Front. Optoelectron. China 2009, 2(4): 379–383
DOI 10.1007/s12200-009-0065-1

RESEARCH ARTICLE

Gain properties and optical-feedback suppression of asymmetrical curved active waveguides

Zigang DUAN (✉)[1], Wei SHI[2], Yan LI[3], Guangyue CHAI[1]

1 Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, Shenzhen University, Shenzhen 518060, China
2 Electrical and Computer Engineering Department, University of British Columbia, Vancouver V6R 1T3, Canada
3 School of Science, Xi'an Shiyou University, Xi'an 710065, China

Abstract Elaborately-designed asymmetrical curved active waveguides are introduced to improve the gain properties of semiconductor optical amplifiers (SOAs) by internal distributed optical-feedback suppression. An analytical model of the double-energy-level system is utilized in the simulation and designed by the finite difference time domain (FDTD) method. Under a 280 mA driving current, the optimized curved SOA with the simple device structure without isolators performs a more than 18 dB fiber-to-fiber gain, 980 μW spontaneous emission power, and 13 dBm saturation power.

Keywords curved active waveguide, feedback restrain, semiconductor optical amplifier (SOA)

1 Introduction

Semiconductor optical amplifiers (SOAs) have been actively studied for more than two decades and still draw great attention due to their wide applications and potential in optical communication and photonic integration [1–4]. EDFA-comparable high-performance SOA modules were achieved in laboratory [5,6] a few years ago, but hardly used for commercial applications. The main problem is that the residual reflectivity, especially of the external cavity formed by the coupling fiber end faces, will induce serious ripple when a traveling-wave SOA works under a high driving current ($<$ 100 mA). To solve this problem, Tiemeijer et al. [5,6] developed a unidirectional SOA module including two optical isolators that were used to constrain the optical feedback caused by the external cavity, an 8° angled strip and four non-spherical collimator lenses that were used to enhance the coupling efficiency; this acquired a very-low residual reflectivity of 10^{-6}, 33 dB fiber-to-fiber gain, and less than 7 dB noise under 400 mA driving current. However, the alignment and package of the module is too difficult and costly to be widely used in practice.

In this paper, we will discuss, in theory and experiment, the gain properties of SOAs with elaborated-designed asymmetrical curved active waveguides which can constrain gain ripple and enhance fiber-to-fiber gain by internal distributed optical-feedback suppression but not the external optical isolation. The scheme of internal distributed feedback suppression avoids additional difficulties for packaging and is much simpler and more economical than the method using external isolators.

2 Simulation and design

2.1 Principle

As shown in Fig. 1, an asymmetrical curved waveguide discussed in this paper consists of four circularly curved sections with different radii and two straight sections. In

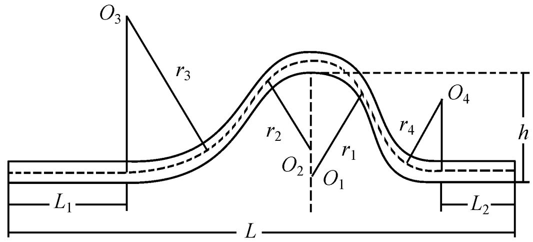

Fig. 1 Schematic of asymmetrical active waveguide

Received July 20, 2009; accepted August 25, 2009

E-mail: zgduan@szu.edu.cn

Fig. 1, L and h are the linear length and the height of the curved waveguide, respectively. L_1 and L_2 are the lengths of two straight sections. r_1, r_2, r_3, and r_4 are the radii of four circularly curved sections. r_1 and r_4 are geometrically interdependent. r_2 and r_3 are geometrically interdependent. The different sections have a uniform width without offset. We assume the traveling direction from the left to the right to be forward.

