360° Tunable Microwave Phase Shifter Based on Silicon-on-Insulator Dual-Microring Resonator

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***Abstract*—We demonstrate tunable microwave phase shifters based on electrically tunable silicon-on-insulator dual-microring resonators. A quasi-linear phase shift of 360° with ~2dB radio frequency power variation at a microwave frequency of 40GHz is obtained.**

Keywords-Integrated optics devices; microwave photonics; radio frequency photonics; silicon microring resonator.

I. Introduction

Microwave photonics has lately received increasing interests [1]. Photonic components, providing compact size, large bandwidth, immunity to electromagnetic interference and low weight, have been widely demonstrated in microwave systems. Microwave phase shifters with a full 2π phase shifting range are key components in many microwave applications, such as microwave filters. So far, several schemes for phase shifting including wavelength conversion [2], stimulated Brillouin scattering [3], slow-light effects in semiconductor devices [4] have been reported. Recently, silicon-on-insulator (SOI) microring resonators (MRRs) have also been used as phase shifters [5,6]. A 0-260° shifting range was realized in [5] with thermo-optical tuning from a high-power control light. Previously, we also demonstrated an electrically tunable phase shifter based on MRR with a phase-shifting range of 0-336° in [6]. However, it is difficult to realize a full 2π phase shift by using a single MRR. Furthermore, the radio frequency (RF) power varies dramatically during the phase shifting operation. Here, we demonstrate microwave phase shifters with tuning range larger than 2π by using two cascaded MRRs with independent electrically controllable micro heaters. A quasi-linear phase shifting rang of 0~360° with only 2dB RF power variation is obtained. These devices can be easily integrated with photonic and electronic circuits.

II. Design

Fig. 1(a) shows the schematic drawing of an all-pass dual-microring resonator (DMRR). The two cascaded rings are designed to have identical geometries. Figs. 1(b) and 1(c) illustrate the transmission and the phase for the DMRR at the through port with different resonance offsets (ω_{MRR2}-ω_{MRR1}) between the two MRRs. As shown in Fig. 1(c), the optical phases experience a monotonic phase change from negative to positive detuning. If, in this case, an optical signal carrying a microwave signal with two peaks of the desired frequency spacing is input to the DMRR, the phase difference of the two peaks of the transmitted field can be tuned by changing the resonance frequency, and thus realizing a microwave phase shift. As shown in Figs. 1(b) and (c), the transmission spectrum and the phase curve can be altered by offsetting the resonances for the two MRRs. When the resonance offset increases from 0 to 3GHz, the notch bandwidth is increased with reduced notch depth and the notch bottom becomes flat. If the resonance offset increases further, the notch splits into two notches while the phase curve acquires a step-like shape. Therefore, the resonance offset can be tuned to a desired value (i.e., 3GHz in this case) to get a wide notch bandwidth, a decreased notch depth and a flattened notch bottom. If the RF phase shifting is operated within this bottom region, one can realize an RF phase shifting in a certain range without RF power variation, since the RF power follows the optical power.

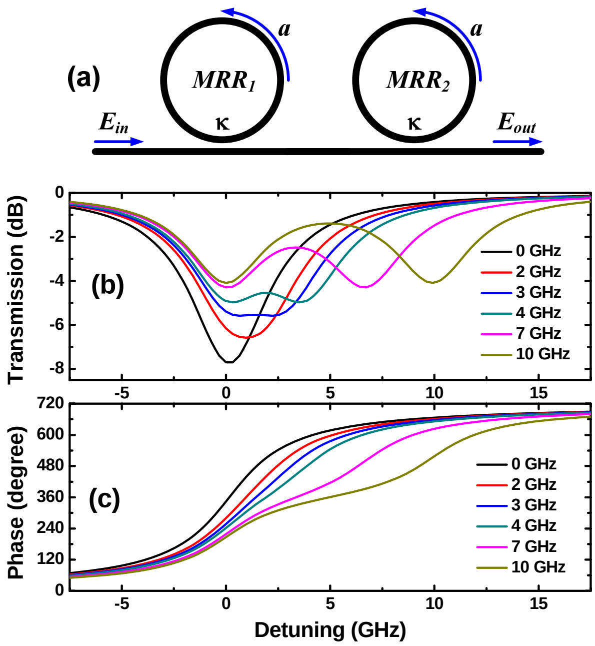

Figure 1. Schematic of a DMRR (a). Calculated transmission (b) and phase (c) as a function of optical detuning from the resonance frequency (ω_{MRR1}) at the through port for the DMRR with different resonance offsets (ω_{MRR2}-ω_{MRR1}) between the two MRRs. Here, amplitude coupling coefficient κ, power transmission coefficient a^2 and the ring diameter are assumed to be 0.2, 0.99 and 35μm, respectively.

