All-optical serial-to-parallel converter based on nonlinear effects in silicon microring resonators

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Abstract We propose and demonstrate the fundamental operation of a novel on-chip microring resonator-type serial-to-parallel conversion scheme for all-optical label processing. We left out a delay between the simultaneously implemented pump pulses and probe bits to be extracted. This enabled us to utilize free-carrier dispersion effect to concurrently blue shift the resonance spectra of the microring resonators at low pump power, and avoid nonlinear loss due to two-photon absorption. We successfully extracted two consecutive bits of probe packets into separate waveguides and verified the potential of our scheme in the intended application.

Keywords: all-optical label processing, free-carrier dispersion, microring resonator, nonlinear optical effects, serial-to-parallel conversion

Classification: Integrated optoelectronics (lasers and optoelectronic devices, silicon photonics, planar lightwave circuits, polymer optical circuits, etc.)

1. Introduction

The rapid growth of internet traffic demands high bandwidth optical communication for short reach transmissions such as datacenter networks. Optical switching and networking have attracted much attention due to the concern of electrical packet switching being eventually limited in terms of bandwidth and power consumption [1]. However, O/E conversion and subsequent signal processing cause the bottleneck of latency and power consumption. All-optical label processing [2, 3, 4, 5, 6, 7, 8] will be a solution for realizing further flexible and low-latency network systems.

An all-optical label processing system fundamentally comprises of two main components: a label/payload separator (LPS) and a serial-to-parallel converter [9, 10]. The former detaches the label bits from the payload, and the latter performs serial-to-parallel conversion (SPC) on the detached label. These parallelized label bits can subsequently be processed electronically [11, 12, 13] or all-optically [10, 14, 15].

Maturity of the silicon complementary metal-oxide-semiconductor (CMOS) technology [16], potential for integration with microelectronics [17], and reduced costs [18] have made silicon the centerpiece as a platform of choice for photonic integration. The high index contrast of silicon-on-insulator (SOI) devices leads to strong optical confinement within the silicon waveguides, thus enhancing optical nonlinearities. As a result, various device applications exploiting the nonlinearity in silicon have been demonstrated [19, 20, 21, 22, 23, 24].

As mentioned before, serial-to-parallel converters play an integral role in photonics-based switching networks. Thus, several SPC schemes have hitherto been reported in the literature [9, 25, 26, 27]. Nevertheless, these schemes are faced with issues such as scaling problems, integration difficulties, shifts of wavelength, and high power consumption. Hence, a realistic solution is to use all-optical switching for label processing by LPS/SPC devices and use subsequent electrically-controlled switching for routing of the payload. A SPC device that operates as shown in Fig. 1 can dramatically reduce the latency and power consumption related to O/E conversion of the payload signal.

We reported on a SPC device based on cascaded Mach-Zehnder interferometers on the silicon photonic platform in our previous work [28]. The device operates by nonlinear optical effects (NLOEs) in silicon. In silicon media, since the influence of free-carrier dispersion (FCD) can be effective over Kerr-induced cross-phase modulation (XPM) even for pump light with low peak power, we will focus on the former in our SPC approach. Since XPM and FCD oppose each other, it is necessary to avoid the former to increase the overall power efficiency. Our previous work shows that whenever there is no overlap between the pump and probe pulses, pump-induced XPM can be avoided. Hence, we leave out a delay between the simultaneously implemented pump pulses and probe (label) bits to be extracted. More-

Fig. 1 Device application in all-optical label processing. Apart from performing SPC, the device acts as a LPS. Pump pulses are synchronized with the serial label bits.
over, this allows us to avoid nonlinear loss due to two-photon absorption (TPA).

In this work, the use of resonating cavities such as microring resonator (MRR) structures further enhances the nonlinear effects and lowers the switching power requirement due to their high quality factors [29, 30]. Moreover, the compactness of MRR devices allows themselves to be integrated on a very large scale [31]. In this letter, we propose and demonstrate the fundamental operation of an on-chip SPC device comprised of cascaded MRR structures, aimed for all-optical label processing. As shown in Fig. 1, our device also acts as a LPS. In this first implementation, our objective is to verify the potential of our scheme in all-optical label processing. Thus, we used a device consisting of two MRRs throughout the experiment, which enabled us to concurrently extract two consecutive bits of probe (label) packets into separate waveguides. Even though SPC of a greater number of label bits is necessary when implementing all-optical label processing, we believe the current simpler demonstration confirms the validity of the proposed approach.

