Methods for Compensation of the Pattern Effect in Semiconductor Optical Amplifiers

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Abstract: The pattern effect in semiconductor optical amplifiers (SOAs) can impair seriously the performance of optical transmission and signal processing systems. In this paper, three methods for compensation of the pattern effect in SOA are studied for their applicability in high-speed optical signal amplification and processing systems and compared regarding the achievable gain, amplitude jitter, and input power dynamic range. The comparison includes the gain-clamped SOA as well as methods that employ an external holding beam and an asymmetrical Mach-Zehnder Interferometer (MZI) structure. Our results have shown that the MZI method with an additional external assist light source provides the best suppression of the amplitude jitter, i.e., an effective reduction of the pattern effect.

1 Introduction

Semiconductor optical amplifiers (SOAs) have extensively been investigated in the last two decades. Their compact construction, high gain, and high nonlinearities allow for use in all-optical signal processing systems and in photonic switching matrixes as efficient and compact optical gates. Degradation of the optical signal caused by the gain saturation in SOA can impact seriously the performance of optical signal processing and transmission systems. At bit-rates comparable with the gain recovery in the SOA and for high powers of the injected signal, a distortion of the signal waveform occurs. This is due to the carrier depletion caused by the increase in stimulated recombination of the carriers for higher signal input powers. At a certain signal power, the gain saturation is reached and the output power is reduced severely. If the bit-rate of the input signal is high, the spacing between two successive pulses is insufficient large so the gain cannot recovers completely. The SOA gain can recover completely only if a bit sequence with several successive zeros occurs. In this case, the first pulse after the series of zero bits experiences a higher gain, while the power level of the following pulses decreases up to the SOA saturation is reached. The change of the carrier density in SOA and, thus, the recovery of the gain depend directly on the pattern of the pulsed optical signal. Therefore, this effect is referred to as the pattern effect in SOA.

In this Paper, three methods for compensation of the pattern effect in SOA including GC-SOA, external assist light, and MZI-based scheme are studied for their applicability in high-speed optical signal amplification and processing systems and compared regarding the achievable gain, amplitude jitter, and input power dynamic range.

2 Methods for Compensation of the Pattern Effect in SOA

Several methods have already been employed to reduce the pattern effect in SOA [1, 2, 3, 4, 5]. Most of them use an additional light source in order to achieve a clamping of the amplifier gain and, consequently, to obtain a compensation of the pattern effect. This additional holding beam can be provided either by an external laser or by the use of an embedded laser construction. If the holding beam is provided by an external light source, its wavelength can be chosen to be either in the gain region or at the transparency point of the SOA. The advantage of the optical speedup at transparency is an increase of the saturation power without reducing the available gain or gain bandwidth [6]. The holding beam can also be generated internally by the use of a specific construction called gain-clamped SOA (GC-SOA), which is obtained by inserting two distributed Bragg reflector selective mirrors at both ends of the active region, thereby ensuring a laser oscillation inside the amplifier. GC-SOAs provide higher linearity and shorter recovery time than conventional SOAs. However, the gain of a GC-SOA is fixed by the design and has typically a low value of about 20 dB. Another specific construction incorporating an integrated vertical cavity surface emitting laser (VCSEL) is called the linear optical amplifier (LOA) [7]. The VCSEL is integrated together with the SOA on an InP substrate and operates along the entire length of the amplifier, thereby providing a constant gain over a large interval of the output powers. The drawbacks of this structure are its relatively low gain (≈ 17 dB) and high operating currents (200 - 300 mA). It is also possible to suppress the pattern effect by using an asymmetrical interferometer. In such a structure, two SOAs are placed in both arms of a Mach-Zehnder interferometer (MZI). Due to the asymmetry in the MZI arms, an incomplete destructive interference occurs at the output coupler for low powers of the input signal and a constructive interference for high optical powers. This leads to a reduction of the structure gain for the leading part of the pulse and to a higher gain for the trailing part, thus the pattern effect is suppressed. The asymmetry of the MZI branches can be obtained either by unequal lengths of the SOAs [5] or by an unequal power distribution over the branches (e.g. by the use of an unbalanced input coupler [8]).

