Fast Silicon Photonics Wavelength-Selective Phase Shifter

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ABSTRACT

A fast wavelength-selective phase shifter realized in silicon-on-insulator technology based on carrier-depletion effect in a microring resonator suitable for photonic processing of microwave signals is designed and experimentally verified. The proposed approach overcomes the bandwidth limitations of standard thermo-optic tuning while providing large spectral shift of the phase characteristic, minimized amplitude modulation, and low optical insertion loss by proper optimization of ring parameters. The results illustrate a maximum optical phase variation of 250° for a transmission change limited to within 4.5 dB, and large electro-optical bandwidth of 10 GHz.

Keywords: Silicon photonics, microwave photonics, RF phase shifters.

1 INTRODUCTION

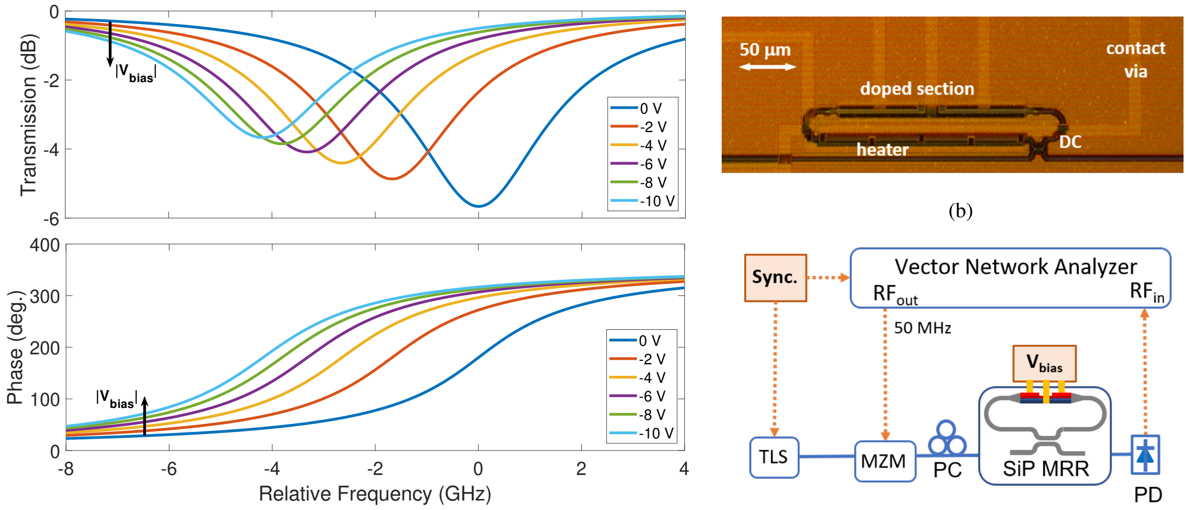
Microring resonators (MRRs) in all-pass configuration have long been proposed and demonstrated as an effective mean for controlling the phase of radio-frequency (RF) signals [1], [2]. In the silicon-on-insulator (SOI) technology, the phase tuning mechanism is commonly implemented using the strong thermo-optic effect of silicon by heating the ring waveguide [2], [3]. In order to avoid the slow transients of thermally-controlled SOI MRRs, which are in the order of few microseconds, the use of fast plasma dispersion effect (PDE) using carrier-injection in a doped MRR has been reported [4]. However, this approach exhibited a limited RF phase tuning range of less than 180° along with a large modulation of the optical insertion loss. This translates in a wide power swing of the processed RF signals when multiple devices are cascaded to produce a full phase control over 360°, as required in several practical applications like for instance beam-steering in phased array antennas [1]-[3]. On the other hand, no attempt on optimizing the design of a MRR embedding pn-doped waveguides for realizing a fast silicon photonics (SiP) microwave phase shifter (PS) through carrier-depletion mechanism has been reported up to now. Carrier-depletion operation is desirable in respect to carrier-injection control mode as it minimizes power consumption, avoids thermal cross-talk due to junction heating, and intrinsically offers larger electro-optical bandwidth.

Here, we present the results of an optimization procedure using a simple analytical model for the fabrication of a carrier-depletion controlled MRR exhibiting a large optical phase excursion of up to 250°, maximum amplitude modulation of ~4 dB, and low average optical insertion loss below 4 dBm. A small-signal bandwidth of around 10 GHz has been assessed, illustrating the potentials of the proposed device for high-speed microwave photonics signal processing applications.

