Optimization of regenerator based on semiconductor optical amplifier for degraded differential phase shift keying signal*

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Real time phase regeneration is necessary for degraded phase modulation format optical communication systems. A regenerator based on the discrimitive gain effect of a semiconductor optical amplifier was proposed in recent years. In this paper, for this type of regenerator, its optimal working condition is found by solving the dynamic equations which describe the variance of the optical field and carrier density in the semiconductor optical amplifier by the finite difference method. The results show that the optimal improvement of signal Q factor can reach more than 2.2 dB.

Keywords: regenerator, semiconductor optical amplifier, Q factor improvement, phase noise

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1. Introduction

Nowadays, phase modulation format is dominant in optical communication systems due to its high sensitivity and enhanced chromatic dispersion and polarization mode dispersion tolerance.[1,2] Besides timing jitter, the primary limitation of a phase modulated system is the accumulation of the phase noise. When phase noise becomes dominant, it will greatly affect the Q factor of a system and induce bit-error-rate (BER) on the receiver side. So, further research on the regeneration of the phase noise degraded phase modulated signals are crucial for the development of optical communication technology. Since differential phase shift keying (DPSK) is the basis of the more complicated phase modulation formats, further research on the regeneration of DPSK signals is still necessary.

Several schemes for DPSK phase regeneration have been proposed, such as a nonlinear optical loop mirror,[3] a phase-sensitive amplifier,[4−6] and a fiber optical parametric amplifier.[7] These regenerators require phase locking between the pump and the signal, and this factor will greatly restrict their application in practice. Recently, a regenerator based on a semiconductor optical amplifier (SOA)[8−10] was reported and because it has a simple structure, needs no phase locking, and could be integrated on a chip, it has the potential to be widely used in practice. Therefore, this regenerator based on SOA will be our focus in this paper.

In previous studies, the structure of the regenerator was proposed, the working mechanism was analysed and regenerator effectiveness was demonstrated by simulations and experiments. However, since the characteristic of the SOA and the working conditions will affect the regeneration effect, the best working condition of this generator has not been discussed yet. So in this paper, we improve the previous study and find out the optimal working condition of the generator by solving the dynamic equations cited from Ref. [8] by the so-called finite difference method.

2. Mathematical model

Figure 1 shows the structure of this SOA-based regenerator. This regenerator consists of two parts: an asymmetric Mach–Zehnder interferometer (AMZI) and a Sagnec loop with an SOA placed exactly in the centre and two polarization controllers (PCs) in the loop. When a degraded DPSK signal $E(t)$ enters into the regenerator from port (d), it will be converted into two on-off keying (OOK) signals (see the inset in

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Fig. 1) through the AMZI by the equation

$$E_1(t) = \frac{1}{2}\left[E(t) - E(t - T_S)\right],$$
$$E_2(t) = \frac{\mathrm{i}}{2}\left[E(t) + E(t - T_S)\right]. \quad (1)$$

Because of the SOA gain saturation phenomenon, the two OOK signals will be amplified differently and encounter different phase shifts. The strong light (mostly signal components) will see more gain than its weak counterpart (mostly noise components). As a result, the noise component is suppressed and we can see that the signal-to-noise ratio (SNR) increases and bit-error-rate (BER) decreases after the signal has passed through the regenerator. It is this gain saturation induced discrimitive gain that enables the DPSK signal regeneration. After being amplified through the SOA, two OOK signals will reenter into the AMZI and be converted back into DPSK signal. Then the regeneration is realized.

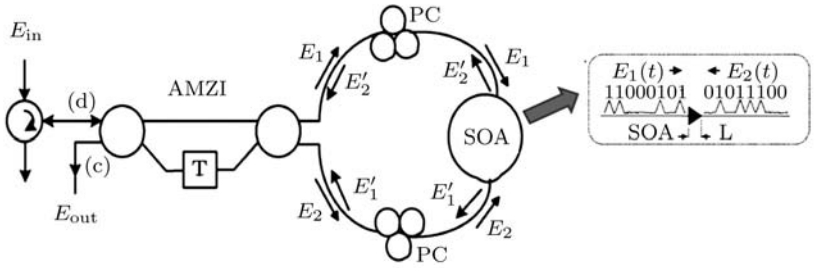


Fig. 1. Structure of the SOA-based regenerator, where the inset shows the converted OOK signals entering into the SOA (The picture is cited from Refs. [8] and [10]).