- **Gain-Clamped SOA**

As already mentioned above, a specific SOA device (GC-SOA) can be used to compensate the pattern effect. In such a device, the clamping of the gain is obtained by forcing the SOA to lase at a wavelength outside the desired bandwidth of the optical amplifier. This leads to a high saturation power and, consequently, to a larger input power dynamic range. Due to the forced laser oscillation inside the amplifier the carrier density saturates and the gain saturates too. As a result, the change of the gain is low whatever the input signal level is. A GC-SOA consists of an active region and two passive or active distributed Bragg reflectors (DBRs) on both sides of the amplifier (see Fig. 1). An optical signal inserted into the amplifier is amplified in the middle gain section, while the two DBR sections together with the gain region form a laser cavity in which laser oscillations at the wavelength λ_{bragg} are obtained. The active DBR sections in Fig. 1b are inserted to compensate for loss and, thus, to improve the noise figure.

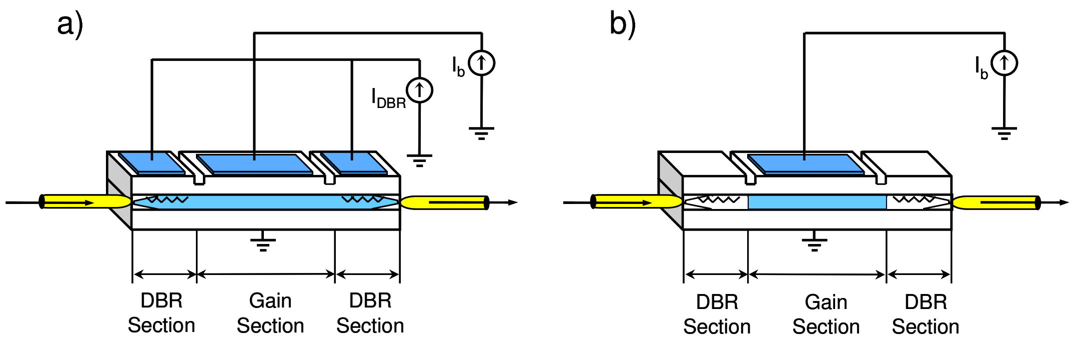


Figure 1: Schematic of the GC-SOA a) with passive DBR sections b) with active DBR sections

- **External Assist Light**

The external assist light is usually inserted into the SOA through an optical circulator as shown in Fig. 2.

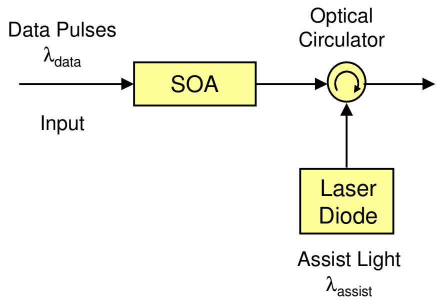


Figure 2: Compensation of the pattern effect in the SOA by the use of an external light source

In general, the basic principle is very similar to the GC-SOA, but this method is more flexible as the gain of the SOA is not fixed by the design and the wavelength of the external laser can be changed. Thus, a better and more stable compensation of the pattern effect can be obtained. The presence of the holding beam can dramatically speed up the carrier recovery inside the amplifier. The recovery of carriers inside the active region of an SOA from an initial state achieved after a short pulse has passed through the amplifier to its steady state defined by the CW holding beam is characterized by a time constant τ_{eff} [2]:

