistent with the theoretical simulation (solid line). The left one is from MR3 and the right one is from the MRs assisted MZI. For microwave measurement, the optical carrier is settled at 1550.66 nm according to the resonance of MR3, and the measured microwave response is shown in Fig. 3(b) (dotted line) and the corresponding simulation with $\phi_{L2} - \phi_{L1} = 0$ is also shown (solid line). The results show that, a bandpass MPF with operating at central frequency of 22 GHz and −3-dB bandwidth of 5 GHz is achieved. In addition, the extinction ratio (ER) is larger than 16 dB. Moreover, the simulation result of $\phi_{L2} - \phi_{L1} = \pi$ is also shown in Fig. 3(b)

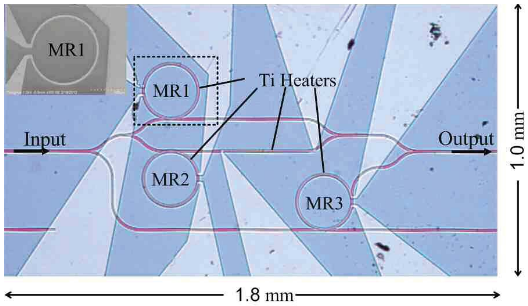

Fig. 2. Optical micrograph of the proposed optical processor. Inset: SEM image of MR1.

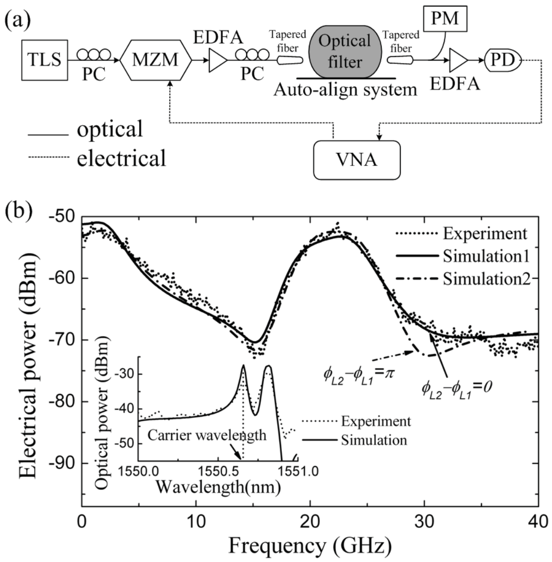

Fig. 3. (a) Schematic measurement system of MPF. (b) Measured microwave responses (dotted line) and corresponding simulation results of $\phi_{L2}-\phi_{L1}=0$ (solid line) and $\phi_{L2}-\phi_{L1}=\pi$ (dotted–dashed line). Inset: Measured (dotted line) and simulated (solid line) optical responses.

(dot dash line). It could been that there is only a little change of operating frequency and bandwidth since the noticeable variation is located at the trough of bandpass response.

As mentioned above, the operating frequency of MPF could be tuned by tuning the median frequency of the resonances of MR1 and MR2. Here, it is achieved by tuning MR1 and MR2 with equal variation of thermal tuning power (proportional to the square of the voltage), which induces equal resonance shift of MR1 and MR2 in the same direction. Then operating frequency of MPF is tuned while the bandwidth keeps constant. Figure 4(a) shows the experimental results. The operating frequency is tuned from 18 to 40 GHz while the −3-dB bandwidth is maintained around 5 GHz. The highest measured operating frequency of 40 GHz is limited by bandwidth of VNA. Actually, the operating frequency can be tuned to 60 GHz or higher in our simulation.

For adjusting the bandwidth, the interval of the two resonances of MR1 and MR2 should be varied. It is achieved by applying opposite variation of thermal tuning power on MR1 and MR2 with the same value, which induces equal resonance shift of MR1and MR2 in opposite direction. Then the bandwidth could be varied with constant operating frequency.

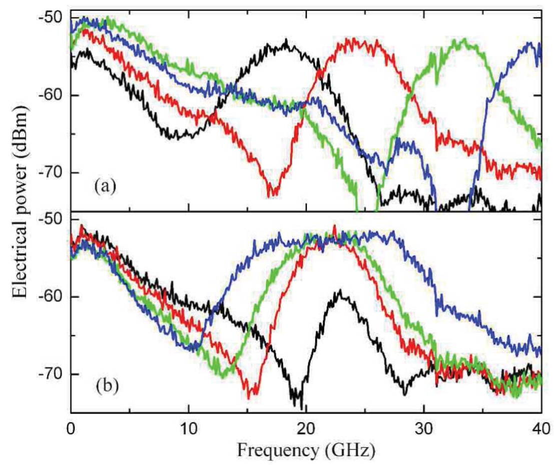

Fig. 4. (a) Tune operating frequency from 18 to 40 GHz with the −3-dB bandwidth of ∼5 GHz. (b) Tune bandwidth from 4 to 15 GHz while maintaining operating frequency of ∼22 GHz.

As shown in Fig. 4(b), with the constant operating frequency of ∼22 GHz, the −3-dB bandwidth is varied from 4 to 15 GHz.

Because two Y-branches are used to split and combine the lights, an insertion loss of ∼6 dB is introduced and there is still some loss due to suppress another sideband signal. Such additional loss could be reduced to improve the performance of MPF if some modified or new structures are employed and the related work is still ongoing.

IV. Conclusion

In summary, an integrated optical processor is proposed and applied to tunable and reconfigurable MPF. According to the experimental results, the operating frequency and −3-dB bandwidth of MPF can be tuned from 18 to 40 GHz and from 4 to 15 GHz, respectively. Actually, the measured operating frequency is limited by the bandwidth of VNA, and in principle, the operating frequency can be tuned to 60 GHz or higher.

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