OPTICAL AMPLIFIERS

HISTORICAL PERSPECTIVE

"Optical fibers will enable unheard-of data transfer capacities!" This has been a mantra for two decades. In the late 1970s, it was understood that high-speed, long-distance communications eventually would be dominated by optical fiber technologies because of silica fiber's extremely low loss and high bandwidth. At silica's wavelength region of minimum attenuation, 1.55 μm, the loss is as low as 0.2 dB/km, and the capacity as high as 25,000 GHz.

Yet, in the late 1980s, when point-to-point 1.55 μm optical-fiber transmission systems were deployed across the Atlantic and Pacific Oceans, the "blazing" speeds of these long-distance systems were a mere 250 Mbit/s. Even experimental systems were limited in speed to approximately 10 Gbit/s. Both operational and experimental systems required optoelectronic signal regenerators every several tens of kilometers, not a very long-distance true "optical" system. The results, of course, were far below the promised potential of the optical fiber's multiterabit/s capacity.

The advent of the erbium-doped fiber-optic amplifier in the late 1980s (1) and its ability to amplify signals with a bandwidth of some 2 THz heralded a true revolution in capacity for optical communication systems. Now operational systems of 100 Gbit/s are planned for imminent deployment, and experimental systems have recently broken the terabit/s barrier (2).

Imagine building an electronic circuit without using electronic amplifiers. The performance would be so limited as to make many circuits undesirable, and circuit designers would be trying all sorts of tricks trying to "eke out" ounces of performance.

This was the situation in optical fiber communications until about 1989 because there was no practical all-optical amplifier. Until then, optical signals required periodic optoelectronic regeneration to overcome inherent optical fiber attenuation and component losses. In regeneration, a weak optical signal is (1) received by a photodetector, (2) converted into an electronic signal, (3) amplified, and finally (4) used to drive a semiconductor laser, thereby reproducing the originally transmitted signal at full strength. Not only are regenerators expensive and waste time in converting the signal from photons to electrons and back again to photons, but they are quite performance limiting because they operate for a signal at only a single bit rate, modulation format, and incoming wavelength.

What was desperately needed was an all-optical amplifier. The ideal amplifier would provide a transparent box and take any input optical signal over a broad range of wavelengths and amplify it without introducing significant signal distortion or noise. It would provide gain to the optical signal while being insensitive to its bit rate, modulation format, power level, or wavelength. It would also be a bonus if the optical amplifier were also cheaper and more reliable than electronic regenerators.

The wish list was answered in full in the late 1980s with the invention of the erbium-doped fiber amplifier (EDFA) by groups at the University of Southampton, AT&T Bell Labs, and Nippon Telephone and Telegraph. As its name implies, the amplifier consists of a meters-long length of glass fiber doped with ions of the rare-earth metal erbium. The fiber acts as an active amplifying medium when the erbium ions experience a population inversion upon being excited to a higher energy level, just as in the active medium of a laser. A pump source can raise the energy level of the erbium ions from their normal lowest energy state to a metastable higher energy state. They remain there for some useful length of time until an incoming signal photon stimulates an ion to fall to a lower energy level, producing a new photon at the same wavelength and phase (i.e., coherent) with respect to the original signal photon.

To pump the erbium ions to a higher-energy state, infrared radiation from a diode laser emitting at 0.98 μm or 1.48 μm, wavelengths preferentially absorbed by erbium, is coupled into the fiber amplifier along with the 1.55 μm signal. Because the pumped-up erbium ions have only a finite lifetime of several milliseconds, they eventually spontaneously decay to a lower energy level when not stimulated by a signal photon. This spontaneous energy drop emits a photon but this time at a random wavelength and phase. The stimulated and spontaneous emissions are considered, respectively, as gain and additive noise.

As soon as the erbium-doped fiber amplifier was announced, it rapidly stole center stage as a "great equalizer" that benefited a multitude of optical systems, including long distance, soliton, and multiwavelength. The fiber amplifier has several critical advantages over traditional optoelectronic regenerators, including

1. Erbium ions naturally emit light over the wavelength range from 1.53 μm to 1.56 μm (i.e., ≈3 THz); this is the range of the fiber's minimum attenuation, and also it means that the fiber amplifiers can amplify many different-wavelength signals (i.e., wavelength-division multiplexing, WDM) simultaneously over a wide region (see Fig. 1).
2. Gain as high as 40 dB can be routinely achieved with 20 dB to 30 dB gain amplifiers now commercially available.

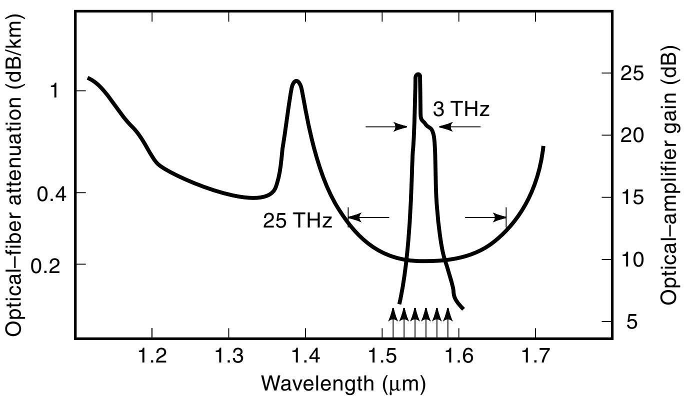


Figure 1. Spectra for the loss of the optical fiber and the gain of the erbium-doped optical amplifier.

3. The amplifier noise figure (based on the additive spontaneous noise) is only about 4 dB to 5 dB. That is nearly as low as the theoretical quantum limit of 3 dB.
4. The optical coupling loss is minimal because both the transmission fiber and the erbium-doped fiber have a circular cross section.
5. The gain is practically independent of the polarization of the signal because the erbium-doped fiber is circularly symmetrical.

Another key advantage of fiber amplifiers is that, compared to the time of an individual digital bit, the lifetime of erbium in its metastable state ranges from milliseconds for a single amplifier to microseconds for a chain of amplifiers. Such a long lifetime becomes extremely important when an incoming signal is too intense to be accommodated by the finite available amplifier gain, thereby causing the effective gain for this signal to diminish. For example, a 100 mW pump source can't give a 1 W output from a 1 mW input signal, given a normally 30 dB gain amplifier! Critically, the long erbium lifetime ensures that the amplifier's gain will NOT fluctuate quickly, certainly not over the time period of a nanosecond-long digital bit. Such gain fluctuations would produce output bits having a varying amplitude simply due to a varying gain.

Despite all of these key advantages, the fiber amplifier does not solve all of our problems. Whereas a regenerator produces a perfect output signal, the EDFA only amplifies, thereby allowing deleterious effects, such as fiber-induced dispersion (see insert box) and nonlinear effects, to accumulate unimpeded along a transmission path. Still, this disadvantage is a small price to pay for all of the considerable benefits.

Within three years after it was introduced, the fiber amplifier claimed two astounding achievements. In 1991, the fiber amplifier was used as a preamplifier enabling the receiver to recover digital bits having 20 times less optical power. Thus the fiber amplifier became equivalent in performance to heterodyne systems but was easier to implement because a stable local oscillating laser was not required. The next year, a single 5 Gbit/s channel was transmitted uninterrupted along 9,000 km of fiber, the longest distance on earth necessitating transmission of a nonregenerated signal.

These early results were just the beginning. Since then, the erbium-doped fiber amplifier has been a key enabling technology for the recently achieved terabit-per-second optical transmission systems.

BASIC CONCEPTS

Much of the most relevant recent advances in optical communications (i.e., long-distance, multichannel, and soliton systems) can be traced to the incorporation of optical amplifiers. As a simple introduction, optical amplifiers can be thought of as a laser (gain medium) with a low feedback mechanism whose excited carriers amplify an incident signal but do not generate their own coherent signal (3).

Similar to electronic amplifiers, optical amplifiers are used to compensate for signal attenuation resulting from distribution, transmission, or component-insertion losses (4,5). As shown in Fig. 2, all amplifiers provide signal gain G, but also introduce additive noise (variance = σ^2) into the system. Amplifiers require some form of external power to provide the energy for amplification. A voltage source is required for the electrical amplifier, and a current or optical source is required for the optical amplifier. This current or optical source is used to pump carriers into a higher excited energy level. Then given an incident signal photon, some of these carriers experience stimulated emission and emit a photon at the input signal wavelength. Now we discuss the fundamental characteristics, systems issues, and potential applications for optical amplifiers in optical communication systems.

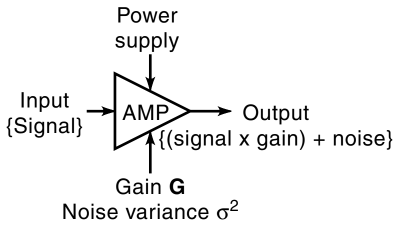


Figure 2. Basic amplifier characteristics.

The original motivation for the recent widespread research was to replace the regenerators in long-haul transoceanic fiber-optic systems which were located every ≈50 km along the entire multimegameter span. Such regenerators correct for fiber attenuation and chromatic dispersion by detecting an optical signal and then retransmitting it as a new signal using its own internal laser, as illustrated in Fig. 3. Regenerators (being a hybrid of optics and electronics) are expensive, electronically bit-rate, and modulation-format specific, and waste much power and time in converting the signal from photons to electrons and back again to photons. In contrast, the optical amplifier is ideally a transparent box which provides gain and is also insensitive to the bit-rate, modulation-format, power, and wavelengths of the signal(s) passing through it. The signals remain in optical form during amplification, and optical amplifiers are potentially cheaper and more reliable than regenerators. However, the optical amplifier is not an ideal device because (1) it provides only a limited amount of output power before the gain diminishes because only a finite number of excited carriers is available to amplify an intense input signal; (2) the gain spectrum is not necessarily flat over the entire region in which signals may be transmitted; (3) the additive noise causes a degradation in receiver sensitivity; and (4) fiber dispersion and nonlinear effects are allowed to accumulate unimpeded. We note here that for ultralong-distance systems (1) the signal wavelength must be near 1.55 μm for lowest attenuation and (2) dispersion-shifted fiber must be used so that the dispersion parameter is close to zero for the ≈1.55 μm signal wavelength.