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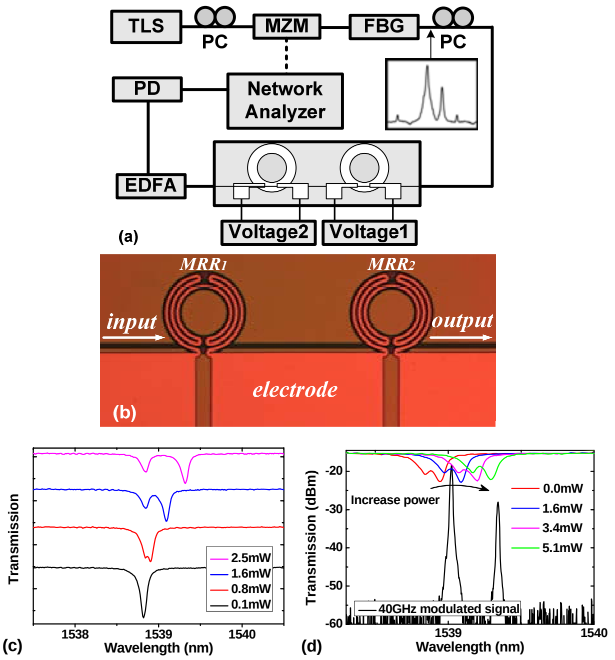

Figure 2. (a) Experimental setup for microwave phase shift measurements. (b) Optical microscope picture of the fabricated DMRR with micro heaters. (c) Measured transmission spectrum of the device with different applied power on the micro heater for MRR_1. (d) Mesured transmission spectrum of the device with extra applied power on both micro heaters (see the color curves) and the generated 40GHz microwave signal with central wavelength of 1539nm (see the black curve).

III. Experiment

The experimental setup used to measure the fabricated device is shown schematically in Fig. 2(a). Light from a tunable laser source (TLS) was modulated through a Mach-Zehnder modulator (MZM) by a microwave signal from the network analyzer. A fiber Bragg grating (FBG) notch filter was used to filter out one sideband of the modulated signal. After that, the optical signal, with the envelope modulated at the microwave frequency in the time domain (i.e., with two peaks of the desired frequency spacing in the spectral domain (see Fig.2 (d))) was generated and sent into the fabricated DMRR as shown in Fig. 2(b). All the structures were made on an SOI wafer with 250-nm thick top silicon layer and the waveguide width is 450nm. The coupling gaps between the two rings and the straight waveguide are 150nm. As shown in Fig. 2(c), the transmission spectrum can be altered by applying power on one of the micro heaters (i.e., the heater for MRR_1). In the measurement, we set 0.8mW as the reference power applied on MRR_1 to get a suitable resonance offset between the two MRRs. The polarization of the input light was adjusted to the quasi transverse electrical (TE) mode with a fiber polarization controller (PC). By equally increasing the extra electrical power applied to both micro heaters simultaneously, the resonance frequency of the DMRR can be tuned with respect to one of the peaks of the optical signal as illustrated in Fig. 2(d) and then the phase difference between the two peaks can be changed. Amplified by an erbium-doped fiber amplifier (EDFA), the output signal was detected by a high-speed photo detector (PD), and converted to the microwave signal. Then the network analyzer was used to extract the information of phase and power changes of the microwave signal.

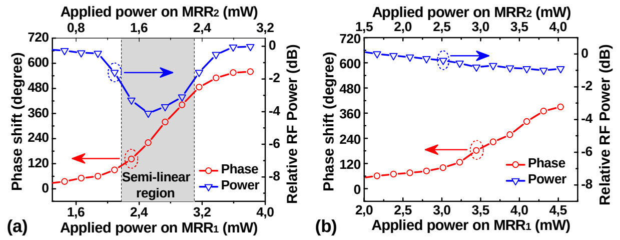

Figure 3. Measured RF phase shift and relative RF power versus the applied power on both micro heaters for the MRRs with ring-to-waveguide coupling gaps of 150nm (a) and 100nm (b).

The measured RF phase shift and RF power variation as a function of the applied electrical power on both micro heaters are also shown in Fig. 3(a). A continuously tunable RF phase shift is demonstrated, and the maximum RF phase shift of 540° is achieved with the RF power variation of ~4dB. However, if the device is operated within the gray region shown in Fig. 3(a), one can obtain not only a quasi-linear phase shift of 360°, but also an RF power variation of only 2dB. In this case, the total required operation power is ~2mW. We also tested another DMRR with a smaller ring-to-waveguide gap of 100nm which corresponds to a lower quality (Q)-factor for the resonator. As shown in Fig. 3 (b), a phase shift larger than 360° is still achieved. Although the maximum phase shift is reduced from 540° to 390°, the total RF power variation in the whole tuning range is only 1dB which is smaller than that of the high-Q device.

IV. Conclusion

We have introduced microwave phase shifters based on electrically tunable SOI DMRRs. A quasi-linear 360° phase shift has been achieved at a microwave frequency of 40GHz with 2dB RF power variation. A phase shift of 390° has also been demonstrated with only 1dB RF power variation using a DMRR with lower Q-factor. These devices are believed to be potentially useful in microwave applications.

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