A serial-cascaded double-microring-based silicon photonic circuit for high-speed on-chip clock-recovery applications

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Abstract: We fabricate a silicon microring-based photonic circuit comprising a passive NRZ-to-PRZ signal-format converter and a serial-cascaded modulator for clock-recovery applications. We demonstrate on the same chip 5-Gbit/s format conversion and 5-GHz sampling with 64-ps-width pulses.

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Silicon microring resonators offer one of the basic building blocks for highly compact high-index-contrast photonic integrated circuits (PICs) due to their various device merits including narrowband wavelength selectivity and high-speed modulation when integrated with a diode structure [1, 2]. Optical signal processing devices and circuits using silicon microring resonators are therefore attracting significant attention. Previously [3-5], some of us proposed and demonstrated passive non-return-to-zero (NRZ) to pseudo-return-to-zero (PRZ) digital signal format converters using a silicon microring-based notch filter. Such passive format converters are essential for recovering the clock from the NRZ-format signal, which can be adopted as a data format for on-chip optical communications.

Here, we report our latest progress in this arena toward high-speed on-chip clock-recovery using silicon microring resonator-based technologies. We fabricate a silicon photonic circuit comprising a passive signal-format converter and a serial-cascaded high-speed modulator. Using two discrete resonance wavelengths of these two microrings, we demonstrate on the same chip 5-Gbit/s NRZ-to-PRZ format conversion and 5-GHz sampling with 64-ps-width optical pulses.

Figure 1 schematically shows the PIC and its principle. Figure 1(a) illustrates the signal transmission through the circuit. Microring A (Ring A) resonator-based electro-optic (EO) tunable notch filter serves as an NRZ-to-PRZ converter [3-5]. Microring B (Ring B) resonator-based injection-type modulator of the same resonance wavelength as Ring A serves as a phase comparator. Both Ring A and Ring B are surrounded by lateral p-i-n diodes of identical design. In practical clock-recovery applications, modulator Ring B can be driven by an external phase-locked loop for optical output phase detection.

Figure 1(b),(c) illustrates in the optical spectral domain and the RF frequency domain the principle of the format conversion using narrowband notch filtering [3-5]. We assume a 10-Gbit/s NRZ input signal with 20-ps rise/fall times. The input NRZ signal contains a strong carrier (\(\lambda_0\)) component with broad sidebands (see (b)) but no clock component (see (c)). Whereas, after the narrowband notch filtering, the carrier component is strongly suppressed yet the sidebands remain (see (b)), resulting in PRZ waveforms which correspond to the NRZ waveform edges. The PRZ pulses RF spectrum contains a strong clock component (see (c)).

Fig. 1 Illustrations of the clock-recovery silicon PIC and its principle. (a) Top-view schematic of the circuit. The NRZ waveform is format-converted into a PRZ waveform by a passive filter and sampled by an externally synchronized injection-based modulator. Vo: local clock drive. (b) Calculated 10-Gbit/s NRZ-to-PRZ format conversion in the optical spectral domain using narrowband notch filtering. (c) Calculated RF spectra of the NRZ signal showing no clock component and of the PRZ signal showing a strong clock component. (d) Schematic of the PRZ pulse sampling by modulating the microring-based modulator at the clock frequency. Five lines correspond to (i) the input PRZ signal, (ii) the clock driving signal, (iii) the resulting sampling optical pulses, (iv) the in-phase sampled optical outputs, and (v) the phase-mismatched sampled optical outputs. The dotted-line envelopes of the output pulse train indicate the degree of phase mismatch between the PRZ pulses and the local clock.
Figure 1(d) illustrates the pulse sampling of the converted PRZ waveform using the microring resonator-based modulator. In order to generate periodic optical sampling pulses in the vicinity of $\lambda_0$ using a clock signal, we negatively offset the driving voltage applied to the modulator such that during every modulation period there exhibits only a short duration (10s of ps) for forward biasing the p-i-n diode and thereby blueshifting the modulator resonance wavelength. The optical transmission at $\lambda_0$ is thereby modulated, with periodic pulses of 10s of ps widths. The pulses then periodically sample the PRZ signal. When the input signal pulses and the sampling pulses are in-phase, the optical output pulses exhibits a flat distribution of pulse heights. Otherwise, the optical output yields a slowly varying envelop corresponding to the temporal walk off between the signal and the local clock.

![Figure 1](image1.png)

We fabricate such silicon PIC on a silicon-on-insulator (SOI) wafer with a 0.34-μm-thick silicon device layer on a 1-μm-thick buried-oxide layer. The wire waveguide and the microrings have a designed waveguide width of 0.4 μm. The gap spacing between the waveguide and the microring is 0.35 μm. Both racetrack microrings are designed identically with arc radii of 25 μm and interaction lengths of 15 μm. The intrinsic region width of the lateral p-i-n diode across each microring is 1 μm. The devices are defined by i-line (365 nm) photolithography, and etched by CF₄-based reactive-ion plasma etching. The fabrication process is CMOS compatible. The inset of Fig. 2(a) shows the optical micrograph of the fabricated circuit.

