Continuously tunable reflective-type optical delay lines using microring resonators

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Abstract: We present a reflective-type optical delay line using waveguide side-coupled 13 microring resonators terminated with a sagnac loop reflector. Light passes through the microring resonator sequence twice, doubling the delay-bandwidth product. Group delay is tuned by p-i-p type microheaters integrated directly in the microring waveguides. Experiment demonstrates that the delay line can potentially buffer 18 bits and the delay can be continuously tuned for 100 ps with a power tuning efficiency of 0.34 ps/mW. Eye diagrams of a 20-Gbps PRBS signal after 10 and 110 ps delays are also examined.

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OCIS codes: (230.3120) Integrated optics devices; (230.5750) Resonators.

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1. Introduction

Tunable delay lines have widely been used in data synchronization, buffering and signal processing of wideband data stream in optical network [1–4]. Due to its compact size and compatibility with complementary-metal-oxide-semiconductor (CMOS) technologies, on-chip silicon tunable delay lines have potential applications in future integrated photonic systems, especially inter- and intra-chip interconnects [5–7]. A large group delay can be achieved on a chip by designing a long waveguide in a spiral shape [8]. Unfortunately, dynamic long-range continuous tuning is of a big challenge for such delay lines. Optical resonance structures can considerably reduce the waveguide length while maintaining a large group delay around resonances. Group delay tuning is also possible by shifting the resonance wavelengths. Among the various resonance structures, microring resonators have the key merits of compact size, simple structure, and large delay [9, 10]. However, for a single microring resonator, the delay-bandwidth product is fixed at approximately $2/\pi$ for an all-pass filter (APF) configuration [11, 12]. To further improve the delay performance, cascaded microring resonator structures can be employed, which is a feasible approach to fulfill many practical requirements. Delay lines based on cascaded microrings exist in two basic configurations: coupled resonator optical waveguides (CROWs) [10, 13–16] and side-coupled integrated spaced sequence of resonators (SCISSORs) [17–19]. With some disordering and imperfection, SCISSORs exhibit the smoother spectral profiles than the CROWs (CROWs usually exhibit a noisy spectrum caused by the small fluctuation in the coupling strength between rings particularly in the silicon high-index contrast system) [19]. The resonance frequencies and coupling coefficients in the SCISSORs also need to be well controlled to get a smooth and flat delay spectrum.

In this paper, we present a novel reflective-type delay line consisting of a SCISSOR structure terminated with a sagnac loop reflector at one end. The sagnac loop reflects the incoming light back to the SCISSOR, and thus all the microrings in this structure are passed twice. In other words, the degenerate resonance modes (clockwise and counter-clockwise modes) are both excited in each microring. In this way, the delay-bandwidth product per microring is doubled. As a result, the number of microrings and thus the device footprint and power consumption on tuning is reduced by half for a certain buffering capacity. Moreover, it also imposes less stringent fabrication requirement on the alignment of microring resonators. The reflected signal can be separated from the incoming one by using a circulator. Although all-silicon on-chip circulators are difficult to make, hybrid bonding of magneto-optic materials has recently been demonstrated as a feasible way to implement nonreciprocal devices [20–22].

For optical buffers in digital systems, the group delay dispersion (GDD) is manifested as signal distortion and increased intersymbol interference that limits the buffering capacity. Our reflective-type delay line uses thermally tuned silicon microring resonators in a balanced configuration to provide large delay bandwidth and continuous tuning [17, 18]. Group delay...
is tuned by using $p$-$i$-$p$ resistive micro-heaters [23] integrated directly inside the microring resonators.

