Interferometric method of suppressing the pattern effect in a semiconductor optical amplifier

Qianfan Xu, Minyu Yao, Yi Dong, and Jianfeng Zhang

Department of Electronics Engineering, Tsinghua University, Beijing 100084, China

Received June 27, 2000

A new idea of using change in index of refraction to suppress gain variation in a saturated semiconductor optical amplifier (SOA) is presented. This kind of gain compensation has the advantage of high speed because it involves two phenomena that always accompany each other. This compensation can be achieved with a nonsymmetrical Mach–Zehnder interferometer structure. Calculated results show that with this structure the input and output power of the SOA can be extended to nearly 10 dB from the former small-signal limit when less than 1-dB gain variation is permitted. Numerical simulations with an advanced dynamic model of the SOA agree with the calculated results. © 2000 Optical Society of America

OCIS codes: 140.4480, 030.1670, 130.5990, 190.5940, 250.4480.

The semiconductor optical amplifier (SOA) is very attractive for its wide gain spectrum, capacity for integration with other devices, and potential low cost. However, its applications are severely limited owing to the pattern effect caused by the gain saturation, which results in distortion of the pulse shape and cross talk between symbols and channels. Quite a few methods, including electronic feedback,[1] compensation by a saturable absorber,[2,3] reduction of the carrier lifetime by injection of cw light,[4,5] and clamping of the gain by laser oscillation inside the device,[6,7] have been put forward to solve this problem. However, these methods have not given a satisfactory solution to this problem, mainly because of their speed limitations.

When a SOA reaches a saturated state, a decrease in carrier density will result in simultaneous variation of the gain and the index of refraction. So a better way to compensate for gain variation, which is the main source of the pattern effect, is to use the phase variation of the output signal. This can be achieved with a Mach–Zehnder interferometer (MZI) structure. Obviously this compensation method will not suffer any speed limitation and is bit-rate and waveform transparent as long as only interband processes are considered. In this Letter we describe the proposed structure, including the principle and the expected performance.

When the gain of a SOA varies with input signal power, the phase difference between the output and the input light will also vary, and their variations have a fixed relationship. So we can make the output light interfere with the input light in a MZI. By properly adjusting the two arms of the MZI, we can make sure that the two lights undergo destructive interference when the gain is high and constructive interference when the gain is saturated, so that the gain variation is greatly reduced. The basic structure of the device that we propose is shown in Fig. 1(a); one arm gives the phase-shifted light with gain and the other gives the unshifted light for compensation.

In a SOA the relationship between the change of amplitude and the phase of the optical field along the amplifier is[8]

$$\partial\phi/\partial z = -\frac{1}{2}\alpha g\,, \tag{1}$$

where gain coefficient g is defined by $g = (\mathrm{d}P/\mathrm{d}z)/P$, α is the linewidth-enhancement factor, and ϕ is the phase of the optical field. By integrating Eq. (1) over the amplifier length, we can obtain the local gain of the SOA as

$$G = \exp\left[\int_0^L g(z)\mathrm{d}z\right] = \exp(-2\Delta\phi/\alpha)\,. \tag{2}$$

In the small-signal region, i.e., when G equals small-signal gain G_0, if the two arms of the MZI have a phase-delay difference of π, the overall gain from the input port to the output port of the interferometric structure should be

$$G_{t0} = (\sqrt{G_0} - 1)^2/2\,. \tag{3}$$

When the input power increases and the SOA is working in a saturated state, so that the phase of its output light changes by π, the overall gain of the device will be

$$G_{t1} = (\sqrt{G_1} + 1)^2/2\,, \tag{4}$$

where $G_1 = G_0\exp(-2\pi/\alpha)$ is the gain of the SOA at that saturated condition.

For different values of α we can choose

$$G_0 = 4[1 - \exp(-\pi/\alpha)]^{-2} \tag{5}$$

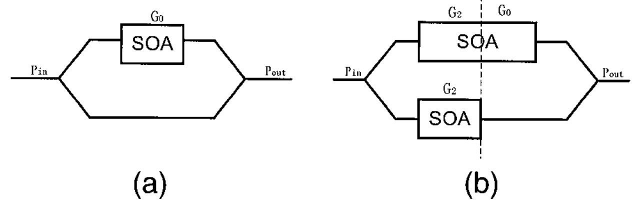

Fig. 1. Structure of the proposed device.

 © 2000 Optical Society of America

to make $G_{t1} = G_{t0}$, which means the overall gain of the device can be held to its small-signal value even when the SOA reaches its saturated state. Also, the ripples of the gain are usually very small when the phase change of the SOA is from 0 to π, as will be shown below.

If we take linewidth-enhancement factor α to be a typical value of 10, then, by Eq. (5), G_0 of the SOA should be chosen to be ~55 (17.4 dB). The saturated gain is calculated and shown in Fig. 2, in which the input powers of the device are normalized by the saturated power of the SOA.