When propagating in curved waveguides, light encounters radiation losses [7] and the mode profile shifts to the outer edge of the bend [7,8], which causes a field mismatch at the junction between a straight and a curved waveguide. This mismatch also exists between two curved sections with different radii. Because of the field mismatch, scattering will occur when light propagates across an interface between two adjacent sections. Forward and backward light encounter different coupling losses at an interface. Since the waveguide is asymmetrical, the total loss for the forward and the backward light throughout the whole waveguide is different. Thus, it is possible to find a proper waveguide structure which induces great total loss for backward light but much less total loss for forward light. In addition, both radiation losses and coupling losses depend strongly on the bend radii. The asymmetrical loss/gain distribution can bring different amplification effects for the forward and backward light. Therefore, a well-designed curved waveguide can suppress optical feedback and meanwhile keep forward amplification. The feedback suppression enables the SOA with such a waveguide to work under a higher driving current and to have more carriers contributing to forward amplification.

2.2 Calculation model

A calculation model, as shown in Fig. 2, is introduced to find effective asymmetrical active waveguides. A Gaussian-beam signal of 1 ps impulse duration [8] is emitted at the position of the feedback receiver and then coupled into the SOA. The SOA waveguide is composed of the active layer and the cladding. The SOA's facets are antireflection (AR) coated. An absorbing boundary [9] is used to approximate the infinite field-diffusion space. The output light is coupled into a single-mode fiber. The reflected light caused by the fiber end face is coupled reversely into the SOA. The output and the feedback energy are calculated at the output and the feedback receiver, respectively.

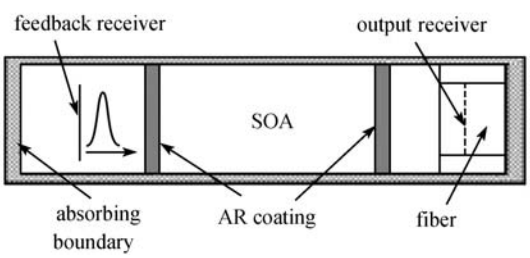

Fig. 2 Calculation model

We define two parameters, P_c and R_f, as the criteria to estimate the gain enhancement and feedback suppression of a curved SOA. P_c is the ratio of the output energy of the curved active waveguide to that of the straight one. R_f is the ratio of the feedback energy of the curved active waveguide to that of the straight one. The aim of the design is to find proper active asymmetrical waveguides with high P_c and low R_f.

2.3 Double-energy-level system

Because of the energy level splitting in semiconductors, the energy band theory is necessary to describe the optical-application process in an SOA completely. However, we focus only on the optical energy transmission and amplification without discussing band-related properties like noise and gain saturation. Therefore, we can use a double-energy-level system [10,11] to investigate the gain properties of active waveguides for calculation efficiency.

The complex polarization vector ($\boldsymbol{P}$) in an active isotropic dielectric consists of the linear non-resonant dielectric polarization part ($\boldsymbol{P}_{\text{host}}$) and the linear resonant respond dielectric polarization part ($\boldsymbol{P}_{\text{at}}$):

$$\boldsymbol{P} = \boldsymbol{P}_{\text{host}} + \boldsymbol{P}_{\text{at}}. \tag{1}$$

$\boldsymbol{P}_{\text{at}}$ reflects the influence of the radioactive transitions to the polarization vector. Its differential in time domain can be described as

$$\frac{\mathrm{d}P_{\text{at}}}{\mathrm{d}t} = \frac{3\mathrm{j}}{8\pi^2}(\Delta N\lambda^3\gamma_{\text{rad}}\varepsilon)E(t) + \frac{3\Delta\lambda^3\gamma_{\text{rad}}\varepsilon}{4\pi^2}\left(\omega_a + \frac{\mathrm{j}\Delta\omega_a}{2}\right) \cdot \exp\left(\frac{\Delta\omega - 2\mathrm{j}\omega_a}{2}\right)\int_0^t E(\tau)\mathrm{d}\tau, \tag{2}$$

where $\Delta\omega_a$ is given by

$$\Delta\omega_a = \gamma + \frac{2}{T_0},$$

γ_{rad} is the recombination rate, λ is the quantum transition wavelength corresponding to the resonant frequency (ω_a), ΔN is the population-density difference between the low and the high energy levels, T_0 is the decaying relaxation time of an electric dipole, and ε is the dielectric constant. By solving the Maxwell equations with the polarization vector described above, we can acquire the field distribution and, further more, the output and the feedback energy.

