Continuously Tunable, Wavelength-Selective Buffering in Optical Packet Switching Networks

Jie Yang, Nicolas K. Fontaine, Zhong Pan, Aytug O. Karalar, Stevan S. Djordjevic, Chunxin Yang, Wei Chen, Sai Chu, Brent E. Little, Fellow, IEEE, and S. J. B. Yoo

Abstract—This letter investigates system performance of slow-light variable optical buffer based on cascaded stages of tunable silica microresonator rings. Continuous tunability is achieved by adjusting the resonance of each ring on the compact photonic integrated circuit. The all-pass configuration allows selectively applying variable delays to wavelengths of choice without losing any packets in an optical packet switching network.

Index Terms—All-pass filters, optical packet switching (OPS), ring resonators, slow light, variable optical buffer.

I. INTRODUCTION

VARIABLE optical buffers capable of controllably delaying optical packets without converting to electrical signals can significantly benefit the development of future all-optical networking systems. Compared to the conventional store-and-forward packet switching schemes, optical-label switching (OLS) router architecture employs pipelined optical packet switching (OPS) with all-optical contention resolution in wavelength, time, and space domains [1]. In addition to limited fixed delays, even a small amount of variable buffering can greatly improve the throughput in such OLS routers [2]. Utilizing variable optical buffers with microring resonators in all-pass configuration enables us to apply the desired amount of delay to desired packets on a specific wavelength channel as necessary, while leaving packets on other wavelength channels unaffected. Fig. 1(a) shows an example of such variable buffers in the input queue of a switching fabric, and Fig. 1(b) shows an example in an output queue [2]. The former provides queuing for all packets arriving on a specific input wavelength port, whereas the latter offers selective wavelength-aware buffering without causing any head-of-line blocking.

This letter discusses experimental studies of variable slow-light optical buffers (VOBs) realized by integrating cascaded thermally tunable ring resonator stages. This technique offers more flexibility and controllability than static buffering approaches, such as the scheme demonstrated in [3] on a Si platform, and more scalability than continuous delays implemented in a complex switching structure [4]. An alternative scheme that utilizes quantum mechanical adiabatic transition has been reported on a Si platform [5].

II. THEORETICAL DESIGN

Fig. 1(c) illustrates the all-pass VOB structure. The essential building block of the VOB is a microresonator ring coupled to the bus waveguide. As the multiwavelength optical signals pass through each ring, selected wavelength signals resonate with the ring while other wavelength signals stay on the main bus waveguide. Optical signals at resonance will experience a longer group delay compared to signals off-resonance. For a given free-spectral range, the power coupling coefficient between the ring and bus waveguides ($k$) determines the width and strength of the resonance and the phase shift ($\phi$) determines the location of the resonance. Fig. 1(d) shows simulated transmission spectra for three $k$ values when $\phi = 0$. The waveguide coupling designs and thermooptic phase shifts have been applied to achieve the desired spectral width and resonance frequency for each ring. Multiple stages of such rings need to be cascaded to achieve relatively flat group delay values across the signal modulation bandwidths of interest. There is a tradeoff between the amount of delay and bandwidth of the cascaded ring structure as the delay bandwidth product (DBP) is constant.

Fig. 1(d) illustrates this effect. Bringing the resonance frequencies of each ring close together enhances the delay, at the
expense of the bandwidth. Fig. 2(e) shows the 8-ring VOB (DBP of 4) design for 2.5-GHz-wide flat delay of 2 ns. The 32-ring VOB design shown in Fig. 2(a) only realizes a delay of 450 ps, but the much wider bandwidth (40 GHz) potentially allows it to support optical signals at a higher bit rate (DBP of 18). To minimize the distortion introduced, the delay must be uniform across the entire signal bandwidth. Meanwhile, a high extinction ratio at the edge of the delay bandwidth and nondelay bandwidth is crucial for wavelength-selective buffering. Fig. 2(a) and (e) illustrates 32-ring and 8-ring structures designed with proper power coupling coefficient (κ) and resonant wavelength of each ring to achieve uniform group delays across 40- and 2.5-GHz bandwidths, respectively.

Table I shows the design parameters of the 8-ring structure. The VOB structures are fabricated by using the proprietary Hydex material with 17% refractive index contrast and 0.15-dB/cm loss [6] to precisely achieve the designed κ values by defining the width and the length of the gap between the ring and the bus waveguide. The difference between the observed group delay responses (Fig. 2(b) and (f), red) and the simulated results (Fig. 2(b) and (f), black) is less than 30 ps for the 8-ring VOB and less than 120 ps for the 32-ring VOB over the entire spectrum, indicating a precise match between the fabricated and designed power coupling coefficients (κ).

Proper adjustments on the resonance frequency of each stage of the fabricated VOB can provide continuously tunable delay. Both VOB devices are calibrated using the feedback from measurements of the complex transmission, power transmission and group delay, by an optical vector network analyzer [7] capable of resolving narrow ring resonances with greater than 10-ps group delay resolution.

