A Wavelength Tunable Optical Buffer Based on Self-Pulsation in an Active Microring Resonator

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***Abstract*—A wavelength tunable optical buffer with the ability to achieve data recovery based on self-pulsation in an active microring resonator is proposed and experimentally demonstrated. The key component in the optical buffer is the microring resonator which is implemented based on an InP–InGaAsP material system incorporating two semiconductor optical amplifiers and a phase modulator, ensuring an ultrahigh *Q*-factor and a tunable resonance wavelength for fast self-pulsation operating at gigahertz frequencies. An optical carrier modulated by an arbitrary pulse sequence is used to trigger the self-pulsation in the microring resonator, while its output is coupled to a fiber-optic delay line in an optoelectronic delayed feedback configuration, a recursive system for data storage. Optical buffering and data recovery at 1 Gb/s are experimentally demonstrated, which is the fastest optical buffer ever reported based on self-pulsation in a microring resonator. The proposed optical buffer can be employed to perform critical telecommunication buffer functions including writing, storage, reshaping, healing, and erasing.**

***Index Terms*—Optical buffering, optical pulse generation, optical resonators.**

I. Introduction

An optical buffer, which stores optical signals for a short period of time, can find numerous applications such as optical storage [1], optical packet switching [2], and all-optical signal processing [3]. As one of the fundamental building blocks in an all-optical system, an all-optical buffer can provide optical storage directly in the optical domain without the need for optical-to-electrical and electrical-to-optical conversions, which will increase the signal processing speed and reduce the power consumption as compared with an electronic buffer. In the last few years, numerous approaches have been proposed to implement optical buffers. At present, five major approaches have been employed for the implementation of optical buffers. The first approach is to use an optical delay-line with a long time delay for the storage of an optical signal [4], [5], the second is to use the slow light effect in an optical medium to decrease the group velocity for optical buffering [6]–[10], the third is to use the optical Kerr effect to copy and sustain an optical bit as a temporal soliton in an optical cavity [11], the fourth is to use the class II excitability [12] in an array of cascaded microring resonators to achieve optical delay [13], and the fifth is to use the two stable states as ‘0’ and ‘1’ in photonic crystal nanocavities for optical buffering [14].

Specifically, in the first approach, a length of optical fiber or waveguide is used to provide a desired time delay for data buffering. In 2004, Yeo *et al.* experimentally demonstrated an optical fiber delay-line buffer with an adjustable time delay to provide dynamical reconfigurability of optical buffering within nanoseconds [4]. In such a delay-line-based optical buffer, the time delay is offered by the physical length of the optical fiber; as a result, the size of the buffering system is inevitably large if a considerable amount of delay is needed. Recent advances in photonic integrated circuits (PICs) have led to the development of ultra-long optical delay line on a silicon chip for optical buffering. At present, a delay line as long as 250 m has been demonstrated on a silicon chip over an area of 9.5 cm $\times$ 9.5 cm [5]. Delay line buffers provide a practical solution for all-optical buffering with a large bandwidth. However, these delay-line buffers need optical switches to route the light in the delay-line structure to achieve a reconfigurable time delay, which would increase system complexity and introduce extra losses.

In the second approach, an optical buffer is implemented based on the slow light effect in an optical material that has strong dispersion. In such a material, optical waves with different wavelengths propagate at different speeds and thus the group velocity of the optical waves can be reduced. By making the dispersion of the material sufficiently strong, the group velocity can be significantly reduced, to be less than the speed of light in vacuum, which can be used to provide the time delay in an optical buffer. To date, numerous techniques to implement optical buffers based on slow light effects in various materials have been reported. These slow light mechanisms include electromagnetically induced transparency [6], coherent population oscillations [7], stimulated Brillouin scattering effects [8], optical parametric amplifying [9], and resonating in an optical waveguide [10]. Although slow light effects open up great opportunities to manipulate the speed of light and thus implement optical buffers, there are challenges such as small bandwidth and large losses.

