All-optical temporal differentiation of ultra-high-speed picosecond pulses based on compact silicon microring resonator

G. Zhou, L. Zhang, F. Li, X. Hu, T. Wang, Q. Li, M. Qiu and Y. Su

A high-speed all-optical temporal differentiator based on a compact silicon microring resonator with a radius of 20 μm is demonstrated. 80 Gbit/s signal differentiation is experimentally realised.

Introduction: Recent years have witnessed intensive interest in and the rapid development of implementations of basic operations with optics thanks to the high potential to increase signal processing speed that is several orders of magnitude higher than that of digital electronics [1]. CMOS-compatible silicon based all-optical signal processing devices could be important basic building blocks, e.g. for mathematical and logical operations [2–5]. The optical processing could overcome the speed and bandwidth limitations of conventional electronic circuits. One of these signal processing devices is the temporal differentiator which has a wide range of applications, including ultrafast all-optical information processing and computing, optical pulse shaping and coding, ultra-wideband microwave signal generation, higher-order Hermite-Gaussian waveforms generation and processing, and direct phase reconstruction of arbitrary optical signals [2]. As a result, it is highly desirable to develop a high-speed silicon based all-optical differentiator. Reference [2] experimentally demonstrated a high-order temporal differentiator based on a long-period fibre grating with a pulse train of 16.7 Mbit/s. Reference [3] proposed a temporal differentiator with a pulse train of 8 Gbit/s employing a $LiNbO_3$ phase modulator. An optical differentiator with a data rate of 10 Gbit/s was experimentally proposed using a long-period fibre grating interferometer [4]. An all-optical temporal differentiator of a single sub-picosecond pulse utilising silicon-on-insulator (SOI) Bragg gratings was proposed in [5]. Experimental realisation of a 13.6 Gbit/s temporal differentiator was reported based on a fibre Bragg grating [1]. In [6], we demonstrated an all-optical temporal differentiator based on a compact silicon microring resonator, which was used for 10 Gbit/s signal differentiation. The speed is mainly limited by the bandwidth of the ring resonator, which is 0.34 nm in [6]. In this Letter, using a silicon ring resonator with bandwidth of 2.5 nm and radius of 20 μm, we experimentally demonstrate an optical temporal differentiator for an 80 Gbit/s OTDM picosecond pulsed signal. To the best of our knowledge, it is the most compact silicon based all-optical differentiator for a signal with a data rate of up to 80 Gbit/s.

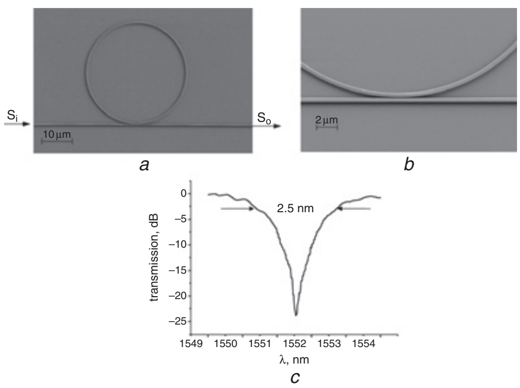

Fig. 1 *SEM photo of fabricated single coupled silicon microring resonator (cross-section of silicon waveguide 450 × 250 nm²); zoom-in view of coupling region; measured transmission spectrum of silicon ring resonator*

a SEM photo
b Zoom-in view
c Measured transmission spectrum

Principle: Fig. 1*a* shows the schematic diagram and also the scanning electron microscope (SEM) picture of a single coupled microring resonator. A ring is evanescently coupled to a single straight waveguide. According to [6], under the situations that the frequency detuning is less than the 3 dB bandwidth of the ring resonator, and the ring resonator works in the critical coupling region ($\tau_i = \tau_e$) [7], the transfer function of the microring resonator can be approximated as:

$$T(\omega) = \frac{s_o}{s_i} = j\tau(\omega - \omega_0) \qquad (1)$$

where ω_0 is the resonance frequency, τ is the reciprocal of photon lifetime as $1/\tau = 1/\tau_i + 1/\tau_e$, $1/\tau_i$ is the power decay rate due to the intrinsic loss and $1/\tau_e$ is the power coupling loss to the straight waveguide from the ring. Equation (1) is a typical function for the first-order temporal differentiator. Thus, the ring resonator can be used as an all-optical temporal differentiator in principle.

Device fabrication: To achieve temporal differentiation of an 80 Gbit/s signal, the silicon microring is required to work in quasi-critical coupling situations and possess a large 3 dB bandwidth. The fabricated silicon microring with a radius of 20 μm and an air gap (between the straight waveguide and the ring) of 100 nm exhibits a relatively deep notch and a large 3 dB bandwidth. We fabricated the device on a silicon-on-insulator (SOI) wafer with a 250 nm-thick silicon slab on top of a 3 μm silica buffer layer, employing E-beam lithography, reactive ion etching and wet chemistry. The cross-section of the silicon waveguide is 450 × 250 nm². Wet chemistry for oxidising 20 Å of silicon surface is carried out to reduce surface roughness to lower the loss. Figs. 1*a* and *b* depict SEM photos of the fabricated silicon microring. The measured transmission spectrum of the silicon microring is shown in Fig. 1*c*. The notch depth at the resonance is about 25 dB, implying that the ring resonator works close to the critical coupling condition. The achieved 3 dB bandwidth of the ring resonator is about 2.5 nm at the resonance wavelength of 1551.73 nm, which is suitable for the differentiation of the 80 Gbit/s OTDM signal with a 3 dB bandwidth of 1.5 nm.