2. Device configuration and principle of operation

A schematic of the proposed all-optical SPC device is shown in Fig. 2. The number of the cascaded MRRs is equal to that of the bits of the probe signal. The probe is a serial signal, which comprises of data such as label bits of a packet header, as shown in Fig. 1. A distinct pump signal is used to exert NLOEs into each MRR, by means of which the probe is converted to a parallel signal. In this scheme of SPC, both pump and probe signals are of TE polarization. The probe signal is input from $P_{\text{in}}$ in the lower MRR. The path length $Q_1S_1Q_2$ corresponds to the pulse interval of the probe signal. The pump signal is tuned to one resonant wavelength of the MRRs. In contrast, the wavelength of probe light is slightly detuned to the shorter wavelength side from a separate resonant wavelength. Hence, when the pump pulses are not input, the probe signal propagates to the through ports $S_1$ and $S_2$, reaching $V$.

On the other hand, when pump pulses are simultaneously input from $T_1$ and $T_2$, a spectral shift in the resonance spectrum of each MRR occurs. This is a consequence of the change in the refractive indices of the MRRs due to the exerted NLOEs. Since we intend to avoid TPA and Kerr-induced spectral red shift, and use FCD-induced blue shift in our application, we temporally separate the pump pulse from the probe by leaving out a delay between them, where the former is made to propagate ahead of the latter. Here, the intensity of the pump signal is adjusted so that FCD-induced blue shift pulls the probe signal into resonance. Accordingly, the probe pulses synchronized with the pump are coupled to the ring resonators at $Q_1$ and $Q_2$, and simultaneously output from $U_1$ and $U_2$, without reaching $S_1$ and $S_2$, respectively. These pulses can be regarded as a parallel signal.

Photo-generated free-carriers (FCs) simultaneously give rise to both FCD and free-carrier absorption (FCA). In the silicon waveguides of our device, FCs are accumulated within several tens of picoseconds, while the FC lifetime is in the order of a few nanoseconds. We intend to use our device to concurrently extract only the label bits of an optical packet during a scenario such as the one shown in Fig. 1. Thus, high-speed pulse extraction is possible, whereas some interval of a few nanoseconds between the label and payload is needed to avoid the effect of FC lifetime. In contrast to the FC lifetime, the length of a typical payload is in the order of a few microseconds. FCA is a nonlinear loss mechanism [32, 33] that is significant when the span of the pump pulse is much shorter than the FC lifetime. However, since the pumping interval is equivalent to the packet length, and is longer than the FC lifetime by several orders, our device can be used without any FC-induced latency during the intended application.

Let us consider the instance where a 2-bit optical packet “11” is input to the SPC device. Fig. 3 shows a schematic

![Fig. 2 Proposed configuration of SPC device with cascaded silicon MRRs.](image)

![Fig. 3 Temporal dependency of the optical output at positions (a) input $P$, (b) drop port $U_1$, (c) through port $Q_1$, and (d) drop port $U_2$ of the SPC scheme shown in Fig. 2. The vertical dashed line denotes the instant the pump pulses are simultaneously exerted. The dotted curves are the corresponding zero levels at each output modulated by FCD.](image)
of the temporal response corresponding to the optical output at distinct positions within the SPC device. The vertical dashed line represents the instant the pump pulses are simultaneously exerted from \( T_1 \) and \( T_2 \). The input signal at the port \( P \) is as shown in Fig. 3(a). Fig. 3(b) shows the temporal response at the drop port \( U_1 \). Since the probe wavelength is detuned from the resonant wavelength, only a minute amount of power is coupled to the drop port in the absence of the pump signal. This is the cause behind the short amplitude of the coupled first bit. Exerting the pump signal brings about two major effects. First, the carriers accumulated within the MRRs result in a spectral blue shift and cause a rise in the zero levels of the drop ports, as shown by the bell-shaped dotted curve of Fig. 3(b), which resembles the temporal dependence of FCs. Second, the probe bits that follow the pump are pulled into resonance due to the undergone spectral blue shift. As a result, the second bit is extracted at \( U_1 \) while sitting on the altered zero level. The output corresponding to the through port \( Q_1 \) is shown in Fig. 3(c). Since the pump pulse appears after the first probe bit, the latter propagates to the through port \( Q_1 \) without coupling to the MRR. In contrast, the second probe bit is pulled into resonance due to the influence of the preceding pump pulse. Also, the temporal dependence of the zero level of the through port is modified such that it opposes that of the drop port. Since most of the second bit is switched at the drop port, only a minute amount of its power lies on the altered zero level at \( Q_1 \). Finally, Fig. 3(d) shows the temporal response at the drop port \( U_2 \). The dotted curve corresponds to the resultant zero level. The shape is due to the superposition of the new pump-induced zero level and the one reaching \( Q_2 \) from \( Q_1 \). Since most of the second bit is coupled at \( U_1 \), only a minute amount of the bit is found in the extracted signal at \( U_2 \). However, most of the first bit is extracted, for which a similar explanation to Fig. 3(b) can be given. As seen from Fig. 3(b) and (d), the probe bits synchronized with the pump pulses are extracted simultaneously from drop ports \( U_1 \) and \( U_2 \).