In the third approach, an optical buffer is implemented by exciting temporal cavity solitons in a resonator. Temporal

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cavity solitons exist as temporally localized pulses in a resonator pumped by an externally driving field, which can be excited through a phase-insensitive and wavelength-insensitive process [11]. By modulating the data bits on the driving optical beam, the temporal cavity solitons are excited in a sequence corresponding to the data bits. Leo *et al.* demonstrated an optical buffer based on temporal cavity solitons, which could capture a 40 kbit sequence from a 25 Gb/s optical data stream and provide continuously looped optical read-out of the data at the original data rate of 25 Gb/s [11]. However, this approach can only enable optical buffering for optical wavelengths close to the resonance wavelength of the cavity. Additionally, this optical buffer requires a strong optical input signal to excite the Kerr nonlinearity and the writing procedure is very complicated. Furthermore, erasing of the data was not experimentally demonstrated.

In the fourth approach, the time delay for achieving optical buffering can be obtained by an excitable photonic neural circuit [13]. A microring resonator can be excitable if it is pumped by a continuous-wave (CW) light wave with a sufficiently high power at the blue side of its resonance due to the thermal and free-carrier nonlinearities [13]. Van Vaerenbergh *et al.* proposed an optical delay line based on an array of excitable silicon-on-insulator (SOI) microring resonators. With a time delay of 200 ns obtained by simulation, the proposed delay line can be employed for information buffering at a speed of MHz in a spiking neural network. However, the buffering speed is limited to MHz frequencies.

In the fifth approach, photonic crystal nanocavities are used to store optical signals based on the transmittance bistability [14]. In a photonic crystal nanocavity, the cavity resonance wavelength can be shifted by varying the input optical power due to optical nonlinearity. As a result, the transmittance of optical signals via the cavity can be switched by changing the input optical power, and the transmittance exhibits bistability as a function of the input power. By assigning the two bistable states as '0' and '1', an optical buffer is obtained. An optical pulse can then be used to change the bistable states for memory operation allowing writing and erasing of data. This approach can provide a large bandwidth for optical buffering, and a buffering speed as high as 40 Gb/s was experimentally demonstrated in [14]. However, since a nanocavity offers only one bit storage, multi-bits have to be stored in an array of nanocavities. Consequently, the writing, erasing, and reading are very difficult since selective coupling of an optical pulse to a specific cavity in the nanocavity array is needed.

In this paper, we propose a novel approach to the implementation of a wavelength tunable optical buffer based on self-pulsation in an active microring resonator at a high bit rate (up to GHz). Self-pulsation oscillations in the MHz range based on slow thermal oscillations have been demonstrated [12]. To increase the speed of self-pulsation oscillations for optical buffering, slow thermal oscillations should be suppressed to allow pure and fast coupled electron-photon oscillations at GHz range [14]. In this work, we demonstrate the generation of GHz oscillations based on coupled electron-photon dynamics in an ultrahigh-Q resonator with a buffering data rate of 1 Gb/s. To our knowledge, this is the fastest pure GHz oscillations in the absence of slow thermal oscillations reported to date using microring resonators [12]. The proposed optical buffer is experimentally evaluated. Optical buffering and data recovery at 1 Gb/s are demonstrated. As the buffering time is determined by the length of the optical delay line in the system, a desired buffering time can be obtained by choosing the length of the optical delay line. However, since the buffering capacity, which is the maximum number of bits that can be stored in the buffer, is determined by the ratio between the loop delay time and the self-pulsation time, for a fixed delay line we can store a data sequence with the number of bits equal to or smaller than the buffering capacity. Compared with other optical buffers reported in [4]–[14], the proposed optical buffer offers a few advantages. 1) There is no need to use multiple cascaded integrated devices to realize an optical memory with a bit storage higher than one bit. 2) The proposed optical buffer offers a GHz-range optical buffering speed with a tunable wavelength. 3) Data erasing and data recovery capabilities are also available with the proposed optical buffer which are demonstrated experimentally.