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_e} + \frac{\gamma \Gamma a L \alpha_{int}}{A} \frac{P_{assist}}{h\nu_{assist}} , \qquad (1)$$

where a is the differential gain coefficient, τ_e is the carrier life time, and Γ denote the optical confined factor. A, L, and α_{int} are the effective area of the active region, the length, and the intrinsic losses of the SOA, respectively. P_{assist} and ν_{assist} are the power and the frequency of the external assist light. In equation (1), γ is given by:

$$\gamma = \left[\frac{1}{\alpha_{int} L} + \frac{1}{\ln G_s} + \left(\frac{1}{\ln G_s} \right)^2 \right] G_s + \left(\frac{1}{\ln G_s} \right)^2 \quad , \tag{2}$$

where G_s represents the single pass gain through the SOA associated with the number of carriers in the steady state N_{st}. It is given by:

$$G_s = exp\left\{ \left[\frac{\Gamma a}{AL} (N_{st} - N_0) - \alpha_{int} \right] L \right\} \quad . \tag{3}$$

Fig. 3 shows the dependency of τ_{eff} on the power of the inserted CW light. The curves are plotted for a bulk SOA with A=0.5 · 10^{-12} m^2 and L = 350, 750, and 1000 µm. Other parameters used here are: τ_e = 365 ps, Γ = 0.3, a = 3 · 10^{-20} m^2, α_{int} = 27 cm^{-1}, and ν_{assist} = 193.55 THz.

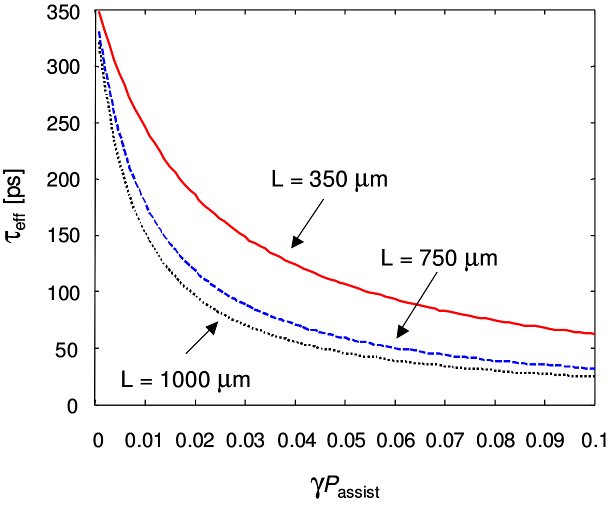


Figure 3: τ_{eff} for various assist light powers

It can be seen that the carriers in the SOA recovers much faster for larger powers of the assist light source. For example, τ_{eff} can be reduced from 350 ps to less than 100 ps by increasing the P_{assist}. Consequently, the gain is recovered much faster, and thus, the pattern effect is reduced. However, an increase of the power of the external assist light causes a gain reduction due to the carrier depletion associated with the increase of stimulated emission in the active region.

- **Asymmetrical MZI Structure**

An interferometric method for suppressing the pattern effect in SOA by the use of a nonsymmetrical Mach-Zehnder interferometer structure [5] is shown in Fig. 4a. The SOA is placed in one arm of the interferometer, while the phase change of the optical signal in the other arm can be adjusted by a phase shifter. By accurately adjusting the phase shifter one can ensure that destructive interference occurs when the gain of the amplifier is high. Otherwise, by increasing the input power, the gain of the SOA saturates and the two optical signals interfere constructively because of the phase change in the SOA caused by the carrier density induced change of the refractive index.

