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Loadable and erasable optical buffer based on a semiconductor optical amplifier with background noise suppression

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Abstract. A loadable and erasable fiber loop optical buffer based on a semiconductor optical amplifier (SOA) is presented. Two SOAs in our configuration not only provide nonlinear phase shift to implement buffer function, but also compensate for the propagation attenuation during long time storage. In particular, we present a simplified model to investigate the influence of background noise to the optical buffer performance. Both theoretical and experimental results reveal that the background noise can be suppressed by intentionally increasing the fiber loop loss. We also demonstrate that the packet pattern is well maintained after a storage time of 145 μs without self-oscillation. [DOI: 10.1117/1.2541394]

Subject terms: semiconductor optical amplifier; optic buffer; noise suppression.

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1 Introduction

Semiconductor optical amplifier (SOA)-based all-optical devices, in areas like wavelength conversion, 3R (reamplification, reshaping, retiming) regeneration, optical logic gates, and fiber loop optical buffers, have been widely studied in recent years.[1–4] Such SOA-based devices offer advantages such as signal amplification, wavelength controllability, and low control pulse energy. However, an inherent drawback of SOA-based devices is that the output signal contains amplified spontaneous emission (ASE) noise, which is especially serious when the SOA is placed in a closed fiber loop configuration.[5] To date, the reported optical buffers can be generally grouped into two categories: the fiber loop type and the slow light type. The slow light type appears very promising; however, there is a tradeoff between bandwidth and storage time, and the input/output signal in some conditions is difficult to couple within optical fibers. One of the key issues for the fiber loop optical buffer is the deterioration of the stored signal quality due to ASE accumulation. ASE noise is normally generated by an optical amplifier installed in the fiber loop, which is essential to compensate for power loss during storage. If ASE noise is not properly treated, there will be self-oscillations in the closed fiber loop. Eventually, when the lasing oscillation conditions are satisfied, the fiber loop optical buffer may become a ring fiber laser. To overcome this problem, another terahertz optical asymmetric demultiplexer (TOAD) was introduced into the fiber loop to suppress the ASE accumulation by regenerating the packet every roundtrip.[5,6] However, such a method increases the system cost and complexity. In this work, we demonstrate an SOA-based dual-loop optical buffer (DLOB) with loadable and erasable functions. In particular, we present a simplified model to investigate the influence of background noise on the optical buffer performance. Our theoretical model suggests that the background noise increases exponentially with the reduction of the fiber loop loss, which is confirmed by the experimental measurement. In fact, our theoretical model is applicable to various SOA-based fiber loop configurations. To the best of our knowledge, it is the first time that a passive method is applied to suppress the background noise of a DLOB.

2 Theory

The configuration of our DLOB with "erase" function is shown in Fig. 1.[7] The four side ports (port 1 to 4, port 3 to 6) of a 3 × 3 collinear coupler are connected accordingly to form a horizontal "figure eight." Two polarization controllers (PCs) are used to bias the two loops. Four wavelength demultiplexers (WDMs) with a 0.4-nm bandwidth and two SOAs are employed to generate a nonlinear phase shift (NPS) difference between signals propagating in clockwise (CW) and counter-clockwise (CCW) directions in each loop, with the assistance of a control light. A packet signal, launched in port C1 of the circulator, is split by the 3 × 3 collinear coupler into two signals with equal power travel-

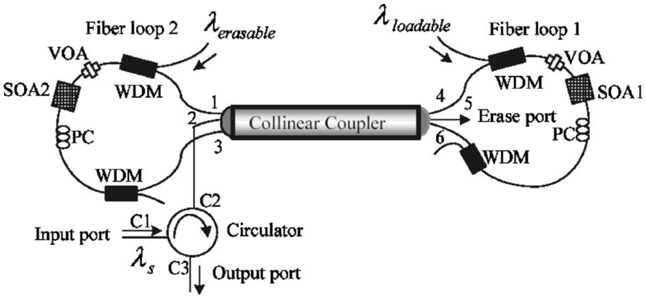

Fig. 1 Schematic diagram of a dual loop optical buffer (DLOB) with loadable and erasable functions.