The three basic system configurations envisioned for incorporating optical amplifiers are shown in Fig. 4 (6). The first configuration places the amplifier immediately following the laser transmitter to act as a "power," or "postamplifier." This boosts the signal power so that the detected signal is still above the thermal noise level of the receiver. Any noise introduced by the power amplifier is similarly attenuated together with the signal as they are transmitted through the lossy system. The main figure of merit for the amplifier is a high saturation output power. The second configuration places the am-

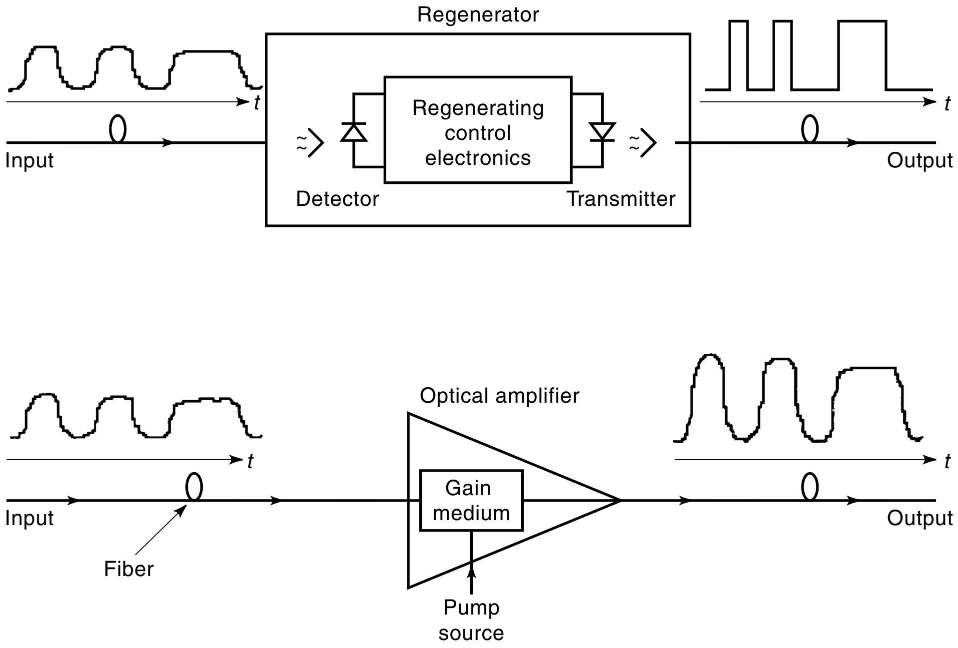


Figure 3. Schematic of an optoelectronic regenerator and an optical amplifier.

plifier "in-line" for incorporation at one or more places along the transmission path. The in-line amplifier(s) corrects for periodic signal attenuation due to fiber-attenuation or network-distribution splitting losses (7). The third possibility places the amplifier directly before the receiver, thus functioning as a "preamplifier." In this case the signal has already been significantly attenuated along the transmission path. The main figures of merit are high gain and low additive noise because the entire amplifier output is immediately detected. As such, the receiver is limited by the amplifier noise, not by the receiver thermal noise.

Before discussing generic details of amplified systems, we briefly introduce the two most prominent (at present) optical amplifiers. Semiconductor optical amplifiers (SOA) (8–12) and erbium-doped fiber-optic amplifiers (EDFA) (13–15) each consists of an active medium which has its "carriers" or "ions" inverted into an excited energy level. This population inversion enables an externally input optical field to initiate stimulated emission and experience coherent gain. The population inversion is achieved by absorbing energy from a pump source. Furthermore, an external signal must be efficiently coupled into and out of the amplifier.

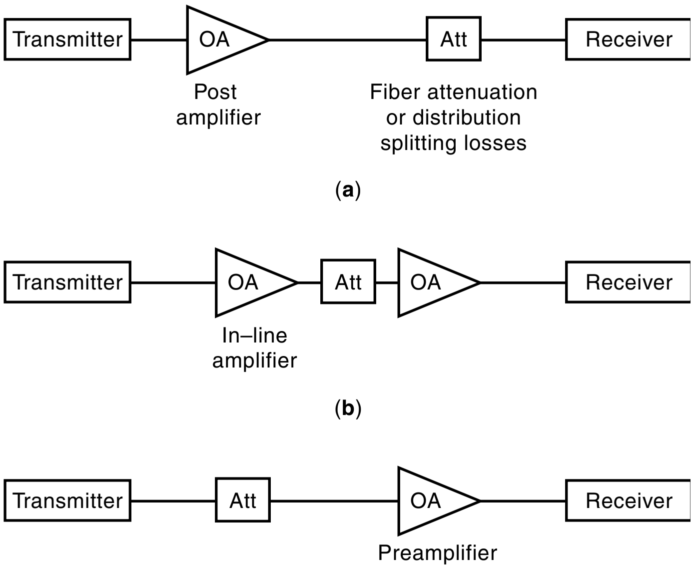
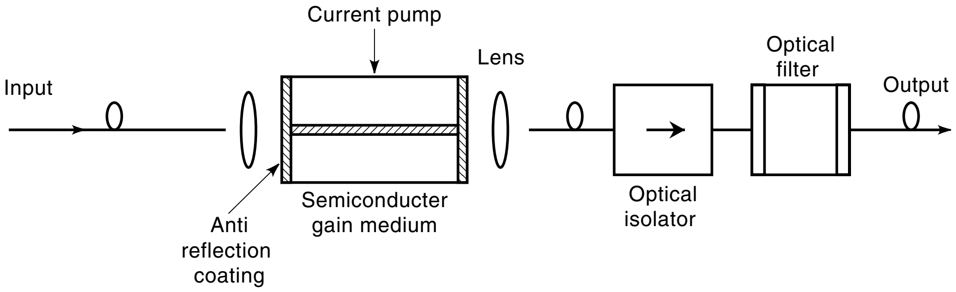
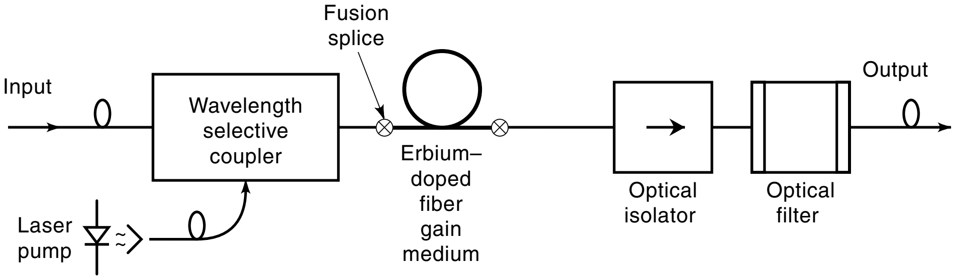


Figure 4. Three generic configurations for incorporating optical amplifiers into transmission or distribution systems.

Figure 5 depicts the basic amplifier building blocks for the SOA and the EDFA. The traveling-wave (TW) SOA is nothing more than a semiconductor laser without facet reflections. An electrical current inverts the medium by transferring electrons from the valence band to the conduction band, producing spontaneous emission (fluorescence) and the potential for stimulated emission if an external optical field is present. The stimulated emission is the signal gain. However, the spontaneous emission itself is amplified [i.e., amplified spontaneous emission (ASE)] and is considered the randomly fluctuating noncoherent amplifier noise. If we are dealing with a circular-waveguide, fiber-based communication system (16), an external signal must be coupled into and out of the amplifier's rectangular active region producing a mode field mismatch and, consequently, insertion losses. On the other hand, the fiber amplifier is a length of glass fiber which has been doped with a rare-earth metal, such as erbium ions. These ions act as an active medium with the potential to experience a population inversion and emit spontaneous and stimulated emission light near a desirable signal wavelength. The pump is typically another light source whose wavelength is preferentially absorbed by the erbium ions. The pump and signal are combined and coupled into the erbium-doped fiber by a wavelength-selective coupler. The pump and signal may co- or counterpropagate with respect to each other inside, the doped length of fiber. Therefore, light absorbed by the doped fiber at the pump wavelength produces gain for a signal at a different wavelength. The insertion losses are minimal because the transmission and the active medium are both fiber-based.



(**a**) Semiconductor amplifier



(**b**) Erbium–doped fiber gain medium amplifier

Figure 5. Block diagram of a semiconductor and a fiber amplifier. The optical isolator and optical filter are included although they may not be required under all circumstances.

Both types of amplifiers are susceptible to external reflections that adversely affect the stimulated and spontaneous emission rates and the frequency-selectivity of the cavity. As a result, an optical isolator, which permits light to pass only in one direction and prevents reflections back into the amplifier, is typically required for both types of amplifiers.

PHOTOABSORPTION AND PHOTOEMISSION

Photons have an energy which depends on the wavelength λ of light (17):

$$E = hc/\lambda = h\nu \tag{1}$$

where c is the speed of light. Furthermore, semiconductors have an energy band gap between the electron-rich valence band and the hole-rich conduction bands. If a photon is incident on a semiconductor, the photon is absorbed if its energy is larger than the energy band gap. In such a case, the photon's energy is transferred to a valence electron pushing it up into the conduction band and freeing it to move through the semiconductor. This is known as stimulated absorption (18).

Alternatively, photons are emitted from a semiconductor if an electron in the conduction band drops down into the valence band by an energy ΔE, thereby combining with a hole in the valence band and emitting a photon of the same energy as ΔE. This process of photon emission occurs because of two different processes, as illustrated in Fig. 6 (18). In the first process, called spontaneous emission, a finite-lifetime electron in the conduction band randomly combines with a hole to emit a photon. These electrons exist in the conduction band because of prior pumping into the higher energy level, typically by electrical biasing (i.e., current injection). Because the electrons fill an energy well in the conduction band with a distribution in energy states (see Fig. 7), the energy drop in the electron upon spontaneous recombination produces uncorrelated, incoherent photons at many different wavelengths (i.e., energies), producing a wide spectral bandwidth in which photon emission can occur. These random photons can be considered noise in the optical system.

In the second process, called stimulated emission, a single photon of a given energy is incident on a semiconductor and causes electron-hole recombination. This stimulated recombination results in the emission of a photon of the same energy

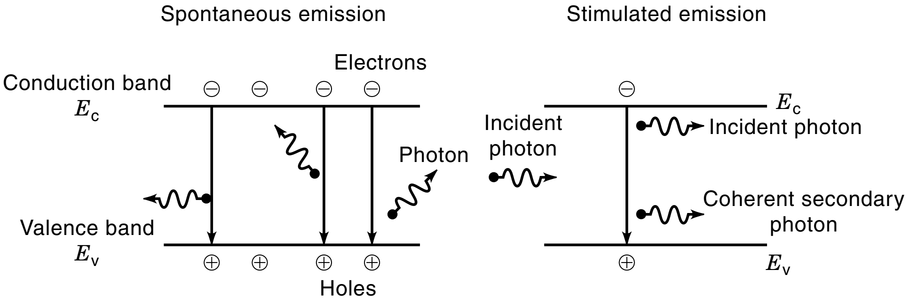


Figure 6. Spontaneous and stimulated emission in a semiconductor.