The parameters used in calculation are listed in Table 1 and Table 2.

As shown in Fig. 3, both the output and feedback energy of a curved waveguide is less than that of the corresponding strait waveguide when the inverted population density is at a low level because of the radiation and coupling losses. The P_c and R_f increase as the inverted population

Table 1 Dielectric constants (ε) used in calculation

material	dielectric constant
waveguide cladding (InP)	10.24
fiber core (SiO_2)	2.1216
fiber cladding (SiO_2)	2.1188
AR coating	10.5

Table 2 Geometrical parameters used in calculation

geometrical parameters	constant/μm
length of SOA	101.720
L_1	9.688
L_2	6.781
thickness of active layer	1.000
width of active layer	2.000
thickness of AR coating	0.388
radius of fiber	5.000

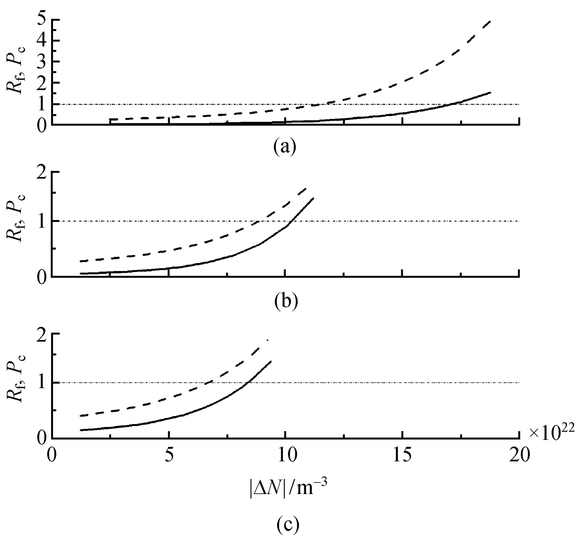

Fig. 3 R_f (real line) and P_c (dashed line) of three representative configurations. (a) r_1 = 19.5 μm, r_2 = 194.5 μm; (b) r_1 = 76.5 μm, r_2 = 139.1 μm; (c) r_1 = 93.1 μm, r_2 = 64.2 μm

density increases because the curved waveguides are a little longer than the straight waveguide when they have the same linear length. All the three curved waveguides present gain enhancement and feedback suppression, i.e., when $R_f = 1$, $P_c > 1$, which means that the gain is enhanced without feedback increase. Among the three curved SOAs, Fig. 3(a) presents the best property of feedback suppression: P_c increases much faster than R_f does and it has the maximum P_c (3.65) when $R_f = 1$, i.e., for the same optical feedback, the gain of the curved SOA is about 5.6 dB higher than the straight one.

3 Experiment

3.1 Fabrication

A multiple-quantum-well (MQW) SOA chip whose geometric parameters are six times as large as Fig. 3(a)'s has been fabricated. The InGaAsP waveguide is grown on an InP substrate by the metal organic chemical vapor deposition (MOCVD). The active layer consists of three 10 nm compressively strained wells separated by four 5 nm tensile strained wells. The peak wavelength is designed as 1360 nm and, because of the band-filling effect, will shift to near 1310 nm when the SOA works under a high driving current. The curved waveguide is defined by the p-type electrode and hence a gain waveguide, which is different from the calculation and design and would induce performance deterioration. However, we just use this chip to test the scheme of internal distributed feedback suppression. The SiO dielectric films are formed by electronic beam evaporation on the chip facets as AR coatings. The residual reflectivity of chip facets after AR coating is about 5×10^{-4}. Two end-metalized fibers are aligned and fixed with the chip under driving condition to achieve the maximum spontaneous-emission output power from the fibers. Figure 4 is the photograph of the SOA chip being aligned with coupling fibers. Figure 5 is the photograph of the device after package. The device has been aged before the performance estimation.