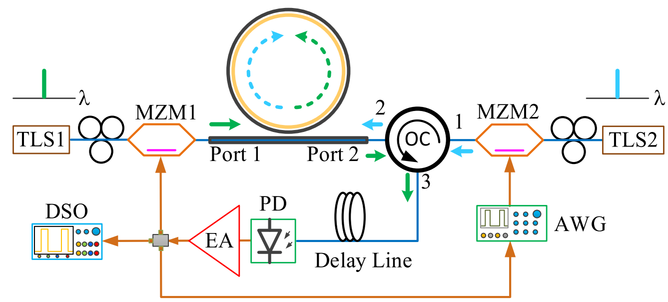

Fig. 1. Schematic of the proposed optical buffer based on a ring resonator. TLS: tunable laser source; MZM: Mach–Zehnder modulator; OC: optical circulator; PD: photodetector; AWG: arbitrary waveform generator; EA: electric amplifier; DSO: digital storage oscilloscope.

II. Principle

The schematic of the proposed optical buffer is shown in Fig. 1. As can be seen, a microring resonator is incorporated in an optoelectronic delay-line loop to provide self-pulsation for optical buffering. In the proposed configuration, the microring resonator works as a nonlinear node that is triggered to generate a self-pulsating signal in response to an incoming signal, enabling to write, reshape and restore the information in the optical buffer, while the delay line in the configuration is used as a temporal buffer to store the information. The self-pulsation in the proposed system is a result of strong nonlinearities in the resonator, and a result from the balance between the nonlinear response and the photon cavity lifetime [15]–[18]. In our system, when a light wave with a high power density is coupled into the microring resonator, free carriers are generated as a result of two-photon absorption (TPA) [17], which changes the effective refractive index of the ring resonator. Since the free carriers have very short lifetimes, the resonance wavelength change of the ring resonator caused by the interaction between the free-carrier dispersion and the TPA is unstable [18]. As a result, self-pulsation is triggered, and the achievement of a self-sustained oscillation requires a positive feedback mechanism which is provided by the dynamical tuning of the cavity resonance as a function of the carrier density that modulates the stored energy in the cavity. The frequency of the self-pulsation, which in our case is in the GHz range, is determined by the lifetime of the free-carriers generated by two-photon absorption in the ring resonator [15]. This differs substantially from the self-oscillations created by the competition between thermal and free carrier effects, which is limited to MHz frequencies [12]. By using the InP–InGaAsP material system, which is reported to be very efficient in suppressing heat accumulation [14], thermal-optic induced low speed self-pulsation is absent in our microring resonators. Taking advantage of the fast self-pulsating oscillations, a fast optical buffer can be achieved using the self-pulsation in an active microring resonator triggered by the input optical signal carrying data with its wavelength close to one resonance wavelength of the microring resonator. The self-pulsation in the microring resonator can be controlled according to the data in the input optical signal, and thus the generated pulse train is used to re-shape, restore and heal the incoming data bits whereas a recursive optoelectronic loop is employed for signal storage as shown in Fig. 1. To enable wavelength tunable optical buffering, a phase modulator (PM) is also incorporated inside the ring resonator to laterally shift the resonance wavelength to make it close to the wavelength of the input optical signal.

As shown in Fig. 1, the output of an active microring resonator is coupled to a long delay line in an optoelectronic delayed feedback configuration, which consists of a tunable laser source (TLS1), a Mach–Zehnder modulator (MZM1), a microring resonator, an optical delay line, a photodetector (PD), and an electronic amplifier. The data buffering is realized as follows. By tuning the wavelength of TLS1 close to one resonance wavelength of the microring resonator, a self-pulsation signal can be triggered and stored in the closed loop configuration in response to an incoming signal, therefore, data buffering can be achieved in this recursive system, and the buffering time is determined by the length of the optical delay line. The optical signal from TLS2 with a wavelength close to the resonance wavelength of the ring resonator is modulated by a data sequence and injected into the optical buffer to provide the initial excitation of self-pulsation in the microring resonator. Without injection of the binary pulse sequence, the microring resonator operates in an unlocking regime without nonlinear self-oscillations being observed. Then, by modulating the injected optical signal with a sequence of data, the microring resonator starts to operate in the nonlinear self-oscillation regime if the incoming modulated data sequence has a sufficiently high energy. The first output pulse excited by the optical signal is fed back to the input (Port 1 shown in Fig. 1) after being delayed by a long delay time which initiates another self-pulsation pulse at the output. This recursive process results in a train of output pulses encoded by the modulated data sequence at a fixed interval determined by the length of the delay-line. We would like to highlight that the data sequence is successfully written after only a single roundtrip.