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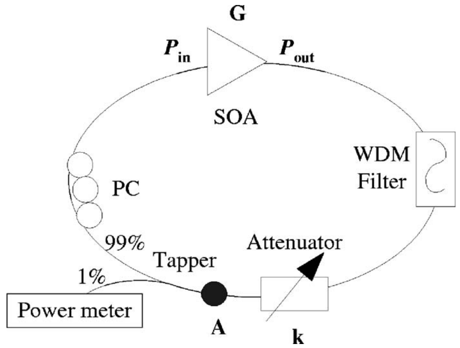

Fig. 2 A simplified model for investigation of background noise in a fiber loop optical buffer.

ing in CW and CCW directions in loop 1 without NPS. The CW and CCW signals meet again at ports 4 and 6 after one full circulation in loop 1. They combine and appear at port C3 of the circulator under the condition that the two signals are biased to have the same state of polarization. If we introduce a "load" signal $\lambda_{loadable}$ synchronized with the CW signal into SOA1, and the NPS difference between the CW and CCW signals is equal to π, the combined signal will not leave the optical buffer but transfer into loop 2. No signal will appear at port C3 of the circulator, which means the input signal has been loaded in the DLOB. After the signal circulates several times in the horizontal figure-eight, we inject another "read" signal $\lambda_{loadable}$ to the SOA1 to generate another π NPS between signals propagating in two directions in fiber loop 1. The stored signal will leave the figure-eight fiber loop and appear at port C3 of the circulator. If we want to erase the data circulating in the fiber loop, we can inject another signal, named "erase" signal $\lambda_{erasable}$, into fiber loop 2. With the help of SOA2, once the NPS difference between the CW and CCW signals in this loop reaches π, the data will appear at port 5 of the 3×3 coupler. Thus, there will be no data in the optical buffer, and the buffer is ready for the next packet storage. The storage time for this optical buffer can be adjusted to integer times of the fiber loop delay. Two SOAs in the fiber loop not only compensate the power attenuation during storage, but also generate adequate NPS to realize "load" and "erase" functions of the optical buffer. One critical issue of the current configuration is that the ASE noise may impose limitation on the storage time, as the total noise power will be cumulated with the storage time. While in the previous noise analysis the SOA in the fiber loop is working under a switching mode,[8] the SOA in our configuration is biased with constant current. Therefore, in the following investigation, we consider noise in the fiber loop as a linear combination of: 1. the noise subject to the packet signal and 2. the background noise without the packet signal. These two noise components are characterized by the noise figure (NF) and noise power, respectively. From our experimental results, we can see that the background noise is the main problem for achieving long storage time. We assume that the main noise source comes from SOA, and all the loss due to various components can be summarized as one attenuator. Then we can simplify the DLOB structure model into a fiber ring resonator with an SOA, a filter, and a passive attenuator (Fig. 2). Considering the statistic property of noise power, we divide the noise power into two parts: one is the average power, and the other is the power fluctuation. If we treat the average power of noise as zero, the SOA gain and the output variation of the noise photon number are derived, respectively, as

$$G = \frac{P_{\text{out}}}{P_{\text{in}}} = G_0 \exp\left\{-\frac{(G-1)}{G}\frac{\overline{P}_{\text{out}}}{P_{\text{sat}}}\right\}, \tag{1}$$

and

$$\sigma_{\text{out}}^2 = G(\sigma_{\text{in}}^2/h\nu\Delta\nu) + (G-1)n_{sp} + 2G(G-1)n_{sp}(\sigma_{\text{in}}^2/h\nu\Delta\nu) + (G-1)^2 n_{sp}. \tag{2}$$

The derivations of Eqs. (1) and (2) are based on theoretical results presented in Refs. 9 and 10, respectively. In Eq. (1), G_0 is the SOA small signal gain. P_{in} and P_{out} are input and output signal powers, respectively. P_{sat} is the saturation output power. $\overline{P}_{\text{out}}$ is the output power, including the average noise power, since we assume that the variation of noise power will not change the SOA status significantly. In Eq. (2), σ_{out}^2, σ_{in}^2, and n_{sp} are the variation of the output noise photon number, the variation of the incident photon number on the SOA, and the population inversion of the active medium, respectively. $h\nu$ and $\Delta\nu$ are the energy of a photon at a certain optical frequency and the bandwidth of the filter, respectively. The four terms on the right-hand side of Eq. (2) represent amplified signal shot noise, spontaneous emission shot noise, beat noise between the signal and spontaneous emission, and beat noise between the spontaneous emission components, respectively.

