All-optical buffer using nonlinear polarization rotation effect of gain-transparent semiconductor optical amplifier

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A cascaded all-optical buffer with large dynamic delay based on polarization rotation of a gain-transparent semiconductor optical amplifier is proposed and demonstrated. The analysis and experimental results indicate that the pulse distortion and pattern effect can be fully improved, and the amplified spontaneous emission noise accumulation can be inhibited effectively as well; the data packets are stored for six round-trips in buffering units 1 and 2, respectively, corresponding to a delay time as long as 33 μs. The proposed buffering scheme can be regarded as an effective reference to the study work of all-optical buffer.

OCIS codes: (060.1810) Buffers, couplers, routers, switches, and multiplexers; (260.5430) Polarization; (250.5980) Semiconductor optical amplifiers; (060.1155) All-optical networks.

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1. Introduction

With the development of new technologies in optical transmission and their applications in optical fiber networks, the transmission capacity of telecommunication networks has increased dramatically in the past few decades, while the switching capacity becomes a bottleneck to the advantages offered by optical fibers. All-optical packet switching (OPS) is considered as a potential technique to break through this switching obstacle, and all-optical buffers are the crucial devices in the OPS network because they possess the ability to prevent collision thanks to their special functionalities of storing and forwarding data packets in the optical format without converting into electrical. Usually, a fiber-type all-optical buffer consists of fiber loops and optical switches and the delay time is determined by the length of the fiber loop and the recirculating times of the packet propagating in the fiber loop. At present, the recirculating times are usually controlled by ON/OFF actions of a semiconductor optical amplifier (SOA). In [1,2], a cascaded recirculating buffer was proposed and a variable delay from 0 to 9999T was demonstrated experimentally, and the reading or writing was implemented by changing the signal light's phase by means of SOA's cross-phase modulation (XPM). References [3,4] confirmed the possibility of delaying multichannel data packets in a double-loop optical buffer with a SOA as the nonlinear phase-shift element. A fiber-loop optical buffer based on an electrically controlled nonlinear polarization rotation switch of conventional SOA was put forward in [5], in which more than 75 different buffering times were achieved in the three-stage-cascaded buffer. A recirculating buffer with SOA's nonlinear polarization rotation as the wavelength converter was given in [6], and the collision of two packets contending one port was resolved in the experimental system. However, in the mentioned fiber-loop optical buffers, the pulse shape in the output bit stream suffered from serious

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distortions due to SOA's nonlinear gain and cross-gain modulation (XGM). The channel crosstalk is also inevitable if the packets are carried on different wavelengths. The situation becomes worse when a large dynamic delay is carried out. Because in the course of the buffer, the optical packets generally pass through a concatenation of SOAs or one SOA many times, the amplified spontaneous emission (ASE) noise from the amplifier(s) will accumulate and substantially degrade the signals, which eventually limits the maximum number of circulations, or the buffering time.

To cope with the above situations, in this paper, an innovative all-optical buffer is proposed, in which nonlinear polarization rotation of the gain-transparent SOA (GT-SOA) is utilized to realize the all-optical switch. By replacing the conventional SOA with the GT-SOA, pulse distortion and pattern effect can be eliminated. Signal-to-noise ratio (SNR) deterioration and extinction ratio (ER) degradation from ASE noise accumulation can also be reduced effectively, and channel crosstalk can be overcome clearly. As the GT-SOA exhibits excellent modulating behavior, it is promising for usage in all-optical wavelength conversion from 1310 to 1550 nm [7], format conversion of OOK-to-BPSK [8], or of OOK-to-QPSK [9]. In this paper, for the first time, to the best of our knowledge, GT-SOA's nonlinear polarization rotation as the all-optical switch is used in an all-optical buffer. Although the output power of the signal light is severely attenuated due to the SOA's structural and material factors, the proposed optical buffering scheme will be a selectable solution for all-optical buffers if these drawbacks are solved in the future.