2 MRR DESIGN AND OPTIMIZATION

For the design of a fast SiP PS using an all-pass MRR embedding a reverse-biased laterally-doped pn-junction waveguide, the relatively weak index change associated with the modulation of the depletion region and the additional optical losses due to free-carriers in the doped waveguide need to be properly accounted for. In order to perform a fast and relatively accurate sweep of the various parameters affecting the MRR response, an analytical model describing the complex transfer function of the pn-doped waveguide as a function of the reverse voltage applied to the junction has been employed [5]. For the dimensioning of the doped waveguide length, L_{pn}, the available doping concentrations for the selected foundry in a multi-project wafer (MPW) run has been estimated based on the provided values for the sheet resistance of the implanted waveguides with p- an n-type dopant. Other parameters affecting the design are the cross-coupling power coefficient, κ, of the directional coupler (DC) between the ring and input-output access bus waveguide, and the overall ring dimension which should be set in accordance to the required free-spectral range (FSR) of the ring resonances. The aim of the simulations is to provide the key physical parameters (i.e., κ and L_{pn}) that lead to a sufficiently large carrier-controlled optical phase shift for an applied maximum voltage below the inverse breakdown threshold of the diode, which has also been calculated based on the retrieved levels of carrier concentrations. At the same time, the Q-factor of the resonator should be kept as low as possible for minimizing the residual amplitude modulation.

As an example of the results of this procedure, Fig. 1(a) shows the calculated optical spectral transmission and phase response of the MRR with $L_{pn} = 200$ μm, and $\kappa = 0.2$ for different levels of the reverse bias voltage V_{bias} applied to the pn-junction. The undoped waveguide section of the MRR has been set such to provide a nominal FSR of 125 GHz, which can be conveniently modified to match the required application targets.



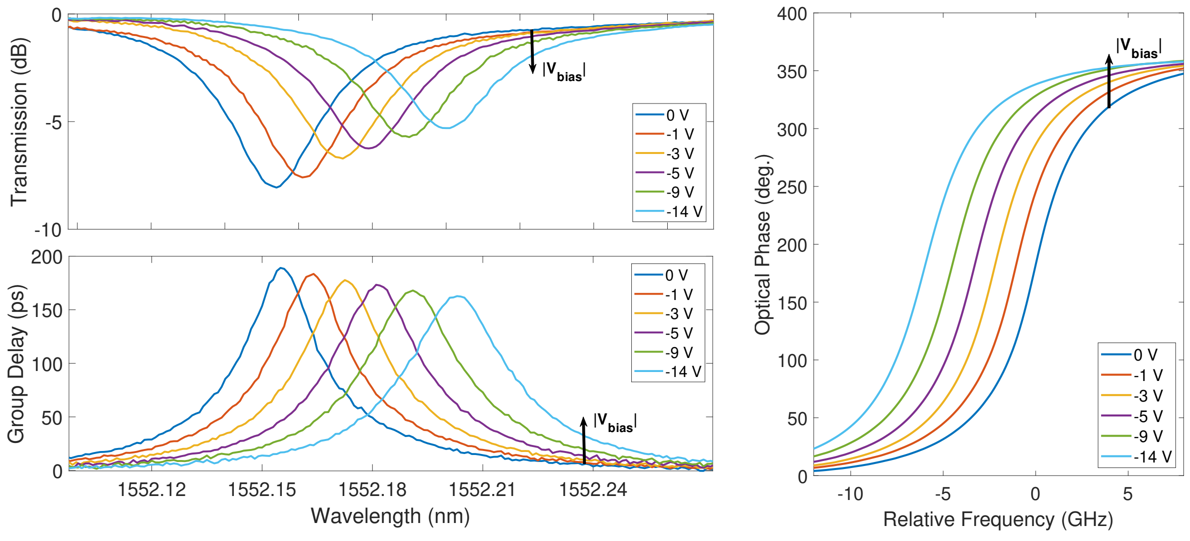
(a) (b) (c)

Figure 1. (a): Simulated spectral transmission and phase characteristic of the MRR for different levels of bias voltage V_{bias} *applied to the pn-doped waveguide junction versus frequency detuning from the unbiased ring resonance (simulation parameters:* $L_{pn} = 200\,\mu m$, $\kappa = 0.2$, *and* $FSR = 125\,GHz$*); (b): Micrograph of fabricated device; (c): Experimental set-up for MRR group-delay characterization.*

