Optically Tuneable Microwave-Photonic Phase Shifter Based on Silicon Microring Resonator

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Abstract *We demonstrate a microwave-photonic phase shifter based on a 20-μm-radius silicon microring resonator, providing a tunable phase shift for a 20-GHz signal in a range of 0 - -4.6 rad.*

Introduction

Microwave-photonic phase shifter has been playing an increasingly important role in microwave signal processing such as phased-array beam-forming. Various techniques for realizing microwave-photonic phase shifters have been demonstrated, including distributed-feedback laser-wavelength converter [1], variable optical directional coupler [2], $LiNbO_3$ modulator [3], and using stimulated Brillouin scattering [4] or cross-phase modulation [5] in optical fibres. However, a practical implementation of arrays with thousands of elements is limited by the size and complexity of the above phase-shifting elements. The use of miniaturized and integrated devices to perform this function is thus of much interest due to advantages of low cost, compact size and on-chip integration.

In this paper we present and demonstrate a novel microwave-photonic phase shifter based on a 20-μm-radius silicon microring resonator. It features variable phase-shift tuning, reduced complexity, compact footprint, and easy integration.

Operation principle

For a single side-coupled microring resonator, shown in Fig. 1 (a), its linear transfer function is denoted by [6]:

$$T(\omega)=\frac{r-a\exp(i\phi)}{1-ra\exp(i\phi)} \qquad (1)$$

where r is the transmission coefficient. a is the single pass attenuation in the ring. $\phi=kL$ is the linear phase shift of the ring, where k and L are the propagation constant and the length of the ring, respectively.

Fig. 1 (b) shows the transmission and phase shift for a ring resonator with a 3-dB resonance bandwidth of 0.1 nm and a resonance notch depth of 6 dB. It shows that a phase shift of π rad is achieved on resonance and the phase shift tuning range is 0-2π rad. For an optical carrier suppressed (OCS) microwave signal, a maximum phase shift of 2π rad can be achieved if the two sidebands are located across the resonance.

For the OCS signal, the output field can be expressed by:

$$E_{in}(t)=A_{-1}\exp\left(j2\pi(\nu_0-f_{RF})t\right)+A_1\exp\left(j2\pi(\nu_0+f_{RF})t\right) \qquad (2)$$

where A_{-1} and A_1 are the amplitudes of the -1 order sideband and +1 order sideband, respectively. The spectrum of OCS is plotted in Fig. 1 (c). If this signal is optically processed to change the two sidebands by a factor of $A\exp(j\theta)$ and $A'\exp(j\theta')$, respectively, the optical field then becomes:

$$E_{out}(t)=AA_{-1}\exp\left(j2\pi(\nu_0-f_{RF})t+j\theta\right)+A'A_1\exp\left(j2\pi(\nu_0+f_{RF})t+j\theta'\right) \qquad (3)$$

where A (A') and θ (θ') denote the amplitude loss and phase shift, respectively. The output signal is detected by a photo detector and the AC part of the output current from the photodetector (PD) is

$$i_{AC}(t)=2RAA'A_{-1}A_1\cos\left(2\pi\times 2f_{RF}t+\theta'-\theta\right) \qquad (4)$$

where R is the responsivity of the photodetector (PD). Thus the incurred phase shift from the resonance has completely transferred to the output signal.

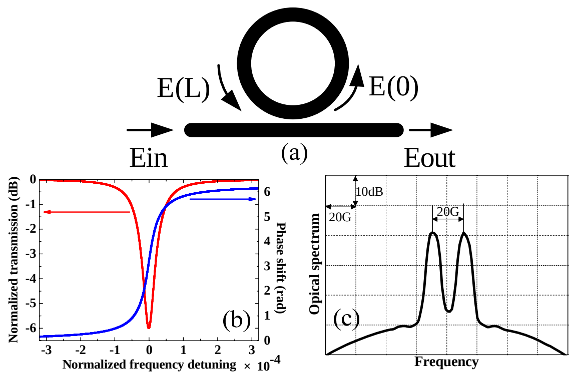

Fig. 1. (a) Scheme of a ring resonator and (b) its corresponding transmission and phase shift curve.(c) The spectrum of 20G OCS signal.

The phase shift can be tuned by thermal nonlinear effect [7], [8]. As the thermo-optic coefficient is very large in silicon, this effect has a low power threshold and therefore the phase shift of the signal can be tuned by controlling the pump light power with a low value.

Device characterization

The 20-μm-radius silicon microring resonator in our experiment is fabricated on a silicon-on-insulator (SOI) wafer with a 250-nm-thick silicon slab on top of a 3-μm silica buffer layer. The cross section of the silicon waveguide is 450×250 nm. The microring is side coupled to the straight waveguide with an air gap of 120 nm. The scanning electron microscope

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(SEM) photo of the silicon microring resonator and its spectral response are shown in Fig. 2. The resonance at 1548.5 nm has a 6-dB notch and the 3-dB bandwidth is ~0.1 nm.

