High-speed fourth-order photonic differentiator based on silicon self-coupled optical-waveguide resonator

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Abstract **— We propose and experimentally demonstrate the first on-chip fourth-order photonic differentiator implemented by silicon four-stage self-coupled optical-waveguide (FS-SCOW) resonator. Fourth-order differentiation of picosecond pulse signal at a high processing speed of 40 Gb/s is achieved.**

Keywords **— all–optical information processing, fourth-order differentiator, self-coupled optical waveguide (SCOW).**

I. Introduction

All-optical computing and information processing based on photonic devices are advantageous in high-speed processing by virtue of the superiority in overcoming the bandwidth bottleneck of electronic devices [1]. As expected for photonic differentiators, they can offer processing bandwidth orders of magnitude lager than their electronic counterparts [2-4]. Various schemes have been proposed to realize first-order photonic differentiators [2-4]. On the other hand, high-order differentiators are also of great significance and widely employed in optical pulse shaping and analog signal processing [5]. To date, high-order photonic differentiators have been implemented by fiber Bragg gratings (FBGs) [6], programmable pulse shapers [7], cascaded micro-resonators [5, 8], and so forth. Amongst them, high-order differentiators based on compact micro-resonators have been considered promising candidate for photonic integrated circuits (PICs) due to the compactness, low power consumption, and capability of large-scale integration. In Ref. [5], integrated second- and third-order photonic differentiators were realized using cascaded micro-ring resonators (MRRs). However, the processing speed was limited to 5-Gb/s due to high quality factors of MRRs. In our previous work [8], a second-order photonic differentiator based on silicon self-coupled optical-waveguide (SCOW) resonator was demonstrated with increased processing speed of 40 Gb/s.

In this paper, we propose and demonstrate the first on-chip fourth-order photonic differentiator, which is implemented by silicon four-stage self-coupled optical-waveguide (FS-SCOW) resonator on a silicon-on-insulator (SOI) platform. Experiments are carried out for 10-Gb/s, 20-Gb/s, and 40-Gb/s optical time domain multiplexed (OTDM) picosecond pulse signals, and an excellent agreement between theoretical fourth-order differentiations and experimental results is obtained.

II. Operation Principle and Device Fabrication

Fig. 1(a) illustrates the schematic diagram of the proposed silicon FS-SCOW resonator, which consists of four cascaded SCOW resonators. For each SCOW resonator, there are two degenerate modes circulating in opposite directions, thus leading to split resonance notches in the transmission spectrum [9]. When there is weak coupling in the coupling regions shown in Fig. 1(a), the split resonance notches of SCOW resonator exhibit much larger bandwidth as compared to that of a single

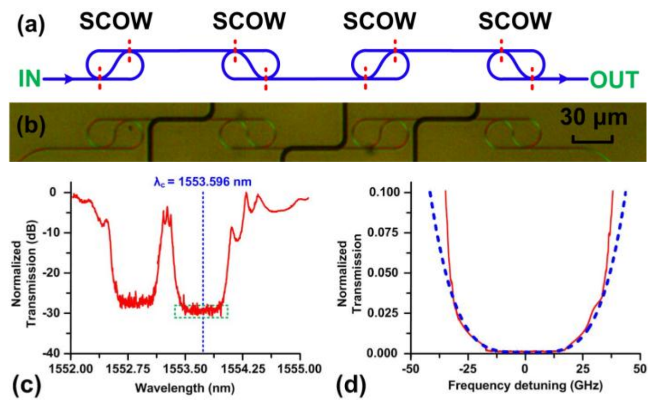

Fig. 1. (a) Schematic diagram of the proposed FS-SCOW resonator. The red dashed lines represent the coupling regions of individual SCOW resonators. (b) Micrograph of the fabricated device. (c) Measured transmission spectrum of the silicon FS-SCOW resonator. (d) Zoom-in view of the quartic-like resonance notch marked with cyan dashed box in (c).

microring resonator [8]. The increased notch bandwidth of SCOW resonator leads to increased processing speed, and also alleviates the difficulties in the alignment of resonance wavelengths of cascaded SCOW resonators. By using the silicon FS-SCOW resonator, we obtain quadric-like resonance notches with increased bandwidth and depth, as shown in Fig. 1(c) and (d).

