10-Gb/s Wavelength Transparent Optically Controlled Buffer Using Photonic-Crystal-Fiber-Based Nonlinear Optical Loop Mirror

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***Abstract*—We have proposed and experimentally demonstrated a 10-Gb/s optically controlled buffer using a photonic-crystal-fiber (PCF)-based nonlinear optical loop mirror for all-optical packet-switched networks. The 10-Gb/s data can be stored in the buffer up to a period of 2.5 μs. By using the cross-phase modulation property between the control signal and the data signal inside the PCF, the total length of the fiber used in the buffer can be shortened to 30.9 m. The stored data packets are retrieved after they are stored in the memory for $2, 4, \ldots,$ and 12 round-trips. Independent bit-error-rate (BER) measurements have been carried out. The maximum power penalty is 3.3 dB at 1550 nm. The proposed buffer is wavelength transparent. For data packets stored in the C-band, the maximum power penalty after the data are stored in the memory for 12 round-trips is 3.5 dB at the BER of 10^{-9}.**

***Index Terms*—All-optical devices, all-optical packet switching, fiber, nonlinear optics, optical communications, optical memories.**

I. Introduction

All-optical packet switching eliminates the need for optical–electrical–optical conversion and are ideal for high speed networks of the future. Optical buffer is a key element in all-optical packet-switched networks as it can resolve the packet contention problem. Since the photon has zero rest mass, light must keep traveling in the storage medium. Two types of optical buffers have been proposed and demonstrated: the slow-light type [1], [2] and the fiber-loop type [3]–[6]. The former can reduce the group velocity of light to the range of 10 m/s [2]. However, coupling of the processed light with optical fiber is difficult. The latter can be further divided into semiconductor optical amplifier (SOA) assisted and non-SOA assisted fiber loops. For the non-SOA assisted fiber-loop type, the storage time can be up to 1 ms but the setup is bulky because typically at least several kilometer length fibers are required for the fiber loop [4], [5]. The SOA assisted fiber-loop can be quite compact but the data rate is limited [6]. In this letter, we propose and demonstrate an optically controlled buffer using a photonic-crystal-fiber (PCF)-based nonlinear optical loop mirror (NOLM). The data rate is 10 Gb/s which, to the best of our knowledge, is the fastest among both SOA-based and non-SOA-based fiber-loop buffers. The total loop length used is 30.9 m which is a reasonable compact size for integration. The data can be stored in the buffer up to 2.5 μs. By using a dispersion flattened PCF, the proposed optically controlled buffer is wavelength transparent in the entire C-band [7].

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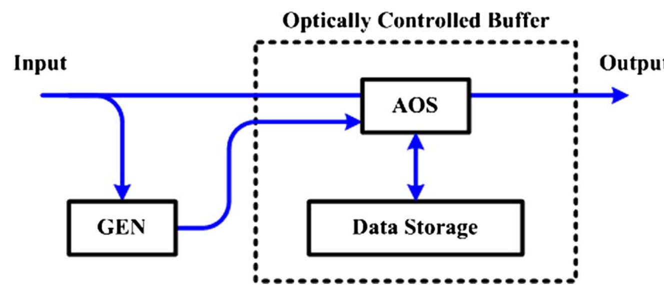

Fig. 1. Schematic of the architecture of the proposed optically controlled buffer. The optically controlled buffer is shown in dotted box.

II. Operation Principle

Fig. 1 shows the schematic of the architecture of the proposed optically controlled buffer using the PCF-based NOLM. The proposed buffer is comprised of one all-optical switch (AOS) and data storage. When an incoming data packet at wavelength λ_d enters the input port, a copy of the data packet is sent into the control packet generator (GEN). The GEN can be constructed by using a Fabry–Pérot laser diode [8]. Depending on the address header of the data packet, the GEN will generate a control packet at wavelength λ_c which will then set the state of AOS to "load." The data packet then goes into the storage instead of the output port. The data packet will keep going around the data storage and the AOS as long as another control packet is not present. If another control packet enters AOS, the state of AOS will be set as "read." The data packet will then leave the data storage and exit through the output port. We use cross-phase