2. Device design and fabrication

![Figure 1](image-url)

Figure 1(a) shows the schematic drawing of the reflective-type SCISSOR delay line consisting of 13 identical racetrack microring resonators and a sagnac loop reflector at the right end. The waveguide is 500 nm wide and 220 nm high with a slab thickness of 60 nm. The radius of the microring resonators is 10 $\mu$m. The coupling length is 16 $\mu$m and the gap is 0.25 $\mu$m to ensure the resonators work in the over-coupling regime to generate slow-light. The 1 × 2 multimode interference (MMI) coupler in the sagnac loop is 5 $\mu$m wide and 23.6 $\mu$m long. To actively tune the microring resonators, we embed a lateral $p$-$i$-$p$ junction across each microring waveguide to work as a resistive micro-heater. The inset shows the cross-sectional schematic of the $p$-$i$-$p$ micro-heater. The two highly doped $p^+$ regions are 600 nm away from the edges of the ridge waveguide. When an external voltage is applied on the $p$-$i$-$p$ junction, heat will be generated inside the waveguide, leading to a local hot spot. Hence, the refractive index of the waveguide changes due to the thermo-optic effect of silicon. The fabrication of $p$-$i$-$p$ micro-heaters is compatible with that of electrical tuning diodes (e.g., $p$-$i$-$n$ and $p$-$n$ diodes), without need to change the fabrication process or add extra steps. Since the generated heat directly interacts with the waveguide optical mode, the tuning speed and power efficiency can be potentially improved compared with conventional metal heaters as discussed in detail in ref [23].

The device was fabricated using standard CMOS fabrication processes on a silicon-on-insulator (SOI) wafer with a top silicon layer thickness of 220 nm and a buried oxide layer thickness of 2 $\mu$m. The top silicon layer is lightly $p$-type doped with a resistivity of 10 to 15 ohm·cm (corresponding to a hole concentration of $\sim 10^{15}$ cm$^{-3}$). 248-nm deep ultra-violet (DUV) photolithography and plasma dry etched was used to define the device patterns. Ion implantation was used for doping to a concentration level of $\sim 10^{20}$ cm$^{-3}$. A 1.5 $\mu$m thick silicon dioxide layer was deposited using plasma-enhanced chemical vapor deposition (PECVD) before Aluminum (Al) layer was sputtered and patterned. In order to tune each microring, we used gold (Au) wire bonding to connect the on-chip Al pads to the Au metal lines on a printed circuit board (PCB).

Figure 1(b) show the optical microscope image of the fabricated device with electrical connections. The device has a total dimension of 3 mm × 0.27 mm = 0.81 mm$^2$. Figure 1(c) is
the zoom-in view of the Sagnac loop reflector. Figure 1(d) illustrates the chip after wire-bonding with the PCB. The dimension of the Al pads is $150 \times 150 \mu m^2$. The diameter of the Au bonding wires is about 25 $\mu m$. The Au wires on the PCB are 150 $\mu m$ wide and their separation gap is 135 $\mu m$. The device is designed to operate in the transverse-electric (TE) polarization (electric-field parallel to the device plane). Light was coupled into and out of the device through on-chip inverse tapers with a tip width of 180 nm. A near-infrared camera (photonic science, SWIR 1/4 VGA camera) is used to confirm light is coupled from the input lensed fiber into the delay line.

3. Experiments and results

![Experimental setup](image)

Fig. 2. (a) Experimental setup for modulation phase shift method. PC: polarization controller; AM: amplitude modulator; PD: photodetector; RF: radio frequency signal; DUT: device under test. (b) Measured optical power spectrum of the device without active tuning. (c) Corresponding group delay spectrum.

We used the Agilent loss and dispersion analyzer (86038B) to characterize the device transmission performances. The group delay spectrum was obtained by using the modulation phase shift method. The experimental setup is shown in Fig. 2(a). Light from a wavelength-scanning laser is amplitude-modulated by a radio frequency (RF) signal with a frequency $f_{m} = 700$ MHz and coupled to the device under test. The reflected light is separated from the input one using a circulator and finally detected by a photodetector. The phase change through the device is extracted by comparing with the reference RF signal. Group delay is calculated by differentiating the phase with respect to the angular frequency.