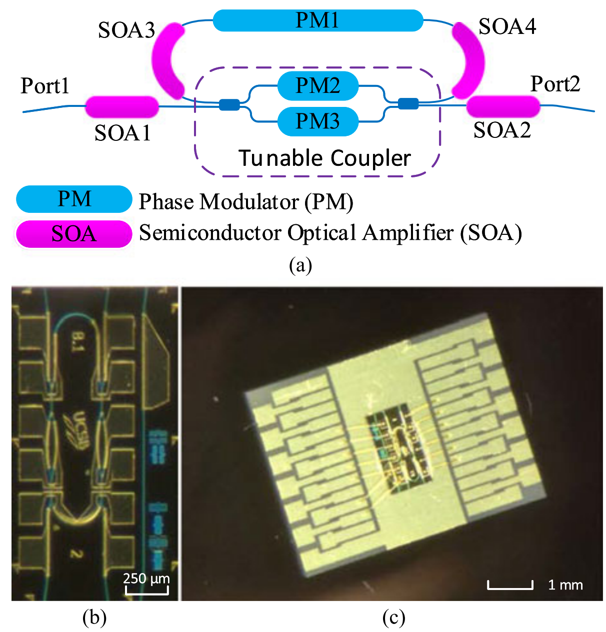

Fig. 2. (a) Schematic of the active microring resonator. (b) Fabricated microring resonator prototype (c) with wire bonding to a carrier.

The key component in the proposed optical buffer is the active microring resonator, as shown in Fig. 2(a), since it provides the nonlinear node of the buffering system. The output of which is coupled to a bus waveguide by a tunable coupler. Since the self-pulsation of the microring resonator can be triggered even with a strongly degraded pattern, the optical buffer is able to perform reshaping and restoring of a degraded data sequence. The tunable coupler is implemented by an MZI with a PM in each of the two arms. Two multimode interference couplers are used to combine and split optical power at the two ends of the MZI. By injecting a current to one of the two PMs, the coupling ratio of the tunable coupler can be tuned from 0 to 100%. There are also two semiconductor optical amplifiers (SOAs) at the input and output of the microring resonator to compensate for the coupling loss between the optical fiber and the resonator. Two additional SOAs are incorporated in the microring resonator to manage the insertion loss and thus achieve a high Q-factor. To achieve a tunable resonance wavelength, a PM is also incorporated inside the microring resonator. By changing the current injected into the PM, the resonance wavelength of the microring resonator can be laterally shifted. In this way, the designed microring resonator can provide an ultrahigh Q-factor and a tunable resonance wavelength. Since the resonance wavelength of the microring resonator is tunable due to the PM in the microring resonator, the incorporation of the active ring resonator in the proposed optical buffer would enable high speed and wavelength tunable optical data buffering.

III. Experimental Results

The microring resonator is fabricated in an InP–InGaAsP material system, as shown in Fig. 2(b) and wire bonded to a carrier for easy accessing to the SOAs and PMs in the microring resonator, as shown in Fig. 2(c). The epitaxial structure for

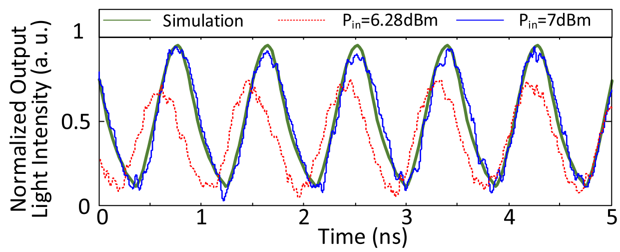

Fig. 3. Simulation and experimental results. Green solid line shows the simulation self-pulsation in the microring resonator. Red dashed line and blue solid line show the self-pulsation with a CW signal of 6.28 dBm and 7 dBm, respectively.