The designed device is fabricated on an 8-inch SOI wafer. A micrograph of the fabricated device is shown in Fig. 1(b). The cross-section of the waveguide is 450 nm × 220 nm, and the gap size in the coupling regions is 180 nm. 248-nm deep ultraviolet photolithography is utilized to define the pattern, and an inductively coupled plasma etching process is used to etch the top silicon layer. Grating couplers for transverse electric (TE) polarization are employed at two ends to couple light into and out of the chip with single-mode fibers. The measured transmission spectrum of the fabricated device is shown in Fig. 1(c). The on-chip insertion loss is ~11 dB. Zoom-in view of a quadric-like resonance notch in Fig. 1(c) is illustrated in Fig. 1(d), which closely approximates to the ideal quartic curve within a 65.2-GHz-wide band centered on the wavelength of 1553.596 nm.

III. High-order Differentiation Experiment

We use the experimental setup shown in Fig. 2 to test the performance of the fabricated device as a fourth-order temporal differentiator. A 10-GHz radio frequency (RF) clock from a pulse pattern generator (PPG) is amplified and used as a driving signal for a picosecond laser (PSL). The output of the PSL is a picosecond pulse train with a repetition frequency of 10 GHz, whose spectrum is shown in Fig. 3(a). The temporal waveform of a single pulse is shown in Fig. 3(b). The full width half

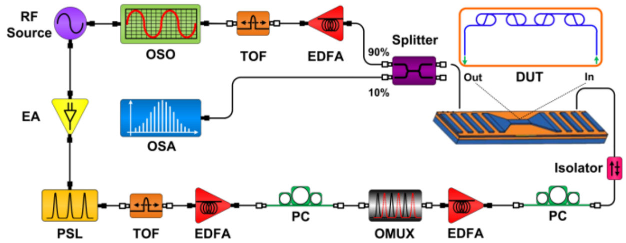

Fig. 2. Experimental setup for fourth-order differentiation using the fabricated device. EA: electrical amplifier, PC: polarization controller.

maximum (FWHM) of the Gaussian-like pulse is ~2.6 ps. To match the bandwidth of the fabricated device and reduce the influence of the device's sideband spectrum, a tunable optical filter (TOF) is utilized to pre-shape the generated picosecond pulse train. The spectrum and the temporal waveform after the TOF are shown in Fig. 3(c) and (d), respectively. After pre-shaping, the FWHM of the picosecond pulse is broadened to ~8.6 ps. An optical multiplexer (OMUX) is employed to generate 10-Gb/s, 20-Gb/s and 40-Gb/s OTDM signals. After amplified by an erbium-doped fiber amplifier (EDFA), the OTDM signal is sent to the device under test (DUT). The output signal from the DUT is split into two parts. One part is fed into the optical spectrum analyzer (OSA), and the other is amplified by another EDFA with one more BPF to suppress the ASE noise before finally sent to a 500-GHz optical sampling oscilloscope (OSO). The optical spectrum and temporal waveform after the fabricated device are shown in Fig. 3(e) and (f), respectively. One can see that the experimentally obtained output pulse waveform fits well with the simulated fourth-order differentiation of Gaussian pulse.

The experimental results of the 10-Gb/s, 20-Gb/s and 40-Gb/s OTDM signals are shown in Fig. 4(a), (b), and (c), respectively. The shape discrepancies and uneven pedestals are

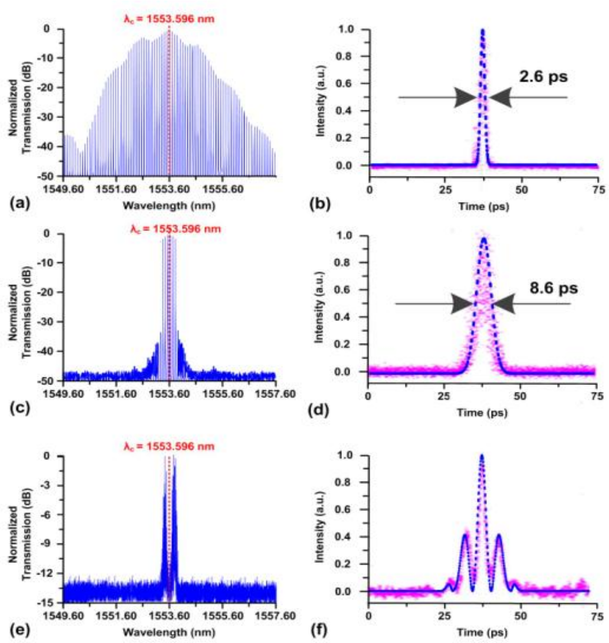

Fig. 3. (a) and (b): optical spectrum and temporal waveform of the generated picosecond pulse, respectively. (c) and (d): optical spectrum and temporal waveform after the pre-shaping, respectively. (e) and (f): optical spectrum and temporal waveform after the silicon FS-SCOW resonator, respectively. The simulations are correspondingly shown by the blue dashed curves.