3. Experiment

Our device was fabricated on an SOI wafer with a silicon core thickness of 220 nm and a buried oxide (BOX) layer. Each MRR structure comprised of a coupling gap of 0.15 \( \mu \)m and a radius of 10 \( \mu \)m. The width of the waveguides was set to 430 nm. To efficiently couple light from the external fiber into the waveguide, and vice versa, we installed spot-size converters based on inverse tapers having a tip width of 80 nm, and a 3-\( \mu \)m-wide SiO\(_2\) waveguide closest to the facet, at the input and output of each waveguide. Tantalum thermal heaters formed on the over-cladding of MRRs were used to adjust any resonant peak mismatch between the cascaded MRRs due to fabrication errors. The consecutive MRRs were separated by a delay line that was designed to correspond to the pulse interval of the probe signal. Fig. 4 illustrates the microscopic image of the fabricated device.

The length of the delay line was configured such that it corresponds to a 200-ps pulse interval of the probe signal (bitrate = 5 Gbps). The probe signal is input from port \( A \). The leading probe pulse propagates to the through port of the lower MRR, then along the delay line and reaches the upper MRR, when the following probe pulse just reaches the lower MRR. Next, pump pulses are simultaneously input from ports \( C \) and \( E \), causing each probe pulse to be extracted simultaneously from ports \( B \) and \( D \).

Next, transmittance spectra for the TE mode from input port \( A \) to the drop ports \( B \) and \( D \) were measured. Since there was a slight lateral mismatch between the spectra, the MRR connected to port \( B \) was heated by flowing a current of ~10 mA through the thermal heater, and its spectrum was red shifted to align with that of port \( D \). The result is shown in Fig. 5. The rough 15-dB-difference between the spectra corresponds to the residual of the first MRR and loss due to propagation along the delay line. The former will not be an issue during temporal operation since only the probe bit that experiences the spectral blue shift will be extracted at the drop port.

Finally, Fig. 6 shows the setup we used to perform pump-probe measurements on our device. The input and output waveguides of the device under test were connected to an optical fiber array having a 250-\( \mu \)m pitch. Two tunable laser diodes (TLDs) were used as optical sources for pump and probe lights. Continuous wave (CW) signals thus out-

![Fig. 4 Microscopic image of the (a) fabricated SPC device and (b) its constituent MRR structure.](image-url)

![Fig. 5 Measured transmittance from port A to ports B and D for TE mode.](image-url)

![Fig. 6 Schematic diagram of the pump-probe setup. TLD: tunable laser diode, PPG: pulsed-pattern generator, EDFA: erbium-doped fiber amplifier, PC: polarization controller, BPF: band-pass filter and APD: avalanche photodiode. Input and output ports of the device shown in Fig. 4 are shown in color.](image-url)
put from the TLDs were made into signals by electro-optical modulators. We used a pulsed-pattern generator having synchronous two outputs to control the pulse width and timing. The pulses were amplified by erbium-doped fiber amplifiers (EDFAs), and both pump and probe polarizations were set to TE at the polarization controllers (PCs). The 3-dB splitter equally divided the power of the pump signal between two outputs which were then connected to ports C and E. Probe light output from the PC was delivered to port A. A current source was used to tune the thermal heaters of our device. The outputs B and D were connected to a matrix switch, which allowed us to switch among the oscilloscope, spectrum analyzer and power meter.