2. Principle and Configuration

When an incident signal beam at 1550 nm and a control beam at 1310 nm are simultaneously injected into the active region of a SOA with the ASE spectrum in a 1.3 μm window, the signal beam will experience no gain since its photon energy is lower than the SOA's band-gap energy. The refraction index of SOA's active region will change with the carrier density modulated by the intensity of control light. This means that the signal beam experiences phase modulation due to the refraction index change. This phase change can be used to design an all-optical switch.

The proposed all-optical buffer based on the polarization rotation switch of GT-SOA is shown in Fig. 1,

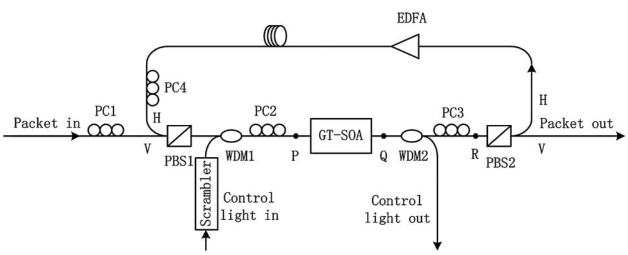

Fig. 1. Basic structure of the all-optical buffer.

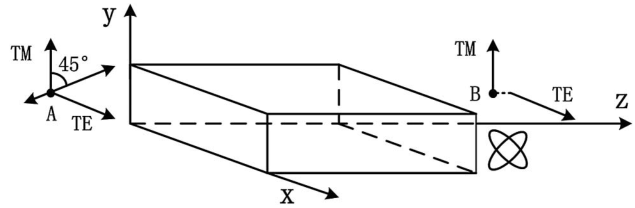

Fig. 2. Reference coordinate system of GT-SOA.

where the delay loop is composed of a GT-SOA, two polarizing beam splitters (PBSs), and an erbium-doped fiber amplifier (EDFA), a length of fiber delay line (FDL), a scrambler, and several polarization controllers (PCs). The signal beam (carrying data packet) inputting from the V port of PBS1 is ensured to be a linear polarization state along the V direction by adjusting PC1. PC2 changes its electrical field direction in point P to be 45° with the x and y axes of the SOA (shown in Fig. 2). The polarization vector is given by

$$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ 1 \end{bmatrix}. \tag{1}$$

The signal beam can be decomposed into transverse electric (TE) mode and transverse magnetic (TM) mode. The two perpendicular modes propagate independently from each other in the SOA. If the optical packet is not required to be delayed in the fiber loop, a hold beam at 1310 nm is injected into the SOA from the 1310 port of WDM1. TE and TM components pick up the different gains and different phases. Therefore the output optical field in point Q is usually elliptical polarization (state 1), which can be expressed as

$$\frac{1}{\sqrt{2}}\begin{bmatrix} g^{\mathrm{TE}} e^{j\phi_{01}^{\mathrm{TE}}} \\ g^{\mathrm{TM}} e^{j\phi_{01}^{\mathrm{TM}}} \end{bmatrix} = \frac{e^{j\phi_{01}^{\mathrm{TE}}}}{\sqrt{2}}\begin{bmatrix} g^{\mathrm{TE}} \\ g^{\mathrm{TM}} e^{j\Delta\phi_1} \end{bmatrix}, \tag{2}$$

where g^{TE} and g^{TM} are the linear gains, ϕ_{01}^{TE} and ϕ_{01}^{TM} are the phase shifts of TE and TM modes, and their phase difference is $\Delta\phi_1 = \phi_{01}^{\mathrm{TM}} - \phi_{01}^{\mathrm{TE}}$. In the GT-SOA, g^{TE} and g^{TM} are approximately equal (demonstrated in the following testing); they can be represented by g. By adjusting PC3, state 1 in point Q can be changed to a linear polarization state (state 2) in point R, where the electrical vector can be written as

$$e^{j\phi_0}\begin{bmatrix} A \\ B \end{bmatrix}, \tag{3}$$

where A, B are the electrical field intensities in the x and y axes, and ϕ_0 is the common phase. The optical packet in state 2 is assumed to output from the V port of PBS2. The unitary matrix of PC3 (U) can be deduced as [10]