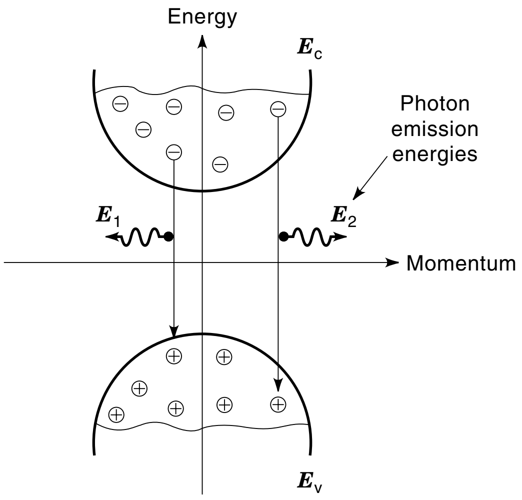


Figure 7. Energy-band diagram versus momentum in a direct-band-gap semiconductor. E_1 and E_2 represent possible energies of emitted photons.

as the original incident photon, thus producing two photons from an initial photon. If the electron population in the conduction band is high enough to sustain continued stimulated emission, then an incident photon at wavelength λ_i produces two, four, etc., photons, all of which are coherent with each other and at the same wavelength as the original photon. This process produces gain, and the medium is considered active. As the wave traverses through an active medium, it is amplified as shown in Fig. 8. The gain G depends on the gain coefficient per unit length g and the length L of the medium (19):

$$G(\lambda) = \frac{\text{signal output power}}{\text{signal input power}} = \exp[g(\lambda)] \tag{2}$$

The relative rates for stimulated and spontaneous emission are determined by the external pumping and the electron populations in the various energy bands.

SNR BACKGROUND IN GENERIC OPTICAL SYSTEMS

In any optical system, the ultimate measure of performance is the signal-to-noise ratio (SNR) of a recovered signal (20). The higher the SNR when recovering data, the lower the probability of error, or bit-error-rate (BER) in a digital system, or the loss of fidelity in an analog system. Analog and digital systems are two basic types of communications. Analog reproduces a given waveform exactly and is compatible with present cable-television systems, but the carrier-to-noise ratio required for near-error-free transmission must be extremely high (21). On the other hand, digital systems are compatible with the way in which computers and the modern telephone network communicate, and one need only distinguish between a “0” and “1” bit (22). The signal-to-noise ratio required is much smaller than in analog, and therefore digital systems are easier to implement and maintain. We devote the material in this chapter to digital systems.

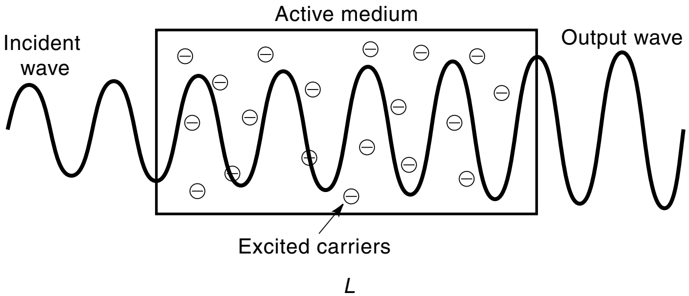


Figure 8. Amplification of a wave as it propagates through an active medium.

The following is a treatment of the general issues associated with the signal-to-noise ratio in nonamplified optical systems.

The two main noise sources generated in all photodetectors are thermal noise σ^2_{th}, and shot noise σ^2_{sh}, (23). Three important characteristics of these noises are that (1) they have a statistical variance, (2) they cover all possible frequencies (i.e., white noise) which are supported by the system’s electrical detection bandwidth, and (3) they can be approximated by a Gaussian amplitude distribution centered around the intended photocurrent mean. The Gaussian distribution is centered at a high current level for a “1” bit and a low current level for a “0” bit.

Thermal noise is caused by thermal energy in the detector. This thermal energy is randomly absorbed by electrons, which are pushed up into the conduction band, and will be mistakenly detected as photocurrent. This thermal noise power is independent of incident optical power and has a statistical variance given by (23):

$$\sigma^2_{\text{th}} = \frac{4kTB_e}{\Omega} \tag{3}$$

where B_e is the detector’s low-pass-filter electrical bandwidth, k is Boltzmann’s constant, T is the detector’s absolute temperature, and Ω is the detector’s resistance. The shot noise is caused by the quantum randomness of generating carriers in a detector at random times. It is the most fundamental quantum limit of photodetection because one can never eliminate this noise term. The shot noise variance power is given by (23)

$$\sigma^2_{\text{sh}} = 2q\left(\frac{q}{h\nu}\right)PB_e \tag{4}$$

and is proportional to the absorbed optical power. In direct-detection systems, thermal noise usually dominates shot noise.

The signal is defined as the mean power in the modulated signal, and the noise is the statistical variance in the modulated signal (20). To detect a digital bit and accurately decide if it is a “1” or “0” bit, the signal power must be much larger than the noise power. If the noise is too large, then a false “0” or false “1” may be detected. SNR is considered an indispensable quantity in evaluating a system’s performance.

The electrically measured optical signal power mean is directly related to the square of the generated photocurrent in a photodetector (23):

$$S = I^2_{\text{ph}} = \left(\frac{\eta q P_S}{h\nu}\right)^2 \tag{5}$$

The signal power is proportional to the amount of power available for a decision circuit to decide if a “1” or “0” bit was transmitted. Therefore, the effective signal power is the high level in a “1” bit relative to the low level in a “0” bit. This relationship of $(P_{\text{“1”}}/P_{\text{“0”}})$ is known as the contrast ratio and is optimally equal to infinity, that is, the “0” bit is transmitted with zero power. When the light is not completely turned “OFF” during a “0” bit, then the contrast ratio between the “1” and “0” bits is reduced. Such a reduction affects the effective signal power as a subtractive term.

We consider that all of the noise terms are the power in the signal variance. Because these noise terms represent independent incoherent statistical variations in the detector current, we can decouple each term and simply add them together in a total noise term σ^2_{tot}. Typically, in nonamplified systems, thermal noise dominates over the shot noise in direct detection, giving rise to the term thermal-noise-limited system reception. These noise powers increase with bandwidth and cover all possible frequencies, and the noise powers are limited only by limiting the frequencies supported by the system. The receiver bandwidth must be at least 50 to 70% of the bit rate to recover the transmitted bits adequately without incurring a power penalty. Recall that a receiver bandwidth of approximately half the bit rate smooths the bit transitions but the center of each bit, where the digital decision is performed, is relatively unaffected. In a well-operated system, any higher bandwidth would not increase the recovered signal much but would allow more noise to be recovered. The receiver almost always has a low-pass filter to limit the unwanted high-frequency noise. As an example, for detection a 2 Gbit/s signal requires twice the electrical bandwidth of a 1 Gbit/s signal. Therefore, twice the noise is produced, and twice the signal power is necessary to achieve the same SNR, thereby incurring a 3 dB system decrease in sensitivity. Combining all of the previous, the SNR in decibels (dB) for direct detection is given by

$$\text{SNR} = 10\log\left\{\frac{(P'_{\text{“1”}} - P'_{\text{“0”}})^2}{\left[\dfrac{4kT}{\Omega} + 2q\left(\dfrac{q}{h\nu}\right)P_{\text{S}}\right]B_{\text{e}}}\right\} \qquad (6)$$

The key to deriving the BER, or probability of error, is to find the probability that a “0” is above I_{th} and a “1” is below I_{th} (22). The BER is directly related to the SNR. A higher signal or lower noise contributes to a lower probability of error.

AMPLIFIER GAIN AND NOISE

In general, the total gain G of the active medium is related to the gain coefficient per unit length g and the length L of the active medium:

$$G = \exp(gL) \qquad (7)$$

The gain coefficient represents the likelihood that a stimulated emission event occurs such that an excited carrier transits from the upper energy level to the lower energy level causing a photon to be emitted at a wavelength corresponding to the energy level difference. The gain for an input signal occurs when an input photon produces a stimulated emission event, emitting a photon which is coherent and at the same wavelength as the original photon.

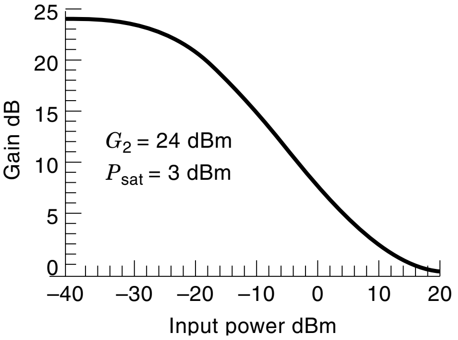


Figure 9. Normalized TW-amplifier gain versus input signal power demonstrating the effects of gain saturation.

The gain of an amplifier changes depending on the input optical conditions and can become saturated. Essentially, a weak input optical signal can experience a certain amount of gain by initiating stimulated emission of the inverted carriers. However, if an incoming signal is so large that there simply are an insufficient number of inverted carriers to allow stimulated emission for all of the incoming photons, then the total gain for this intense input signal will be less than for a weak input signal. For intense signals, the amplifier gain is diminished, and the amplifier itself is considered saturated. Another way of thinking about saturation is that the absorbed pump power can only provide a maximum number of excited carriers, and therefore an incoming large signal cannot be amplified to the point where more power is output from the amplifier than was initially provided by the pump source. The saturation input (or output) power is usually considered to be that input (or output) power which reduces the small-signal gain by 3 dB. The transcendental equation describing the gain is (5)

$$G = G_0\exp\left[-\frac{(G-1)}{G}\frac{P_{\text{out}}}{P_{\text{sat}}}\right] = \exp(gz) \qquad (8)$$

where G_0 is the unsaturated total gain and P_{sat} represents the maximum (i.e., saturated) amount of optical power which can be output from the amplifier. P_{sat} depends on the active medium, the signal wavelength, the carrier lifetime, and the mode overlap between the optical field and the carriers. Figure 9 shows how the gain is reduced for an increase in the input optical signal power.

The noise in an amplifier is inherently due to the random incoherent spontaneous emission of excited carriers. Each spontaneously decaying carrier radiates a photon in any solid angle. The fraction of the spontaneous emission emitted within the critical angle of the waveguiding region and coupled into the optically guiding region itself causes further stimulated emission producing amplified spontaneous emission (ASE). This ASE is quite broadband and occurs over the entire 50 nm to 100 nm material gain bandwidth. Additionally, because there is only a finite number of excited carriers, then there is a tradeoff between gain and noise, that is, an increase in the carriers utilized for the ASE noise results in fewer available carriers to provide signal gain. This is an additional reason why we wish to suppress forward or backward

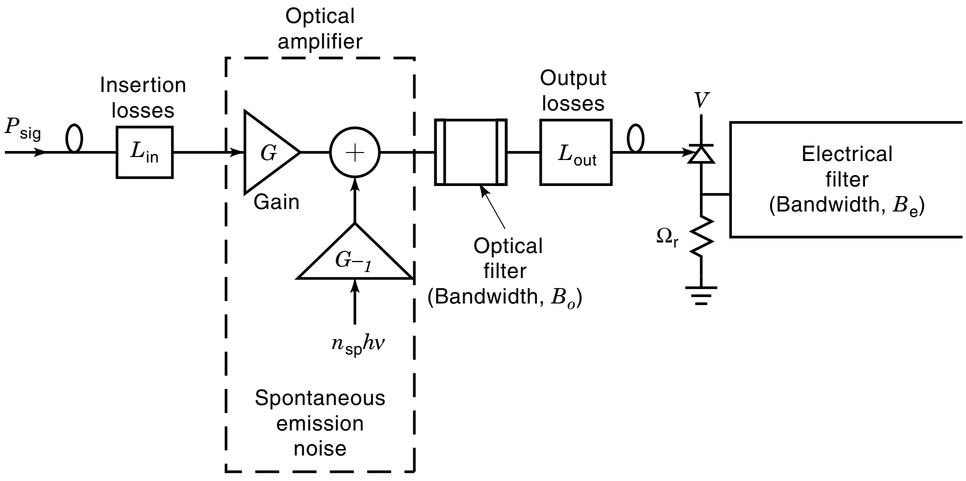


Figure 10. Block diagram of a signal passing through a typical optical amplifier and then being detected. (After Ref. 24.)

reflections into the active medium because any reflected wave depletes the available gain and increases the noise component.