3 DEVICE FABRICATION AND EXPERIMENTAL CHARACTERIZATION

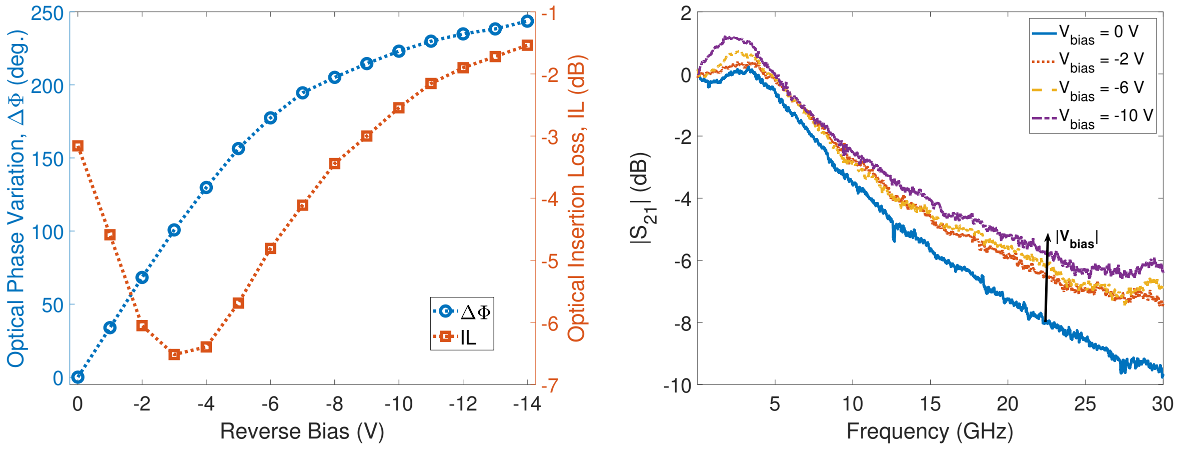
The fast selective PS has been fabricated using a SiP MPW run [6]. A micrograph of the fabricated device is shown in Fig. 1(b). Besides the pn-doped waveguide section, a resistive heater is placed in proximity to a portion of the MRR undoped waveguide to provide an additional broad tuning mechanism, as required for precise resonance alignment when multiple MRRs are cascaded to achieve full 360° phase shift control.

The group-delay characteristics of the MRR for different levels of V_{bias} have then been measured using a standard phase shift method [7] with the setup illustrated in Fig. 1(c). As shown, a 50-MHz tone from a network analyser (NA) driving a Mach-Zehnder modulator (MZM) is used to modulate the output light from a tunable laser source (TLS), whose wavelength is scanned with 1-pm step resolution. After traversing the MRR, the modulated optical signal is down-converted by a photodiode (PD) and fed back to the NA, where the phase variation of the RF signal as the laser wavelength sweeps around ring resonance is evaluated to provide a measure of MRR group delay [7]. The transmission spectra at different values of V_{bias} have also been monitored on an optical spectrum analyser. The corresponding results are illustrated in Fig. 2(a); the MRR optical phase characteristics are then retrieved by numerically integrating the measured group-delay curves, and are reported in Fig. 2(b). A good qualitative agreement between numerical results and measured data is observed, with a small mismatch between the experimental traces and the design simulations of Fig. 1(a) due to the approximations in the analytical model. Numerical fitting of the measurements can then be used for calibrating the parameters of the model for this specific fabrication process and further improving the design procedure.



(a) (b)

Figure 2. (a): Measured MRR spectral transmission and group delay response at different levels of reverse bias voltage V_{bias} *applied to the pn-doped waveguide junction; (b): Corresponding optical phase characteristics of the MRR.*



(a) (b)

Figure 3. (a): Optical phase variation and insertion loss of the MRR at a frequency detuning of -3 *GHz from the 0 V bias resonance versus* V_{bias}*; (b): Measured electro-optical bandwidth of the fast SiP selective phase shifter at different levels of reverse bias voltage* V_{bias}*.*

The optical phase variation $\Delta\phi$ and insertion loss (IL) over the full considered voltage swing at a detuning of -3 GHz in respect to the unbiased resonant frequency are plotted in Fig. 3(a), showing a large phase change of up to ~250° at the maximum reverse bias voltage, with a residual optical intensity modulation of ~4.5 dB, and an average IL of 3.7 dB. The transmission change reduces to within 3 dB for a phase swing of 210° when V_{bias} ranges between 0 V and -8 V. Such a wide excursion of the MRR optical phase characteristic in conjunction with its wavelength-selective nature can be used to change the phase of RF signals single-sideband modulating an optical carrier tuned in proximity of a ring resonance, as the changes in the carrier phase due to an applied control voltage translates into phase shifts of the downconverted RF signal [1]-[3]. Finally, the high-speed operation of the selective PS based on carrier-depletion effect has been assessed by measuring the electro-optical bandwidth of the device under small-signal regime using a NA. The results indicate a -3 dB point for the magnitude of the S_{21} parameter measured from the NA comprised between 9 GHz and 12 GHz, depending on the applied bias condition.

4 CONCLUSION

A silicon-photonics microring resonator embedding a pn-doped waveguide specifically designed for implementing a novel fast wavelength-selective phase shifter through carrier-depletion mechanism has been presented. The device has been properly dimensioned for optimizing its performances in terms of optical phase variation, residual amplitude modulation, and average insertion loss level using the available doping concentrations from a multiple-users fabrication process. Experimental characterization confirms a large optical phase shift range in excess of 200° when the transmission variation is as low as 3 dB. The measured electro-optical bandwidth offers a fast reconfiguration time of the device in the order of few hundreds of picoseconds, thus effectively overcoming speed limitations of standard thermo-optic tuning in silicon on insulator technology. Such characteristics can be conveniently exploited for realizing rapidly reconfigurable phase control of radio-frequency signals with moderate power excursion.

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