The variations of the optical fields and the inverted carrier density in the SOA can be described by the following dynamic equations:

$$\frac{\partial E_1}{\partial z} + \frac{1}{v_g}\frac{\partial E_1}{\partial t} = \frac{1}{2}\left[\Gamma g(1 - \mathrm{i}\alpha)E_1 - \gamma E_1\right], \quad (2)$$

$$\frac{\partial E_2}{\partial z} + \frac{1}{v_g}\frac{\partial E_2}{\partial t} = \frac{1}{2}\left[\Gamma g(1 - \mathrm{i}\alpha)E_2 - \gamma E_2\right], \quad (3)$$

$$\frac{\partial N}{\partial t} = \frac{J}{qd} - \frac{N}{\tau_c} - \frac{\Gamma g(|E_1|^2 + |E_2|^2)}{h\nu l w}, \quad (4)$$

$$g = A_g(N - N_0), \quad (5)$$

where J is SOA injected current density, N_0 is carrier density of transparency, ν is signal frequency, q is unit electron charges, h is Planck constant, v_g is group velocity, A_g is differential gain, l, w, d are the length, width, and thickness of the SOA active region, respectively. The three terms on the right-hand side of Eq. (4) show that SOA injected current can increase SOA inverted carrier density, while spontaneous radiation and input light induced stimulated radiation produce the opposite effect. The variation of inverted carrier density N leads to the variation of the SOA gain coefficient g (Eq. (5)), and then to the variations of the electric field (including the power and the phase) of the input light E_1 and E_2 (Eqs. (2) and (3)). In the equations, there are many factors that can affect the effect of the regeneration including the SOA properties such as gain relaxation time τ_c and Henry factor α, system operating conditions such as the SOA injected current I and input signal power P. One may also expect the noise (including amplitude noise and phase noise) in the input signal also to be considered. Next, we will discuss these impacted factors by simulation.

Transfer to the retarding time $T = t \mp (z/v_g)$ in Eqs. (2)$\sim$(5) and then solve them by the finite difference method. In this process, the input signal is divided by $i = 1, 2, \ldots, n_t$ sections and the SOA active region by $j = 1, 2, \ldots, n$ sections, where n_t and n are number of sections of the SOA input signal and active region, respectively. Then we will obtain the following recursion formula:

$$g_{i,j} = A_g(N_{i,j} - N_0), \quad (6)$$

$$E_{i,j}^{(1),(2)} = E_{i,1}^{(1),(2)} \exp\frac{1}{2}\left[\Gamma g_{i,j}(1 + \mathrm{i}\alpha)\right]\frac{jl}{n}, \quad (7)$$

$$N_{i+1,j} = N_{i-1,j} + 2\Delta t\left(\frac{J}{qd} - \frac{N_{i,j}}{\tau_c} - \frac{\Gamma g_{i,j}\left(\left|E_{i,j}^{(1)}\right|^2 + \left|E_{i,j}^{(2)}\right|^2\right)}{h\nu l w}\right). \quad (8)$$

Here we should mention that the linear loss γ in the active region has been ignored. For the first step of

the calculation, the forward difference method can be used for reasonable calculation precision, that is,

$$N_{2,j} = N_{1,j} + \Delta t \left(\frac{J}{qd} - \frac{N_{1,j}}{\tau_c} - \frac{\Gamma g_{1,j} \left(\left| E_{1,j}^{(1)} \right|^2 + \left| E_{1,j}^{(2)} \right|^2 \right)}{h\nu l w} \right). \quad (9)$$

3. Simulation results

In order to find the optimal condition, a simulation system with 2048-bit-long 40 Gbit/s return-to-zeros (RZ) DPSK pseudorandom binary sequence (PRBS) with 33% duty cycle signal passing through the regenerator is built up (system setup is shown in Fig. 2). In this system, the input signal is degraded by the phase noise emulator in the following way:

$$E = E_0(1 + N_A)\, e^{iN_P}, \quad (10)$$

where N_A is the added amplitude noise rate, and N_P is the added phase noise rate. Here it should be emphasized that for specific values of N_A and N_P, the range of the input amplitude and phase noise are actually $-N_A \sim +N_A$ and $-N_P \sim +N_P$, respectively. After the signal passes through the regenerator, balanced detection scheme follows to demodulate the signal. Signal Q factor is calculated after the balanced detection, and the signal Q factor improvement is used to evaluate the regeneration effect of the degraded signal.

