51
Semiconductor Optical Amplifiers

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51.1   Introduction

The deployment of optical amplifiers in fiber optic communications systems has received widespread attention over the past several years. Signal repeaters are needed to overcome inherent transmission losses including fiber absorption and scattering, distribution losses, and connector and component losses. Traditional repeaters are based on optoelectronic conversion where the optical signal is periodically converted to an electronic signal, remodulated onto a new optical signal, and then transmitted onto the next fiber section. An alternative approach is to use repeaters based on optical amplification. In optical repeaters, the signal is amplified directly without conversion to electronics. This approach offers distinct advantages including longer repeater spacings, simultaneous multichannel amplification, and a bandwidth commensurate with the transmission window of the optical fiber. The deployment of optical amplifiers in operational networks has reduced maintenance costs and provided a path for upgrading the existing fiberplants since the amplifiers and fibers are transparent to signal bandwidth.

Two classes of optical amplifiers are used in fiber-based systems: active fiber amplifiers and semiconductor optical amplifiers (SOAs). In this chapter we concentrate on semiconductor amplifiers. Fiber-based amplifiers have advanced more rapidly into the deployment phase due to their high-output saturation power, high gain, polarization insensitivity, and long excited state lifetime that reduces crosstalk effects. Fiber amplifiers have been successfully used in the 1.55-μm fiber transmission window but are not ideally suited for the 1.31-μm fiber transmission window. Fiber amplifiers are covered in detail in the companion chapter in this handbook. Recent developments in SOAs have led to dramatic improvements in gain, saturation power, polarization sensitivity, and crosstalk rejection. Semiconductor amplifiers also have certain characteristics that make their use in optical networks very desirable: (1) they have a flat gain bandwidth over a relatively wide wavelength range that allows them to simultaneously amplify
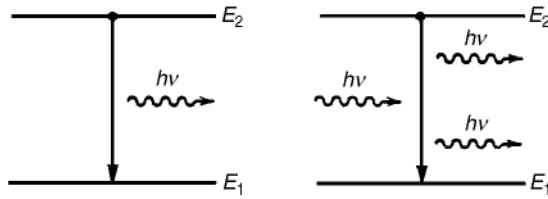
FIGURE 51.1 Spontaneous and stimulated emission occuring between the two energy states of an atom.

signals of different wavelengths, (2) they are simple devices that can be integrated with other semiconductor based circuits, (3) their gain can be switched at high speeds to provide a modulation function, and (4) their current can be monitored to provide simultaneous amplification and detection. Additionally, interest in semiconductor amplifiers has been motivated by their ability to operate in the 1.3-μm fiber transmission window. For these reasons, semiconductor optical amplifiers continue to be studied and offer a complementary optical amplification component to fiber based amplifiers.

In this chapter, we first discuss the principle of operation of SOAs followed by amplifier design considerations. The gain characteristics are described next with discussion on small-signal gain, wavelength dependence, gain saturation, dynamic range, polarization sensitivity, and noise. Amplification of optical pulses and multichannel amplification are treated followed by a brief discussion of applications.

51.2   Principle of Operation

A semiconductor optical amplifier operates on the principle of stimulated emission due to interaction between input photons and excited state electrons and is similar to a laser in its principle of operation. The semiconductor can be treated as a two energy level system with a ground state (valence band) and excited state (conduction band), as shown in Fig. 51.1. Current is injected into the semiconductor to provide an excess of electrons in the conduction band. When a photon is externally introduced into the amplifier, it can cause an electron in the conduction band to recombine with a hole in the valence band, resulting in emission of a second photon identical to the incident photon (**stimulated emission**). As these photons propagate in the semiconductor, the stimulated emission process occurs over and over again, resulting in **stimulated amplification** of the optical input. Since an SOA can amplify input photons, we can assign it a gain. As will be discussed in further detail, the **material gain** is only a function of the basic device composition and operating conditions, whereas the **amplifier gain** defines the relationship between the input and output optical power.

In addition to amplification of the input photons (signal), it is important to consider how noise is generated within the amplifier when an electron in the conduction band spontaneously recombines with a hole without the aid of a photon. This process, known as **spontaneous emission**, results in an emitted photon with energy equal to the energy difference between the electron and hole. Photons created from spontaneous emission will propagate in the amplifier and experience gain through stimulated emission. This process leads to amplification of spontaneous emission and is called **amplified spontaneous emission (ASE)**. ASE is a noise mechanism as it is not related to the input signal and is a random process. Additionally, ASE takes away amplifier gain that would otherwise be available to the signal.