A fairly typical amplified channel block diagram is shown in Fig. 10 (24). The signal P_{sig} may initially pass through some lossy components with a lumped insertion loss of L_{in}. Then the amplifier provides gain G and adds noise of variance σ^2. Because the modulated input signal is typically narrowband whereas the ASE spectrum of the TW amplifier is quite broad (10's of nm), an optical filter of bandwidth B_0 is usually present to pass the signal and block much of the ASE noise. We can also lump any insertion losses at the output of the amplifier in one term L_{out}. (We do not include L_{in} and L_{out} in the following analysis. The reader should note that the effect of L_{in} is to attenuate the optical signal power P_{sig}, whereas L_{out} attenuates both P_{sig} and the spontaneous emission power P_{sp}.) The optical detector has a characteristic resistance Ω_{r}, and the entire receiver has an electrical bandwidth B_{e} to pass the modulated baseband signal and block all higher frequency noise terms. The signal is in one polarization, but the ASE occurs in both polarizations.

The equation that describes the light power P along the length of an amplifier in one polarization is (3)

$$P(z) = P_{\text{sig}}e^{gz} + n_{\text{sp}}h\nu(\Delta\nu)(e^{gz} - 1) \tag{9}$$

where the first term describes the signal, the second term describes the noise in one polarization, z is the length along the amplifier, P_{sig} is the signal power input to the amplifier. N_2 is the carrier population in the higher energy level, N_1 is the population in the lower energy state, $h\nu$ is the photon energy, and $\Delta\nu$ is the optical bandwidth of the active medium. We define the spontaneous emission factor n_{sp} as a measure of the efficiency of the carrier population inversion by (25, 26)

$$n_{\text{sp}} = \frac{N_2}{N_2 - N_1} \tag{10}$$

A higher value for n_{sp} implies that more ASE noise is generated in the amplifier in proportion to the generated gain. Based on this definition, the quantum-limited minimum value for n_{sp} in any amplifier is equal to 1. The second term for $P(z)$ is more clearly understood when defining the total ASE noise power P_{sp} over the gain bandwidth $\Delta\nu$ in one polarization as (25)

$$P_{\text{sp}} = n_{\text{sp}}(G - 1)h\nu(\Delta\nu) \tag{11}$$

We have approximated the spectral density of the ASE power as nearly uniform over the entire bandwidth and equal to $[n_{\text{sp}}(G{-}1)h\nu]$.

We are interested in the electrical noise which is ultimately generated in the optical detector and which governs the overall sensitivity of the system (27). As discussed previously, two noise terms common to all detectors are the shot noise σ^2_{sh}, and the thermal noise σ^2_{th}. The incoherent ASE noise terms generated in the amplifier are very broadband and are very dependent on the optical and electrical bandwidths of the corresponding filters.

Because the detector is inherently a squared-law device which responds to the intensity (i.e., square) of the incoming optical field, a "beat" term is produced if two different optical waves are incident, $A(t)$ and $B(t)$. Squaring of $(A + B)$ produces A^2 plus B^2 plus the beat term of $2AB$. Based on trigonometric identities, the beat term includes the cosine of the sum and difference frequencies between $A(t)$ and $B(t)$. Because the frequencies in the previous equation are ultrahigh optical frequencies (THz) not detectable by the photodetector, the sum frequency term is not detected and only the difference frequency appears at the electrical output. The two waves in our system that impinge on the detector are the signal and the ASE noise. Therefore, A^2 represents the signal power, B^2 represents the ASE noise power, and $2AB$ represents the signal-spontaneous electrical beat noise. However, the situation is more complicated because the ASE does not exist at a specific wavelength but is broadband and consists of an infinite number of incoherent waves each at a different frequency within the gain spectrum. Therefore, we must integrate over the entire ASE noise passing through the optical and electrical filters, and then beat (i.e., multiply) each thin bandwidth "slice" of ASE with the approximately single-frequency signal term. Then the resulting signal-spontaneous beat noise $\sigma^2_{\text{slg-sp}}$ that falls within the optical filter and electrical detector bandwidths is given by (25)

$$\sigma^2_{\text{sig-sp}} = 4q\left(\frac{q}{h\nu}\right)P_{\text{sig}}G(G-1)n_{\text{sp}}B_{\text{e}} \tag{12}$$

The B^2, or ASE noise power, term must also be evaluated because it is not at a single frequency or phase and therefore produces beat terms between one part of the ASE spectrum and another. After integration and convolution, the spontaneous electrical beat noise $\sigma^2_{\text{sp-sp}}$ is given by (25).

$$\sigma^2_{\text{sp}-\text{sp}} = 4q^2(G-1)^2 n^2_{\text{sp}} B_{\text{e}} B_{\text{o}} \tag{13}$$

Note that $\sigma^2_{\text{sig-sp}}$ and $\sigma^2_{\text{sp-sp}}$ can be reduced by small optical and electrical filter bandwidths but cannot be eliminated because some ASE must pass the through the filters within the same bandwidth as the signal. Additionally, the majority of the signal-spontaneous beat noise is generated from the small frequency portion (within a few gigahertz) of the ASE immediately surrounding the signal and so cannot be reduced significantly.

The SNR for our optically-amplified system is

$$\text{SNR} = \frac{(GP_{\text{sip}})^2}{\sigma^2_{\text{sh}} + \sigma^2_{\text{th}} + \sigma^2_{\text{sig-sp}} + \sigma^2_{\text{sp-sp}}} \tag{14}$$

We simplify this expression by making three generally valid assumptions: (1) the shot noise is small compared to all other terms; (2) the receiver noise is dominated by the ASE noise, not by the thermal noise (typically true for systems employing a preamplifier before the detector); and (3) $G \gg 1$. After making the appropriate substitutions, the SNR is approximated as

$$\text{SNR} = \frac{P^2_{\text{sig}}}{[2P_{\text{sig}} n_{\text{sp}} h\nu + 2n^2_{\text{sp}}(h\nu)^2 B_{\text{o}}]2B_{\text{e}}} \tag{15}$$

Given all of our assumptions, the SNR does not change much with an increase in gain because the thermal noise is overwhelmed by the ASE-generated terms and any higher gain increases the signal and noise at nearly the same rate.

As with an electrical amplifier, an important parameter of an optical amplifier is the noise figure NF given by

$$\text{NF} = \frac{\text{SNR}_{\text{in}}}{\text{SNR}_{\text{out}}} \tag{16}$$

where the SNR_{in} and SNR_{out} are the electrically equivalent SNRs of the optical wave going into and coming out of the amplifier. The absolute lowest (i.e., quantum-limited) NF is $2n_{\text{sp}}$. Because the minimum n_{sp} is one for complete inversion, the quantum-limited NF for an amplifier, given the previous approximations, is 2 dB or 3 dB. The typical noise figure for a semiconductor amplifier is 6 dB to 8 dB (5,28) and for an EDFA is ≈4 to 5 dB.

Based on this analysis, we emphasize that an amplified system (excluding the "postamplifier" configuration) should be operated so that the receiver SNR is spontaneous-beat-noise limited and not thermal-beat-noise limited. We wish to increase the signal gain to the point where an increase in the signal gain also increases the signal-spontaneous beat noise proportionally, at which point we have achieved the highest SNR possible for our system.

SEMICONDUCTOR AMPLIFIERS

The semiconductor active medium is a rectangular waveguide which provides gain to an optical signal that is propagating through it (29). Signal gain occurs when (1) carriers are excited from the valence to the conduction band in this quasi two-level energy system; and (b) an externally input signal initiates stimulated emission when propagating through the material. We can roughly approximate the bandwidth of the unsaturated spectral gain coefficient $g(\lambda)$ of the active medium as an inverse parabola. The center wavelength is typically designed to be near either 1.3 μm or 1.55 μm which correspond to the two fiber-loss minima and are the most useful for optical systems. Because carriers have an energy distribution within each energy band, gain can occur over a wide range of wavelengths (≈50 nm to 100 nm). The unsaturated semiconductor gain G_{o} depends on the level of pumping, the carrier lifetime, the saturation power, and the signal wavelength.

When considering an SOA, there may be reflections at the right and left boundaries, or facets, of the amplifier. These reflections have a profound impact on the gain achievable from the amplifier. The following is a frequency-dependent gain expression in the presence of boundary reflections G_{r} (8):

$$G_{\text{r}} = \frac{(1-R_1)(1-R_2)G_{\text{o}}}{(1-G_{\text{o}}\sqrt{R_1R_2})^2 + 4G_{\text{o}}\sqrt{R_1R_2}\sin^2\left[\dfrac{(\omega-\omega_{\text{o}})L}{\left(\dfrac{c}{n}\right)}\right]} \tag{17}$$

in which R_1 and R_2 are the power reflectivities at the two boundaries and ω_{o} is the center frequency of the gain spectrum. The denominator in this equation is periodic and produces periodic Fabry–Perot resonances in the gain spectrum. If the reflections are suppressed and $R_1 = R_2 = 0$, then the gain ripples disappear, and this device becomes a wideband TW amplifier. Two methods for suppressing facet reflections in an SOA are (1) using an antireflection coating which substantially reduces boundary reflections (30); and (2) using a buried nonguiding, passive window region between the end of the central active layer and each of the facets in which the optical wave diverges before being reflected at the facet, thereby coupling very little reflected energy back into the amplifying waveguide (31).

Unlike fiber amplifiers which are round, the semiconductor gain medium which is rectangular (not square) and has different crystal planes, has a gain that depends on the polarization of the light propagating in the waveguide. Recent work attempts to minimize this differential by creating a nearly square cross-sectional active area, thereby making the TE and TM fill-factors similar. A difference of <1 dB has been produced by using this method and by using multiple-quantum-well and strained-layer material (32). If the semiconductor amplifier is integrated on the same chip following a fixed linear-polarization laser transmitter, then only a single polarization passes through the amplifier, and any polarization dependence is not a problem.