an SOA in the device includes an InP substrate, an *n*-dopant layer, a 300 nm waveguide layer, a ∼250 nm confinement tuning layer (CTL), 5 quantum wells (QWs), a 1.7 μm Zn *p*-dopant layer, a 150 nm contact layer, and a metal layer. In such an epitaxial structure, the CTL pushes the QWs away from the waveguide layer to reduce the confinement factor and improve the saturation power. For a PM in the device, a *p*-dopant layer is grown on top of the waveguide layer without the CTL and QWs. For a passive waveguide, the contact layer is covered by a *p*-cap layer. In the InP–InGaAsP material system, heat can escape effectively [14], which would minimize the temperature increase due to the thermal effect. In addition, the device has a heterostructure, which allows the generated carriers to be confined in the InGaAsP region due to the band gap difference between the waveguide layer and the cladding layers. Therefore, a strong interplay between the carriers generated in the waveguide and the propagation light wave is obtained, which would enhance the self-pulsation effect. The length of the ring resonator is 3 mm, which provides a free spectral range (FSR) of 27.2 GHz or 0.22 nm at 1550 nm. The 3-dB bandwidth of the resonance notch is 22 pm, which is also tunable by tuning the gain in the ring resonator and the coupling coefficient between the ring resonator and the bus waveguide.

The self-pulsation in the fabricated microring resonator is first experimentally demonstrated. To do so, a CW light wave from a TLS (Agilent, N7714A) centered at 1558.775 nm is coupled into the microring resonator, which has a wavelength that is 25 pm apart from one of the resonance wavelengths of the microring resonator at 1558.8 nm. As shown in Fig. 3, a pulse train with a pulse width of 536.7 ps and a repetition rate of 1.12 GHz is generated when the input optical power is 7 dBm, which is close to the theoretically calculated pulse train by simulation with a free-carrier lifetime of 890 ps. Therefore, an on-off keying (OOK) data sequence with a rate less than 1.12 Gb/s can be used to trigger the self-pulsation in the ring resonator, meaning that the speed of the self-pulsation oscillations sets an upper limit of the bit rate that can be supported in the buffer. Due to the injection currents to the two SOAs inside the ring resonator, the insertion loss is largely compensated, which enables the resonator to have an ultrahigh *Q*-factor up to 31 million [19]. In the experiment, the *Q*-factor of the ring resonator is measured to be ∼1 million, which is good enough to achieve effective self-pulsation. The pulse duration and magnitude can be slightly tuned by changing the input optical power [12]. When the input

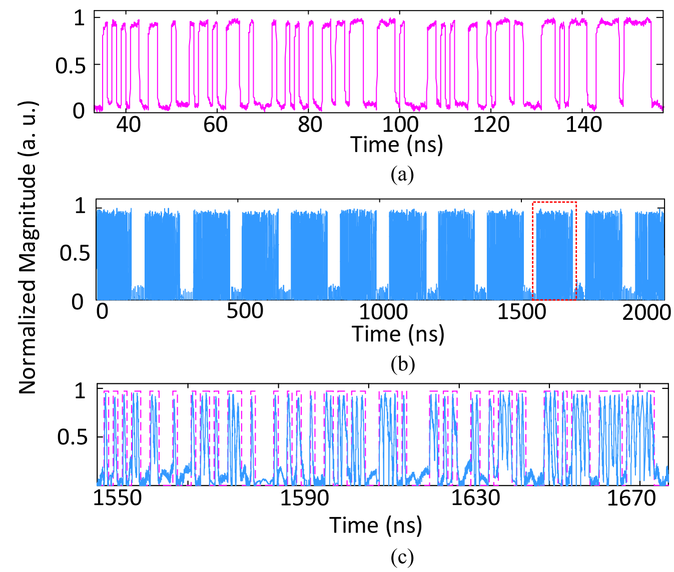

Fig. 4. Experimental results. (a) Input 1 Gb/s 2^7-1 PRBS data sequence generated by an AWG. (b) Observed pulse train at the output of the optical buffer. (c) Solid line represents the detailed data sequence marked in (b) by a dashed box, and the dashed line represents the data used to generate the 2^7-1 PRBS.