In OPS networks with cascaded optical routers, noise accumulations, and signal degradations are important considerations. It is thus imperative that variable optical delays can be provided with as little signal distortions as possible. In this demonstration, a 10-Gb/s ON–OFF keying (OOK) amplitude modulated signal is used for testing the 32-ring VOB, and 1.25-Gb/s OOK modulation is used for the 8-ring VOB. Pattern distortion will arise if variations in group delay and nonuniform loss exist within the data modulation bandwidth [8]. The calibration process optimizes the transfer characteristics of the VOBs for high delay and flat passband (minimum ripple). Fig. 2(b)–(d) shows the flattened group delay and transmission across 40 GHz preserving signal integrity for up to a 20-Gb/s OOK signal, at the maximum (357 ps), medium (117 ps), and minimum (0 ps) delay setting with 0-GHz offset frequency for the 32-ring VOB, respectively. The fiber-to-fiber insertion loss is less than 7 dB in all settings, with ripple less than 1.5 dB. Fig. 2(f)–(h) shows the 8-ring VOB delay spectra at the maximum (2483 ps), medium (1006 ps), and minimum (0 ps) delay setting at 0-GHz offset frequency, respectively. The maximum fiber-to-fiber insertion loss of 3 dB is observed when achieving the maximum delay on A₁. Note that the optical signal at wavelength λ₂ is outside the delay bandwidth and will, therefore, not experience any delay or loss. The 8-ring VOB is designed to have narrow (∼2.5 GHz) and strong resonances to enhance the delay. Therefore, it suffers more loss and is less uniform than the 32-ring VOB. The thermal tuning to properly positioning all 8 rings for the maximum delay, however, is relatively difficult. The signal bandwidth for delay of the 8-ring VOB is 2 GHz at the 2483-ps setting, 4 GHz at the 1006-ps setting, and >35 GHz at the <10-ps setting, allowing the 1.25-Gb/s OOK signal to be variably buffered with little distortion. Delay-bandwidth products of 4 for the 8-ring structure and 15 for the 32-ring structure have been achieved, scaling approximately linearly with the number of rings.

III. RESULTS AND DISCUSSION

The OPS testbed utilizes a transmitter consisting of a tunable laser modulated by a LiNbO₃ modulator driven with an amplified electrical 10-Gb/s data stream with 2⁷–1 pseudorandom bit sequence (PRBS) from a pattern generator. Before the bit-error rate (BER) tester, a 10-Gb/s receiver is used in conjunction with either a 7.53-GHz filter for 10-Gb/s experiment or a 0.997-GHz filter for 1.25-Gb/s experiment. Experiments were designed for short packet switching and the longer PRBS sequence experiments are currently in progress. Since the measured delay across
Fig. 3. Delay patterns at (a) 10 Gb/s using the 32-ring VOB; and (b) 1.25 Gb/s for in-band wavelength and out-of-band wavelength using 8-ring VOB.

Fig. 4. (a) BER measurements and eye diagrams for 32-ring VOB at 10 Gb/s. (b) BER measurements and eye diagrams for 8-ring VOB at 1.25 Gb/s.

the bandwidth is flat, similar results can be expected when using a longer PRBS.

Fig. 3(a) and (b) shows continuous delays with minimal attenuation and pattern distortion provided by both VOBs. Longer delay brings in more signal degradation primarily because more loss and spectral filtering are introduced. The VOB can be tuned to provide continuous delay to data at one specific wavelength while not affecting data at other wavelengths. Fig. 3(b) shows the delayed patterns for a wavelength that experiences delay (λ1) and a wavelength that experiences no delay (λ2).

Fig. 4(a) and (b) shows the eye diagram and BER measurement results. All BER curves reach below $10^{-11}$ for 1.25-Gb/s signals and below $10^{-12}$ for 10 Gb/s, indicating error-free operation. Distortion of the signal is caused only by nonuniformity in the frequency domain. Since the measured delay across the bandwidth is flat, similar results can be expected when using a longer PRBS. The optical eye diagrams show little jitter with a clear opening. Due to the low loss nature of the all-pass structure, less than 0.5-dB power penalty is introduced by each device in all cases except for the 2483 setting of the 8-ring VOB. Severe distortions occur as we push the delay limit of the 8-ring VOB by overlapping the resonance frequency at a narrow bandwidth, primarily due to the sensitive wavelength tolerance. Achieving a uniform delay across 2.5 GHz is extremely challenging, and approximately 2.1-dB power penalty is observed in this case. Cascading multiple stages of devices, such as the 32-ring VOB, can increase the DBP, which allow us to obtain the desired long delay without pushing the bandwidth to its limit; therefore, less total distortion is introduced. The experimental results indicate continuous delays up to 357 ps with 40-GHz bandwidth for a 32-ring structure and continuous delays up to 2483 ps for an 8-ring structure VOB on the desired wavelength, while transmitting packets on other wavelengths without any delay.

IV. SUMMARY AND FUTURE WORK

This letter demonstrates wavelength-selective, variable optical buffering based on silica microresonator ring devices. Error-free operation has been achieved for up to 2483-ps delay using the 8-ring device at 1.25 Gb/s, and up to 357-ps delay using the 32-ring device at 10 Gb/s. Tradeoffs between delay, bandwidth, power loss, and signal quality have also been experimentally investigated. The silica structure tunes to its limit; therefore, less total distortion is introduced. The optical eye diagrams show little jitter with a clear opening. Due to the low loss nature of the all-pass structure, less than 0.5-dB power penalty is introduced by each device in all cases except for the 2483 setting of the 8-ring VOB. Severe distortions occur as we push the delay limit of the 8-ring VOB by overlapping the resonance frequency at a narrow bandwidth, primarily due to the sensitive wavelength tolerance. Achieving a uniform delay across 2.5 GHz is extremely challenging, and approximately 2.1-dB power penalty is observed in this case. Cascading multiple stages of devices, such as the 32-ring VOB, can increase the DBP, which allow us to obtain the desired long delay without pushing the bandwidth to its limit; therefore, less total distortion is introduced. The experimental results indicate continuous delays up to 357 ps with 40-GHz bandwidth for a 32-ring structure and continuous delays up to 2483 ps for an 8-ring structure VOB on the desired wavelength, while transmitting packets on other wavelengths without any delay.

REFERENCES