Compact high-speed all-optical differential-equation solver on a silicon-on-insulator platform

Jiayang Wu, Liang Zhang, Xinhong Jiang, Mu Xu, Pan Cao, Xiaowen Sun, Xi Yin, and Yikai Su
State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering,
Shanghai Jiao Tong University, Shanghai 200240, China, E-mail: yikaisu@sjtu.edu.cn

Abstract **— We propose and experimentally demonstrate an all-optical temporal ordinary-differential-equation (ODE) solver featuring compact footprint and high processing speed on a silicon-on-insulator platform. The device performance is theoretically studied and verified by 5-Gb/s ODE solving experiment.**

Keywords **— ordinary-differential-equation (ODE), analog signal processing (ASP), silicon-on-insulator (SOI).**

I. INTRODUCTION

All-optical information processing based on photonic devices is advantageous in high-speed processing. Some photonic devices equivalent to corresponding electronic components have been proposed, such as all-optical temporal differentiator [1], temporal integrator [2], and Hilbert transformer [3]. Based on these basic building blocks, more versatile optical information processing systems can be realized.

Several schemes have been proposed to perform real-time signal processing in optical domain. Some analog all-optical processors are based on fiber-grating devices, such as long-period fiber gratings [3] and fiber Bragg gratings [4]. These devices can be used to process ultrafast signals, but exhibit relatively large device footprints. It was also proposed to use all-optical analog-to-digital converter (ADC) to help realizing optical analog signal processing (ASP) [5], but its performance is limited by the relatively low converting speed, and the systems are too complicated for on-chip integration.

Differential equations play a central role in signal processing. In virtually any field of science and technology, e.g., physics, biology, economics, and engineering, in-depth studies in these equations are always required [6]. All constant-coefficient linear ordinary-differential-equations (ODEs) can be modeled as systems with finite number of differentiators, subtractors, splitters and feedback branches [7]. An optical computing device based on this system modeling theory can be easily modified to meet requirements of different ODEs, and can be concatenated to solve higher-order differential equations.

In this paper, we propose and demonstrate an all-optical temporal ODE solving unit on a silicon-on-insulator (SOI) platform consisting of a critically coupled silicon microring resonator (MRR), a photonic substractor, a splitter, and a feedback branch. The proposed device features compact size, high processing speed, and CMOS compatibility. The performance of the proposed device is theoretically investigated and experimentally demonstrated by 5-Gb/s ODE solving with two typical temporal waveforms.

II. DEVICE STRUCTURE AND OPERATION PRINCIPLE

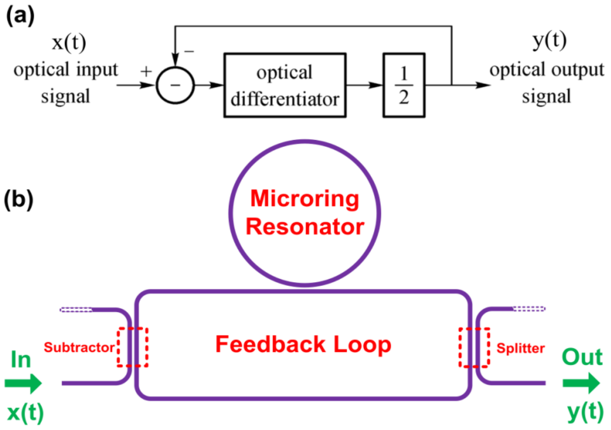

Fig. 1. (a) Block diagram of ODE solving unit. (b) Schematic of the photonic device performing the ODE solving function in (a).

An all-optical temporal ODE solving unit is constructed for the linear first-order ODE system of Eq. (1). The block diagram is shown in Fig. 1(a), where typical elements in classic frame of linear time-invariant ASP systems such as differentiator, subtractor, and splitter are included. A forward path and a feedback branch are also introduced to build the feedback loop of linear differential equation. The layout of corresponding photonic device performing the ODE solving function in Fig. 1(a) is shown in Fig. 1(b). The proposed device provides an optical output with a complex envelop that can be interrelated to the envelop of input optical signal with Eq. (1).

$$y(t)+\frac{1}{2}\frac{dy(t)}{dt}=\frac{1}{2}\frac{dx(t)}{dt} \qquad (1)$$

The subtractor is realized by a 3-dB directional coupler together with an accurate designed feedback loop. To achieve 3-dB coupling feature, the coupling length of the directional coupler is chosen to be 11.56 μm based on our previously fabricated device. The total circumference of the feedback loop is 186 μm, thus there is a phase shift of $(2n+1)\,\pi$ (n is an integer) along the loop to realize optical subtraction. Although there is an additional phase shift of $\pi/2$ caused by the 3-dB directional coupler, it will not affect the device performance since it is outside the loop and can be compensated by those phase shifts in the waveguides of the input and output ports.

Another 3-dB directional coupler is used on the other side of the feedback loop to act as a 3-dB splitter, with one output as the system output and the other as part of the feedback loop. Two cascaded 3-dB directional couplers with an attenuation factor of $1/\sqrt{2}$ for each can be combined as a 1/2 attenuator along the loop, as shown in Fig. 1(a).

To realize the expected function, a 20-μm-radius critically coupled MRR is inserted between the two 3-dB couplers as an optical temporal differentiator [1], for its advantages of compact size and compatibility with on-chip integration.