Figure 2(b) shows the measured transmission spectrum of our device (reflection spectrum). The fiber-to-fiber insertion loss is around 16 dB (off-resonance). The silicon waveguide propagation loss is 3-4 dB/cm measured from test waveguides. The high insertion loss is mainly due to the fiber-waveguide coupling loss, which can be improved by optimizing the inverse tapers [24, 25]. At resonance wavelengths, the device has an extra loss of ~5 dB. Figure 2(c) shows the measured group delay spectrum of the device. The long coupling length between the microring and the bus waveguide guarantees the over-coupling of resonances, which hence generates low-Q resonances ($Q \sim 10^3$). Although each microring is designed to have the same group delay spectrum, the slight mismatch of resonances due to
various fabrication uncertainties inevitably leads to the broadening of the group delay peaks. Therefore, we observe a relatively broad group delay peak in Fig. 2(c). Around the resonance wavelength of 1548.9 nm, the group delay reaches the maximum value of ~116 ps (relative to the off-resonance value). The full-width-half-maximum (FWHM) bandwidth is ~156 GHz. Thus, the delay-bandwidth product or its buffering capacity is ~18, implying that the structure can buffer a maximum of 18 bits. As the delay-bandwidth product for a single waveguide side-coupled microring resonator is approximately $\frac{2}{\pi}$ [11, 12], our 13-microring reflective delay line has an overall delay bandwidth product of $2 \times 13 \times \frac{2}{\pi} \approx 17$, which agrees reasonably well with our experimental measurement.

In our reflective-type SCISSOR delay line, continuous delay tuning is achieved by applying thermo-optic effect. To actively tune the resonators, we connected the p-i-p micro-heaters to external voltage sources. Figure 3(a) shows the measured $I-V$ curve of one of the p-i-p micro-heaters after wire bonding. The curve is inverse symmetric and a little non-linear due to the p-i-p junction behaviors. The resistance slightly decreases with increasing bias voltage. The operation wavelength is set at $\lambda_r = \lambda_0 + \Delta \lambda$ by red-shifting all the microrings $\Delta \lambda$ from their original resonance wavelength $\lambda_0$. The SCISSOR then can work at the balanced operation mode, where half of the microrings are red-shifted by $\Delta \lambda + \delta \lambda$ from $\lambda_0$ and the other half are red-shifted by $\Delta \lambda - \delta \lambda$. Since the thermo-optic effect can only induce a redshift of resonances, it thus requires $\Delta \lambda > \delta \lambda$. Such balanced operation reduces the third and higher orders of GDD [18]. This arrangement only requires two independent controls. In our device, we group the first 7 microrings near the Sagnac loop and apply a bias voltage $V_1$ for red-detuning. The corresponding power consumption is $P_1 = V_1 I_1$, where $I_1$ is the recorded total current through the 7 microrings. The remained 6 microrings are applied with a bias voltage $V_2$ for blue-detuning with power consumption $P_2$.