51.3   Types of Semiconductor Optical Amplifiers

SOAs can be classified as either **subthreshold** or **gain clamped**. Subthreshold amplifiers are lasers operated below threshold, and gain-clamped amplifiers are lasers operated above threshold but used as amplifiers. Subthreshold SOAs can be further classified according to whether optical feedback is used. If the SOA amplifies the optical signal in a single pass, it is referred to as a **traveling wave amplifier (TWA)**, as shown in Fig. 51.2. The second type of subthreshold amplifier is a **resonant amplifier**, which contains
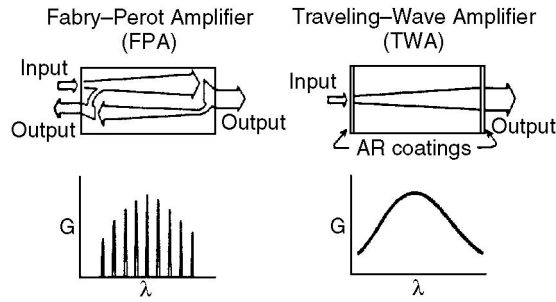
FIGURE 51.2 Classification of semiconductor optical amplifiers. (*Source:* Saitoh, T. and Mukai, T. 1991. In *Coherence, Amplification, and Quantum Effects in Semiconductor Lasers*, Ed. Y. Yamamoto, John Wiley & Sons, New York.)
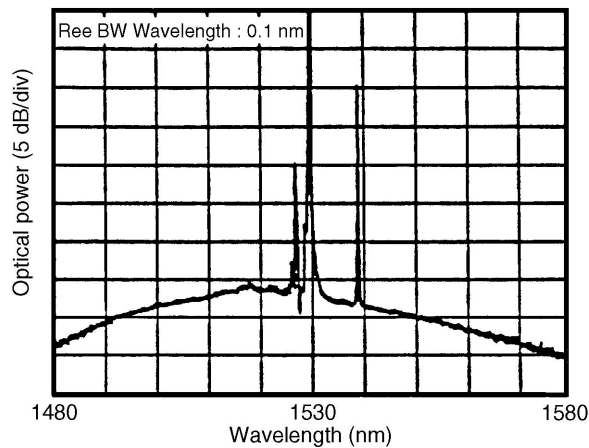

FIGURE 51.3 Output optical spectrum of a gain clamped amplifier with the main lasing mode and the identified amplified signal.

a gain medium and some form of optical feedback. In this case, the gain is resonantly enhanced at the expense of limiting the gain bandwidth to less than that of the TWA case for an equivalent material. An example of a resonant amplifier is the **Fabry–Perot** (FP) **amplifier** shown in Fig. 51.2. The FP amplifier has mirrors at the input and output ends, which form a resonant cavity. The resonant cavity creates an optical **comb filter** that filters the gain profile into uniformly spaced **longitudinal modes** (also see Fig. 51.2). The TWA configuration has a bandwidth limited by the material gain itself but is relatively flat, which is desirable for an optical communications system application. Typical 3-dB bandwidths are on the order of 60–100 nm. Although the FP amplifier exhibits very large gain at wavelengths corresponding to the longitudinal modes, the gain rapidly decreases when the input wavelength is offset from the peak wavelengths. This makes the gain strongly dependent on the input wavelength and sensitive to variations that may occur in an optical communications system.

Gain-clamped semiconductor optical amplifiers operate on the principle that the gain can be held constant by a primary lasing mode and signals can be amplified if their wavelength is located away from the main lasing mode. Laser structures suitable for this approach are **distributed feedback (DFB)** and **distributed Bragg reflector (DBR)** lasers, which lase into a single longitudinal mode. Since only a single mode oscillates, the remainder of the gain profile is available for amplification. Figure 51.3 illustrates the output optical spectra of a gain-clamped amplifier with the main lasing mode and the amplified signal identified. A primary advantage of gain clamped amplifiers is a reduction in crosstalk in multichannel amplification applications discussed in Section 51.7.

51.4   Design Considerations

For optical communications systems, traveling wave SOAs are desirable due to the wide gain bandwidth and relatively small variation in gain over a wide signal wavelength range. Most practical TWAs exhibit some small ripples in the gain spectrum that arise from residual facet reflections. A large effort has been devoted to fabricate amplifiers with low cavity resonances to reduce **gain ripple**. For an amplifier with facet reflectivities R_1 and R_2, the peak-to-valley ratio of the output intensity ripple is given by [Dutta and Simpson, 1993]

$$V = \left[\frac{1 + G_s\sqrt{R_1 R_2}}{1 - G_s\sqrt{R_1 R_2}} \right] \tag{51.1}$$

where G_s is the single-pass gain of the amplifier. For the ideal case R_1, $R_2 \rightarrow 0$, $V = 1$, that is, no ripple at cavity mode frequencies in the output spectrum. A practical value of V should be less than 1 dB. Thus, for an amplifier designed to provide gain $G_s = 25$ dB, the facet reflectivities should be such that $\sqrt{R_1 R_2}$ must be less than 3.6×10^{-4}.

Three principle schemes exist for achieving low facet reflectivities. They are: (1) antireflection dielectric coated amplifiers [Olsson, 1989], (2) buried facet amplifiers [Dutta et al., 1990], and (3) tilted facet amplifiers [Zah et al., 1987]. In practice, very low facet reflectivities are obtained by monitoring the amplifier performance during the coating process. The effective reflectivity can be estimated from the peak-to-peak ripple at the FP mode spacings caused by residual reflectivity. Reflectivities less than 10^{-4} over a small range of wavelengths are possible using antireflection coatings [Olsson, 1989]. In buried facet structures, a transparent window region is inserted between the active layer ends and the facets [Dutta et al., 1990]. The optical beam spreads in this window region before arriving at the semiconductor–air interface. The reflected beam spreads even farther and does not couple efficiently into the active layer. Such structures can provide reflectivities as small as 10^{-4} when used in combination with antireflection dielectric coatings. Another way to suppress the FP modes of the cavity is to slant the waveguide (gain region) from the cleaved facet so that the light incident on it does not couple back into the waveguide [Zah et al., 1987]. The process essentially decreases the effective reflectivity. A combination of antireflection coating and the tilted stripe can produce reflectivities less than 10^{-4}. A disadvantage of this structure is that the effective reflectivity of the higher order modes can increase, causing the appearance of higher order modes at the output which may reduce fiber-coupled power significantly.

Another important consideration in amplifier design is choice of semiconductor material composition. The appropriate semiconductor bandgap must be chosen so that light at the wavelength of interest is amplified. For amplification of light centered around 1.55 μm or 1.31 μm, the InGaAsP semiconductor material system must be used with optical gain centered around the wavelength region of interest.