$$U = \frac{\begin{bmatrix} (\alpha_{PC}^{TE} + \alpha_{PC}^{TM})e^{-j\phi_{PC}^{TE}} & (\alpha_{PC}^{TE} - \alpha_{PC}^{TM})e^{-j\phi_{PC}^{TM}} \\ (\alpha_{PC}^{TE} - \alpha_{PC}^{TM})e^{-j\phi_{PC}^{TE}} & -(\alpha_{PC}^{TE} + \alpha_{PC}^{TM})e^{-j\phi_{PC}^{TM}} \end{bmatrix}}{\sqrt{2((\alpha_{PC}^{TE})^2 + (\alpha_{PC}^{TM})^2)}}, \quad (4)$$

where α_{PC}^{TE} and α_{PC}^{TM} represent the loss constants for the TE and TM modes, respectively, and ϕ_{PC}^{TE} and ϕ_{PC}^{TM} are their corresponding phase changes. The equation below must be obeyed:

$$U \frac{1}{\sqrt{2}} \begin{bmatrix} g e^{j\phi_{01}^{TE}} \\ g e^{j\phi_{01}^{TM}} \end{bmatrix} = e^{j\phi_0} \begin{bmatrix} A \\ B \end{bmatrix}. \quad (5)$$

If the optical packet needs to be delayed in the fiber loop, a synchronous optical pulse at 1310 nm will be injected into the SOA. By adjusting the optical pulse intensity, the phase difference of the TE and TM modes could be $\Delta\phi_2 = \phi_{02}^{TM} - \phi_{02}^{TE} = \Delta\phi_1 + \pi$. The optical field in point Q is elliptical polarization (state 3), which can be expressed as

$$\frac{e^{j\phi_{02}^{TE}}}{\sqrt{2}} \begin{bmatrix} g \\ -g e^{j\Delta\phi_1} \end{bmatrix}. \quad (6)$$

It is orthogonal to state 1. Keeping PC3 in the same state, state 3 can be transferred to state 4 in point R:

$$e^{j\phi_2} \begin{bmatrix} -B \\ A \end{bmatrix}. \quad (7)$$

State 4 is orthogonal to state 2. Hence the optical packet in state 4 will output from the H port of PBS2 and propagate along the fiber loop. After being amplified and delayed by the packet passing through PBS1 and PC2, at point P, the linear polarization in the H direction will be transformed to the direction of −45° to the x axis. Keeping the hold beam in the SOA, the Jones matrix of the signal light in point Q is

$$\frac{e^{j\phi_{01}^{TE}}}{\sqrt{2}} \begin{bmatrix} g \\ -g e^{j\Delta\phi_1} \end{bmatrix}. \quad (8)$$

This is orthogonal to state 1. After being transferred by PC3, the polarization state at point R is state 4, and the optical packet will appear in the H port of PBS2. As long as the hold beam is kept, the optical packet will propagate along the fiber loop again and again. When the packet is required to be read out, a synchronous optical pulse will be injected, and then the polarization state of the signal light at point Q changes into state 1. After propagating through PC3, the optical packet will output from port V of PBS2.

Considering a four-stage-cascaded configuration, if the delay time for the packet traveling one round-trip in four different buffering units is T, $10T$, $100\,T$, and $1000T$, and the corresponding recirculating times are n_1, n_1, n_3, and n_4, and they are limited to a change from 0 to 9, a large dynamic delay from 0 to $9999T$ can be realized.

3. Testing GT-SOA

In the above analysis, three assumptions must be obeyed: first, gains for both TE and TM modes are equal and do not depend on the control light intensity; second, the polarization state of the control light does not influence the gain and phase of the signal beam; and third, the phase difference of π between the TE and TM modes for the signal beam is realized with an injecting control optical pulse with suitable power. These assumptions can be verified by a testing system shown in Fig. 3. The testing procedure is according to the following steps.

First, the continuous wave (CW) beam at 1550 nm from laser diode 1 (LD1) is injected into GT-SOA with 170 mA current. By adjusting PC1, all the power of the signal beam is output from port H of the PBS. The output power is recorded when changing the power of the input signal beam. Then changing PC1 and letting all the signal light output form port V and recording the corresponding output power, Fig. 4(a) shows the testing results, which indicate that the output power is linear to the input power. The gain for the TE mode is slightly larger than for the TM mode, and the deviation is no more than 0.3 dB, so the gains for TE and TM can be considered to be equal.