In multiple-wavelength systems, the ideal amplifier provides gain equally to all channels over a broad wavelength range without any other effects. However, a few factors inherent in the SOA make wavelength-division-multiplexed multi-

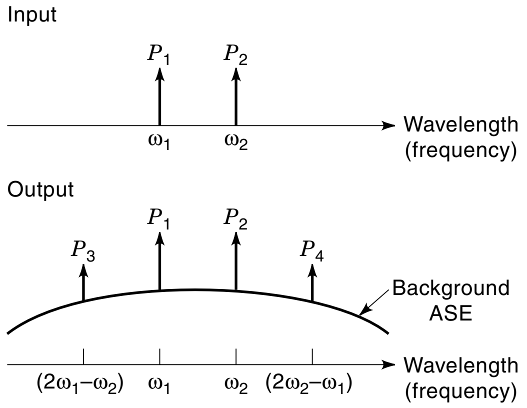


Figure 11. Example of four-wave mixing with two original signals and two newly produced signals.

channel systems more difficult to implement than single-channel systems. These factors include intermodulation distortion and saturation-induced cross talk.

Intermodulation distortion can be explained as follows. When two channels are incident into an amplifier and their combined powers are near the amplifier saturation power, nonlinear effects occur which generate beat frequencies at the cross product of the two optical carrier waves. The carrier density (i.e., gain) is modulated by the interference between any two optical signals and this modulation occurs at the sum and difference beat frequencies which are generated by all of the possible combinations of input channels. This carrier density modulation at the beat frequencies produces additional modulated signals that can interfere with the original desired signals. Figure 11 illustrates this scenario for two input signals that produce four output waves. Therefore, this nonlinear effect is called four-wave mixing, or alternatively, intermodulation distortion (IMD) (33–35). The amplitude of these products is proportional to the difference frequency and the carrier lifetime τ_s (5). The carrier lifetime for semiconductor amplifiers is in the nanosecond range.

Cross talk also occurs in a gain-saturated amplifier. If the intensity of the amplifier input signals increases beyond the saturation input power, then the gain decreases. When the input signal intensity eventually drops, the gain increases to its original unsaturated value. Therefore, the gain and input signal power are inverse functions of each other when the amplifier is saturated. This gain fluctuation occurs as rapidly as the carrier lifetime of the amplifier, again ≈1 ns in a typical SOA, and is comparable to the bit-time in gigabit per second data stream. If we assume two input channels and a homogeneously broadened amplifier which becomes equally saturated across the entire gain bandwidth, then an increase in the input intensity of one channel beyond the input saturation power necessitates a decrease in the gain of both channels, thereby causing cross talk in the second channel. If the gain responds on the same timescale as a bit time in a Gbit/s transmission system, then as one channel is ASK-modulated, the second channel also has its gain modulated within a bit time, producing signal distortion and a system power penalty. This scenario is depicted in Fig. 12. (These two nonlinear effects are negligible for fiber amplifiers because their carrier lifetime is approximately 10 ms, far too long to produce any intermodulation distortion for any reasonably spaced channels and far too long to produce saturation-induced gain fluctuations on the timescale of an individual high-speed bit.)

The following are applications of SOAs in optical communication systems:

1. Long-distance communications. Semiconductor amplifiers have been demonstrated successfully as power-, in-line, and preamplifiers (36). A possible application of semiconductor amplifiers in long-distance communications is for 1.3 μm systems for which the EDFA does not work (37). Because much of the fiber installed worldwide is conventional fiber whose dispersion zero is at 1.3 μm, it is probable that some systems will still operate at 1.3 μm and require amplification. Presently, there is no practical fiber-based amplifier in the 1.3 μm range.
2. Optoelectronic integrated circuits (OEICs). The main advantages of using a semiconductor amplifier as opposed to fiber amplifiers include its small size, potential low cost, and integratability on a chip containing many

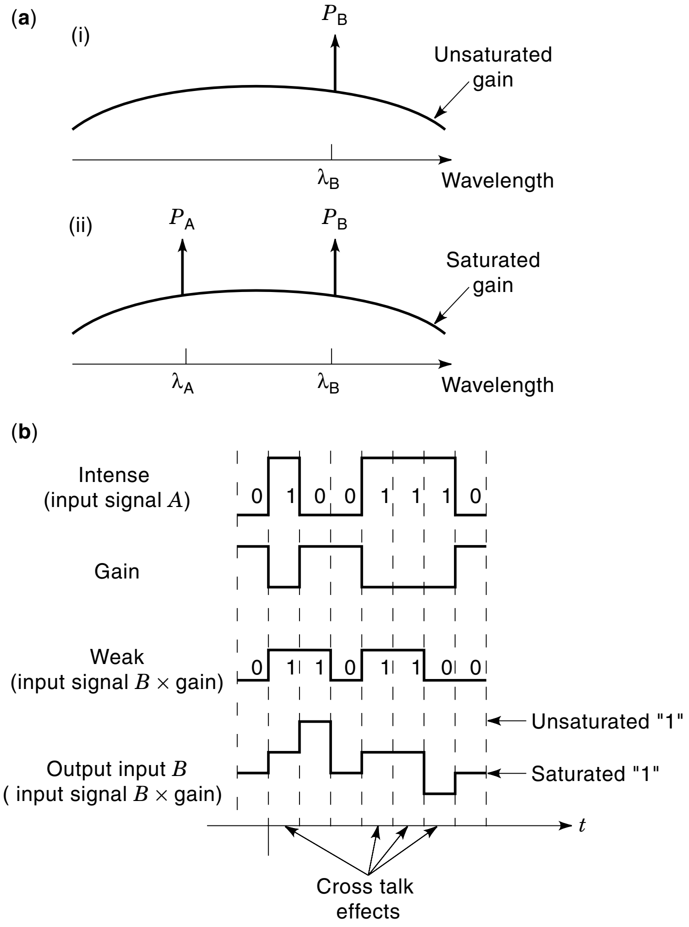


Figure 12. (a) Signal and gain spectra: (i) given a weak signal B producing no saturation, and (ii) given an intense signal A and a weak signal B producing gain saturation. (b) Bit stream sequences for two signals propagating through a semiconductor amplifier. All pulse transitions are sharp because we assume that the response time of the amplifier gain is much greater than the bit rate. If they are comparable, then pulse-rounding effects occur.

other optoelectronic components (i.e., lasers and detectors). For instance, one can integrate a semiconductor amplifier in a photonic integrated circuit (PIC) where the polarization-dependent gain is of no consequence because the polarization is well-defined on the chip (38).

3. Photonic switching gates and modulators. Beyond providing simple gain, a semiconductor amplifier can be used as a high-speed switching element in a photonic system because the semiconductor (1) amplifies if pumped; and (2) absorbs if unpumped. The operation is simply to provide a current pump when an optical data packet is to be passed and discontinue the pump when a data packet is to be blocked.

ERBIUM-DOPED FIBER AMPLIFIERS

The vast majority of excitement in optical amplifiers revolves around using the erbium-doped fiber amplifier in telecommunications (15). The main reasons include (1) Erbium ions (Er^{3+}) emit light in the 1.55 μm loss-minimum band of optical fiber; (2) high gain and low noise is produced; and (3) a circular fiber-based amplifier is inherently compatible with a fiber-optic system. The EDFA has relatively few disadvantages making it an almost ideal and critically important component for long-haul communications.

Fundamental differences between the SOA and the EDFA can be traced mainly to the following attributes:

1. The semiconductor amplifier is, essentially, a two-energy-level system whereas the erbium-doped fiber amplifier is a three-energy-level system (39). In the EDFA, ions are excited from the ground state (population N_0) into an excited state (N_2). These ions quickly decay to the metastable level (N_1) from which both stimulated and spontaneous emission occur as they drop down to the ground state. Additionally, an obvious difference is that the population inversion in the semiconductor amplifier is achieved by a current source whereas the fiber amplifier is inverted by an optical source.
2. The fiber amplifier is meters long whereas the length of the semiconductor amplifier is ≈1 mm. This dramatic difference in length makes the assumption of uniform inversion along the length of the amplifier valid only for the semiconductor amplifier, not for the fiber amplifier.
3. The fiber amplifier is circular, not rectangular, thus eliminating (a) significant attenuation when coupling to a standard optical fiber and (b) any significant polarization-dependence in the gain.
4. The carrier lifetime of erbium ions is in the range of milliseconds to microseconds, whereas the lifetime of semiconductor carriers is nanoseconds. This difference reduces significantly the two nonlinear problems in multiple-wavelength systems of intermodulation distortion (four-wave mixing) and gain-saturation-induced cross talk.

To produce the amplifier gain medium, the silica fiber core of a standard single-mode fiber is doped with erbium ions. Because of the many different energy levels in erbium, several wavelengths are absorbed by the ions. In general, absorption corresponds to a photon causing an ion to make a transition to a higher level of energy difference $\Delta E = h\nu$ matching the energy of the photon (see Fig. 13). Once a photon is absorbed and an ion is excited to a higher energy level than the first excited state, the carrier decays very rapidly to the first excited level. Once the carrier is in the first excited state, it has a very long lifetime of ≈10 ms (13), thereby enabling us to consider the first excited level metastable. Depending on the external optical excitation signal, this ion decays in a stimulated or spontaneous manner to the ground state and emits a photon. The absorption is not as strong for all of the possible wavelengths and is governed critically by the tendency of a pump photon to be absorbed, as determined by the cross-section of the erbium ion with that photon. The two wavelengths that have the strongest absorption coefficients are 0.98 μm and 1.48 μm. Fortunately, high-power multimode laser diodes for the 0.98 μm and 1.48 μm wavelengths are fabricated by using strained-layer, quantum-well material with output power >100 mW that is achievable and commercially available (40). Laser diode pumps are attractive sources because they are compact, reliable, and potentially inexpensive.

Both the absorption and the emission spectra have an associated bandwidth. These bandwidths depend on the spread in wavelengths which can be absorbed or emitted from a given energy level. Such a spread in wavelengths is caused by Stark-splitting of the energy levels, allowing a deviation from an exact wavelength. This is highly desirable because (1) the exact wavelength of the pump laser may not be con-

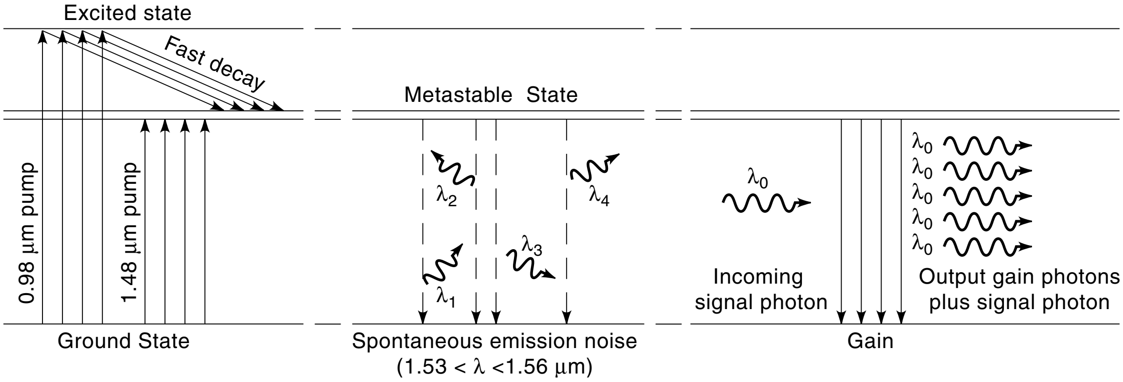


Figure 13. Energy-level diagram for the erbium-doped fiber amplifier.