51.5   Gain Characteristics

The fundamental characteristics of the optical amplifiers such as small-signal gain, gain bandwidth, gain saturation, polarization sensitivity of the gain, and noise are critical to amplifier design and use in systems. The component level behavior of the optical amplifier can be treated in a manner similar to electronic amplifiers.

Small-Signal Gain and Bandwidth of Traveling Wave Amplifiers

The optical power gain of an SOA is measured by injecting light into the amplifier at a particular wavelength and measuring the optical output power at that wavelength. The gain depends on many parameters, including the input signal wavelength, the input signal power, material gains and losses, amplifier length, current injection level, etc. For a TWA operated with low-input optical power, the small-signal gain is
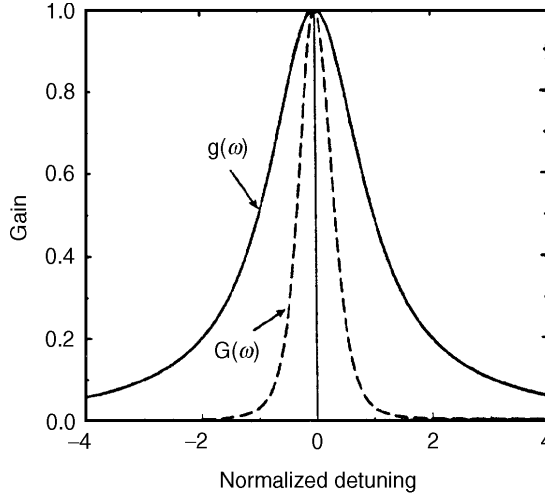
FIGURE 51.4 Lorentzian material gain profile and the corresponding amplifier gain spectrum for an amplifier modeled as a two-level atomic system. (*Source:* Agrawal, G.P. 1995. In *Semiconductor Lasers: Past, Present, and Future*, Ed. G.P. Agrawal, AIP Press.)

given by the unsaturated single-pass gain of the amplifier

$$G_0(\nu) \;=\; \frac{P_{\text{out}}(\nu)}{P_{\text{in}}(\nu)} \;=\; \exp[(\Gamma g_0(\nu) - \alpha_m)L] \qquad (51.2)$$

where Γ is the **optical mode confinement factor**, g_0 is the **unsaturated material gain coefficient**, α_m is the **absorption coefficient**, and L is the amplifier length. The material gain coefficient g_0 has a Lorentzian profile if the amplifier is modeled as a two-level atomic system. An important distinction is made between the material gain bandwidth and the amplifier signal bandwidth. The 3-dB bandwidth (full width at half-maximum) of g_0 is $\Delta\nu_g = 1/\pi T_2$, and the 3-dB bandwidth of the TWA signal gain [Eq. (51.2)], is

$$\Delta\nu_A \;=\; \Delta\nu_g\!\left(\frac{\ell\mathbf{n}2}{\Gamma g_0 L - \ell\mathbf{n}2}\right) \qquad (51.3)$$

Figure 51.4 illustrates that the material gain bandwidth is greater than the amplifier small-signal gain bandwidth.

Small-Signal Gain and Bandwidth of FP Amplifiers

The small-signal power transmission of an FP amplifier shows enhancement of the gain at transmission peaks and is given by [Saitoh and Mukai, 1991]

$$G_0^{FP}(\nu) \;=\; \frac{(1 - R_1)(1 - R_2)G_0(\nu)}{\left(1 - \sqrt{R_1 R_2}\,G_0(\nu)\right)^2 + 4\sqrt{R_1 R_2}\,G_0(\nu)\sin^2[\pi(\nu - \nu_0)/\Delta\nu]} \qquad (51.4)$$

where ν_0 is the cavity resonant frequency and $\Delta\nu$ is the **free spectral range** (also called the longitudinal mode spacing) of the SOA. The single-pass small-signal gain G_0 is given by Eq. (51.2). Note that for $R_1 = R_2 = 0$, G_0^{FP} reduces to that of a TWA. The 3-dB bandwidth B (full width at half-maximum) of an FP
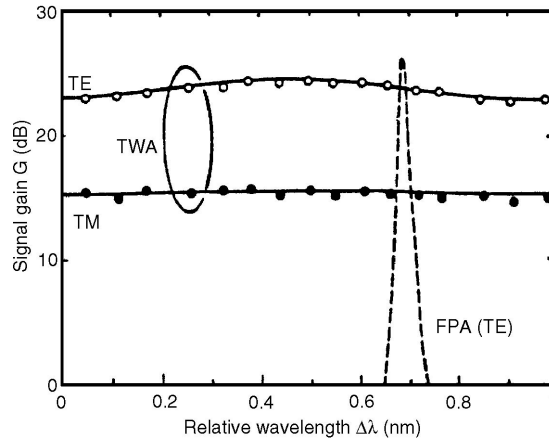
FIGURE 51.5 Unsaturated gain spectra of a TWA and an FP amplifier within one free spectral range. (*Source:* Saitoh, T., Mukai, T., and Noguchi, Y. 1986. In *First Optoelectronics Conference Post-Deadline Papers Technical Digest*, Paper B11-2, The Institute of Electronics and Communications Engineers of Japan, Tokyo.)

amplifier is expressed as [Saitoh and Mukai, 1991]

$$B = \frac{2\Delta n}{\pi} \sin^{-1}\left[\frac{1 - \sqrt{R_1 R_2} G_0}{\left(4 G_0 \sqrt{R_1 R_2}\right)^{1/2}} \right] \tag{51.5}$$

whereas the 3-dB bandwidth of a TWA is three orders of magnitude larger than that of the FP amplifier since it is determined by the full gain width of the amplifier medium itself. Figure 51.5 shows the small-signal (unsaturated) gain spectra of a TWA within one free spectral range [Saitoh, Mukai, and Noguchi, 1986]. Solid curves represent theoretical FP curves fitted to the TWA experimental data. Experimental FP amplifier data are also shown (dashed curve). It can be seen that the signal gain fluctuates smoothly over the entire free spectral range of the TWA in contrast to the FP amplifier, where signal gain is obtained only in the vicinity of the resonant frequencies.