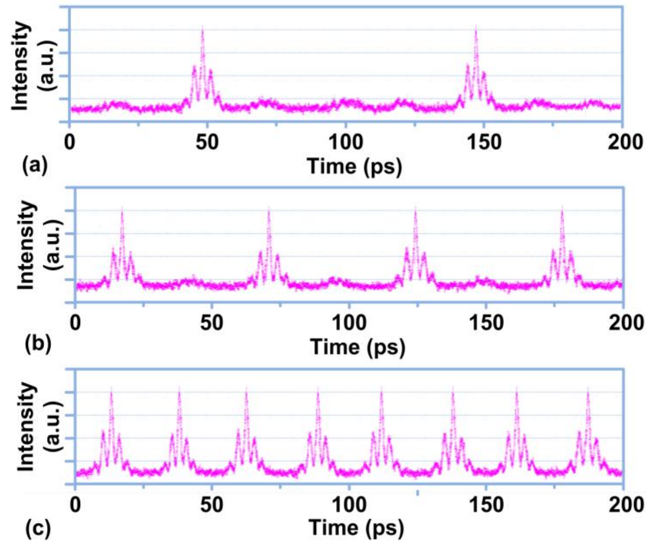

Fig. 4. Experimental observations of the fourth-order differentiations of (a) 10-Gb/s, (b) 20-Gb/s, and (c) 40-Gb/s OTDM pulses, respectively.

mainly caused by the imperfect attenuations and time delays in the multiple-stage propagation paths within the OMUX.

IV. Conclusion

In conclusion, an integrated fourth-order all-optical temporal differentiator based on silicon FS-SCOW resonator has been proposed and experimentally demonstrated. Experiments are performed for the 10-Gb/s, 20-Gb/s, and 40-Gb/s OTDM picosecond pulse trains, and the results show good agreement with simulations.

V. Acknowledgement

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References

[1] L. Venema, "Photonic technologies," *Nature*, vol. 424, pp. 809, 2003.

[2] J. Xu, X. Zhang, J. Dong, D. Liu, and D. Huang, "High speed all optical differentiator based on semiconductor optical amplifier and optical filter," *Opt. Lett*., vol. 32, no. 13, pp. 1872-1874, 2007.

[3] R. Slavik, Y. Park, M. Kulishov, and J. Azana, "Stable all-fiber photonic temporal differentiator using a long-period fiber grating interferometer," *Opt. Commun.*, vol. 282, no. 12, pp. 2339-2342, 2009.

[4] F. Liu, T. Wang, Q. Li, T. Ye, Z. Zhang, M. Qiu, and Y. Su, "Compact optical temporal differentiator based on silicon microring resonator," *Opt. Exp.*, vol. 16, no. 20, pp. 15880-15886, 2008.

[5] J. Dong, A. Zheng, D. Gao, and X. Zhang, "High-order photonic differentiator employing on-chip cascaded microring resonators," *Opt. Lett.*, vol. 38, no.5, pp. 628-630, 2013.

[6] M. Li, D. Janner, J. Yao, and V. Pruneri, "Arbitrary-order all-fiber temporal differentiator based on a fiber Bragg grating: design and experimental demonstration," *Opt. Exp.*, vol. 17, no. 22, pp. 19798-19807, 2009.

[7] J. Dong, Y. Yu, Y. Zhang, B. Luo, T. Yang, and X. Zhang, "Arbitrary-order bandwidth-tunable temporal differentiator using a programmable optical pulse shaper," *IEEE Photon. J.*, vol. 3, no. 6, pp. 996-1003, 2011.

[8] L. Zhang, J. Wu , X. Yin, X. Sun, P. Cao, X. Jiang, and Y. Su, "A high-speed second-order photonic differentiator based on two-stage silicon self-coupled optical waveguide," *IEEE Photon. J.*, vol. 6, no. 2, pp. 1-5, 2014.

[9] L. Zhou, T. Ye, and J. Chen, "Coherent interference induced transparency in self-coupled optical waveguide-based resonators," *Opt. Lett.*, vol. 36, no. 1, pp. 13-15, 2011.

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