Semiconductor optical amplifier used as regenerator for degraded differential phase-shift keying signals*

Xi Li-Xia(席丽霞)[a)†], Li Jian-Ping(李建平)[a)], Du Shu-Cheng(杜树成)[b)], Xu Xia(徐 霞)[a)], and Zhang Xiao-Guang(张晓光)[a)]

[a)] *Key Laboratory of Information Photonics and Optical Communications, Ministry of Education, Beijing University of Posts and Telecommunications, Beijing* 100876, *China*

[b)] *College of Nucleus Science and Technology, Beijing Normal University, Beijing* 100875, *China*

(Received 14 June 2010; revised manuscript received 3 November 2010)

Phase and amplitude regeneration are necessary for degraded differential phase-shift keying communication systems. This paper proposes a regenerator based on semiconductor optical amplifier for differential phase-shift keying signals. The key regeneration mechanism is theoretically analysed. The effectiveness of semiconductor optical amplifier based regenerator is demonstrated by comparing the bit error rate and eye diagrams before and after regeneration for 40-Gbit/s differential phase-shift keying 1080-km transmission systems. The results show that regeneration effects are very well. Bit error rate is less than 10^{-12} with the regenerator.

Keywords: differential phase-shift keying, regeneration, semiconductor optical amplifier, phase noise

PACS: 42.79.Sz, 42.81.Wg, 42.65.Sf **DOI:** 10.1088/1674-1056/20/2/024214

1. Introduction

Differential phase-shift keying (DPSK) format is widely used for long-haul optical fibre communication systems, due to its advantages of 3-dB higher sensitivity in combination with balanced detection and enhanced chromatic dispersion and polarization mode dispersion tolerance.[1,2] Excluding timing jitter, the primary limitation of a DPSK system is the accumulation of linear and nonlinear phase noise. When optical amplifiers are used periodically to compensate for fibre loss, linear phase noises are added at each in-line amplifier due to amplified spontaneous emission (ASE), nonlinear phase noise is induced by the interaction of amplitude noise and the fibre Kerr effect. Experiments have shown that when the nonlinear contribution to phase noise becomes dominant the improvement in receiver sensitivity for balanced DPSK detection can be lost.[3] Therefore, it is important to mitigate the phase noise by means of an optical-signal-processing scheme for advanced DPSK optical transmission systems.

Several schemes for DPSK phase regeneration have been proposed, including mid-link spectral inversion,[4] nonlinear optical loop mirror,[5] and phase-sensitive amplifier.[6−8] But they are rather difficult to realize or have not been demonstrated experimentally. For example, the regenerator based on PSA requires a fairly powerful and coherent pump source, it is difficult to implement in practice. A semiconductor optical regenerative amplifier for phase noise degraded DPSK signals was demonstrated that it was the first practical phase regenerator.[9]

In this paper, a phase regenerator based on semiconductor optical amplifier (SOA) for DPSK signals is designed and analysed, which realizes easily and does not need local pump. A DPSK system with 40-Gbit/s rate and 1080-km transmitted distance is set up. The effectiveness of the proposed phase regenerator is demonstrated in the setting systems.

2. The configuration of SOA-based regenerator

The configuration of the proposed SOA-based regenerator is presented in Fig. 1. An asymmetric Mach–Zehnder interferometer (AMZI) converts input DPSK signals into two mutually anti-symmetric on-off keying (OOK) signals in arms 1 and 2 respectively.

*Project supported by the Scientific Fund for Chinese Universities (Grant No. BUPT 2009RC0413), and the National "863" High Technology Projects (Grant No. 2009AA01Z224).