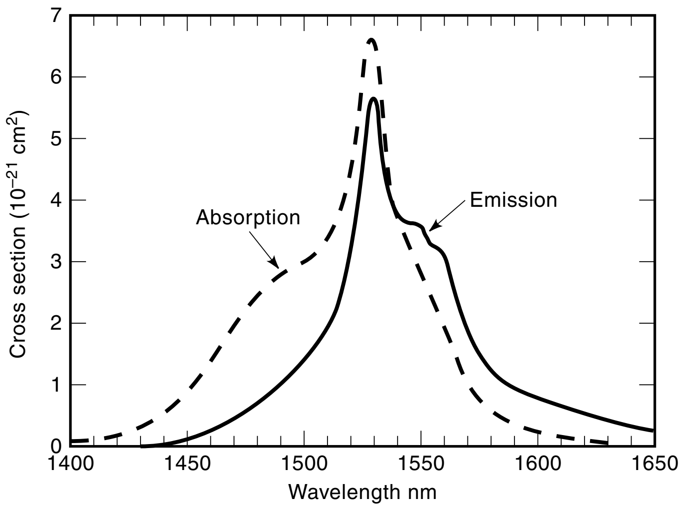


Figure 14. The absorption and fluorescent spectra for erbium near 1.5 μm. (© 1991 IEEE. After Ref. 42.)

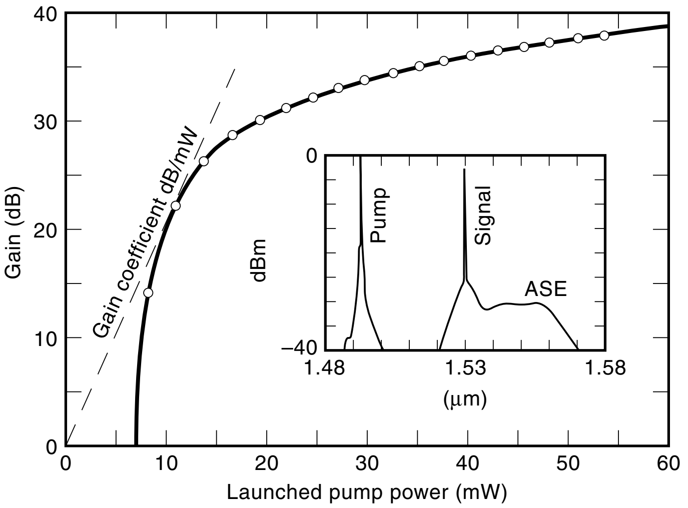


Figure 15. EDFA gain as a function of 1.48 μm pump power. (After Ref. 43.)

trollable and is impossible to fix for a multimode laser; and (2) the input signal may be at one of several wavelengths, especially in a WDM system. Figure 14 shows the cross-section of bandwidth of the 1.48 μm absorption and the 1.55 μm fluorescent (i.e., emission) spectrum of a typical erbium-doped fiber (41,42). The fluorescent spectrum of Fig. 14 was taken from a fiber which contained erbium and also was co-doped with aluminum (43). Co-doping the erbium fiber with another material allows for higher erbium doping concentrations and makes the gain bandwidth somewhat broader and more uniform. Note that the EDFA gain therefore is nonuniform because the gain corresponds very closely to the fluorescent spectra.

Several components may be required for proper operation of an EDFA. Because the erbium-doped gain medium must be pumped optically, the 0.98 μm or 1.48 μm pump light (usually in the form of a diode laser) and the 1.55 μm signal must be combined within the doped fiber to achieve pumping and signal gain. Pigtailed, grating-based, three-port wavelength-division multiplexers (WDM) can perform this coupling function with <0.5 dB of insertion loss and >40 dB of return loss, even when combining wavelengths as close as 1.48 μm and 1.53 μm. Two other components which are not, strictly speaking, essential to an EDFA but which may be required to prevent system degradation, are an optical filter and an optical isolator. An output optical filter of ≈1 nm to 2 nm limits the broadband spontaneous beat noise generated in the detector. Additionally, an optical isolator may be necessary to prevent reflections back into the amplifier which cause the noise figure of the EDFA to increase and may even cause the EDFA to lase if the gain and reflections are sufficiently large.

An experimental curve of the gain dependence on pump power is shown in Fig. 15 (14,43). Minimum pump power is required for the gain to overcome the losses and achieve transparency. Then the gain increases rapidly and is followed by a plateau region which represents the situation when nearly all the available carriers have already been inverted throughout the gain medium.

The noise considerations for an EDFA are quite similar to those for a semiconductor amplifier in that a good population inversion is necessary for a low noise figure (44-46). The individual spectra for the absorption and emission (fluorescence) of light near 1.55 μm in an EDFA is nonuniform and also overlap with each other. This means that if a signal is incident on the amplifier at a wavelength containing significant absorption and emission cross sections, then the signal experiences both gain and absorption, thereby contributing to some additional ASE. This overlap occurs on the short wavelength end of the gain spectra, and so n_{sp} and the NF are higher at shorter wavelengths than at longer wavelengths where the overlap is much less. Figure 16 shows the noise figure as a function of wavelength. The noise figure is clearly higher at the shorter wavelengths (57). Thus, it is advantageous not to operate the signal wavelength at the gain peak of the amplifier but at a higher wavelength which has a lower noise figure. Note that the noise figure is very close to 3 dB, which is the quantum-limited value.

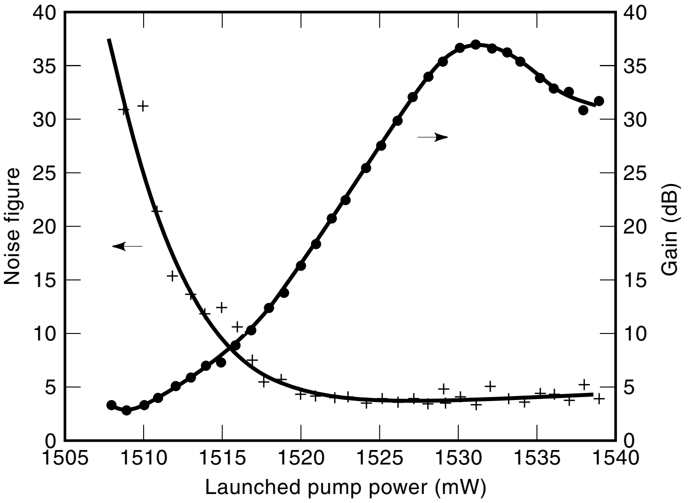


Figure 16. Noise figure as a function of wavelength in an EDFA pumped with 1.48 μm light. (© 1989 IEEE. After Ref. 57.)

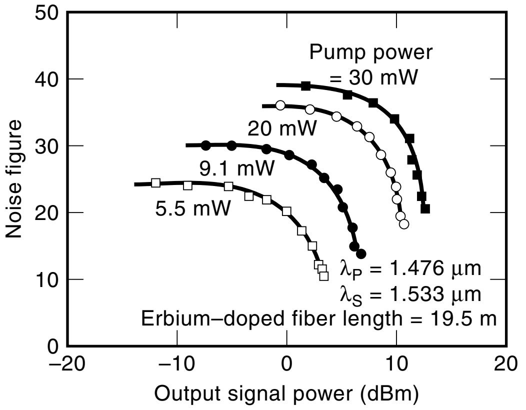


Figure 17. EDFA gain versus output signal power. (After Ref. 49.)

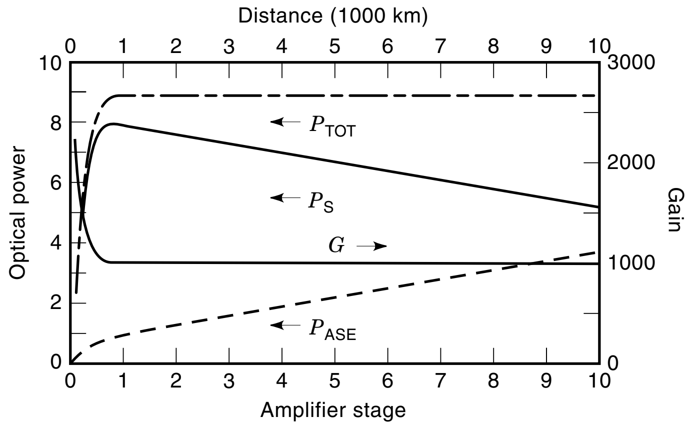


Figure 19. Signal and ASE noise power along an EDFA cascade. (© 1989 IEEE. After Ref. 52.)

The EDFA gain can be compressed to a small value (47) if the amplifier is saturated by an intense input signal (48). An amplifier figure of merit is high output saturation power, which is especially desirable for power-amplifier applications in which we wish to boost the output of a laser diode to a value higher than that which a semiconductor medium provides. The saturation output power is a function of the erbium concentration, the fiber length, and pump power because a higher output power results from an increase in the inverted carriers. Of course, the limit is reached when all of the erbium ions in the fiber length have been inverted. In Fig. 17 we plot the signal gain as a function of signal output power, showing the saturation output power of the amplifier (49). Saturation output power as high as ≈20 dBm has been measured with extremely high pumping and an extremely large number of erbium ions (58).

Recall that two critical problems existed in multichannel operation in SOAs, namely, intermodulation distortion caused by four-wave mixing and gain-saturation-induced cross talk. The relative effects of each of these can be traced to the carrier lifetime (i.e., gain-response time) of an optical amplifier. Semiconductor amplifiers have lifetimes on the order of nanoseconds whereas EDFA lifetimes are in the millisecond range. Both of these two deleterious nonlinear effects are considered negligible in the EDFA because of its extremely long gain-response time. Gain-saturation-induced cross talk is considered negligible for frequencies faster than kilohertz speeds (see Fig. 18) (50). However, recent work has produced gain transients as fast as a few microseconds when an amplifier is operated deep into saturation (51).

EDFAs have highly desirable system qualities which make it certain that they will exist in deployed systems. Following are the basic applications of EDFAs within optical communication systems.