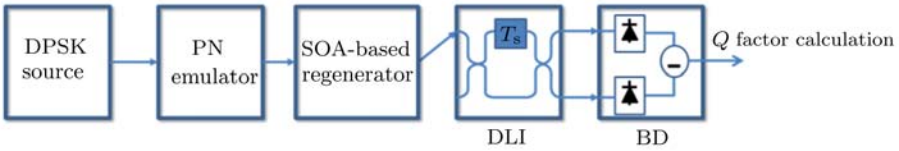


Fig. 2. (colour online) System setup for the simulation. DLI denotes the delay Line Interferometer; BD represents the balanced detector.

3.1. SOA determination

In the first step, the optimal parameters of the SOA that will be used in the regenerator should be determined. As pointed out above, carrier lifetime τ_c and Henry factor α are two SOA factors that may affect the effect of the regenerator. So first choose other parameters appropriately and try to find out the optimal τ_c. We use the following parameters: $\alpha = 4$, $\Gamma = 0.2$, $P = 0$ dBm, $N_A = \pm 0.2$, $N_p = \pm\pi/6$ (in all of the following simulations, we choose the SOA mode confinement factor as $\Gamma = 0.2$); The relationship between carrier lifetime and signal Q factor improvement is obtained as shown in Fig. 3. It can be concluded that with different values of injected current I, smaller τ_c always leads to higher Q factor improvement. Considering the recent SOA producing technique, $\tau_c = 20$ ps is appropriate. Physically, smaller τ_c means that the SOA gain relaxation time will reduce, and then the down slope of its gain curve will become steeper, leading the SOA gain saturation power to be reduced. As mentioned above, the SOA saturation gain is the mechanism that realizes the regeneration.

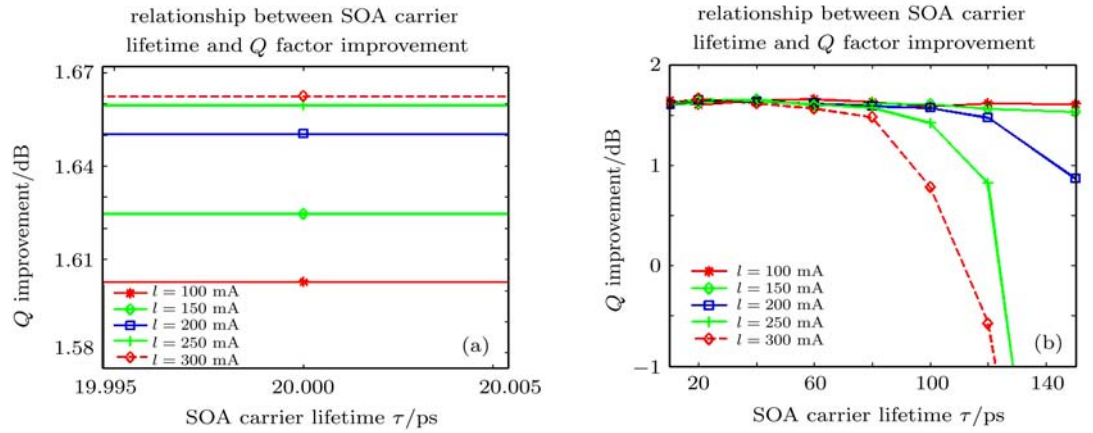


Fig. 3. (colour online) Relationships between Q factor improvement of regenerator and carrier lifetime τ_c of the SOA under the condition of $\alpha = 4$, $\Gamma = 0.2$, $N_A = \pm 0.2$, $N_p = \pm\pi/6$, $P = 0$ dBm, and different values of injected current I.

The optimal α is also discussed. Through simulation, the relationship between the SOA Henry factor α and signal Q factor improvement is shown in Fig. 4. From this figure, it can be seen that when the injected current is small, $\alpha = 1$ leads to the largest Q factor improvement, while when the injected current is large, the result will be $\alpha = 5$. This can be explained from equations in Ref. [8].

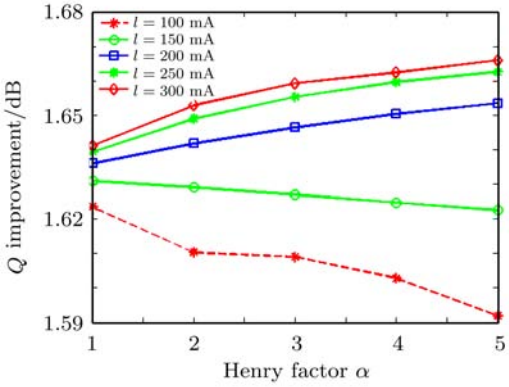


Fig. 4. (colour online) Effects of Henry factor α on the Q factor improvement of regenerator under the condition of $\tau_c = 20$ ps, $\Gamma = 0.2$, $P = 0$ dBm, $N_A = \pm 0.2$, $N_P = \pm\pi/6$ and different values of injected current I.