For each probe signal used throughout the experiment, the wavelength was configured at 1550.35 nm and pulse interval at 200 ps. Moreover, a pump signal of wavelength 1541.9 nm and pulse width 50 ps having a period of 10 ns was used. The peak power of the pump pulse at the input waveguides C and E was estimated to be ~2 W. Only probe light output from ports B and D was extracted by a band-pass filter. Throughout the experiment, we made sure that the pump pulse did not overlap with the extracted probe bit so that the undergone spectral shift was solely due to FCD. As a result, amplitudes of the probe bits that followed the pump pulse increased, since they were pulled into resonance due to the undergone spectral blue shift. Since the extracted bits hatched in blue of Figs. 7 and 8 immediately follow the pump pulses, they exhibit a maximum increase in the amplitude.

Fig. 7 denotes the temporal response of the optical output at ports B and D for the respective second and first bits of the label signal “11”. As seen by the vermilion hatched region, pump pulses were exerted simultaneously from ports C and E to the MRRs. The probe bit that immediately follows the pump pulse is considered as the extracted bit at each output. Here, optical pulses of “1” hatched in blue were extracted at the ports B and D, respectively. Fig. 8 shows several combinations of extracted two consecutive bits of an input label signal “1101” at ports B and D. We found that besides the probe bit that immediately followed the pump pulse, all probe bits that followed were also extracted successively at port B. The probe bits that were intended to be extracted from ports B and D in this verification are hatched in blue. We confirmed a higher level in the optical output for the extracted bit “1”, and a lower level for the extracted bit “0”. Note that the configuration of this study comprised of only two MRRs and a single delay line. As a result, the residual bits sitting on the trail of carrier relaxation were also extracted at the last MRR. During practical use, the number of cascaded MRRs is identical to that of the bits found in the label signal. Thus, a similar extraction of residual bits will not occur during a real application of the proposed SPC scheme, and only the probe bit which immediately follows the pump pulse will be extracted at each port.

4. Conclusion

In this letter, we proposed and reported on the fundamental operation of a novel SPC scheme based on cascaded MRRs on the silicon photonic platform. Here, we made use of FCD to concurrently blue shift the resonance spectra of the MRRs, and extract each bit of the probe label signal into separate waveguides. To focus on FCD effect, we cautiously left out a time delay between the pump signal and the probe bits to be extracted, so that there was no overlap between

![Fig. 7](image7.png)  
**Fig. 7** Probe signal “11” synchronized with the pump signal at output ports B and D of Fig. 4. First and second bits of the packet, hatched in blue, are extracted simultaneously at the outputs. The instant the pump pulses appear is hatched in vermilion.

![Fig. 8](image8.png)  
**Fig. 8** Bits of probe signal “1101” synchronized with the pump signal at output ports B and D of Fig. 4. In (a), first and second bits, in (b), second and third bits, and in (c), the third and fourth bits are extracted simultaneously. The instant the pump pulses appear is hatched in vermilion. Intended extracted bits at each output are hatched in blue.
them. Consequently, we were able to realize SPC at low pump power, and avoid detrimental TPA-induced nonlinear loss, as demonstrated in the literature [28].

The purpose of this work was to verify the potential of the proposed SPC scheme in all-optical label processing. For this reason, we used a simpler device that consisted of only two MRRs even though a greater number will have to be cascaded during a real application of the proposed scheme. During this first implementation, two consecutive bits of optical signals “11” and “1101” having a 200-ps pulse interval (bitrate = 5 Gbps), synchronized with simultaneous pump pulses were concurrently extracted into separate waveguides. In relation to these extracted bits, we demonstrated SPC using FCD effect of silicon. Hence, we have successfully verified the potential of our scheme in the intended application. The peak power of the pump pulse when estimated at the waveguide input was ~2 W during the experiment. This value can be reduced by precisely controlling the delay between the pump and probe pulses [28].

Even though our device is based on FCD of silicon, it will not be restricted by the nanosecond-order free-carrier lifetime during its intended application. The scheme is scalable for multibit label signals by cascading MRRs using low-loss delay lines [34, 35]. Moreover, operation at higher bitrates is feasible by appropriately shortening the length of the delay lines.

Acknowledgments

This study was supported by MIC/SCOPE #162103103; JST Core Research for Evolutional Science and Technology (CREST) #JPMJCR15N6 and #JPMJCR18TF4; JSPS KAKENHI #19H02190 and New Energy and Industrial Technology Development Organization (NEDO).

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