The gain of the proposed device is ~13 dB, with 0.55-dB ripples, for an input power below the turning point. This saturated curve is compared with that of an ordinary SOA with the same small-signal gain. It can be seen that the input dynamic range is extended to a value as large as 9 dB if 0.6 dB is taken as the limit for the largest gain variation. This extended range will greatly facilitate the design of optical gates with SOA's.

For large enough G_0 the phase of the output light of the device at the output port is directly related to that of the SOA. So we expect that the phase change at the output port of the device will be approximately equal to that of the SOA. Thus, in dynamic conditions this device can produce a nearly pure phase change with little variation of gain, from 0 to π. This characteristic may facilitate cross-phase modulation implementation of a SOA in wavelength conversion and all-optical clock recovery.

If the device is used as an amplifier instead of being used in an optical gate, the gain given above is rather small. In this case we can add a preamplifier by use of the structure shown in Fig. 1(b). The SOA's in the two arms of the device have identical structures but different lengths. The part of the device on the left-hand side of the dashed line plays the role of a preamplifier. The difference between the small-signal gains of the two arms, i.e., G_2, should be a little less than G_0 calculated from Eq. (5) for further compensation for the small saturation effect in the preamplifier. For an amplifier the maximum output power for tolerable distortion is very important. Figure 3 shows the calculated gain versus normalized output power for two devices with $\alpha = 10$ and $\alpha = 5$. G_1 and G_2 of the two devices are chosen so that the devices will have a small-signal gain of 25 dB and the smallest possible gain ripple. Compared with the maximum output power of an ordinary SOA with a gain of 25 dB, the maximum output powers of the two devices are extended to 9 and 12 dB, when 0.6- and 1-dB gain variation, respectively, is tolerable. It is clear from Fig. 3 that, for a SOA with smaller α, larger output power can be obtained at the expense of larger gain ripple. When the input power is increased beyond the flat portion of the curves in Fig. 3, the overall gain of the device will decrease so fast because of destructive interference that the output power of the device can even decrease.

We stress that, unlike with clamping of the gain by laser oscillation inside the device, the dynamic characteristic of gain variation of the interferometric device should be the same as the static characteristic. In the dynamic condition the gain is determined not solely by the optical power at the given time spot but rather by a weighted average before that time. However, as long as the maximum power is held below the turning point, the gain will always remain in the flat portion of the saturated curves.

Numerical simulations with a complete large-signal dynamic model of a SOA,[9,10] taking into account longitudinal variations of carrier and photon density, the nonlinear gain-compression effect, and amplified spontaneous emission noise, confirmed the validity of the suppression method idea. We have simulated a device with the structure shown in Fig. 1(a). The SOA in the top arm is assumed to have an amplifier length of 200 μm, an injection current of 110 mA, saturation energy of ~2.6 pJ, a carrier lifetime of ~270 ps, and a linewidth-enhancement factor α of 7.1. The simulated performance of the device when a 40-Gbit/s pseudorandom binary sequence ($2^7 - 1$) signal light with 0.87-mW average power is injected into the device and is equally distributed in the two arms is shown in Fig. 4. The overall gain of the device in this condition

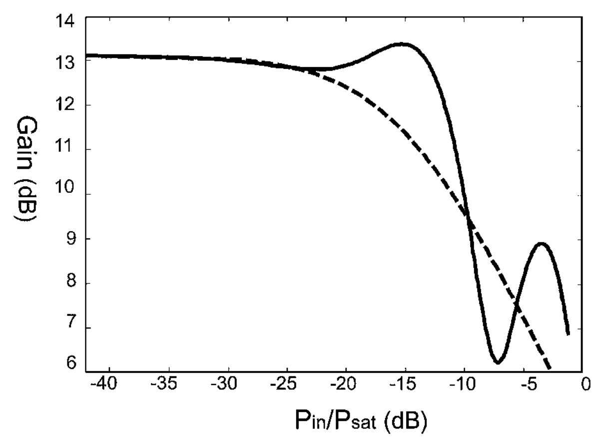

Fig. 2. Gain versus input power P_{in} of (solid curve) the proposed interferometric structure [Fig. 1(a)] and (dashed curve) an ordinary SOA with the same small-signal gain. P_{in} is normalized by the saturated power P_{sat} of the SOA.