3.2. Outside working conditions

After the best SOA is chosen, the regenerator's optimal working condition will be focused. Since discriminative gain is the crucial element that realizes regeneration, for large discriminative gain, one can expect large signal Q factor improvement. For the case where values of injected current I of the SOA range from 0 to 300 mA, the relationship between discriminative gain of the SOA and input signal power P (ranging from -5 dBm $\sim$ 12 dBm) and that between Q factor improvement and input signal power P (ranging from -5 dBm $\sim$ 12 dBm) are simulated in Figs. 5(a) and 5(b) respectively. It is obvious that discriminative gain is proportional to both I and P. Considering the restriction of the SOA that is commercially available now, we choose $I = 300$ mA, $P = 10$ dBm as the optimal parameters. Since the injected current has been determined, $\alpha = 5$ will be the best choice as the Henry factor of the SOA. Physically, larger injected current and input signal power consume more carriers for the strong light, leaving fewer carriers to its weak counterpart. This leads to larger discriminative gain and better effect of the regeneration.

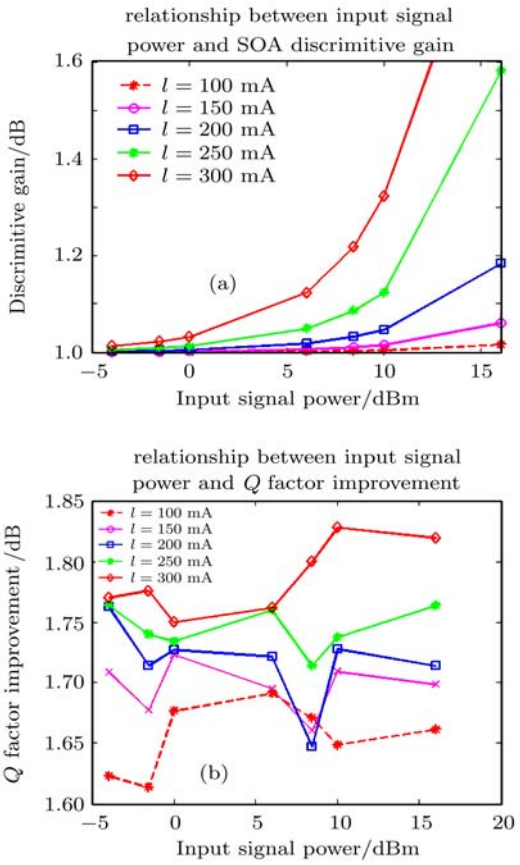


Fig. 5. (colour online) Relationships between discriminative gain of the SOA and input signal power (a) and those between Q factor improvement and input signal power (b) under the condition of $\alpha = 5$, $\tau_c = 20$ ps, $\Gamma = 0.2$, $N_A = \pm 0.2$, $N_P = \pm\pi/6$ and different values of injected current I.

The noise of the input signal is also a great factor, so we should change the parameter N_P to obtain the best condition. Under the condition of $\alpha = 5$, $\tau_c = 20$ ps, $I = 300$ mA, $P = 10$ dBm, $\Gamma = 0.2$, and $N_A = \pm 0.2$, the relationship between the input phase noise of the regenerator and signal Q factor improvement is given in Fig. 6. Figure 6(a) shows that for the phase noise, the best performance of the regenerator appears when $N_P = \pm\pi/5$. The maximal point of this figure shows the optimal Q factor improvement in this regenerator. One can also see the effect of the regenerator from the signal Q factor before and after the signal with different phase noise levels passes through the regenerator (Fig. 6(b)). Besides the input phase noise, it can also be expected that for the amplitude noise of the input signal, the smaller the amplitude noise, the better the signal Q factor improvement is. But in the simulations, we choose a relatively large amplitude noise parameter, namely $N_A = \pm 0.2$. For smaller input N_A, signal Q factor improvement can be larger.