Second, a CW control beam at 1310 nm and the signal beam are introduced into the GT-SOA simultaneously, by changing the control light intensity and adjusting PC1, and all the power of the signal light output from port H, measuring the corresponding output power. Then we let the signal light output from port V by the same method as above, recoding the output power. Figure 4(b) shows the testing results, which show that the control light intensity would not influence the gain of the TE or TM mode of the signal beam. Since the cross section of the active region of GT-SOA is rectangular, the gains for TE and TM are affected by the polarization of the control light, and the optical power assigned to the V or H port will vary with the polarization. In order to eliminate the affect of the polarization of the control light, a polarization scrambler is introduced in the proposed buffer. After passing through the scrambler, the electric vector of the control light distributes evenly in the cross section of the active region. The uneven gain caused by the polarization of control light can be eliminated.

Third, changing the driving current of the SOA, adjusting PC1 to let all the signal light output from

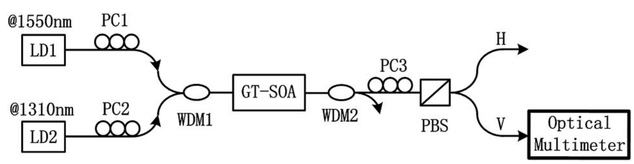

Fig. 3. GT-SOA testing system.

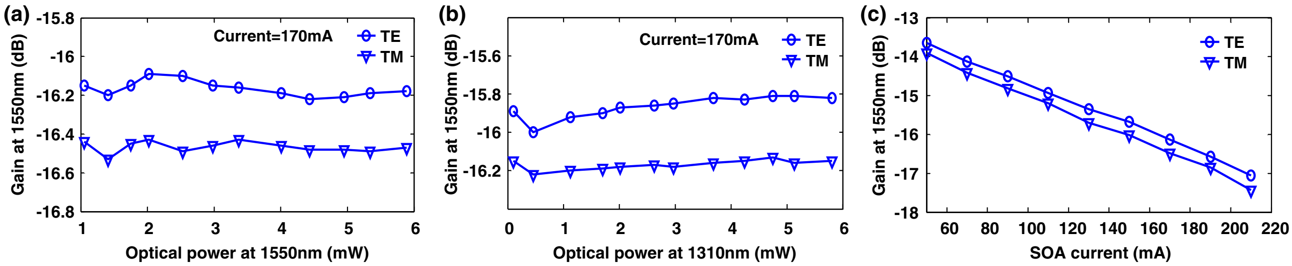

Fig. 4. Gain curves of the signal lights' relationships with (a) signal lights' power, (b) control light power, and (c) bias current in the SOA.

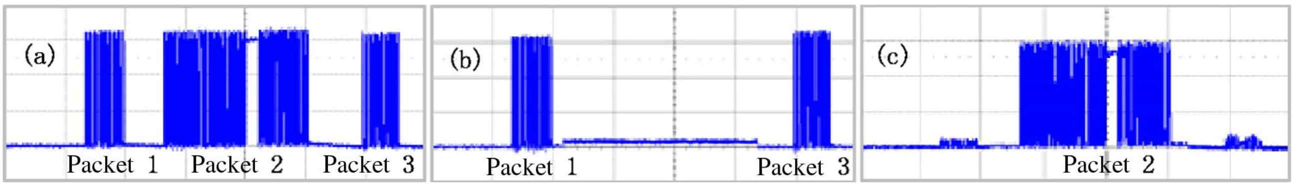

Fig. 5. Testing results of the polarization rotation switch: (a) input packets, (b) output packets from the H port with the control pulse's absence, and (c) output packet with the control pulse's presence.

port H or V, the corresponding powers are measured [shown in Fig. 4(c)]. The experimental results indicate that the gains for the TE and TM modes depend on the electrical current, and the transmission loss increases with the current. When the current reaches 170 mA, a transmission loss as large as −16 dB is measured for the signal beam because of material and structure factors. Therefore, in the proposed optical buffer, an EDFA is introduced to compensate the transmission loss. With the optimization SOA's structure and material the transmission loss can be improved, and the EDFA can then be removed.