†Corresponding author. E-mail: xilixia@263.net

© 2011 Chinese Physical Society and IOP Publishing Ltd

The two output arms are connected with polarization controllers (PCs) and set an SOA among the two PCs to form a Sagnac loop. PCs are set to make the loop operate in its transmission mode. The SOA must be placed in the middle of the loop exactly, which ensures that the travel times of the pulses from the AMZI's outputs to the SOA in arms 1 and 2 are the same. After being amplified by the SOA, the OOK signals reenter the AMZI being converted back to the DPSK signal, which exits through the constructive interference port (c). The noise is partially drained through the destructive interference port (d) and blocked by an isolator, leaving less noise in the output signal at port (c). As a result, the signal noise ratio (SNR) of the DPSK signal passing through the SOA-based regenerator is improved, or under the same inputting signal power conditions, bit error ratio (BER) of the DPSK signal passing through the SOA-based regenerator is decreased.

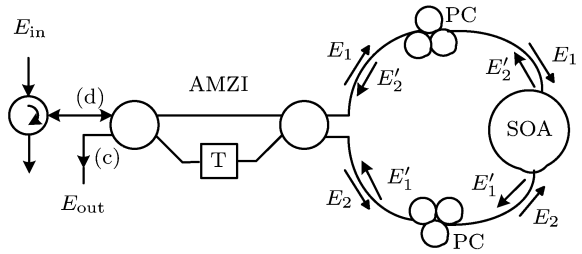


Fig. 1. Structure of the SOA-based regenerator.

Suppose that the input signal is $E(t)$, then after passing through AMZI first, the output signals in each output port of AMZI are

$$\begin{aligned} E_1(t) &= [E(t) - E(t-T)]/2, \\ E_2(t) &= \mathrm{i}\,[E(t) + E(t-T)]/2, \end{aligned} \tag{1}$$

where T represents one bit time delay, equation (1) corresponds to the two mutually anti-symmetric OOK signals. The two signals arrive at SOA at the same time, after passing SOA, they become

$$E_1' = G_1 E_1, \quad E_2' = G_2 E_2, \tag{2}$$

where G_1 and G_2 are the gain for E_1 and E_2, respectively. Then they reenter the AMZ and appear at ports (d) and (c) as

$$\begin{aligned} E_{\rm d}(t) &= [E_2'(t) - E_2'(t-T)]/2 \\ &\quad + \mathrm{i}\,[E_1'(t) + E_1'(t-T)]/2, \\ E_{\rm c}(t) &= \mathrm{i}\,[E_2'(t) + E_2'(t-T)]/2 \\ &\quad - [E_1'(t) - E_1'(t-T)]/2. \end{aligned} \tag{3}$$

3. The operation principle of the SOA-based regenerator

The key mechanism of the SOA-based regenerator which enables improvement of SNR is the discriminative gain provided by the SOA. Assume that E_1 is a mark and E_2 is a space. When a mark reaches the left edge of SOA, its counterpart space will reach the SOA's right edge at the same time. For a space propagating from the right through the SOA, the gain is partially depleted by its counterpart mark which traversed the left region a little earlier. Meanwhile, the mark gets more gain in the right region as its counterpart space causes negligible depletion of gain. It is this differential gain which allows noise discrimination in the spaces.

In order to understand the operation principle more clearly, we have a definition of the discriminative gain ratio $\eta = |G_{\rm m}(T)|/|G_{\rm s}(T)|$ and simulate its values varying with the input signal power. The following dynamical equations in the SOA in the regime of colliding pulses are used to obtain the discriminative gain ratio.

$$\frac{\partial E_1}{\partial z} + \frac{1}{v}\frac{\partial E_1}{\partial t} = \frac{1}{2}[\,g(1-\mathrm{i}\,\alpha)E_1 - \gamma E_1], \tag{4}$$

$$-\frac{\partial E_2}{\partial z} + \frac{1}{v}\frac{\partial E_2}{\partial t} = \frac{1}{2}[\,g(1-\mathrm{i}\,\alpha)E_2 - \gamma E_2], \tag{5}$$

$$\frac{\partial g}{\partial t} = \frac{g_0 - g}{\tau_{\rm c}} - \frac{1}{P_{\rm sat}\tau_{\rm c}}(|E_1|^2 + |E_2|^2)g, \tag{6}$$