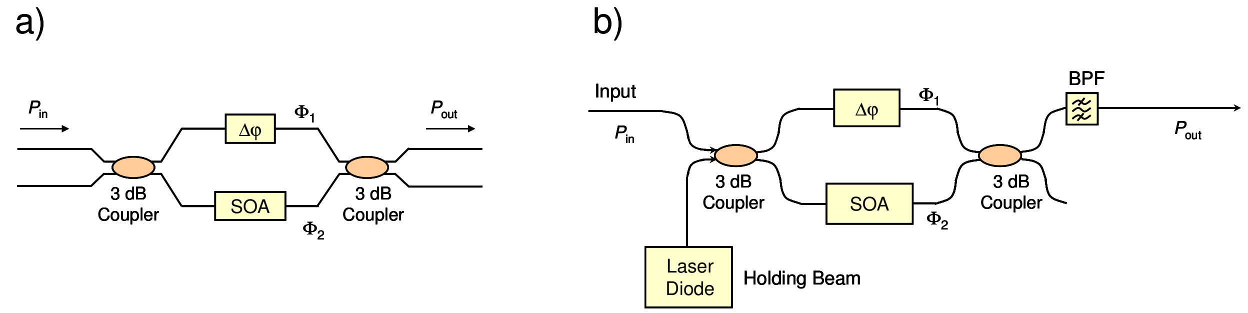


Figure 4: Compensation of the pattern effect by the use of a nonsymmetrical MZI (a – MZI structure only, b – combined structure employing an MZI with an additional holding beam)

In the small-signal regime, the gain of the SOA is the small-signal gain G_0 and if the phase shifter is adjusted such that $\Phi_1 - \Phi_2 = 0$, the output power can be expressed as:

$$P_{out,1} = \frac{P_{in}}{4}\left[1 + G_0 - 2\sqrt{G}\right], \tag{4}$$

where G is the single pass gain of the SOA. When the power of the input signal exceeds the saturation power (P_{sat}), the amplifier gain saturates and the phase of the optical signal is changed by π. In this case, the power at the output of the MZI is given by:

$$P_{out,2} = \frac{P_{in}}{4}\left[1 + G_0 e^{-\frac{2\pi}{\alpha}} - 2\sqrt{G^{-\frac{2\pi}{\alpha}}}\right], \tag{5}$$

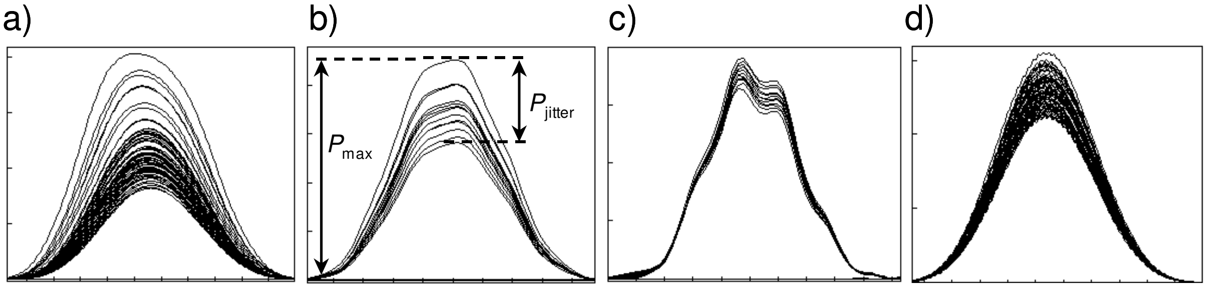
where α denotes the linewidth enhancement factor of the SOA. To reduce the pattern effect the overall gain of the structure should remain the same in both the small-signal and the saturated regime, i.e.,

$$1 + G_0 - 2\sqrt{G} = 1 + G_0 e^{-\frac{2\pi}{\alpha}} - 2\sqrt{G^{-\frac{2\pi}{\alpha}}} \; . \tag{6}$$

Thus, the small-signal gain G_0 and the linewidth enhancement factor α can be chosen such that $G_0 = 4[1 - exp(-\pi/\alpha)]^{-2}$ in order to allow reduction of the gain variation due to the pattern effect. Here, the variation of the phase at the output of the SOA is used to compensate for the gain variation. Thereby, the dynamic power range of the structure is extended in comparison with an SOA that have the same small-signal gain. To improve this method concerning a more effective reduction of the pattern effect and a better stability of the structure, we extend it by an external CW holding beam as shown in Fig. 4b. This combined method (MZI + Holding Beam) together with a GC-SOA with active DBR sections and the method employing a holding beam only are investigated and compared to each other in the following section.