The polarization rotation switch can be demonstrated by the same testing system in Fig. 3, where the optical multimeter is replaced by a real-time oscilloscope (OSC). The signal beam carrying three data packets at 10 Gb/s [shown in Fig. 5(a)], and a control pulse synchronized with packet 2, is generated by changing the current injected into LD2. The power of the hold is about 1 mW, while the control pulse is about 5 mW. The injecting current of the GT-SOA is 170 mA. Adjusting PC1 and PC3, the output signals from the H or V ports are monitored by the OSC [shown in Figs. 5(b) and 5(c)]. The results indicate that packets 1 and 3 output from port H with the control pulse's absence, while packet 2 outputs from port V with its presence. A polarization rotation switch controlled by an optical pulse is realized. The amplitudes of packets 1 and 3 are almost equal to that of packet 2, and the contrast ratio between the ON/OFF states is more than 20 dB. When the current injected into SOA is small, a high control pulse power will be needed in order to change the switch state. A high injected current corresponds to a low control pulse, but the power loss will increase with a high current. Therefore, in the experimental system, a 170 mA current and a 5 mW control pulse are selected.

4. Experimental System for the Optical Buffer

A cascaded experimental system (shown in Fig. 6), consisting of two buffering units, is set up to perform the proposed buffer scheme. The loop length for the first unit is about 100 m, and the second about 1000 m. The currents injected into two GT-SOAs are 170 mA. Adjusting, the power of the hold beam is adjusted to about 1 mW by changing the bias current of LD2 and LD3, while the control pulse power is about 5 mW by adjusting the modulation current. The signal beam from LD1 enters into a Mach–Zehnder modulator (MZM), and it is modulated by the data packet, which is simulated by a 10 Gb/s nonreturn-to-zero pulse sequence generated by a pulse pattern generator (PPG). The packet consists of the label and the payload. The label is 5555_5555h and needs not be delayed, while the payload contains a programmable sequence with 480 bits and is required to be stored in the buffer. A guard time of about 20 ns is inserted between the label and the payload, and the packet repeats every 100 μs. The control unit receives the frame synchronous signal (Sync) and the 10 GHz clock from the PPG, and it is responsible for generating "write" and "read" synchronous electrical pulses. The

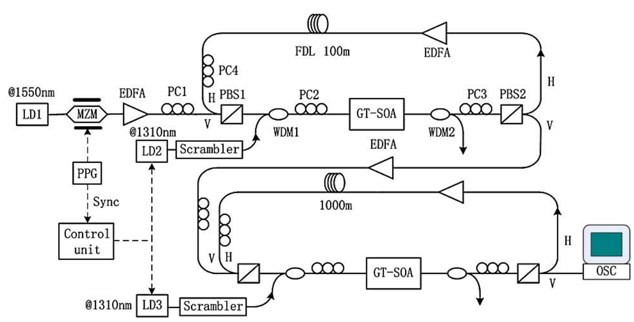

Fig. 6. Experimental system.