where z, t, and v are the distance, time and group velocity in the SOA, respectively; g is the local gain coefficient which is varied with time and propagating distance; α is the line width enhancement factor, which is also called Henry factor, the typical value of α is 3–5, here we take $\alpha = 4$; γ is the linear loss coefficient in the SOA, we neglected it in numerical simulation, which does not qualitatively change the signal dynamics in the SOA; $\tau_{\rm c}$ is the gain relaxation time to its steady-state gain; g_0 is the local gain coefficient for small signal power and $P_{\rm sat}$ is the saturation power. Transferring to the retarding time $T = t \mp z/v$ in Eqs. (4), (5) and (6), respectively, and integrating them, we can express the electric field E_1 and E_2 after passing the SOA

$$E_1'(T) = G_{\rm m}(T)E_1(T), \quad E_2'(T) = G_{\rm s}(T)E_2(T), \tag{7}$$

where

$$G_{\rm m,s}(T) = \exp\left[\int_0^L 0.5g(\pm z, T)(1-\mathrm{i}\,\alpha)\mathrm{d}z\right]. \tag{8}$$

Using the finite difference method, we complete the numerical simulations of the colliding wave Eqs. (4) and (5). Results of the discriminative gain ratio η versus input signal power are obtained, as shown in Fig. 2, which is consistent with the saturation gain theory of SOA.

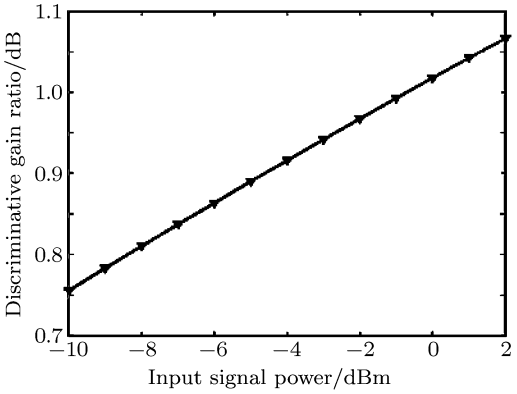


Fig. 2. The discriminative gain ratio η versus input signal power.

4. Effectiveness investigation

In order to investigate the effectiveness of the proposed SOA-based regenerator, 40-Gbit/s carrier suppressed returning to zero (CSRZ) DPSK transmission systems are set up in Optisystem software, the schematic diagram is shown in Fig. 3. A continuous light at 1552.45 nm passes through a dual parallel modulator driven by the 40-Gbit/s differentially encodes non-return to zero (NRZ) data stream, the optical NRZ-DPSK signals is generated. To generate CSRZ-DPSK formats, a Mach–Zehnder (MZ) modulator is placed just after the dual parallel modulator as pulse carver, which is driven by 20-GHz clock signal with amplitude $2V_\pi$. A variable optical attenuator (VOA) is followed by CSRZ-DPSK transmitter, which is used to vary the SNR by adjusting the input signal power. The transmitted links are comprised of single mode fibre (SMF), dispersion-compensating fibre (DCF) and erbium-doped fibre amplifier (EDFA). The DCF is used to compensate the chromatic dispersion of SMF and EDFA is to compensate loss of fibre. The parameters of the transmission line are given in Table 1. In this case, linear and nonlinear phase noises are all considered, linear phase noise comes from the ASE of EDFA and nonlinear phase noise is induced by Kerr effect. The DPSK receiver is comprised of a one bit-delay interferometer and a balanced detector. After the 1080-km propagation, the signals were sent into the receiver directly, or entered into the SOA-based regenerator firstly, then were sent to the receiver. The sampling oscilloscope is used to observe the eye diagram and BER detector is used to measure the BER.