3 Comparison of the Three Compensation Methods

The comparison of the pattern effect compensation methods described above is done by means of numerical simulations and regarding the applicability in high-speed optical signal amplification and processing systems. The SOA model used in the simulations is based on a time-domain modelling method, which allows an effective prediction of the gain and carrier density dynamics inside the SOA [9]. In the simulation set-up, 80 Gbit/s $2^7 - 1$ pseudo random bit sequences were generated from 4 ps (FWHM) short pulses at λ_{data} = 1552.5 nm. These pulses were then amplified in the structures shown in Figs. 1b, 2, and 4b. GC-SOA was modelled using an active region of 400 μm length and two active DBR sections of 100 μm length each. The peak of the gain curve was adjusted to be at 1550 nm and the lasing wavelength at 1510 nm. In the structures employing holding beam (Figs. 2 and 4b), the wavelength of the external light source was chosen to be inside the gain region of the SOA (the length of the SOA chip was 350 μm). The asymmetry of the MZI structure was achieved by placing the SOA into the bottom arm of the interferometer only. The improvement of the eye opening achieved by the use of the three methods for P_{in} = 0 dBm, P_{assist} = 2 dBm, and applied SOA current of 250 mA is shown in Fig. 5.



Without Compensation Holding Beam MZI + Holding Beam GC-SOA

Figure 5: Eye diagrams of the output signal a) without compensation, b) employing an external assist light, c) employing the combined structure (MZI + Holding Beam), and d) by the use of a GC-SOA

Fig. 6 shows the dependence of the gain and the amplitude jitter on the holding beam power for three different currents. It is evident that the scheme employing both the MZI structure and the holding beam shows a lower amplitude jitter than the method employing the holding beam only. However, the gain is smaller because the MZI structure has a higher overall loss. A higher gain can be achieved by choosing the wavelength of the holding beam to be at the transparency point [6]. The difference in gain becomes smaller if the holding beam power is decreased. To achieve an effective suppression of the amplitude jitter ($P_{jitter}/P_{max} < 0.2$), the power of the assist light should be higher than -5 dBm for the combined MZI + Holding Beam structure and higher than 5 dBm if only an external assist light source is used.

The dependencies on the average input power for all three methods are shown in Figs. 7 and 8. It can be seen that the highest gain is achieved by using the holding beam only, while the GC-SOA allows the widest 3 dB input power dynamic range. The lowest amplitude variation has been obtained by the use of the combined MZI + Holding Beam method.

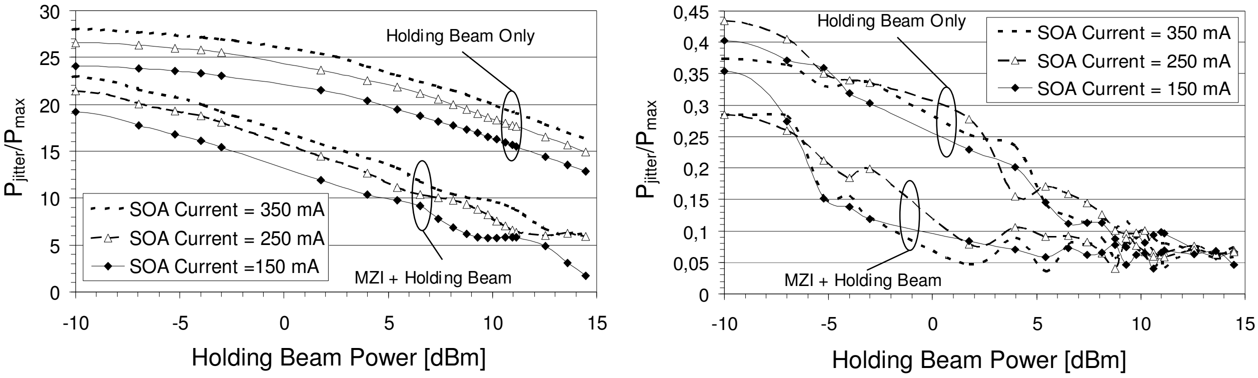


Figure 6: Gain and Pjitter/Pmax as a function of the holding beam power for different applied currents