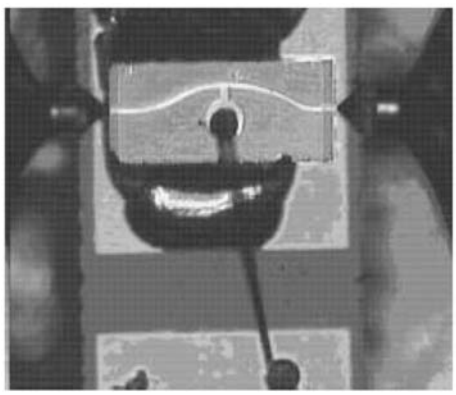

Fig. 4 Photograph of curved SOA chip being aligned with coupling fibers

3.2 Results and discussion

Figures 6 and 7 are the *P-I*/*V-I* curves and the amplified spontaneous emission spectrum under a 300 mA driving current, respectively. The device performs nice linear gain without saturation when the driving current is less than 220 mA and while the maximum spontaneous power of 970 μW is performed. Under a 300 mA driving current, the 3 dB band of the amplified spontaneous emission spectrum

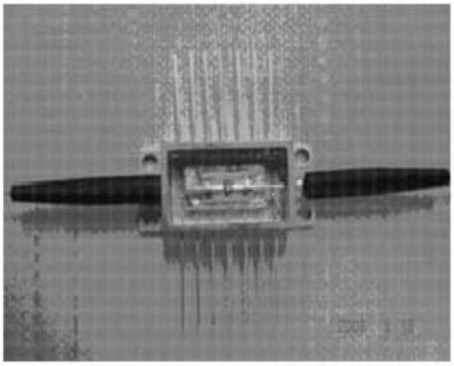

Fig. 5 Photograph of curved SOA device after package

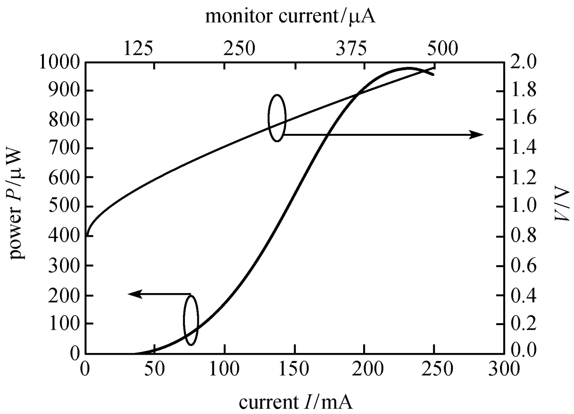

Fig. 6 *P-I* and *V-I* curve

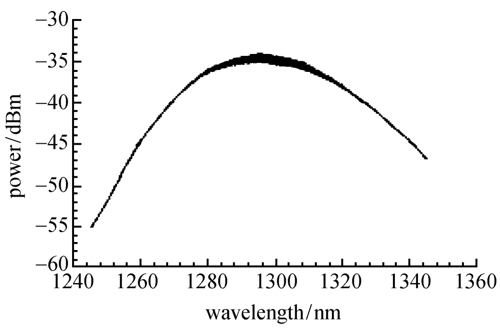

Fig. 7 Amplified spontaneous emission spectrum under a 300 mA driving current

is about 57 nm, the ripple is less than 1 dB, and the spontaneous-emission power from the input and the output fiber are 97 μW and 750 μW, respectively. Figures 8 and 9 are the device's small-signal-gain property as a function of driving current and gain property as a function of output power, respectively. The maximal small-signal gain is more than 18 dB. The saturation output power is about 13 dBm.

For a straight travelling-wave pigtailed SOA without isolators, the driving current can hardly exceed 100 mA because of the serious gain ripple, the spontaneous emission output power from the fiber is commonly less than 90 μW under the driving condition without an input signal, and the fiber-to-fiber small-signal gain is commonly less than 15 dB. Obviously, the method of asymmetrical active waveguide is useful to improve the gain property of SOAs.