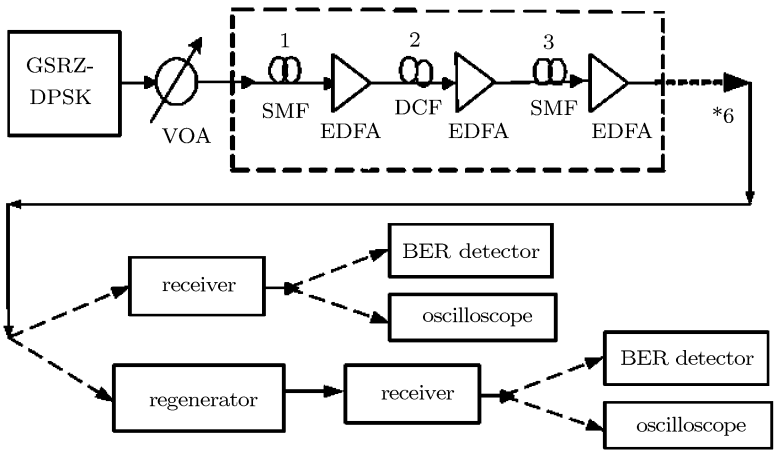


Fig. 3. Schematic diagram for experimental setup.

The effectiveness of SOA-based regenerator is verified by comparing the BER measurements and eye diagrams before and after regeneration. The comparison of BER is shown in Fig. 4. It is shown that, after regeneration, BER are all less than 10^{-12}, the regeneration effects are very well. Eye diagrams are also compared between before and after regeneration, as shown in Fig. 5. We can see that, after regeneration, the eye diagrams opened larger.

Table 1. Transmission line parameters.

fibres 1 and 3 (SMF)	dispersion/(ps/nm·km)	17
	length/km	75
	attenuation/(dB/km)	0.2
	effective area/μm^2	70
	n_2/m^2·W^{-1}	2.6×10^{-20}
fibre 2 (DCF)	dispersion/(ps/nm·km)	–85
	length/km	30
	attenuation/(dB/km)	0.5
	effective area/μm^2	27
	n_2/m^2·W^{-1}	2.6×10^{-20}
amplifier (EDFA)	gain/dB	15
	noise figure/dB	6

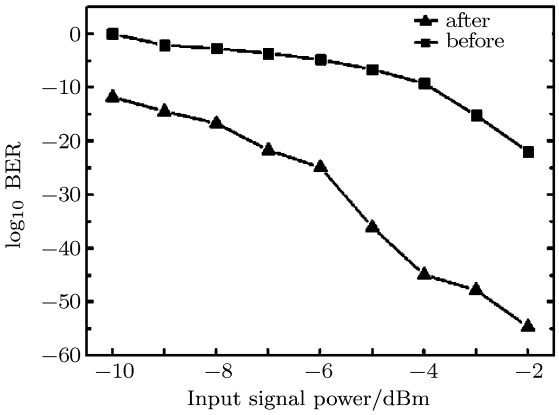


Fig. 4. Comparison of BER before and after regeneration.