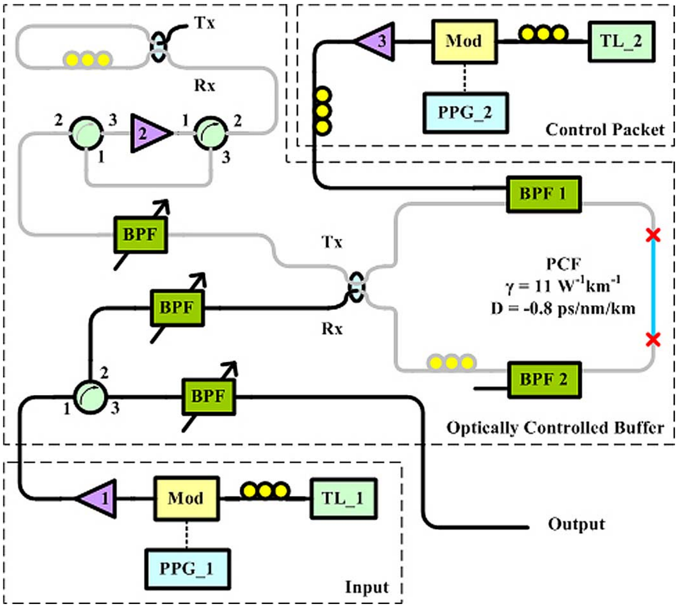

Fig. 2. Experimental setup of the proposed optically controlled buffer using PCF-based NOLM.The gray line represents the 30.9-m-long storage propagation path.

modulation (XPM) in a PCF-based NOLM to implement the AOS. When a data packet enters the input port of the NOLM, it is divided into two signals which counterpropagate through the loop. If a control packet is not present, the data signal will exit the input port by interference at the coupler. If a control packet is present, XPM occurs between the control signal and one branch of the data signal. If the control signal power P_c is large enough, a π phase difference will exist between the counterpropagating signals at the coupler. The relationship between the switched output power P_o, the data signal power P_s, and the phase difference induced $2\gamma P_c L$ is given by [9]

$$P_o = \frac{1}{2} P_s [1 - \cos(2\gamma P_c L)] \qquad (1)$$

where γ is the nonlinear coefficient and L is the interaction length. The data signal will exit through the output port if $2\gamma P_c L = \pi$. The data storage is implemented by an amplifier and a simple optical loop mirror. The amplifier is used to compensate for the propagation loss. The mirror is used to reflect the data packet to the AOS.

III. Experimental Results

Fig. 2 shows the experimental setup of the optically controlled buffer using PCF-based NOLM. The data packets at 1549.48 nm (λ_d) are generated by externally modulating a tunable laser (TL_1) using a 10-Gb/s nonreturn-to-zero (NRZ) pulse pattern generator and a 10-Gb/s $LiNbO_3$ modulator. A 32-bit pseudorandom binary sequence data packet with pattern "1011010111010011 0101011110110100" is generated. Each packet is separated by 32 736 ZERO bits for a guard period of 3.27 μs. The data is amplified by a 13-dB erbium-doped fiber amplifier (EDFA) and filtered by a 1-nm bandpass filter (BPF) before entering into the PCF-based NOLM. A circulator is used between the EDFA and BPF where Port 3 acts as the output port. The PCF-based NOLM is composed of 20.3-m-long PCF and 1.3 m of single-mode fiber (SMF), two reflective BPFs, and a polarization controller (PC). The PCF used in this experiment has a refractive index of 1.7, a nonlinear coefficient of 11 $W^{-1} \cdot km^{-1}$, and a dispersion coefficient of -0.8 ps/nm/km with variations less than 0.05 ps/nm/km over C-band. The total power loss of the PCF used is 2.1 dB. The center wavelengths of the reflective BPFs 1 and 2 are 1557.03 and 1557.11 nm, respectively. The PC in the loop is adjusted such that all of the power of data signal is reflected back to the output port when there is no control signal. The ratio of the reflected and