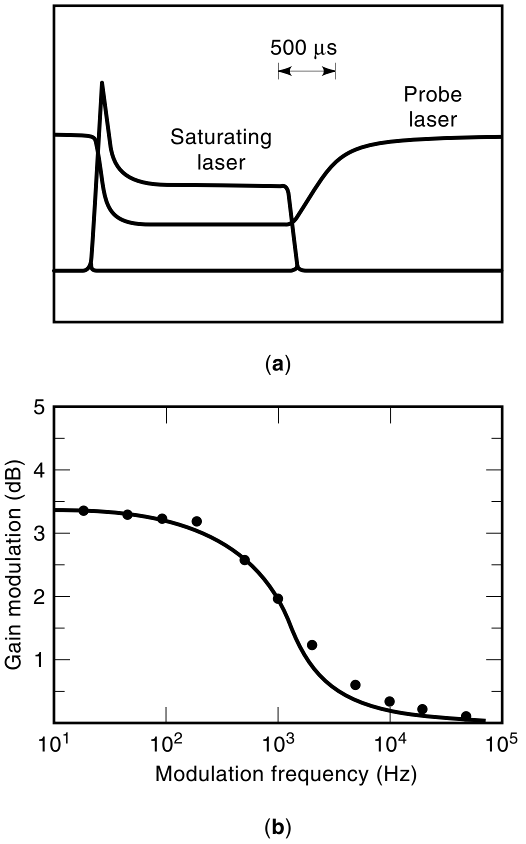


Figure 18. (a) Signal and gain transients in an EDFA. (b) Cross talk between two channels as a function of the rate of amplitude modulation on one of the channels. (After Ref. 50.)

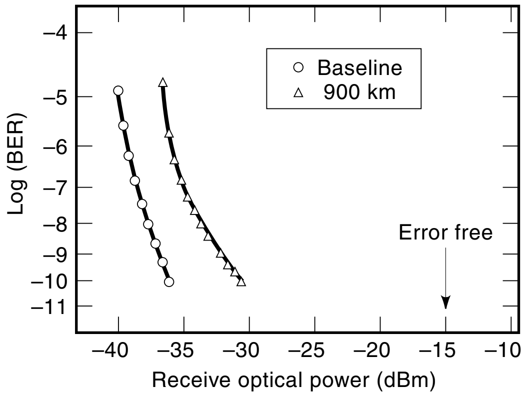


Figure 20. Bit-error-rate curve of the 9,000 km 274-EDFA cascaded system. (After Ref. 53.)

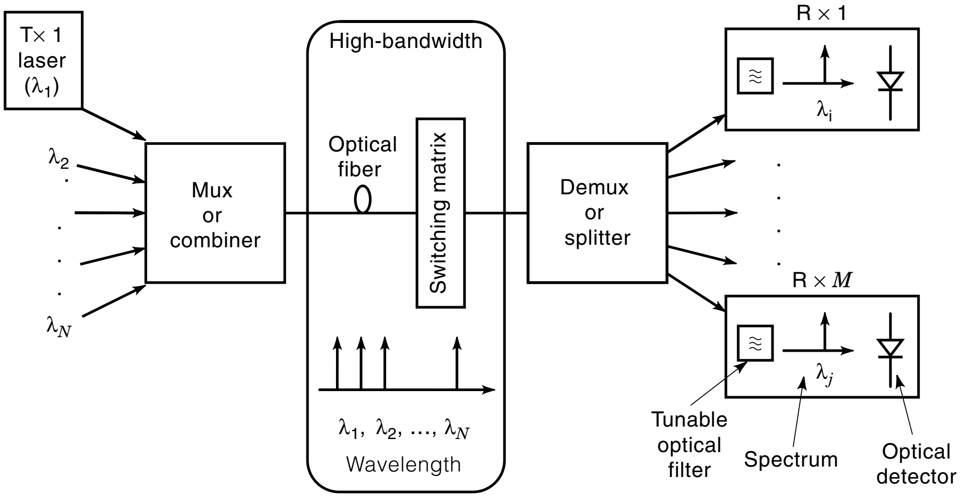


Figure 21. A generic WDM system.

Amplifier Cascades and Long-Distance Communications

Probably the one implementation of critical importance is for long-distance terrestrial and transoceanic communications. The EDFA is an adequate substitute for expensive regenerators, even though EDFAs do not compensate for intramodal chromatic dispersion. A typical EDFA cascade has periodic introduction of gain, noise, and fiber-attenuation losses. The operation of a cascade can be understood by considering the propagation of the signal and ASE as they traverse the system. The input of the first amplifier is simply the signal, whereas the input to all subsequent amplifiers is the output of the previous amplifier which includes both signal and ASE power. The total output power $P_{\mathrm{out},i}$ of the ith amplifier in a cascade is given by (52)

$$P_{\mathrm{out},i} = LG_iP_{\mathrm{out},i-1} + 2n_{\mathrm{sp}}(G_i - 1)h\nu B_{\mathrm{o}} \tag{18}$$

where L is the interamplifier fiber-attenuation and insertion losses, and the gain at each amplifier is not necessarily the small-signal gain but can be a saturated gain value. Figure 19 shows the signal and ASE noise progression when traversing a cascade of many EDFAs (52). As the signal propagates along the cascade, three phenomena occur: (1) the signal slowly decays; (2) the ASE noise slowly accumulates; and (3) the SNR slowly decreases. A fundamental principle of cascaded amplifiers is that the signal and the ASE are both amplified from one amplifier to the next. In fact, because both the signal and ASE from one amplifier are input to the following amplifier, amplifier saturation quickly results, causing the total output power from each EDFA to equilibrate to the same output saturation value.

Early results for 5 Gbit/s and 10 Gbit/s NRZ transmission with 274 cascaded EDFAs have shown that nearly error-free transmission is achieved for distances of 9,000 km, effectively conquering the barrier of repeaterless transmission for any possible distance around the globe (e.g., trans-Pacific distances are ≈9,000 km) (53,54). Figure 20 shows the bit-error-rate curve for early results of this experiment. EDFAs have a remarkable impact on long-distance communications.

Preamplifiers and Power Amplifiers

EDFAs have been successfully used as preamplifiers in receivers (55,56). The results are quite impressive, with a 10^{-9} bit-error-rate sensitivity of −46 dB at 2 Gbit/s for a single-stage experiment and −40 dB at 10 Gbit/s for a double-stage EDFA experiment (57,58). Now it seems clear that direct detection with EDFAs can rival the high sensitivity of coherent detection with a high-power local oscillator. Additionally, EDFAs have shown their ability for impressive power boosting at the output of a laser transmitter. Results showing +27 dBm output power are unheard of with semiconductor amplifiers (59).

MULTIPLE-WAVELENGTH SYSTEMS

One unique feature of an optical fiber is its extremely wide low-loss bandwidth range (60). In the 1.55 μm low-loss window, 25,000 GHz of bandwidth exist. It seems natural to dramatically increase the system capacity by transmitting several different wavelengths simultaneously down a fiber in order to utilize this enormous bandwidth more fully. Such wavelength-division multiplexing (WDM) has recently generated much excitement and research because it has a very high

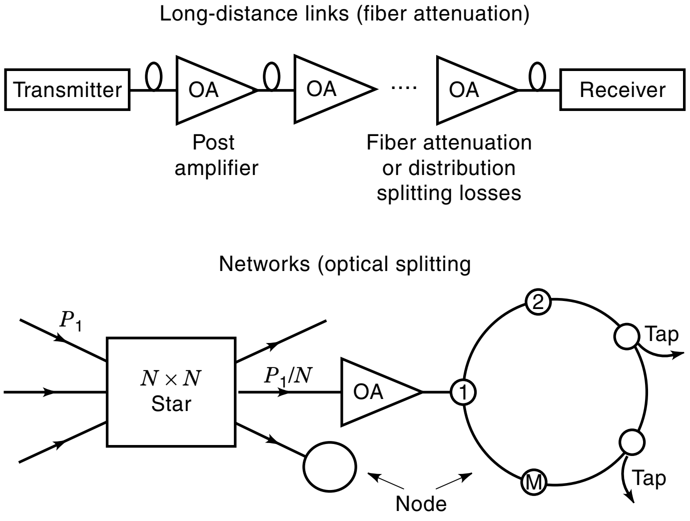


Figure 22. Uses of optical amplification in a WDM point-to-point system and in a network.

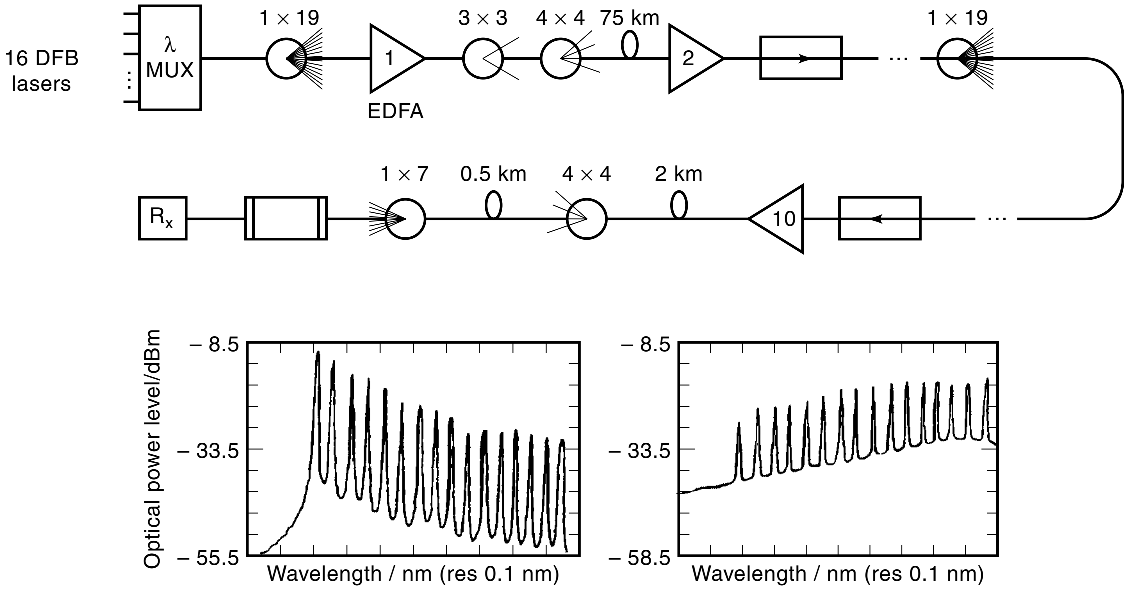


Figure 23. WDM distribution through stars to 40 million users. (© 1990 IEEE. After Ref. 88.)

aggregate system capacity (61,62). At present, it is expected that WDM will be one of the methods of choice for future ultrahigh-bandwidth multichannel systems.

In WDM systems, many independent signals can be transmitted simultaneously on one fiber, and each signal is located at a different wavelength. If wavelength-selective components are implemented, these signals can be routed and detected independently, and the wavelength determines the communication path. One example of system capacity enhancement is the transmission of ten 2.5 Gbit/s signals on one fiber, producing a system capacity of 25 Gbit/s. This wavelength-parallelism circumvents the problem of typical optoelectronic devices whose bandwidths do not exceed a few gigahertz. The wavelength of a signal is also used for routing purposes and defines the data origin, destination, or path. A typical system is shown in Fig. 21. In this example, the wavelength of each transmitter is fixed, and the wavelength of each receiver is tunable.

We emphasize that the optical amplifier has been the most important recent key enabling technology for WDM systems because it simultaneously amplifies signals over a very wide bandwidth (≈25 nm). As shown in Fig. 22, optical amplifiers are used in WDM systems to compensate for: (1) fiber-attenuation losses in transmission, (2) component excess losses, and (3) optical network-splitting losses (63). Additionally, Fig. 23 shows a system in which 10 EDFAs are used to periodically compensate for star-based splitting losses in a 1 to 40 million-way-split 16-channel WDM system (64).