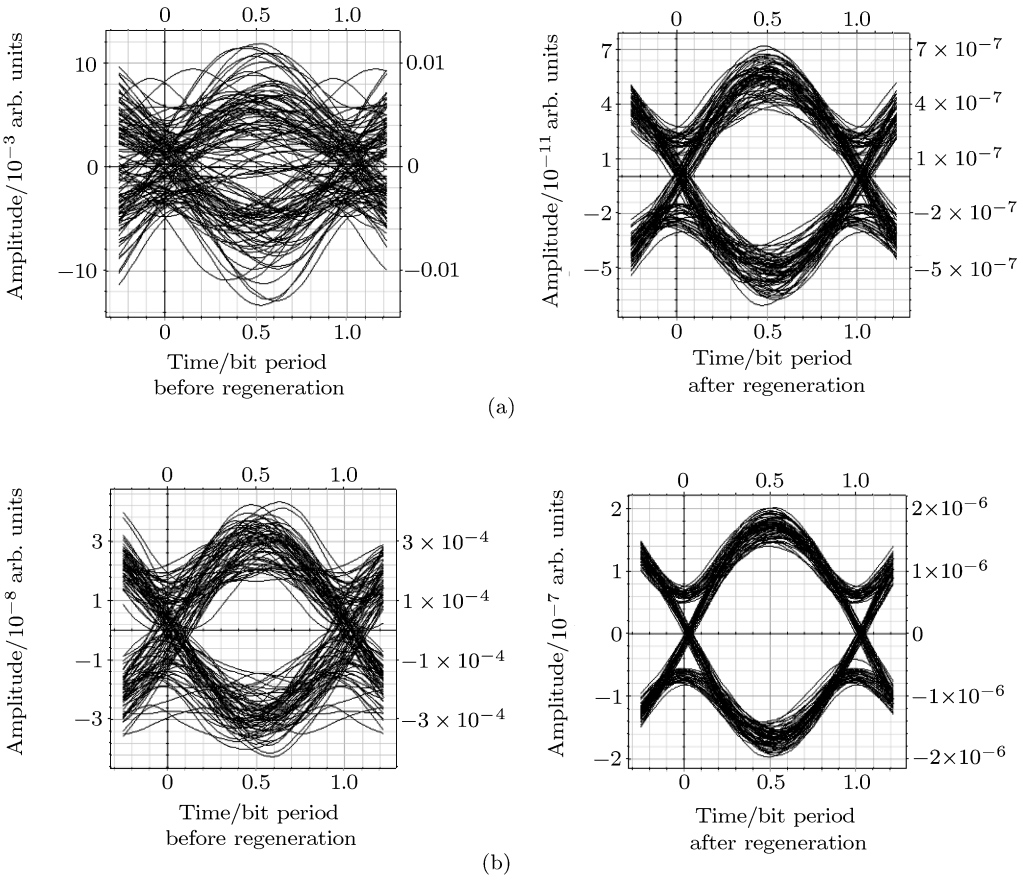


Fig. 5. Comparison of eye diagrams before and after regeneration (a) input –10 dBm signal power, (b) input –5 dBm signal power.

We also verified the effectiveness of SOA-based regenerator in other forms of DPSK systems, such as non-return to zero DPSK and return to zero DPSK. There are same regeneration effects as in CSRZ-DPSK system we will not show the results again.

5. Conclusion

We proposed a novel configuration SOA-based regenerator, whose working principle is based on the discriminative gain for strong mark and weak space. The effectiveness of the proposed SOA-based regenerator is

verified in 40-Gbit/s DPSK 1080-km transmission system. After regeneration, the BER are all less than 10^{-12}. It shows that the regeneration effects are very well and we can put it into practice.

References

[1] Zhao F, Fu M X, Lu Y Q and Liu S H 2007 *Chin. Phys.* **16** 11

[2] Lin Y M, Liang R S, Lu Y Q, Lu H, Guo J B and Liu S H 2007 *Acta Phys. Sin.* **56** 3931 (in Chinese)

[3] Kim H and Gnauck A H 2003 *IEEE Photon. Technol. Lett.* **15** 320

[4] Jansen S L, Borne D van den, Khoe G D, Waardt H de, Monsalve C C, Spalter S and Krummrich P M 2005 *OFC2005* Th05

[5] Striegler A, Meissner M, Cvecek K, Sponsel K, Leuchs G and Schmauss B 2005 *IEEE Photon. Technol. Lett.* **17** 639

[6] Croussore K, Kim C and Li G 2004 *Opt. Lett.* **28** 2357

[7] Croussore K, Kim I, Han Y, Kim C and Li G 2005 *Opt. Express* **13** 3945

[8] Xi L X, Tang X F, Wang S K and Zhang X G 2009 *Acta Phys. Sin.* **58** 6243 (in Chinese)

[9] Devgan P S, Shin M, Grigoryan V S, Lasri J and Kumar P 2005 *OFC2005* PDP34