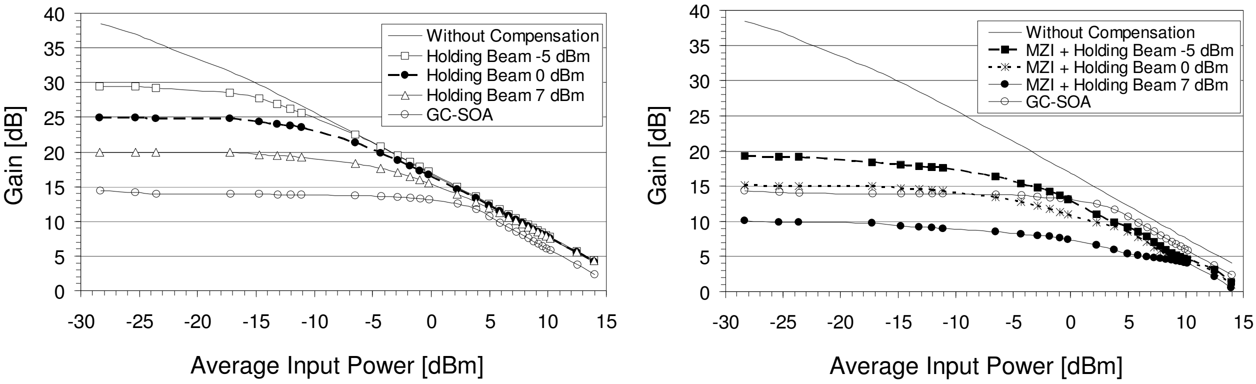


Figure 7: Gain in dependence on the average input power (applied current is 150 mA)

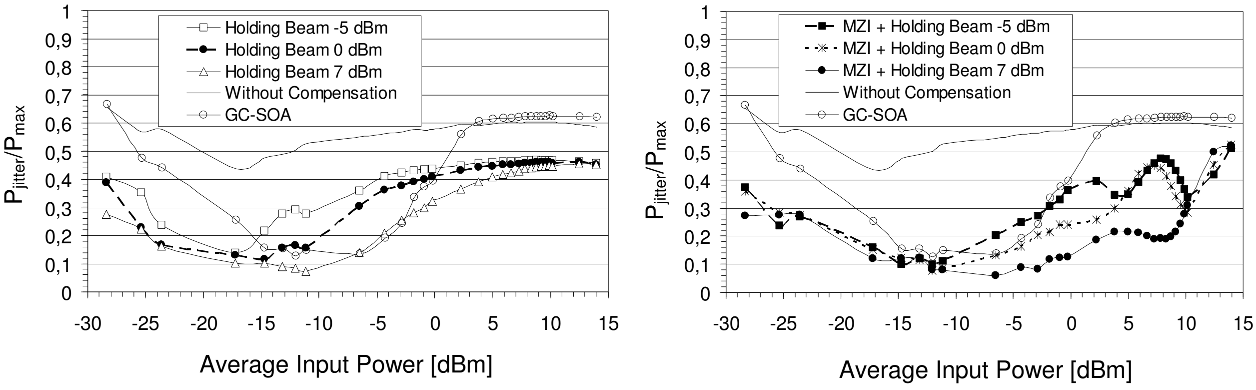


Figure 8: P_{jitter}/P_{max} in dependence on the average input power (applied current is 150 mA)

4 Summary and Conclusions

Three compensation methods are investigated by numerical simulations in order to find an optimal configuration and a set of parameters that allow an efficient compensation of the pattern effect in SOA. The influence of the pattern effect has to be minimized in order to allow an optimal use of SOAs in high-speed optical transmission and processing systems. Three methods including GC-SOA, external assist light, and MZI-based scheme are studied and compared regarding the achievable gain, amplitude jitter, and input power dynamic range. Our results have shown that the method employing an external assist light is the most suitable for optical signal amplification because of providing a relatively high gain. The GC-SOA enables a wide input power dynamic range and an easy integration. The best suppression of the amplitude jitter can be obtained by using the combined MZI + Holding Beam method. Therefore, this method is well suitable for high-speed optical processing applications.

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