optical signal is tuned to 6.28 dBm, the pulse width is reduced to 583.6 ps, and the peak magnitude of the pulse is dropped by 20%. To ensure stable operation, a thermoelectric cooler is used to improve the temperature stability of the device and thus to achieve stable optical buffering. In the experiment, no drifting in the central wavelength of the ring resonator is observed after the system is warmed up which takes about 10 minutes.

In what follows, the experimental investigation of the incorporation of the active ring resonator in the proposed optical buffer, shown in Fig. 1, to achieve optical buffering is discussed. The output of the microring resonator is coupled to a 30-m optical delay line in the optoelectronic delayed feedback configuration to ensure a loop delay larger than the length of the input signal, where a TLS (TLS1, Anritsu, MG9638A), an MZM, the microring resonator, a PD (Newfocus, 25 GHz), and an electronic amplifier in addition to the 30-m optical delay line are used. The optical delay line loop can provide a buffering time of 172 ns. With a self-pulsation pulse repetition rate of 1.12 GHz, the proposed optical buffer can store a 2^7-1 PRBS data sequence with a data rate of 1 Gb/s. The wavelength of the light wave from TLS1 is tuned at 1558.825 nm which is 25 pm apart from one of the resonance wavelengths of the microring resonator which is 1558.8 nm. A 1-Gb/s 2^7-1 PRBS data sequence generated by an arbitrary waveform generator (Tektronix, AWG7102), shown in Fig. 4(a), is modulated on the light wave from TLS2 at 1558.775 nm with a power of 4 dBm, which is injected into the microring resonator through an optical circulator. The signal at the output of the optical buffer is observed by a real-time oscilloscope (Agilent DSO, X93204A), as shown in Fig. 4(b), and the signal is stored in the buffer for ∼100 round trips. Due to the use of two SOAs in the ring resonator and an electrical amplifier in the system, the signal-to-noise ratio (SNR) is decreasing when the signal is recirculating in the loop. After a certain number of

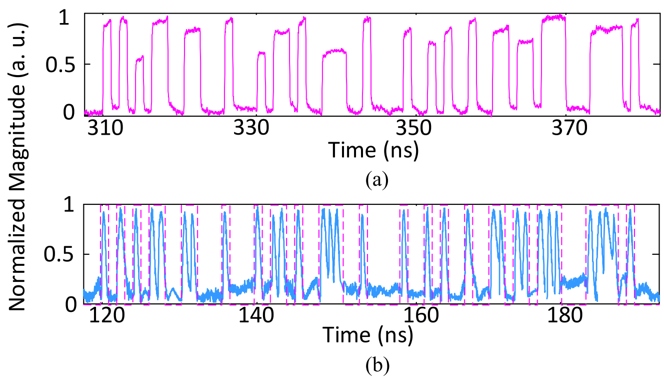

Fig. 5. Experimental results showing self-healing in the proposed optical buffer. (a) Input deteriorated 1 Gb/s data sequence generated by an AWG. (b) Solid line represents the observed pulse train in the optical buffer, and the dashed line represents the data used to generate the 2^7-1 PRBS.

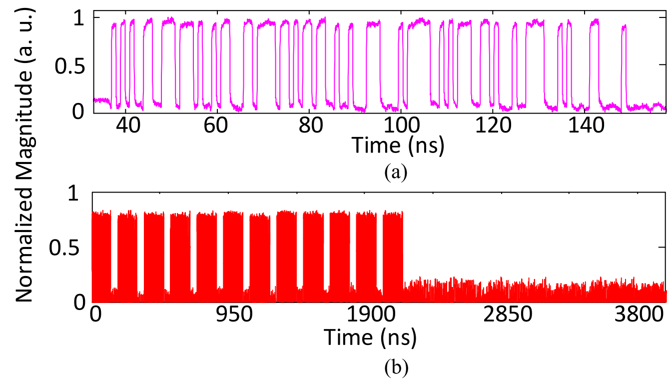

Fig. 6. Experimental results showing data erasing in the proposed optical buffer. (a) The reversed data sequence used to erase the stored data in the optical buffer. (b) Data erasing is observed when the reversed sequence is synchronized with the pulse train in the optical buffer and modulated on the optical wave from TLS2.