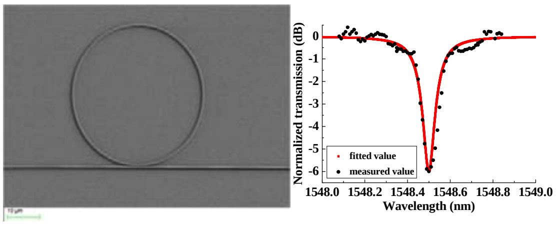

Fig. 2 SEM photo of the silicon microring resonator and its spectral response around 1548.5 nm.

Experiment

Fig. 3 depicts the experimental setup. The probe signal sits at the 1548.5-nm resonance. To facilitate the coupling of control light into the ring, we set the control light to a 1561.0-nm resonance, which has a 16-dB notch depth and a 3-dB bandwidth of ~0.15 nm. A continuous wave (CW) signal from a tunable laser is fed into a single drive MZM, which is biased at the null and driven by a 10-GHz clock signal to produce a 20-GHz OCS signal. Both the pump light and the probe signals are coupled through a 3-dB coupler to the microring resonator by a vertical coupling system [9]. An oscilloscope is used to record the waveforms and measure the phase shift.

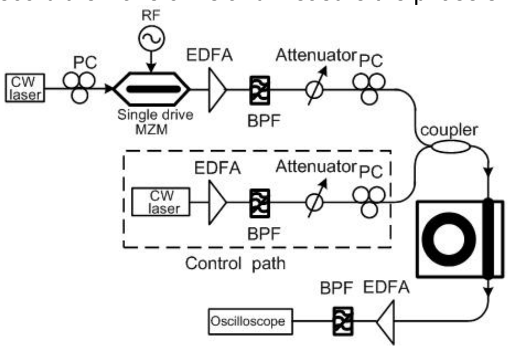

Fig. 3 Experimental setup.

We firstly measure the dependence of the phase shift and the output power on the signal wavelength, as shown in Fig. 4. The maximum phase shift is -4.6 rad (~260°) and the output power variation is less than 2.2 dB, which mainly results from the loss of one sideband in the resonance region. We did not reach the desired maximum phase shift of 2π rad since the 20-GHz spaced sidebands do not completely cross the resonance and thus they did not experience the 2π relative phase shift. For the maximum phase shift of ~ 4.6 rad, the signal waveform still exhibits good quality, as evidenced in Fig. 5.

Fig. 6 shows the dependence of the phase shift on the pump power, with the two sidebands of signals on the right side of the resonance or across the resonance, respectively. The maximum phase shift is the same as that shown in Fig. 4, demonstrating the feasibility of constructing a tuneable phase shifter by thermal nonlinear effect. The estimated required power in the ring resonator to obtain the maximum phase shift is only 20 μW.

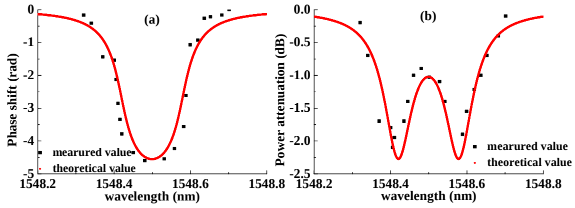

Fig. 4 The dependence of the phase shift and output power on signal wavelength.

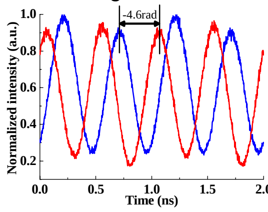

Fig. 5 The waveform of the 20G OCS signal when the maximum phase shift is 4.6 rad.

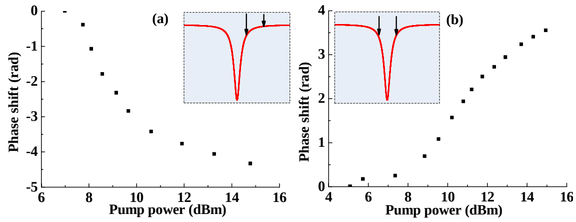

Fig. 6 The dependence of the phase shift on pump power. The insets show the initial position of signal.

Conclusions

We have demonstrated a novel tunable microwave-photonic phase shifter in a silicon-based ring resonator. The prototype device achieved a tunable phase shift from 0 rad to -4.6 rad for the 20-GHz OCS photonic-microwave signal, with only 20-μW pump power. The change (< 2.2dB) in the output power can be minimized by reducing the loss of the ring and optimize the coupling to achieve a desired all-pass filtering characteristic.

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