Experiment setup and results: We performed an experiment to show the performance of the silicon microring resonator as a differentiator for an 80 Gbit/s signal. The experimental setup is depicted in Fig. 2. A 10 GHz radio frequency (RF) clock from a pulse pattern generator (PPG ANRITSE MP1763C) is amplified and used as an electrical driver of a picosecond pulse generator (u2t TMLL 1550), which works in active modelocking state. The output of the TMLL 1550 is a picosecond pluse train with a repetition frequency of 10 GHz and a full width half maximum (FWHM) of 2.7 ps measured by a 500 GHz optical sampling oscilloscope (Alnair Lab EYE-2000C), which is provided in Fig. 3*a*. The 10 GHz picosecond pulses are amplified with an erbium-doped fibre amplifier (EDFA) and input to an optical multiplexer (OMUX), where three stages of multiplexing are employed, to generate an 80 Gbit/s optical time division multiplexing (OTDM) signal, shown in Fig. 3*b*. The shape differences between the pulses of the 80 Gbit/s OTDM signal are mainly caused by the imperfect attenuations and time delays in the three-stage propagation paths within the OMUX. After amplification, the 80 Gbit/s OTDM signal is fed into the silicon microring resonator by vertical coupling. The signal is amplified by another EDFA after the microring resonator to compensate the ~20 dB power loss induced by the vertical coupling system [8]. At last, the signals are recorded using a 500 GHz optical sampling oscilloscope. Fig. 3*c* demonstrates the experimental result of the differentiated 80 Gbit/s OTDM signal (solid curve). Theoretically, the differentiated results of Gaussian pulses are odd-symmetry Hermite-Gaussian pulses (dotted curve in Fig. 3*c*). In Fig. 3*c*, the phenomenon of non-return-to-zero in the middle of the two lobes of the experiment result is mainly induced by the limited bandwidth of the 500 GHz oscilloscope (resolution of 1 ps). The asymmetry of the two lobes is mainly caused by the third-order dispersion of the microring resonator at the resonance wavelength [6]. The shape differences between the differentiated pulses in Fig. 3*c* mostly result from the input 80 Gbit/s OTDM pulse train with unequal amplitude generated from the OMUX as shown in Fig. 3*b*. To verify the impacts of the limited bandwidth of the 500 GHz oscilloscope, the limited notch depth and 3 dB bandwidth of the used silicon ring resonator on the differential results, we performed some simulations using MATLAB. As the input signal in the experiment is difficult to reproduce for simulation owing to the imperfections of the picosecond pulse generator and the OMUX, we used the ideal Gaussian pulses in the simulations. Fig. 3*d* plots the simulated 80 Gbit/s OTDM signals after differentiation considering the limited bandwidth of the 500 GHz oscilloscope, and it is obvious that the middle of the two lobes does not return to zero. Figs. 3*e* and *f* show the simulated waveforms after the silicon ring with a notch depth of 24 dB and 3 dB bandwidth of 2.5 nm (the same parameters as in the experiment), and with notch depth of 30 dB and 3 dB bandwidth of 2.5 nm, respectively. Fig. 3*f* indicates that if the notch depth of the silicon ring resonator increases up to 30 dB, the asymmetry of the two lobes can be reduced. The speed of the differentiator is mainly limited by the 3 dB bandwidth of the microring resonator. By introducing a low-Q factor microring resonator operating near the critical coupling region, the differentiator can be utilised for the signal with hundreds of Gbit/s data rate [6].

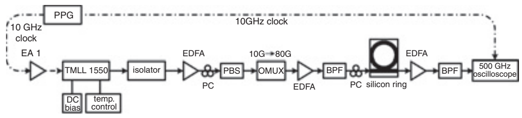

Fig. 2 *Experimental setup of microring resonator based optical differentiator for 80 Gbit/s OTDM signal*

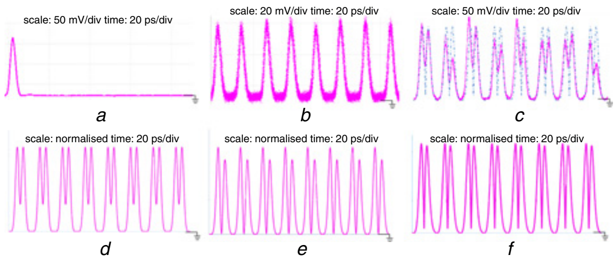

Fig. 3 *10 Gbit/s picosecond pulses (Fig. 3a); 80 Gbit/s signals after optical multiplexer (OMUX) (Fig. 3b); measured (solid) and simulated (dotted, ideal differentiation) 80 Gbit/s output OTDM signals after optical differentiation (Fig. 3c); simulated 80 Gbit/s OTDM signals after differentiation considering the limited bandwidth of 500 GHz oscilloscope (bandwidth of 500GHz) (Fig. 3d); simulations of waveforms after silicon ring (Figs. 3a,f) with same parameters in experiment (notch depth of 24 dB and 3 dB bandwidth of 2.5 nm) (Fig. 3e) and notch depth of 30 dB and 3 dB bandwidth of 2.5 nm (Fig. 3f)*

Conclusion: We have experimentally demonstrated a high-speed all-optical temporal differentiator based on a compact silicon microring resonator. Differentiation for the 80 Gbit/s OTDM signal was experimentally realised, and simulations were also conducted for comparison with experimental results. Our proposed all-optical differentiator could be a competitive candidate for high-speed silicon based integrated photonics.

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G. Zhou, L. Zhang, F. Li, X. Hu, T. Wang and Y. Su (*State Key Lab of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, 800 DongChuan Rd, Shanghai 200240, People's Republic of China*)

E-mail: yikaisu@sjtu.edu.cn

Q. Li and M. Qiu (*School of Information and Communication Technology, Royal Institute of Technology, Electrum 229, Kista 16440, Sweden*)

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