Considering only the background noise without a packet signal, if the ring resonator is in its balance state, which implies that $kG=1$ or $G=1/k$, the output noise power at point A in Fig. 2 can be derived theoretically as

$$P_{\text{noise}}^{\text{in}} = k\sqrt{P_{\Delta\nu}}\left\{\frac{1}{1-k}(\ln kG_0)P_{\text{sat}} + \left(\frac{1}{k}-1\right)n_{sp}P_{\Delta\nu} + \frac{2}{k}n_{sp}(\ln kG_0)P_{\text{sat}} + \left(\frac{1}{k}-1\right)^2 n_{sp}P_{\Delta\nu}\right\}^{1/2}, \tag{3}$$

where k is the attenuation coefficient of the attenuator, and $P_{\Delta\nu}=h\nu\Delta\nu$ is the average power of a photon in the passband of the filter. Equation (3) indicates that the ring resonator will be in a self-oscillation state under the condition of $kG_0>1$, and at this state there are lots of noise sources in the fiber loop, including ASE, shot noise, and beat noise. It is also observed from Eq. (3) that the noise power will increase with P_{sat} drastically. As P_{sat} grows with the bias current, we then infer that the noise power will increase with the bias current growing as well. In the measurement result by Schares et al.,[11] the NPS increases with the SOA length, bias current, and control pulse energy. However, we notice that an increase in bias current will also give rise to high noise power. In Fig. 3, we plot the theoretical and experimental result of the noise power at point A in Fig. 2 versus the attenuation coefficient. During our theoretical simulation, we choose the parameters of SOA as $P_{\text{sat}}=10$ dBm, $\Delta\nu=50$ GHz, $G_0=20$ dB, and $n_{sp}=8$. We insert a tapper, with a power ratio of 1:99, into the ring resonator and try to monitor the noise power fluctuation in the fiber

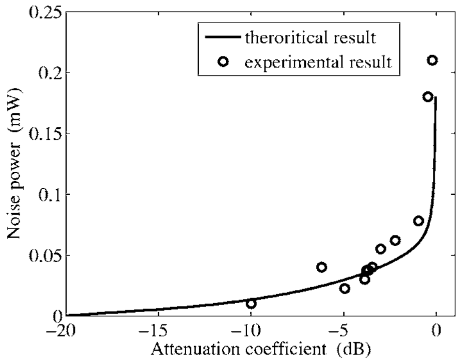

Fig. 3 Comparison of theoretical and experimental results of the background noise at point A in Fig. 2.

loop. The bias current of SOA (InPhenix IPSAD1503) can be adjusted and the corresponding noise power at point A can be calculated accordingly. The experimental results at 180-mA bias current are in good agreement with the theoretical predictions. Therefore, we can conclude that a variable optical attenuator (VOA) can be used to suppress the background noise.

3 Experiment Results

Finally, we demonstrate our experimental results on the background noise suppression for 2.5-Gpbs packet storage. Three distributed feedback (DFB) laser modules with a maximum output power of 10 dBm at different wavelengths are used as the loadable ($\lambda_1 = 1556.56$ nm), erasable ($\lambda_2 = 1553.36$ nm), and packet signal ($\lambda_s = 1559.89$ nm) light sources, respectively. Pulse patterns of the control and packet signals are generated with an acoustic-optical modulator and a LiNbO3 modulator. The two modulators are driven by a function waveform generator and a pulse pattern generator (PPG), respectively. We edit packets with a 100-μs cycle as shown in Fig. 4(a), and set the bias current of SOA at 160 mA. Note in Fig. 4(b) that even when all the packets just pass through the DLOB directly without buffering, the output packets become noisy because of background noise. When the bias current is increased to 200 mA, we cannot observe any packet waveform in Fig. 4(c), as the fiber loop is in self-oscillation. We then insert two variable optical attenuators (VOAs) into the fiber loop. Two packets, both with a 150-μs cycle and a 5-μs length, are generated and shown in Fig. 5(a). Two SOAs in our configuration are both biased with a 200-mAcurrent. The total length of the fiber loop is 3 km; therefore, the delay of one circulation in the horizontal figure-eight is 15 μs. Finally, we generate the corresponding control signals to implement the loadable function. After carefully adjusting, we set the VOA as −5-dB attenuation. The first packet passes through the DLOB directly, whereas the second packet is purposely buffered for 145 μs [Fig. 5(b)]. Comparing the packet waveform and eye diagram in Fig. 5 (inset), we observe that the buffered packets have quite similar shapes with that of the original packet.