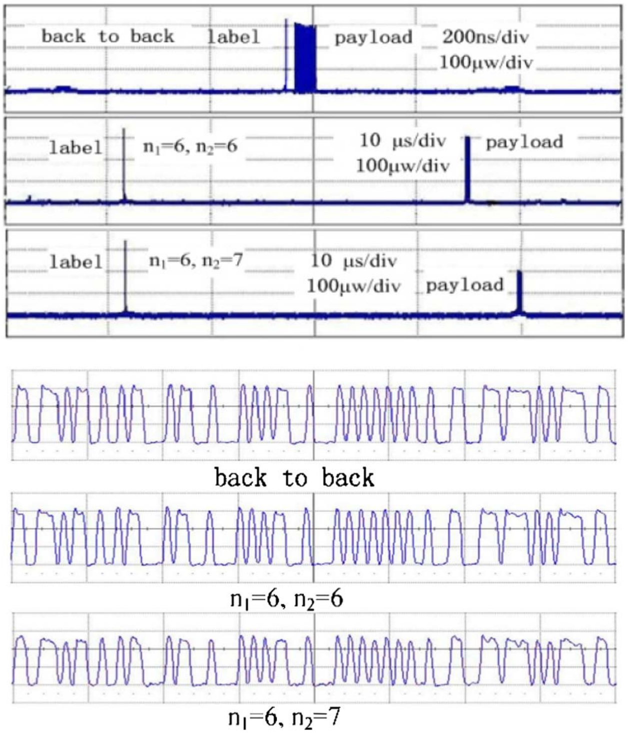

Fig. 7. Output waveforms of the optical buffer and details.

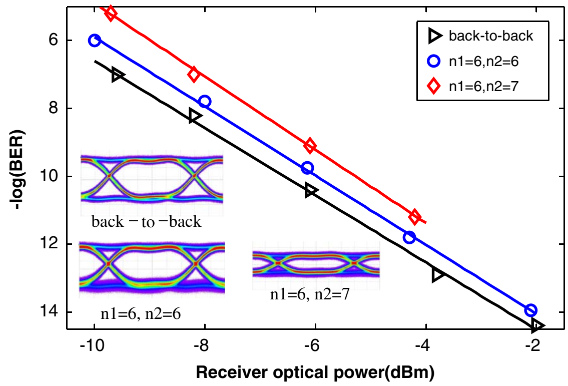

Fig. 8. BER curves and eye-diagrams.

synchronous electrical pulse drives the injected currents of LD2 and LD3 to generate synchronous "write" and "read" optical pulses at 1310 nm according to the delay requirement. The output signals and their details are recorded by the OSC shown in Fig. 7.

The experimental results indicate that the power of the output signal is approximately 600 μW after being buffered for six circulations in the buffering units 1 and 2 successively. Compared with the details of the back-to-back experiment (inserted in Fig. 7), except for a small amount of noise in the "peaks" or "valleys" and small fluctuations of the signal's amplitude, which is due to the EDFA's ASE accumulation and pump power instability, the signal waveforms are nearly perfect. The pulse distortion and the pattern effect due to XGM, nonlinear gain, and carrier recovery time are eliminated. Although the EDFA brings in some noises, the SNR has been improved because of a smaller noise figure of EDFA than a conventional SOA. In [5,11], a polarization rotation switch controlled by changing the current injected into the conventional SOA is employed in the fiber-loop optical buffer. However, the number of circulations is limited by some signal impairments, such as pulse distortion, SNR deterioration, ER degradation, and power imbalance.

In the experiments, it is found that the signal power decreases rapidly when the number of circulations exceeds 7 and the EDFA cannot compensate the power loss by the GT-SOA. When the data packets travel for 10 round-trips, the output signals are completely submerged in the noises. The reason for the limitation of the circulation number is that the saturation power of the EDFA in the experiment is less than 16 mW. It is believed that the performance of the buffer will be improved if the EDFA with a large saturation power could be used. It is envisaged that, with the optimization of the SOA's structure and improvement for material, a large dynamic variable delay from 0 to 9999T can be realized in a four-stage-cascaded buffer.

The bit error ratio (BER) of the output signals and the eye-diagrams can be obtained by the OSC and are shown in Fig. 8. The packet recirculates a total of 12 times in buffering units 1 and 2, and the eye is clear and open, which allows error-free operation. The output signals suffer from SNR deterioration and eye-diagram degeneration resulting from the power loss when the packets travel along the longer loop seven round-trips.

5. Conclusion

We presented a new cascaded optical buffer in which nonlinear polarization rotation of GT-SOA is used as the all-optical switches. In this buffer, the pulse distortion and pattern effect have been eliminated effectively and the SNR has been improved. The data packet is buffered for a total of 12 circulations in buffering units 1 and 2, corresponding to a total delay time of 33 μs. Further research will focus on decreasing the transmission loss of the GT-SOA to raise the performance of the optical buffer. In conclusion, the optical buffering scheme proposed is a useful exploration for all-optical buffers with a large dynamic variable delay.

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