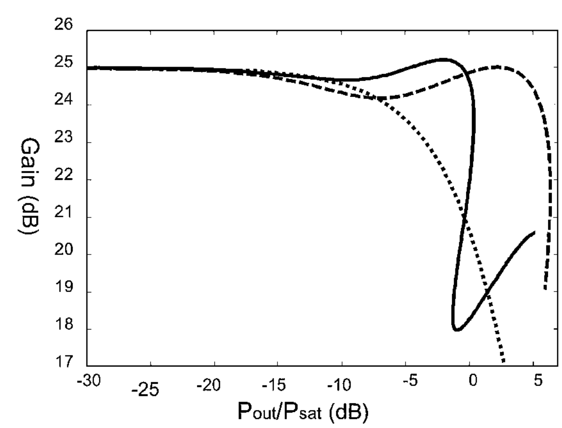

Fig. 3. Gain versus output power P_{out} of (dotted curve) an ordinary SOA and the interferometric structure [Fig. 1(b)] when (solid curve) $\alpha = 10$, $G_1 = 55$ and (dashed curve) $\alpha = 5$, $G_1 = 18.4$. The parameters are chosen so that they have the same small-signal gain. P_{out} is normalized by the saturated power P_{sat} of the SOA.

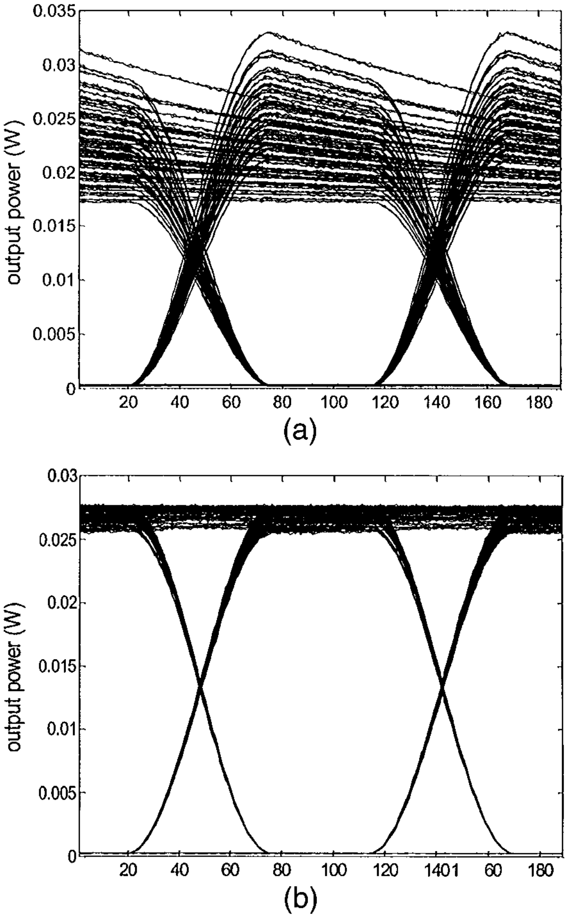

Fig. 4. Simulated performance of the device shown in Fig. 1(a). (a) Eye diagram of the output signal of the SOA at the top arm of the structure, (b) eye diagram of the output signal at the output port of the interferometric structure.

is 11.8 dB. Eye diagrams of the output power of the SOA in the top arm and of the power at the output port of the device are shown in Figs. 4(a) and 4(b), respectively. If we characterize the pattern effect as the ratio of maximum to minimum power of code 1, the pattern effect is reduced from 2.9 to 0.4 dB. No obvious variation of the compensation effect is observed when the bit rate is changed to 100 Gbits/s.

We acknowledge useful information from Wenshan Cai. This work was sponsored by the Ministry of Science Technology [project 863-307-1-3(03)]. M. Yao's e-mail address is yaomy@tsinghua.edu.cn.

References

1. J. A. Constable, I. H. White, A. N. Coles, and D. G. Cunningham, Electron. Lett. **29,** 2042 (1993).
2. K. Inoue, Electron. Lett. **34,** 376 (1998).
3. T. Durhuus, B. Mikkelsen, and K. E. Stubkjaer, J. Lightwave Technol. **10,** 1056 (1992).
4. R. J. Manning and D. A. O. Davies, Opt. Lett. **19,** 889 (1994).
5. S. Banerjee, A. K. Srivstava, Y. Sun, J. W. Sulhoff, K. Kantor, and C. Wolf, in *Digest of Optical Fiber Communication Conference*, 2000 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 2000), paper WM32-1.
6. L. F. Tiemeijer, P. J. A. Thijs, T. V. Dongen, J. J. M. Binsma, E. J. Jansen, and H. R. J. R. van Helleputte, IEEE Photon. Technol. Lett. **7,** 284 (1995).
7. D. Wolfson, S. L. Danielsen, C. Joergenzen, B. Mikkelsen, and K. E. Stubkjaer, IEEE Photon. Technol. Lett. **10,** 1241 (1998).
8. G. P. Agrawal and N. A. Olsson, J. Lightwave Technol. **25,** 2297 (1989).
9. H. Lee, H. Yoon, Y. Kim, and J. Jeong, IEEE J. Quantum Electron. **35,** 1213 (1999).
10. T. Durhuus, B. Mikkelsen, and K. E. Stubkjaer, J. Lightwave Technol. **10,** 1056 (1992).