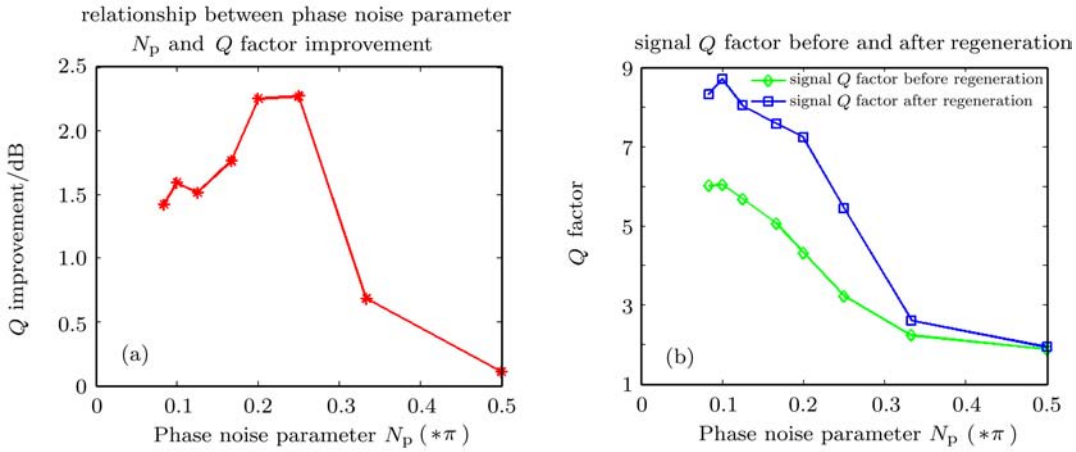


Fig. 6. (colour online) Relationship between Q factor improvement and input phase noise N_p (a), and relationships between Q factor improvement and input phase noise N_p (b), where signal Q factors refer to those respectively before and after the signal with different input phase noise levels passes through the regenerator under the condition of $\alpha = 5$, $\tau_c = 20$ ps, $I = 300$ mA, $P = 10$ dBm, $\Gamma = 0.2$, $N_A = \pm 0.2$.

Until now, we have found an optimal set of parameters, namely $\alpha = 5$, $\tau_c = 20$ ps, $I = 300$ mA, $P = 10$ dBm, $\Gamma = 0.2$, $N_A = \pm 0.2$, and $N_P = \pm\pi/5$. Under this condition, the signal Q factor improvement can reach more than 2.2 dB. The effect of the regeneration can be seen from Fig. 7, and the regeneration is realized.

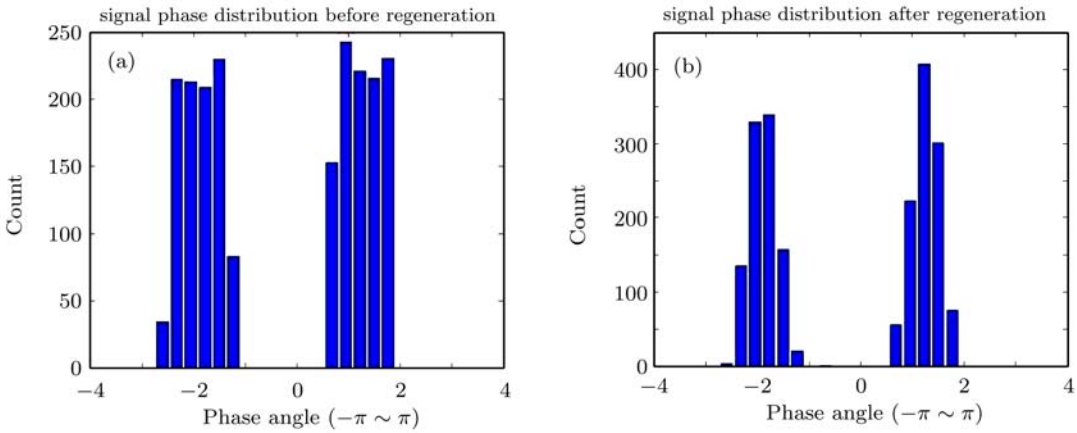


Fig. 7. (colour online) Phase distributions of signal before (a) and after (b) regeneration under the optimal parameters shown above.

4. Conclusion

In this paper, we solve the dynamic equations describing the feature of the SOA and conduct a simulation of a regenerator based on the SOA to find its optimal working condition. Simulation results show that through choosing the SOA with $\alpha = 5$, $\tau_c = 20$ ps, $\Gamma = 0.2$, and adjusting the regenerator working condition to $I = 300$ mA, $P = 10$ dBm, $N_A = \pm 0.2$, and $N_P = \pm\pi/5$, a larger than 2.2-dB Q factor improvement can be obtained. Furthermore, based on this structure, a regenerator for differential quadrature phase shift keying (DQPSK) signals and even higher order of phase modulation formats can be designed and optimized. This will be our further work.

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