Wavelength Dependence of Gain

As seen previously, the amplifier gain varies with the input wavelength for both the TWA and FP cases. The peak and width of the gain can also vary as a function of injection current. The material gain vs. wavelength for a typical amplifier is shown in Fig. 51.6 as a function of injection current. As the injection current increases, the peak gain increases and the location of the peak gain shifts toward shorter wavelengths.

Gain Saturation

The gain of an optical amplifier, much like its electronic counterpart, can be dependent on the input signal level. This condition, known as **gain saturation**, is caused by a reduction in the number of electrons in the conduction band available for stimulated emission and occurs when the rate of input photons is greater than the rate at which electrons used for stimulated emission can be replaced by current injection. The time it takes for the gain to recover is limited by the spontaneous lifetime and can cause intersymbol interference among other effects, as will be described. The **saturated material gain coefficient** is given by

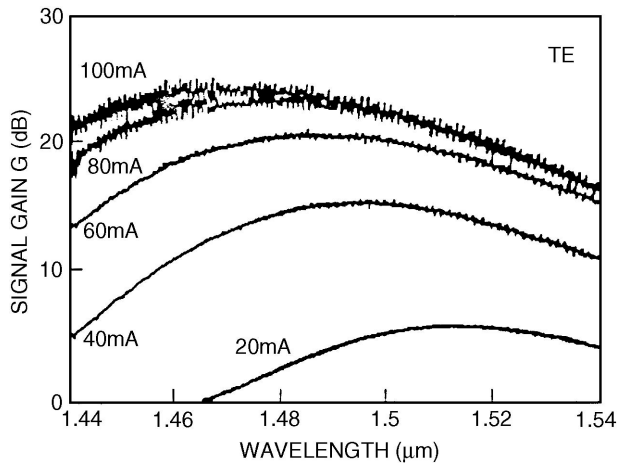$$g(v) = \frac{g_0(v)}{1 + \frac{P}{P_s}} \tag{51.6}$$

FIGURE 51.6 Gain spectrum of a TWA at several current levels. (*Source:* Saitoh, T. and Mukai, T. 1987. *Electron. Lett.*, 23:218.)
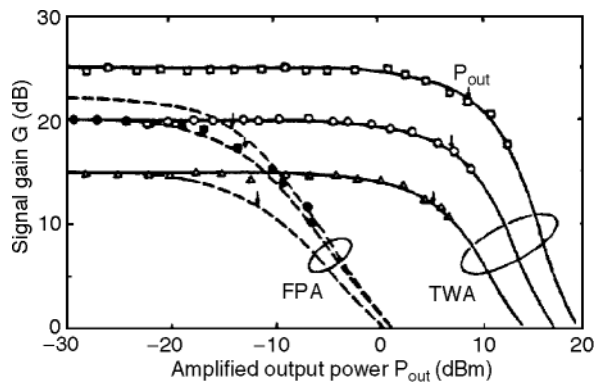

FIGURE 51.7 Theoretical and experimental signal gain of a TWA and FP amplifier as a function of amplified output power. (*Source:* Saitoh, T. and Mukai, T. 1987. *Electron. Lett.*, 23:218.)

where g_0 is the unsaturated material gain coefficient, P is the total optical power in the active layer of the amplifier, and P_s is the saturation power defined as the light intensity that reduces the material gain g to half its value ($g_0/2$). In general, the optical saturation power is related to the carrier lifetime but can be reduced as the optical intensity in the amplifier increases. The single-pass saturated signal gain $G(v)$ is given by [Saitoh and Mukai, 1991]

$$G(v) = G_0(v)\exp\left[-\frac{P_{out} - P_{in}}{P_s}\right] = G_0\exp\left[-\frac{G-1}{G}\frac{P_{out}}{P_s}\right] \qquad (51.7)$$

where P_{in} and P_{out} are the input and the output optical powers and G_0 is the unsaturated gain given by Eq. (51.2). Figure 51.7 shows experimental gain saturation characteristics of both FP and TWAs [Saitoh and Mukai, 1987] along with theoretical curves.