The measured group delay tuning spectra are shown in Fig. 3(b). When all 13-microring resonators are applied with the same voltage of 12 V ($P_1 = 155.4$ mW and $P_2 = 133.2$ mW), the resonances are red-shifted 1.1 nm from their original positions. We observe a delay peak of ~110 ps with a bandwidth of ~1.35 nm (~168 GHz) at 1550.0 nm. Such red-shifted wavelength is used as the operation wavelength for our following balanced detuning. It should be noted that the delay and bandwidth values are little different from the passive measurement, which may be probably due to the performance variation of microheaters (redshift value is not exactly equal). As $V_1$ is slightly decreased to 11.5 V ($P_1 = 140$ mW) and $V_2$ increased to 12.2 V ($P_2 = 138.6$ mW), the peak delay is reduced to ~85 ps and the bandwidth increased to ~1.7 nm (~212 GHz). When $V_1 = 11$ V ($P_1 = 125.4$ mW) and $V_2 = 12.4$ V ($P_2 = 144.2$ mW), we see that the group delay peak is starting to split. The peak delay is reduced to ~68 ps with a bandwidth of ~1.9 nm (~237 GHz). With a further detuning of the resonances, there appears a pronounced valley in the group delay spectrum at the operation wavelength. The smallest delay is 10 ps when $V_1 = 7$ V ($P_1 = 42.1$ mW) and $V_2 = 13.2$ V ($P_2 = 168.3$ mW). Larger delays can be achieved by simply increasing the number of microrings in our device. Figure 3(c) shows the power consumptions on the two sets of microrings ($P_1, P_2$) and on the entire device ($P_3$) as a function of group delay. The total power consumption of the device is below 290 mW, enabling a continuous group delay tuning from 10 ps to 110 ps. The average power tuning efficiency is around 0.34 ps/mW. In fact, the power consumption depends on the operation wavelength. The closer the operation wavelength is to the original one, the lower the power consumption is. However, it also suffers from a reduced tuning range due to the limitation of $\delta \lambda < \Delta \lambda$. 

Received 29 Oct 2013; revised 10 Dec 2013; accepted 23 Dec 2013; published 7 Jan 2014

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13 January 2014 | Vol. 22, No. 1 | DOI:10.1364/OE.22.000817 | OPTICS EXPRESS 821
Fig. 3. (a) Measured I-V curve of the p-i-p junction after wire bonding. (b) Group delay tuning spectra of the device. (c) Power consumption versus group delay.

Fig. 4. (a) Experimental setup for optical signal transmission measurement. PPG: pulse pattern generator; BPF: band-pass filter; OSC: Oscilloscope. (b)-(d) Eye diagrams of 20 Gbps $2^{23} - 1$ PRBS signal output from the device with (b) no delay at off-resonance wavelength, (c) 10 ps group delay, and (d) 110 ps group delay.
Next we examine the quality of the delayed optical signal through the device by measuring the eye diagrams. The experimental setup is shown in Fig. 4(a). A continuous wave (CW) light at 1550 nm wavelength is generated by a tunable laser. TE polarization is set by using a polarization controller before modulation. The modulator was driven by a 20 Gbps non-return-to-zero (NRZ) $2^{31}-1$ PRBS signal generated by a pulse pattern generator (PPG). The output signal from the device is amplified by an erbium-doped fiber amplifier (EDFA), followed by a band pass filter (BPF) to suppress the amplified spontaneous emission (ASE) noise. Eye diagrams of the optical signal transmitting through the device were recorded by a 32 GHz bandwidth oscilloscope (OSC). Figure 4(b) shows the eye diagram off-resonance. Figures 4(c) and 4(d) show the eye diagrams after 10 ps and 110 ps group delays, respectively. The Q factor of the three eye diagrams are all around 10. The optical signal magnitude is reduced when the group delay is increased to 110 ps, primarily due to the increased insertion loss. For the 20 Gbps optical signal (bit period 50 ps), our delay line can buffer $110/50 = 2.2$ bits. If higher speed optical signal were used, it could buffer more up to 18 bits ultimately bounded by the delay-bandwidth product.

4. Conclusion

We presented a novel reflective-type SCISSOR delay line in which a sagnac loop reflector is used to double the delay-bandwidth product. The optical delay was characterized by using the modulation phase-shift method. In the 13-stage delay line, the maximum achievable delay is 110 ps with a bandwidth of ~168 GHz, resulting in a buffering capacity of 18 bits. Optical transmission measurement using a 20 Gbps $2^{31}-1$ PRBS signal confirms the signal fidelity after 10 and 110 ps delays.

Acknowledgments

This work was supported in part by the 973 program (ID2011CB301700), the 863 program (2013AA014402), the National Natural Science Foundation of China (NSFC) (61007039, 61001074, 61127016), the Science and Technology Commission of Shanghai Municipality (STCSM) Project (12XD1406400). We also acknowledge IME Singapore for device fabrication.