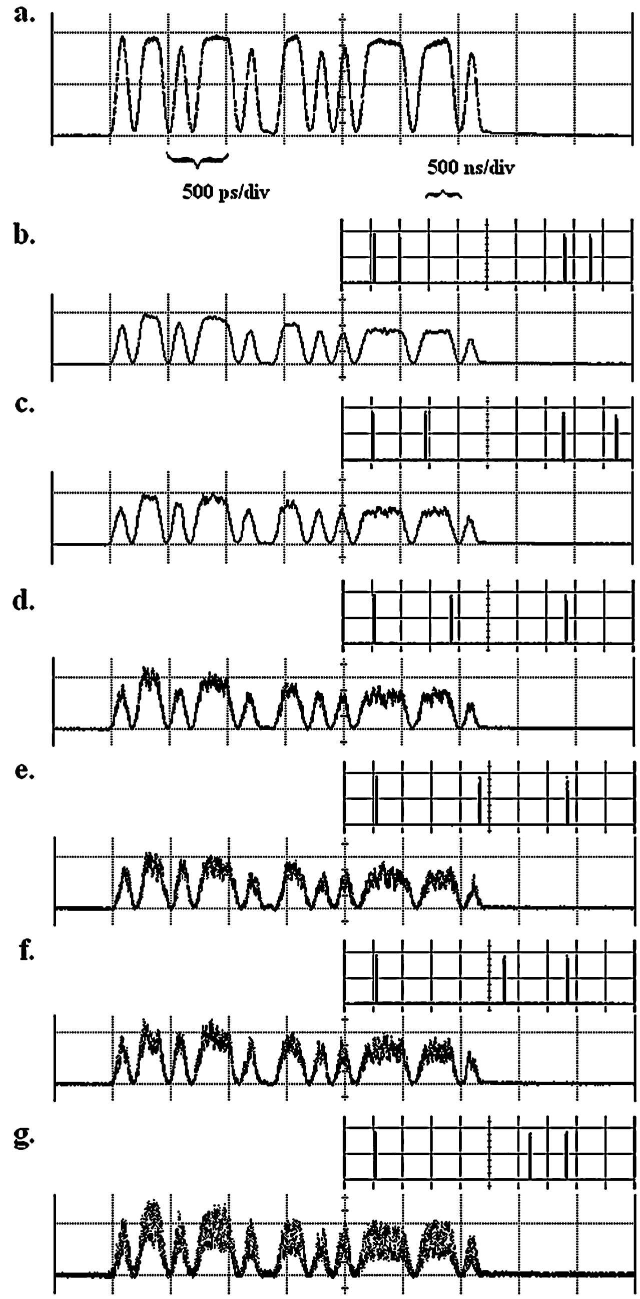

Fig. 3. Synchronized timing diagrams of the optically controlled buffer: (a) the input datapackets at input; the read out after (b) two round-trips; (c) four round-trips; (d) six round-trips; (e) eight round-trips; (f) ten round-trips; and (g) 12 round-trips. The time scale and vertical scale are 500 ps/div and 20 mV/div, resepectively. The inset is the corresponding control packet for that output with a time scale of 500 ns/div and a vertical scale of 100 mV/div.

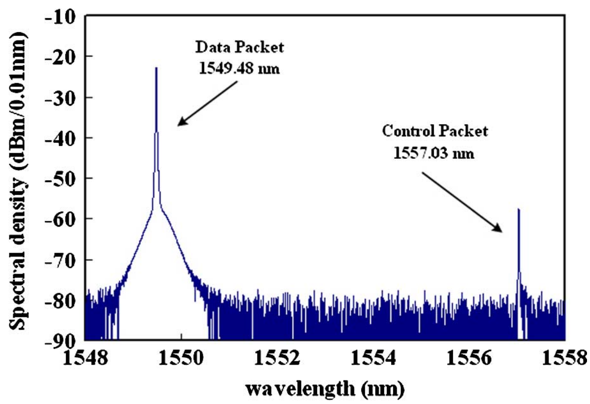

Fig. 4. Spectrum at the output port.