Dynamic Range

The dynamic range is defined as the range of input power for which the amplifier gain will remain constant. The gain saturation curves shown in Fig. 51.8 [Adams et al., 1985] show the relationship between input power and gain for various current injection levels. The flat regions are the unsaturated regions.
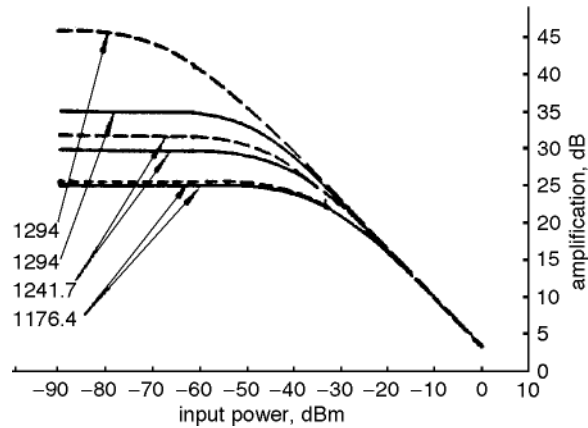
FIGURE 51.8   Effect of amplifier injection current on variation in gain as a function of optical input power. Flat regions are unsaturated gain. Range of unsaturated gain vs. input power changes as a function of unsaturated gain. Values indicated on curves are for injected current density. Dashed curves are obtained without taking into account ASE. (*Source:* Adams, M.J. et al. 1985 *IEEE Proceedings* Part J, 132:58.)
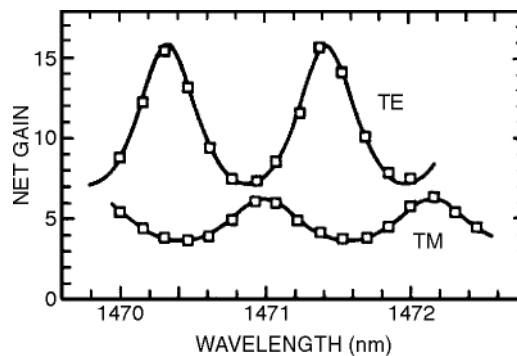

FIGURE 51.9   Theoretical and experimental gain spectra of TE- and TM-polarized input signals. (*Source:* Jopson, R.M. et al. 1986. *Electron. Lett.*, 22:1105.)

As the gain increases, the 3-dB rolloff moves toward lower input power, leading to a decrease in dynamic range.

Polarization Sensitivity

In general, the optical gain of an SOA is **polarization dependent**. It differs for the transverse-electric (TE) and transverse-magnetic (TM) polarizations. Figure 51.9 shows the gain spectra of a TWA for both TE and TM polarization states [Jopson et al., 1986]. The polarization-dependent gain feature of an amplifier is undesirable for lightwave system applications where the polarization state changes with propagation along the fiber.

Several methods of reducing or compensating for the gain difference between polarizations have been demonstrated [Saitoh and Mukai, 1991]. A successful technique that leads to polarization dependent gain on the order of 1 dB involves the use of material strain [Dubovetsky et al., 1994]. The measured gain as a function of injection current for TE and TM polarized light for a tilted-facet amplifier is shown in Fig. 51.10 [Zah et al., 1987]. Figure 51.11 shows the measured optical gain plotted as a function of output power for regular double heterostructure (DH) and multi-quantum well (MQW) amplifiers
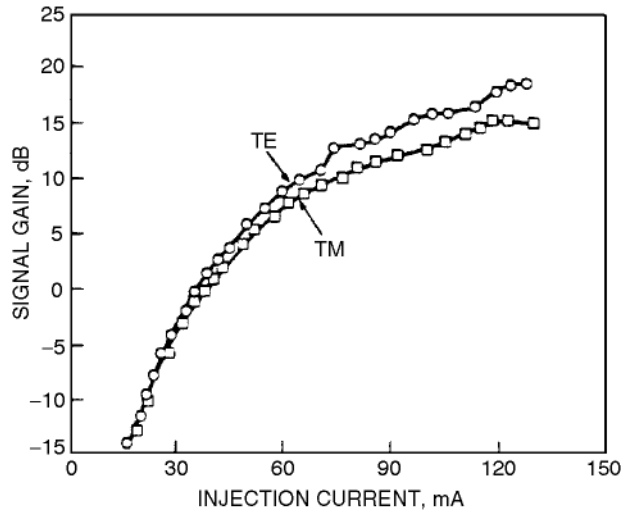
FIGURE 51.10   Measured gain as a function of injection current. (*Source:* Zah, C.E. et al. 1987. *Electron. Lett.*, 23:990.)
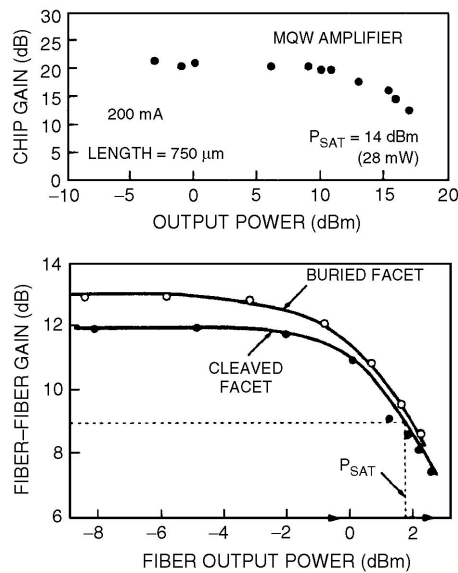

FIGURE 51.11   Measured gain as a function of output power for regular double heterostructure and multiquantum well amplifiers. (*Source:* Dutta, N.K. and Simpson, J.R. 1993. *Progress in Optics*, Ed. E. Wolf, Vol. 31, North-Holland, Amsterdam.)

[Dutta and Simpson, 1993]. The multiquantum well amplifier result is shown for the TE mode, whereas the gain difference between TE and TM modes for double heterostructure amplifiers was less than 1 dB.