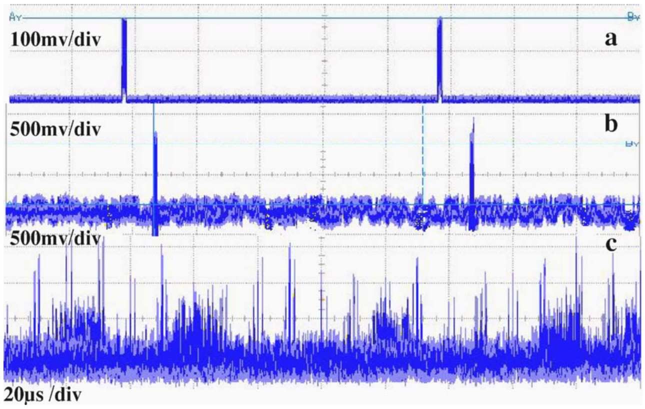

Fig. 4 Background noise influence on the performance of the DLOB. (a) Packet waveform before entering into DLOB. (b) Packet waveform after transmitting DLOB as the bias current for SOA 160 mA. (c) Packet waveform after transmitting DLOB as the bias current for SOA 200 mA.

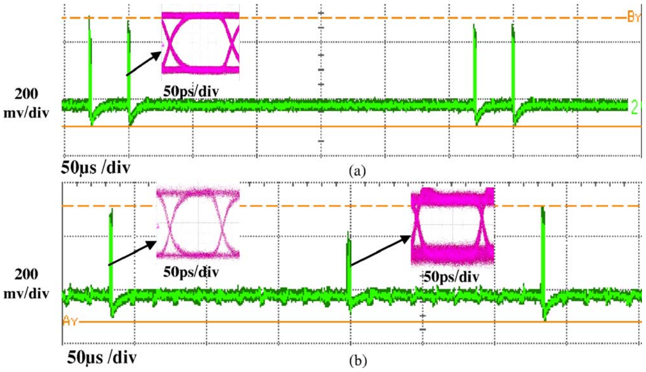

Fig. 5 (a) Two-packet profile before buffer. (b) Two-packet profile observed at DLOB output ports. The first packet passes the node directly and the second packet is buffered for 145 μs.

Later, we change the control signal pattern to observe the “erase” function of DLOB. After loading two packets into the DLOB, the first packet appears at the output port after a storage time of 40 μs, and the second is erased after 30-μs storage, according to different control signals. The top waveform in Fig. 6 is observed at the node output port, and the bottom waveform in Fig. 6 is measured at the erasable port. Though we can see some crosstalk between those two ports, we still successfully demonstrated the “erase” function. After measurement, the extinction ratios of all operations are more than 15 dB.

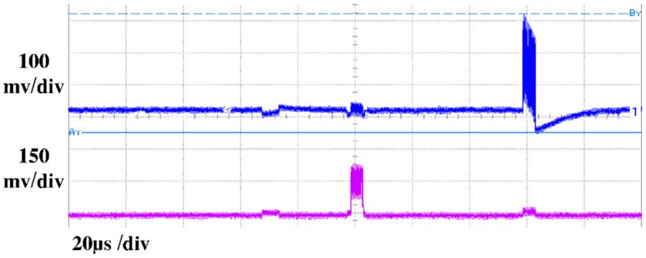

Fig. 6 Demonstration of the erasable function.

4 Conclusion

In conclusion, we report a novel SOA-based optical buffer with loadable and erasable functions. The background noise characteristic of an SOA-based fiber loop is investigated both theoretically and experimentally, and we propose to reduce the background noise power by adding a VOA in the fiber loop. Though the packet signal may suffer from the attenuation in our configuration, two SOAs can well compensate the power loss. Once the fiber loop is prevented from self-oscillation, the packet signal can be maintained quite well after a storage time of 145 μs due to background noise suppression.

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