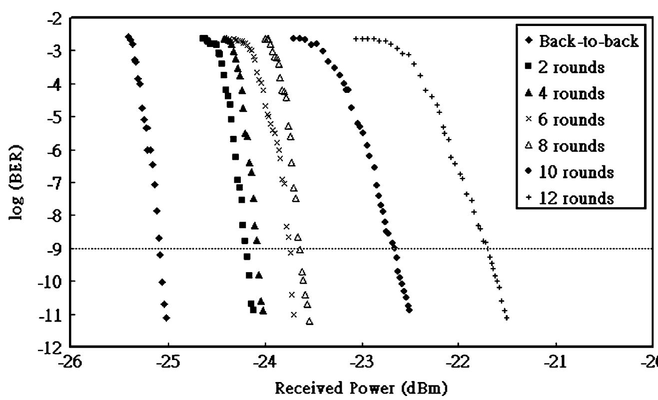

Fig. 5. BER measurements for $2, 4, \ldots,$ and 12 round-trip output of the optical buffer.

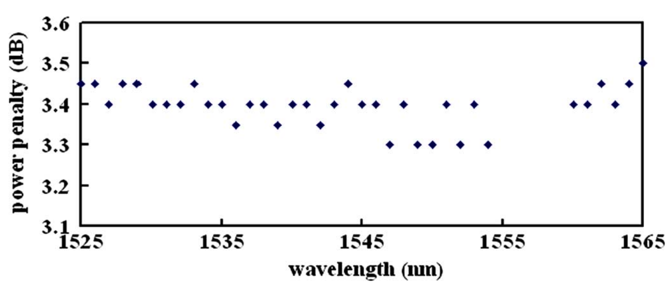

Fig. 6. Power penalty at BER of 10^{-9} for 12 round-trips over the C-band.

transmitted power is 30 dB. The control signal at 1557.03 nm (λ_c) is generated by externally modulating another tunable laser TL_2 using a 10-Gb/s NRZ pulse pattern generator and a 2.5-Gb/s $LiNbO_3$ modulator. A consecutive 32 bits of ONE is generated which is then followed by a guard period 3.27 μs. The control signal is then amplified by a high-power EDFA with maximum output power of 27 dBm. The average and the peak power of the amplified control signal are 25.5 and 38.5 dBm, respectively. The control packet is synchronized electrically with the data packet before entering into the PCF. The total power loss in the PCF-based NOLM is 4.8 dB which is compensated by the amplifier EDFA_2. A simple optical loop mirror made of 1.4 m of SMF is connected after the EDFA_2. The polarization state of the PC in the loop is tuned such that all of power is reflected. Two circulators are used before and after EDFA_2 to complete the path. The data signal circulated in the buffer in this path until another control packet switches it out of the buffer. Since the fiber connecting the two loop mirrors has a length of 7.9 m, one round-trip in the buffer consists of 20.3 m of PCF and 18.5 m of SMF which corresponds a round-trip time of ~208 ns. Experimentally, we measured round-trip time to be ~212 ns. To read the data from the buffer, another consecutive 32 bits of ONE control packet is generated after $k \times 212$ ns, where $k = 2, 4, \ldots, 12$ is the number of round-trips in the buffer. Fig. 3(a) shows the synchronized timing diagrams of the input data packets at input. Fig. 3(b)–(g) shows the synchronized timing diagrams of the signals at the optical buffer after $2, 4, \ldots,$ and 12 round-trips, respectively. The insets are the corresponding control packets for the output in the time scale of 500 ns/div. Fig. 4 shows the wavelength spectrum at output port. Fig. 5 shows bit-error-rate (BER) measurement for the data with a period of 32 768 bits at the output port after $2, 4, \ldots,$ and 12 round-trips. The power penalty at BER of 10^{-9} is 3.3 dB after the data packet is stored in the buffer for 2.5 μs. Fig. 6 shows the power penalty at BER of 10^{-9} after 12 round-trips in the buffer over the C-band.

IV. Conclusion and Discussion

We have successfully demonstrated a 10-Gb/s optically controlled buffer using a PCF-based NOLM with a total of 30.9-m-long fiber. The 10-Gb/s data can be stored into the buffer up to a period of 2.5 μs. The storage time is limited by the ASE noise accumulated in each round-trip from the EDFA_2 which is used to compensate for the power loss in the PCF. The proposed buffer is wavelength transparent over the C-band. Since the proposed optical buffer is fiber-based, it can operate at a bit-rate beyond 10 Gb/s. Due to the use of a short length of PCF, integration is possible.

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