Amplifier Noise

Semiconductor optical amplifiers add noise to the amplified optical signal in the form of amplified spontaneous emission. This noise can reduce the signal-to-noise ratio of the detected output and can reduce the overall gain available to the signal through gain saturation. ASE forms a noise floor with a wavelength dependence approximately that of the gain. Figure 51.12 shows a typical optical spectrum at
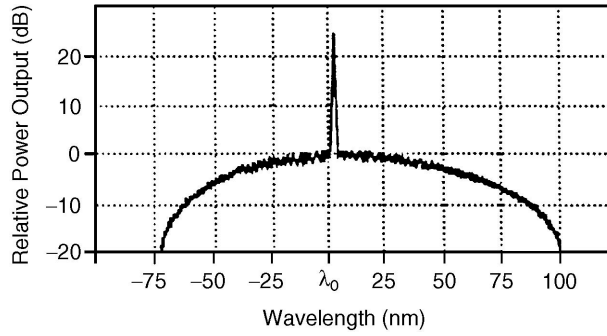
FIGURE 51.12 A typical optical spectrum at the output with the amplified signal and the amplified spontaneous emission. (*Source:* BT&D Technologies, Publication No. DS007, 1992.)

the output with the amplified signal and the ASE. Semiconductor optical amplifiers can be characterized by a noise figure. Typical noise figures are in the range of 5–8 dB and can be calculated from the carrier density due to current injection N, the carrier density required to reach transparency N_0, the saturated gain g, and the internal amplifier losses a_{int} [Saitoh and Mukai, 1991]:

$$F_n = \frac{SNR_{in}}{SNR_{out}} = 2\left(\frac{N}{N-N_0}\right)\left(\frac{g}{g-\alpha_{int}}\right) \tag{51.8}$$

In calculating signal-to-noise ratio, it is useful to consider the total output of an SOA after it has been converted to an electronic signal using a photodetector. Here we consider direct detection where a square law detector is used to convert the optical signal to an electrical signal. In addition to the amplified signal, several noise terms result from interaction between signal and noise in the square law detection process [Mukai, Yamamoto, and Kimura, 1982; Yamamoto, 1980]: amplified signal shot noise, spontaneous emission shot noise, signal-spontaneous beat noise, spontaneous-spontaneous beat noise, and signal excess noise. The first and third types of noise are proportional to the signal power, whereas the second and fourth types of noise are generated from the ASE that exists independently of the input signal. For a single amplifier, the two beat noise terms dominate as they are G times stronger [Saitoh and Mukai, 1991] than the shot noise contributions. The spontaneous-spontaneous beat noise can be reduced by loading a narrowband optical filter matched to the signal frequency, since this noise arises from the beat between the ASE components over a wide gain spectrum [Saitoh and Mukai, 1991]. For a direct detection system with a high-gain optical amplifier prior to the photodetector, the electrical SNR is given by [Jopson and Darcie, 1991]

$$SNR_{dd} = \frac{(P_{in}/h\nu)^2}{[FP_{in}/h\nu + (F/2)^2 \delta\nu_{opt}]B_e} \tag{51.9}$$

where the input power to the amplifier is P_{in}, the optical bandwidth of the output of the amplifier is $\delta\nu_{opt}$, the receiver electrical bandwidth is B_e, the amplifier noise figure is F, and the optical frequency is ν.

51.6 Pulse Amplification

The large bandwidth of a TWA suggests that they are capable of amplifying very fast optical pulses without significant pulse distortion. However, the output pulses can be distorted either when the optical power exceeds the saturation power or when the pulse width gets short compared to the carrier lifetime [Agrawal and Olsson, 1989].
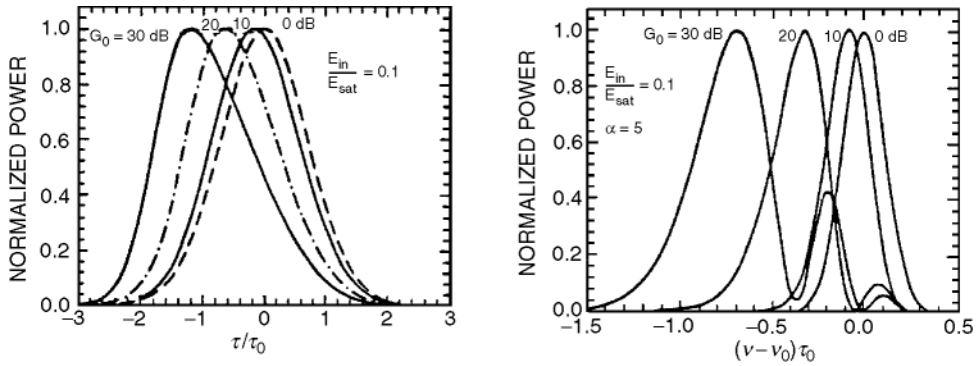
FIGURE 51.13 Output pulse shapes and spectra for several values of the unsaturated gain when the input pulse is Gaussian. The ratio of input pulse energy to the saturation energy is 0.1. (*Source:* Agrawal, G.P. and Olsson, N.A. 1989. *IEEE J. Quant. Electron.*, 25:2297.)
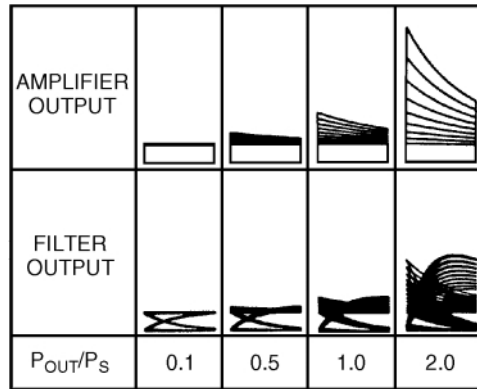

FIGURE 51.14 Effect of gain saturation of binary bit eye diagram. Upper figures show amplifier output as output power varies with saturation power. Decrease in bit height as a function of time is due to time constant of gain saturation. Lower figures show effect of electronic bandpass filtering prior to level discrimination in an optical receiver. Bit period is half the gain saturation time constant. (*Source:* Jopson, R.M. and Darcie, T.E. 1991. In *Coherence, Amplification, and Quantum Effects in Semiconductor Lasers*, Ed. Y. Yamamoto, John Wiley & Sons, New York.)