The nearly ideal characteristics of the erbium-doped fiber amplifier make it the amplifier of choice for systems requiring WDM transmission. However, one characteristic which makes the EDFA the clear choice over semiconductor optical amplifiers is the long carrier lifetime of erbium compared to the short carrier lifetime of conduction-band electrons in an SOA (65). The long carrier lifetime of erbium guarantees that the gain will not change on the timescale of a single bit resulting in (1) negligible cross talk if the amplifier is operated near gain saturation, and (2) negligible four-wave mixing. Therefore, we exclusively discuss EDFAs for WDM amplification unless otherwise stated.

The EDFA is an almost ideal optical amplifier for WDM systems except for one major flaw. The gain is not uniform with wavelength whereas the interamplifier losses are nearly wavelength-independent (66-69). For a single amplifier, the gain exhibits a peak at 1.531 μm and a relatively flat region near 1.557 μm. If we place several channels at different wavelengths, as in Fig. 24, each channel experiences a different gain causing a differential in signal power and in the signal-to-noise ratio. Note that the ASE and gain spectra are very nearly the same.

If several channels are located on the relatively flat shoulder region of the gain spectrum, then the gain differential after a single amplifier is within just a few decibels. However, when a cascade of EDFAs is used to periodically compensate

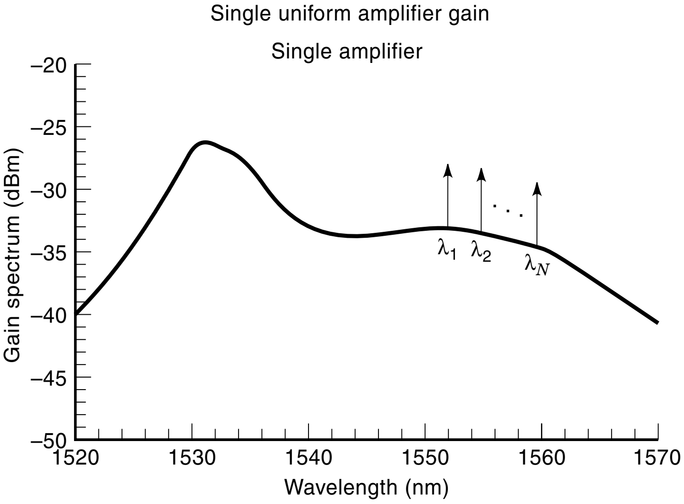


Figure 24. Several WDM channels are placed at different wavelengths within the nonuniform EDFA gain spectrum.

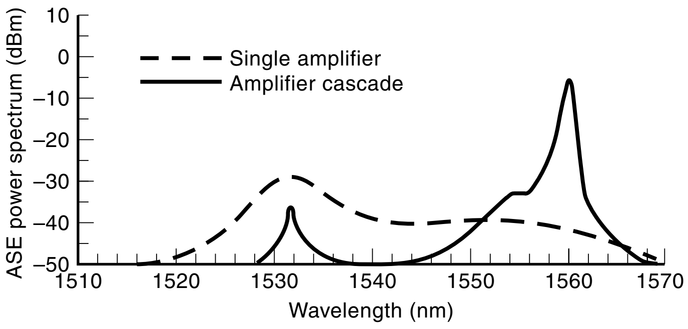


Figure 25. Nonuniform gain spectrum at the output of single EDFA and after a cascade of 200 EDFA's. There are no input signals present. (© 1995 IEEE. After Ref. 92.)

for losses, the differential in gain and resultant SNR becomes quite severe. A large differential in SNR among many channels is quite deleterious for proper system performance. Figure 25 shows the gain spectrum after a single amplifier and after 200 cascaded amplifiers, both in the absence of any input signals. The gain does not accumulate linearly from stage to stage, and the resultant wavelength-dependent gain dramatically changes shape in a cascade. The peak at 1.531 μm is attenuated, and a newly generated peak appears near 1.560 μm (69). This shift in the gain to longer wavelengths can be explained by the relative overlap of the emission (i.e., gain) and absorption (i.e., loss) cross sections of erbium (70). More loss than gain occurs at the shorter wavelengths, and more gain than loss at the longer wavelengths. Along the cascade, gain is gradually "pulled" away from the shorter wavelengths and is available at the longer wavelengths. The relative overlap of the cross sections determines that $\approx$1.560 μm experiences a gain peak.

There are several methods used to equalize the nonuniform EDFA gain, including

1. preemphasis: the powers of the input channels are selectively attenuated, and the higher attenuation values are used for the wavelengths which receive the higher EDFA gain (71). Figure 26 shows the results for four 2.5 Gbit/s channels transmitted over 9,000 km using 294 cascaded EDFAs. This technique is viable only in a WDM point-to-point system.
2. passive notch filters: a notch, or attenuation, filter at 1.531 μm can be used in short cascades to attenuate the shorter-wavelength gain peak (72), and a notch filter at 1.560 μm can be used in longer cascades to attenuate the newly generated longer wavelength 1.560 μm gain peak (73).
3. telemetry: a simple algorithm can be used in which information about the output signals is transmitted back to the input side (74).
4. active equalization: active equalization with feedback can be used for more accurate compensation. In theory, the nonuniform EDFA gain can be compensated for by providing a nonuniform loss element which is the exact inverse of the gain. One possibility is to use an acousto-optic tunable filter (AOTF) to act as the nonuniform loss element. The AOTF is faster than the EDFA gain dynamics, and the AOTF can have multiple-independent loss resonances (75).

APPLICATIONS TO SOLITONS

We have been discussing the basics of optical transmission, while always keeping in mind that there is some fundamental speed and distance limit when conventional digital pulses are propagating. The limitations exist either because (1) fiber chromatic dispersion temporally spreads the pulse or (2) in the case of near zero dispersion, fiber nonlinearities distort the pulse shape and cause pulses on different wavelengths to interact. However, a class of pulses exists which retains its shape indefinitely, allowing for the potential of ultrahigh-speed (>20 Gbit/s) optical transmission per channel over multimegameter distances. These pulses, known as solitons (76,77), have few fundamental limits for single channels and hold the exciting promise that the not so near future need for ever higher data rates anywhere in the world will be met by this technology.

At a critical pulse shape and power, the nonlinear effects in the optical fiber completely cancel the pulse spreading effects of dispersion. If we employ optical amplifiers so that the fiber loss is compensated for by the EDFA gain, then we can maintain the appropriate power levels for the soliton pulse over very long distances. An intuitive way of understanding the soliton is that the pulse power creates an index "well"

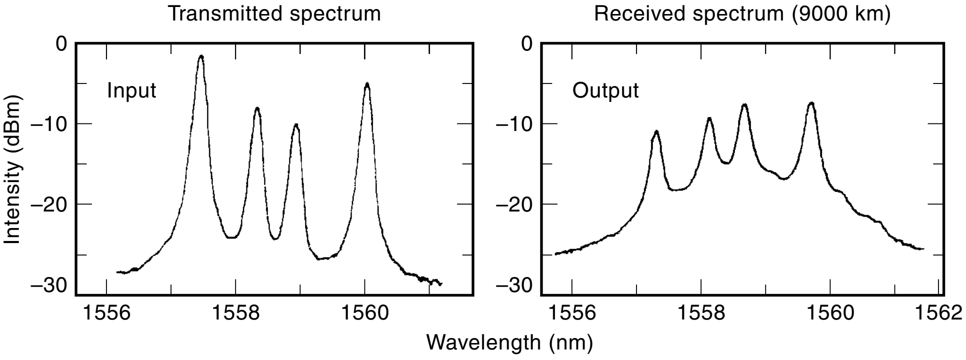


Figure 26. Four 2.5 Gbit/s channels transmitted over 9,000 km. (© 1994 OSA. After Ref. 95.)

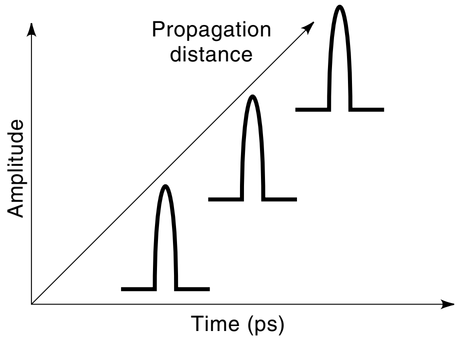


Figure 27. The fundamental soliton propagating along an optical fiber.

which travels along with the pulse. The leading edge of the pulse, which would normally travel faster, is retarded because the intense pulse center changes the index. The trailing edge, which would normally fall behind, speeds up because of the pulse center. Therefore the pulse is nondispersive as it travels (see Fig. 27).

Solitons could not exist if optical amplification were not used to compensate for the fiber loss. To this end EDFAs have been the key enabling technology for long-distance soliton technology. EDFAs can be placed every 10 km to 30 km along an ultralong-distance link and still provide the appropriate soliton power conditions mentioned previously. The robust soliton behavior is manifest in its ability to accommodate lumped amplification and in not requiring that the loss is absolutely zero at every point along the fiber.

FUTURE TRENDS

The progress in deployed optical systems has achieved an astounding rate of growth during the past 15 years. One fascinating point is that the overwhelming amount of scientific and technological progress has occurred only during the past 20 years. In fact, an interesting trend observed by Dr. Tingye Li of AT&T Bell Laboratories is that optical communications technology has enabled the doubling of the bit rate-distance transmission product every year (see Fig. 28) (78). This trend has been sustained by depending on different technologies, such as the inventions of the single-mode fiber, the single-frequency laser, and the EDFA. In 1997, we have broken the 1 Tbit/s capacity barrier because of the combination of EDFAs and WDM. The optical amplifier has truly heralded a revolution in optical systems!

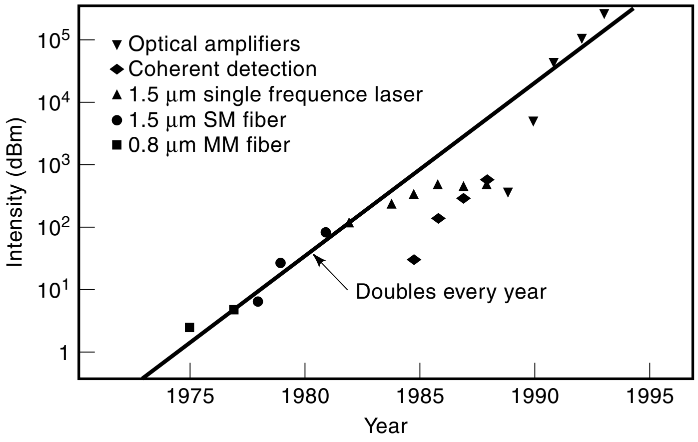


Figure 28. Bit rate-distance product as a function of year for different optical technologies. (After Ref. 78.)

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OPTICAL ANALYSIS OF THIN FILMS.

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