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III. DEVICE FABRICATION AND MEASURED SPECTRUM

Based on the above principle, the designed device is fabricated on an 8-inch SOI wafer. A micrograph of the fabricated device is shown in Fig. 2(a). The structural parameters are in accordance with the previous discussion. 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 are employed at two ends to couple light into and out of the chip with single-mode fibers. Thermal-optic microheaters are fabricated along the feedback loop to precisely control the phase shift for optical subtraction.

The spectral response of normalized transmission intensity measured with the fabricated device is shown in Fig. 2(b) by the blue solid curve. One can see that there are two kinds of resonance notches, one is the 'M' notch with $2n\pi$ (n is an integer) phase shift along the feedback loop, and the other is the 'Y' notch with $(2n+1)\pi$ (n is an integer) phase shift that we desire. The measured curve is then fitted by the red dashed curve obtained by using the scattering matrix method. The fitting parameters are transmission coefficients of the 3-dB couplers $r_1 = r_2 \approx 0.7102$, transmission coefficient of the MRR $r \approx 0.9778$, loss factor $\alpha \approx 320$/m, and group index $n_g \approx 4.3320$. The resonance notch depth of the MRR is 26 dB, implying that the MRR is very close to critical coupling condition [1].

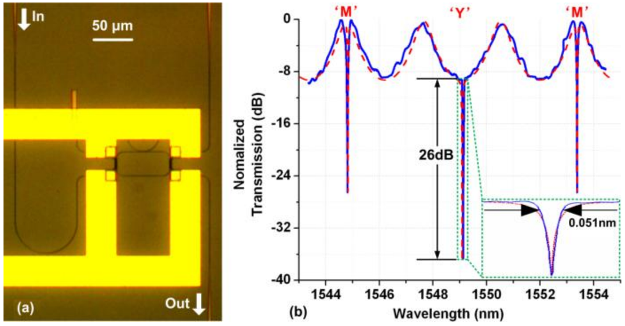

Fig. 2. (a) Micrograph of the fabricated device. (b) Experimentally measured (blue solid curve) and fitted (red dashed curve) transmission intensity spectrum. Inset shows zoom-in view of the 'Y' notch.

IV. ODE SOLVING EXPERIMENT

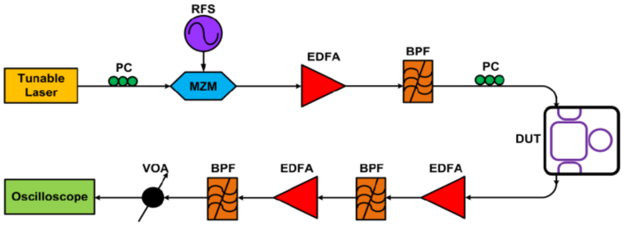

Fig. 3. Experimental setup for ODE solving using the fabricated device. MZM: Mach-Zehnder Modulator, PC: Polarization Controller, RFS: Radio Frequency Synthesizer, BPF: Band Pass Filter, DUT: Device Under Test, VOA: Variable Optical Attenuator.

We use the experimental setup shown in Fig. 3 to test the performance of the fabricated device as an ODE solving unit. The wavelength of the CW light is fixed at the resonance wavelength of the 'Y' notch in Fig. 2(b). When the MZM is biased at the transmission null and driven by a 5-Gb/s electronic sinusoidal signal, the generated carrier-suppressed return-to-zero (CS-RZ) signal with 67% duty cycle in Fig. 4(e) possesses similar property as optical sinusoidal signal. When the bias voltage of the MZM is set at the quadrature point of the transmission curve and also driven by the sinusoidal signal, we obtain optical Gaussian-like pulses with 50% duty cycle in Fig. 4(f). The corresponding output waveforms that we observed are shown in Fig. 4(g) and Fig. 4(h), respectively. The simulated input and output waveforms of Eq. (1) are also shown in Fig. 4(a) ~ (d), and one can see that the experimentally observed output waveforms are very close to theoretical solutions of the ODE.

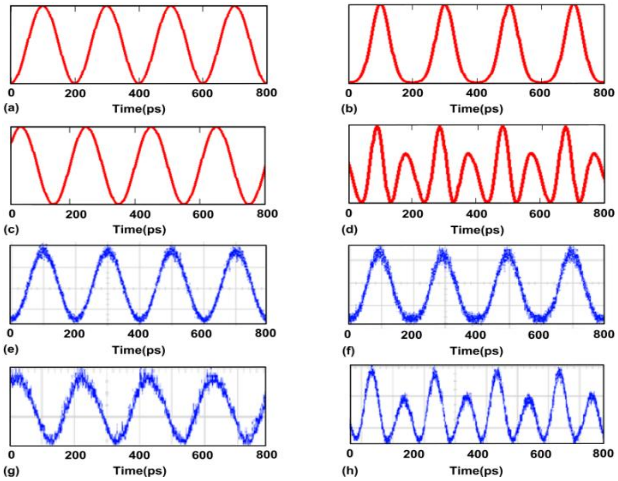

Fig. 4. Simulated input waveforms of (a) 5-Gb/s sinusoidal pulses, (b) 5-Gb/s Gaussian pulses and their corresponding output waveforms (c), (d). Experimentally observed input and output waveforms are correspondingly shown in (e) ~ (h).

V. CONCLUSION

In conclusion, a compact high-speed all-optical temporal ODE solving unit has been proposed and experimentally demonstrated on a SOI platform, with footprint of only 70 μm × 70 μm and computing speed of 5 Gb/s. The comparisons between theoretical solutions and experimentally measured outputs also testify the effectiveness of the proposed all-optical ODE solver.

VI. ACKNOWLEDGEMENT

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