The Gaussian pulse and its spectrum for various small-signal gains G_0 when the pulse width τ_p is much smaller compared to carrier lifetime τ_c is shown in Fig. 51.13 [Agrawal and Olsson, 1989]. The input pulse energy E_{in} is equal to 0.1 times the saturation energy E_{sat} of the SOA. The pulse gets distorted such that its leading edge becomes sharper compared with the trailing edge. When the pulse width is on the order of the carrier lifetime, saturation can lead to a closing of the eye of a pseudo-random bit stream, as shown in Fig. 51.14 [Jopson and Darcie, 1991]. If a sequence of short pulses (bits) are injected, where the bit duration is less than the carrier lifetime, **bit patterning** can occur.

When the pulse width is comparable to τ_c, the saturated gain has time to recover during the pulse. Figure 51.15(a) shows [Agrawal and Olsson, 1989] the effect of gain recovery on the output pulse shape when the input pulse is Gaussian. As the input pulse width is increased, the output pulse becomes less asymmetric and becomes broader than the input pulse. The gain recovery mainly affects the trailing edge of the pulse. In the presence of partial gain recovery, the output spectrum also becomes less asymmetric and the spectral shift becomes smaller. When $t_p \gg t_c$, the gain recovery is complete and the output pulse as well as its spectrum become symmetric. Figure 51.15(b) shows [Agrawal and Olsson, 1989] the output
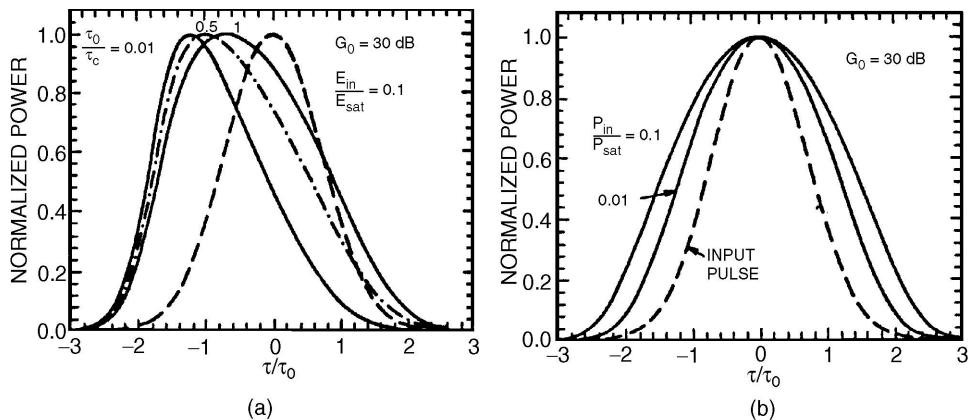
FIGURE 51.15 Output pulse shapes for (a) several values of pulse width in the partial gain recovery regime and (b) several values of input power when the pulse width is much larger than the carrier life time. (*Source:* Agrawal, G.P. and Olsson, N.A. 1989. *IEEE J. Quant. Electron.*, 25:2297.)
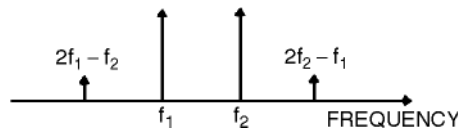

FIGURE 51.16 Generation of new frequencies due to FWM interaction between the signals at frequencies f_1 and f_2.

pulses when $t_p \gg t_c$. The pulse is also broadened because the peak experiences less amplification than the wings because of gain saturation.

51.7 Multichannel Amplification

A TWA can greatly simplify optical repeaters used in **wavelength-division multiplexed** (WDM) systems, since its wide gain bandwidth allows a single amplifier to simultaneously amplify signals of different wavelengths. In practice, however, several phenomena in SOAs can induce **interchannel crosstalk: cross-gain modulation (XGM)** and **four-wave mixing (FWM)**. To understand XGM, the optical power in Eq. (51.6) should be replaced by the total power in all channels. Thus, the gain of a specific channel is saturated not only by its own power but also by the power of other channels. If channel powers change depending on bit patterns, as in amplitude-shift keying (ASK), then the signal gain of one channel changes from bit to bit, and the change also depends on the bit pattern of the other channels [Agrawal, 1995]. The amplified signal appears to fluctuate randomly, which degrades the signal-to-noise ratio at the receiver. This crosstalk can be largely avoided by operating SOAs in the unsaturated regime. It is absent for phase-shift keying (PSK) and frequency-shift keying (FSK) systems, since the power in each channel, and therefore the total power, remains constant with time [Agrawal, 1995].