round trips, the SNR will become too low and the signal may not be detected correctly. In Fig. 4(b), it can be seen that the buffering interval is 172 ns which is determined by the length of the optical delay line. Fig. 4(c) shows one of the buffered pulse sequences which carries the same data as those in the input optical signal. However, each buffered signal bit is a triggered self-pulsation pulse which has a fixed pulse shape determined by the self-pulsation instead of the input signal. This unique operation principle of an optical buffer based on self-pulsation limits its application in maintaining data format but enables new applications such as data recovery.

Since the self-pulsation has a fixed pulse shape, it can be used for data recovery. For a bit sequence where the amplitude of the bits is not evenly distributed, as shown in Fig. 5(a), the proposed system will also perform single-pass healing by restoring and self-adjusting the received bits to a fixed amplitude, as shown in Fig. 5(b). By using such an optical buffer, the bit error rate (BER) performance can be improved. In the experiment, a distorted signal as shown in Fig. 5(a) is modulated on an optical carrier and transmitted over a 25-km optical fiber with a BER of 7×10^{-3} at the receiver measured by a bit error rate tester (BERT, Agilent N4901B). By using the proposed optical buffer, an error free transmission (BER $< 10^{-13}$) of the recovered signal over the same optical fiber has been achieved. Therefore, the proposed optical buffer is insensitive (in a certain range) to the exact shape or amplitude of the addressing signal.

To demonstrate the data erasing functionality, a reversed data sequence, as shown in Fig. 6(a), which is synchronized with the pulse train in the optical buffer, is modulated on the light wave from TLS2 to reset the data in the optical buffer [20]. As shown in Fig. 6(b), the stored data in the optical buffer is erased. For the above mentioned operations of optical buffering, self-healing, and data erasing, the ring resonator is working under the same conditions with the injection currents given in Table I. An experiment to validate the wavelength tunability of the proposed optical buffer is also implemented. By changing the injection current of the PM in the ring, the notch location of the FSR is tuned as shown in Fig. 7(a), which enables the wavelength tunability of the optical buffer. For example, the optical buffering is validated when the wavelength of TLS2 is tuned to 1558.95 nm, 1559.0 nm, and 1559.05 nm as shown in Fig. 7(b), (c) and (d).

TABLE I
INJECTION CURRENTS OF THE SOAS AND THE PMS

Component	Injection Current	Gain
SOA1	24.904 mA	∼3.6 dB
SOA2	24.952 mA	∼3.6 dB
SOA3	19.583 mA	∼1.1 dB
SOA4	19.654 mA	∼1.1 dB
PM1	0.133 mA	N/A
PM2	0	N/A
PM3	1.325 mA	N/A

In the experiment, a 1-Gb/s 2^7-1 PRBS data sequence is successfully buffered in the proposed optical buffer, which is the fastest optical buffer ever reported based on self-pulsation in a microring resonator. The highest speed is limited by the speed of self-pulsation in the ring resonator, which sets the upper speed limit of writing two consecutive bits in the buffer. Nevertheless, microring resonators based on materials with a shorter free carrier lifetime can provide a higher speed [15], which opens up the possibility of even higher bit rates. The total power consumption of the microring resonator is 173 mW including 99 mW by the input/output SOAs (SOA1 and SOA2), which can be avoided in an integrated system where all units can be fabricated on a single chip; thus the fiber coupling loss for a ring resonator is eliminated. In this case, the total power consumption for such a ring resonator can be reduced to below 70 mW. For real applications, a single SOA in a ring resonator is enough to compensate for the total roundtrip loss. As a result, the total power consumption can be further reduced. In addition, the optical delay line can also be integrated in the chip [5], which can further reduce the foot print of the proposed optical buffer.