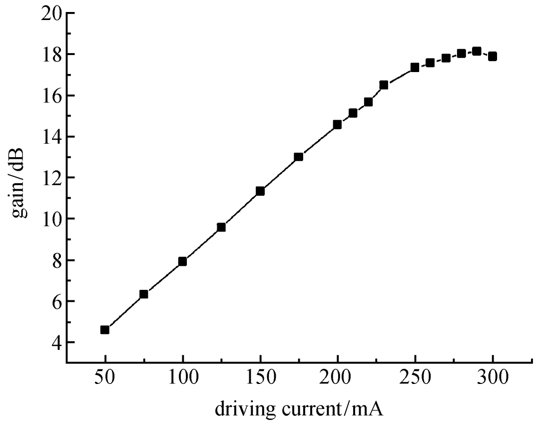

Fig. 8 Small-signal gain, as a function of driving current, with 4 μW input signal

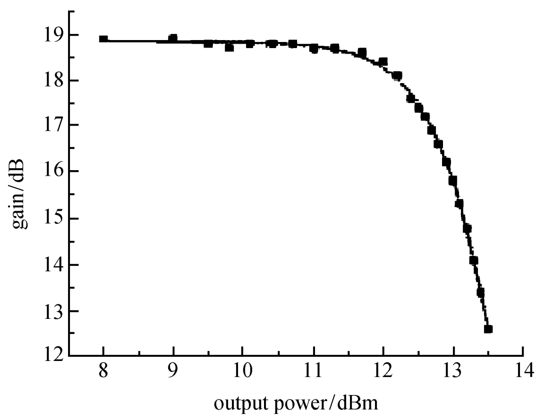

Fig. 9 Gain, as a function of output power

4 Conclusion

The internal distributed optical-feedback suppression of the asymmetrical curved active waveguides is investigated by modeling and simulation. In experimentation, the SOA with the elaborately-designed asymmetrical curved active waveguide shows remarkable improvement of the gain properties. The performance of the SOA can be further improved by combining this scheme with other feedback-suppression technologies such as angled stripe.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant No. 60377012).

References

1. Cruz F C, Stowe M C, Ye J. Tapered semiconductor amplifiers for optical frequency combs in the near infrared. Optics Letters, 2006, 31(9): 1337–1339
2. Hessler T P, Dupertuis M-A, Deveaud B, Emery J-Y, Dagens B. Optical speedup at transparency of the gain recovery in semiconductor optical amplifiers. Applied Physics Letters, 2002, 81(17): 3119–3121
3. Wang Y, Zhang X L, Huang D X. All-optical NOT and XOR logic operation at 2.5 Gb/s based on semiconductor optical amplifier loop mirror. Chinese Physics, 2004, 13(6): 882–886
4. Herrera J, Ramos F, Marti J. Compensation for dispersion-induced carrier suppression effect in microwave/millimetre-wave optical links using optical phase conjugation in semiconductor optical amplifiers. Electronics Letters, 2006, 42(4): 238–239
5. Tiemeijer L F, Groeneveld C M. Packaged high gain unidirectional 1300 nm MQW laser amplifiers. In: Proceedings of the 45th Electronic Components and Technology Conference. 1995, 751–758
6. Tiemeijer L F, Thijs P J A, van Dongen T, Binsma J J M, Jansen E J. Polarization resolved, complete characterization of 1310 nm fiber pigtailed multiple-quantum-well optical amplifiers. Journal of Lightwave Technology, 1996, 14(6): 1524–1533
7. Marcuse D. Theory of Dielectric Optical Waveguides. Boston: Academic Press, 1974
8. Agrawal G P, Olsson N A. Self-phase modulation and spectral broadening of optical pulses in semiconductor laser amplifiers. IEEE Journal of Quantum Electronics, 1989, 25(11): 2297–2306
9. Taflove A, Hagness S C. Computational Electrodynamics: the Finite-Difference Time-Domain Method. London: Artech House Publishers, 2000
10. Siegman A E. Lasers. California: University Science Books Press, 1986
11. Waterhouse R B. The use of shorting posts to improve the scanning range of probe-fed microstrip patch phased arrays. IEEE Transactions on Antennas and Propagation, 1996, 44(3): 302–309