The four-wave mixing causes the generation of new optical frequencies in closely spaced WDM systems. This phenomenon is similar to interharmonic distortion in electronic systems. The presence of multiple wavelengths in the amplifier results in nonlinear amplification. Two wavelengths can generate additional optical frequencies, as shown in Figure 51.16. If these frequencies coincide with existing channels, crosstalk results. This crosstalk can be incoherent [Darcie and Jopson, 1988] or coherent [Blumenthal and Kothari, 1996] in direct detection systems and limitations on the input power can be computed for each case [Darcie and Jopson, 1988; Blumenthal and Kothari, 1996] for a given number of channels,
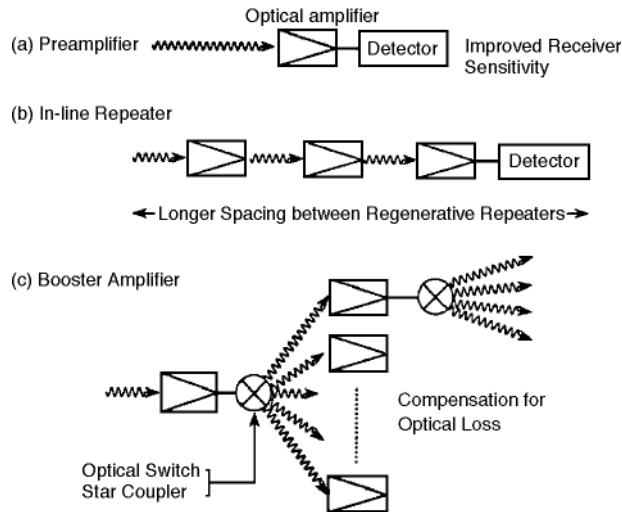
FIGURE 51.17 Configurations for SOA applications. (*Source:* Yamamoto, Y. and Mukai, T. 1989. *Optical Quant. Electron.*, 21:S1.)

channel spacing, and amplifier gain. Unequal channel spacing can be used to minimize crosstalk effects due to FWM [Forghieri et al., 1994].

51.8   Applications

Semiconductor optical amplifiers have multiple potential uses in optical communication systems (see Fig. 51.17). Power boosting, optical preamplification prior to photodetection, compensation of distribution losses, and in-line amplification are examples of transmission applications. In-line amplifiers eliminate the need for electronic regenerators and allow multichannel amplification. As a booster amplifier, the transmission distance can be increased by 10 to 100 km. SQAs can be integrated with a semiconductor laser to obtain a high-power, narrow-linewidth optical source useful for coherent communication systems [Koch and Koren, 1991; Glance et al., 1992]. Transmission distance can also be increased by putting an amplifier to operate the receiver in the shot noise limit.

Another potential application of SOAs is in the area of **dispersion compensation**. Midpoint dispersion compensation in a fiber link is achieved by using the SOA to perform frequency conversion through four-wave mixing [Tatham, Sherlock and Westbrook, 1993]. This process inverts the ordering of the optical spectrum within the pulse, thereby reversing the effect of dispersion in the second section of fiber. An SOA can also be used as a booster amplifier to balance the effect of **frequency chirp** in direct drive semiconductor lasers [Yazaki et al., 1992].

A third class of application, **photonic switching**, may require switching of signals in space and/or wavelength. SOAs can be integrated in **space switches** as transmission gates [Gustavsson et al., 1992] with very high-extinction ratio in the off state. SOAs can also be used to translate signals between wavelengths using wavelength conversion techniques such as cross-gain saturation [Valiente, Simon, and LeLigne, 1993] or four-wave mixing [Zhou et al., 1994].

Acknowledgments

Defining Terms

Absorption coefficient: Amount of optical power absorbed in material per unit length.

Amplified spontaneous emission (ASE): Stimulated replication of photons that were originally generated by spontaneous emission.

Amplifier gain: Ratio of optical power at input of amplifier to optical power at output of amplifier.

Bit patterning: Influence of a previous bit on subsequent bits in a bit stream due to gain saturation effects.

Comb filter: Transfer function of resonant structure that has repeating periodic passband.

Cross-gain modulation (XGM): Modulation of amplifier gain at one wavelength due to variation in signal at another wavelength.

Dispersion compensation: Realignment of phases for different spectral components in a pulse so that pulse broadening can be reduced.

Distributed Bragg reflector laser (DBR): Laser structure with Bragg reflectors at ends of cavity.

Distributed feedback laser (DFB): Laser structure with Bragg reflector in middle of cavity and without mirrors at ends.

Fabry–Perot (FP) amplifier: Resonant amplifier using mirrors at input and output for feedback.

Four-wave mixing (FWM): Generation of new frequencies, or intermodulation products, through gain nonlinearity.

Free spectral range: Spacing between longitudinal modes in resonant cavity.

Frequency chirp: Change in optical frequency as a function of time across a modulated optical signal.

Gain clamped: Operation of gain structure above condition where gain equals cavity losses.

Gain ripple: Periodic variation in gain over amplifier bandwidth.

Gain saturation: Reduction in gain due to increase in optical power.

Interchannel crosstalk: Transfer of information between channels due to a physical crosstalk mechanism.

Longitudinal modes: Single passband of a resonant cavity with comb-filter type transfer function.

Material gain: Number of photons generated per incident photon per unit length of material.

Optical mode confinement factor: Amount of optical signal that passes through amplifying medium.

Photonic switching: Switching or redirection of optical signals without conversion to electronics.

Polarization dependent: Variation in gain for different orientations of optical field.

Resonant amplifier: Amplifier with gain and feedback.

Saturated material gain: Optical signal-level dependent gain.

Space switches: Connection through spatially discrete elements.

Spontaneous emission: Emission of a photon by random transition from a high-energy state to a low-energy state.

Stimulated amplification: Stimulated replication of photons through stimulated emission.

Stimulated emission: Emission of a photon due to transition from a high-energy state to a low-energy state that was caused by an initial photon.

Subthreshold: Operation of gain structure below condition where gain equals cavity losses.

Traveling wave amplifier (TWA): Single-pass amplifier with optical gain.

Unsaturated material gain coefficient: Gain provided to optical signal that is not signal-level dependent.

Wavelength-division multiplexing (WDM): Transmission of simultaneous channels on parallel optical wavelengths.

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