The ultrahigh-Q ring resonator can also be implemented in other material systems such as a SOI platform with III-V SOAs either bonded or grown on the silicon substrate to provide the required optical gains [21]. The silicon platform can provide more compact waveguide structures as compared with the

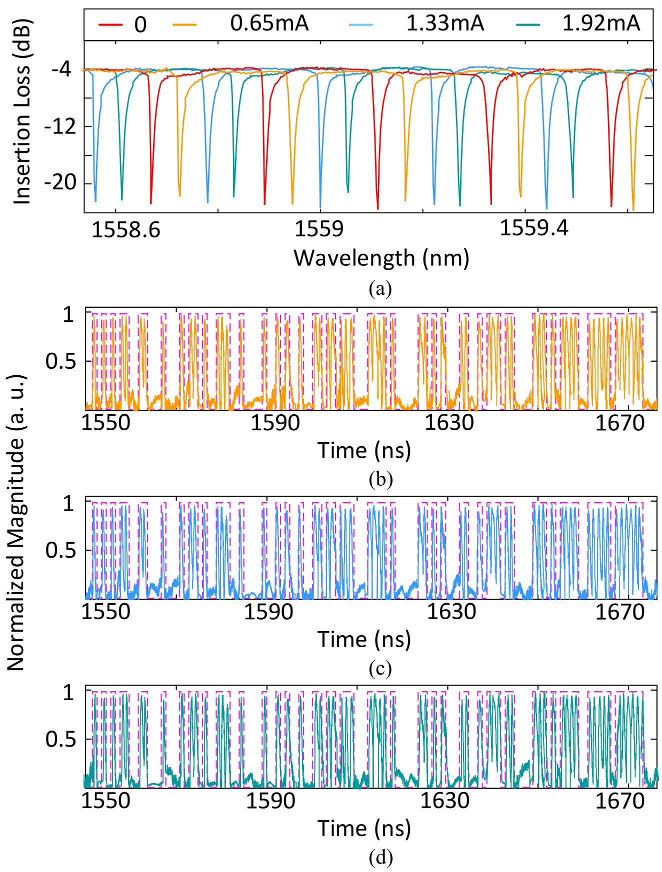

Fig. 7. Experimental results. (a) Tunable resonance wavelength of the microring resonator when different injection currents are applied to PM1. The solid line represents the data sequence in the optical buffer when the wavelength of TLS2 is tuned to (b) 1558.95 nm, (c) 1559.0 nm, and (d) 1559.05 nm, in which the injection currents applied to PM1 are 0.65 mA, 1.33 mA, and 1.92 mA, respectively. The dashed line represents the data used to generate the 2^7-1 PRBS.

III–V material system due to the large refractive index contrast between silicon and silica, which leads to a smaller foot print.

IV. Conclusion

We have proposed and experimentally demonstrated a novel wavelength tunable optical buffer based on self-pulsation in an active microring resonator that functions as a nonlinear node in the buffering system to enable writing, restoring, reshaping and regeneration (after a delay line) of stored bits of information. The key component in the proposed optical buffer is the active microring resonator. Since four SOAs were incorporated, the insertion losses can be effectively compensated, which ensures an ultrahigh Q factor to make the self-pulsation to be easily started. In addition, a PM was also incorporated in the ring resonator and by adjusting the injection current to the PM, the FSR of the ring resonator is laterally shifted, which was used to adjust a resonance wavelength close to the wavelength of the input optical signal, thus ensuring wavelength tunable optical buffering. The proposed microring resonator was fabricated in an InP–InGaAsP material system. The incorporation of the fabricated microring resonator in the proposed optical buffer was experimentally evaluated. By applying a 1-Gb/s optical data sequence to the system, optical buffering of the sequence was experimentally demonstrated. This is, to the best of our knowledge, the fastest self-pulsation optical buffer ever reported to date. In addition, the use of the buffer system to perform data recovery and data erasing was also demonstrated. The proposed wavelength tunable optical buffer suggests high potential for fast optical storage and data healing in optical communications.

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