Figure 2(a) schematically shows the experimental setup for our device characterization. We use a bit error rate tester (BERT) to generate a high-speed NRZ signal. We also use a signal generator as an external clock input for the BERT and as the driving clock to the microring B modulator.

Figure 2(b) shows the measured TE-polarized (electric field parallel to the chip) transmission spectra in the vicinity of 1552.5 nm, with two discrete resonances ($\lambda_{cA} = 1552.88$ nm for Ring A, $\lambda_{cB} = 1552.38$ nm for Ring B). We attribute the wavelength misalignment of ~ 0.5 nm to fabrication imperfections. The resonance quality (Q) factor is ~ 4,000 (corresponding to a bandwidth of 50 GHz), with an extinction ratio (ER) of ~ 12 dB. When the modulator Ring B is forward biased with a voltage of 0.9 V, we obtain an on-off ratio of ~ 11 dB at carrier wavelength $\lambda_{cB}$. Here, for proof-of-concept experiments, we choose these two discrete resonance wavelengths as the carrier wavelengths to demonstrate NRZ-to-PRZ waveform conversion and sampling pulse generation on the same chip.

![Figure 2](image2.png)

Fig. 2 Experimental setup for device characterization. BERT: bit error rate tester, Clk: clock. Inset: optical micrograph of the fabricated double-racetrack-microring circuit. (b) Measured TE-polarized transmission spectra showing two discrete resonances at 1552.88 nm for Ring A and 1552.38 nm for Ring B. The dashed-line displays the spectrum with 0.9 V bias on Ring B, showing an on-off ratio of ~ 11 dB at resonance $\lambda_{cB}$.

![Figure 3](image3.png)

Fig. 3 Measured transmissions of a 5-Gbit/s (a) NRZ optical signal at an off-resonance wavelength and (b) converted PRZ signal at carrier wavelength $\lambda_{cA}$. (c) Measured 5-GHz on-chip clock driving signal. (d) Measured sampling pulses with 64-ps width and a 5-GHz repetition rate at carrier wavelength $\lambda_{cB}$. 
We perform the NRZ-to-PRZ waveform conversion using Ring A at carrier wavelength $\lambda_{cA}$. Figures 3(a)-(b) show the measured 5-Gbit/s signal transmission waveforms at an off-resonance wavelength $\lambda_{off}$ and at $\lambda_{cA}$. The off-resonance transmission shows an NRZ signal with a 10%-to-90% rise time of 24 ps and a 90%-to-10% fall time of 38 ps. In contrast, the on-resonance waveform at $\lambda_{cA}$ displays a PRZ signal following the NRZ waveform edges, with a ~ 32-ps pulse width and a peak ER of 6 dB. The different ERs for the leading/trailing edges are mainly due to the asymmetric rise/fall times [5].

We measure the sampling pulse generation using Ring B at $\lambda_{cB}$. We apply a 5-GHz clock signal onto the p-i-n diode of Ring B. Figure 3(c) shows the measured on-chip driving signal, with a ~ 1.3-V forward bias and ~ 2.8-V reverse bias (peak-to-peak voltage $V_{pp}$ ~ 4.1 V). Figure 3(d) shows the obtained sampling pulse train upon such driving signal, with gating window of ~ 64 ps in a 5-GHz repetition rate. The matching between the gating window and the PRZ pulse widths should be crucial for proper phase locking. Here, the pulse gating window is twice as wide as the PRZ pulse width. The relatively wide gating window is mainly limited by the low Q-factor of our fabricated microrings.

Proper design and fabrication for both the microring waveform converter and the microring modulator should be of the essence. Here, although both microrings are identical in design, the fabrication imperfection still causes wavelength misalignment which forbids us from demonstrating the format conversion and sampling at the same carrier wavelength.

In order to align the mismatched resonances, it is possible to apply a DC bias voltage to blue-shift the converter resonance wavelength. Nonetheless, our experiments indicated that the accompanied free-carrier absorption loss can make the waveguide-microring become under-coupled, resulting in a distorted PRZ waveform with a substantial background corresponding to the flat portions of the NRZ waveform [5]. Thus, a better design of the passive converter enabling resonance wavelength trimming yet without severely perturbing the waveguide-microring coupling is essential. We believe that our previously demonstrated interferometer-based microring filters with a waveguide-coupled feedback [6, 7] offer more functional designs.

In summary, we fabricated a silicon photonic integrated circuit with two serially cascaded microring resonators acting as a NRZ-to-PRZ waveform converter and a sampling pulse generator. Such circuit can be driven with an external phase-locked loop for on-chip high-speed clock-recovery applications. We demonstrated 5-Gbit/s NRZ-to-PRZ waveform conversion and 5-GHz sampling pulse generation using two different carrier wavelengths on the same chip. Future designs will focus on modifying the format converter with resonance wavelength tenability using interferometer-based microring filters.

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