

Module 10 - Optical Amplifiers



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Introduction

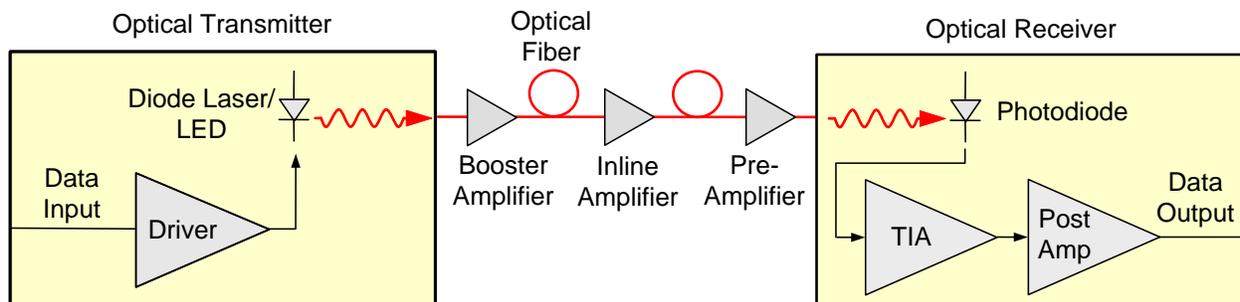


Figure 10.1. Optical amplifiers in a fiber optic data link.

Optical amplifiers are used extensively in fiber optic data links. **Figure 10.1** shows three ways in which optical amplifiers can be used to enhance the performance of optical data links. A booster amplifier is used to increase the optical output of an optical transmitter just before the signal enters an optical fiber to compensate for attenuation of the signal as it travels in the optical fiber. An inline amplifier is used to restore (regenerate) the optical signal to its original power level. An optical pre-amplifier is used at the end of the optical fiber link in order to increase the sensitivity (minimum signal required to achieve a desired Signal-to-Noise ration) of an optical receiver.

10.1 Amplifier Types

There are three important types of optical amplifiers: the erbium-doped fiber amplifier (EDFA), the semiconductor optical amplifier (SOA), and the fiber Raman amplifier. We introduce each of these amplifiers in the following subsections.

Erbium-Doped Fiber Amplifiers

An erbium-doped fiber amplifier (EDFA) is illustrated in **Figure 10.2**.

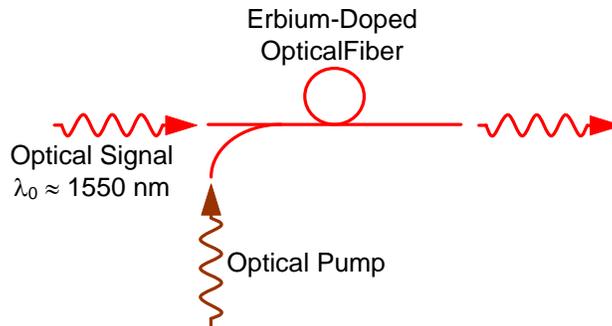


Figure 10.2. An erbium-doped fiber amplifier.

The amplifying (gain) medium is a glass optical fiber doped with erbium ions. The erbium is pumped to a state of population inversion with a separate optical input. Erbium can be pumped at 980nm or 1480nm to provide gain for wavelengths that are in the neighborhood of 1550 nm – the optical wavelengths that suffer minimum attenuation in optical fibers. EDFAs have low noise and can amplify many wavelengths simultaneously, making the EDFA the amplifier of choice for most applications in optical communications.

Semiconductor Optical Amplifiers (SOA)

A semiconductor optical amplifier (SOA) is pictured in **Figure 10.3**. The gain medium is undoped InGaAsP. This material can be tailored to provide optical amplification at wavelengths near 1.3 μm or near 1.5 μm – important wavelengths for optical communications. Other

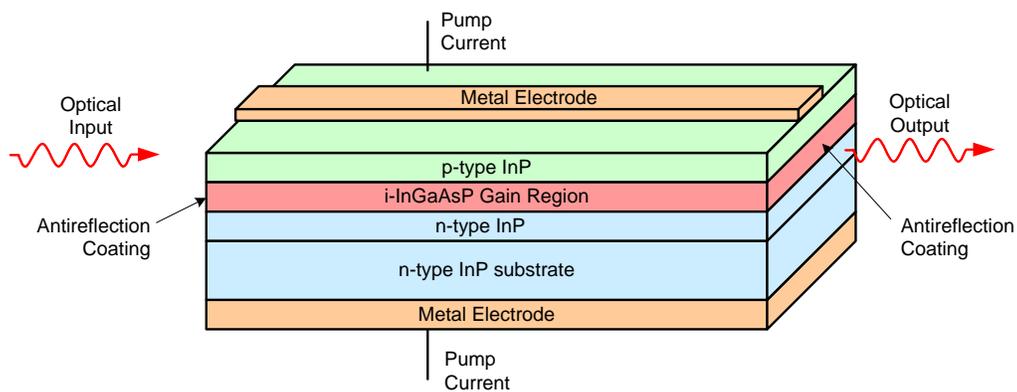


Figure 10.3. A semiconductor optical amplifier.

semiconductors can be used to amplify optical signals at other wavelengths. The input and output faces of the amplifier are antireflection coated in order to prevent optical feedback to the gain

medium, which could cause lasing and destabilize the amplification process. An SOA is pumped with electrical current. SOAs are noisier than EDFAs and generally handle less power. However, SOAs are less expensive and are, therefore, suitable for use in local area networks where the best performance is not required but cost is an important factor.

Fiber Raman Amplifiers

A fiber Raman amplifier is unique in that it uses undoped optical fiber as the gain medium (figure 4). Here, power is transferred from an external optical pump to the optical signal via a nonlinear optical process known as Raman scattering. The wavelengths that experience optical gain are determined by the wavelength of the optical pump, so the Raman amplifier can be tailored to amplify a given optical wavelength by proper selection of the pump wavelength. This nonlinear optical effect is relatively small and depends on the intensity of the pump signal, so Raman amplification is distributed over a long span of optical fiber. Typically, the optical pump is introduced at the end of a length of fiber in order to provide optical gain that increases towards the end of the fiber. In this way, a Raman amplifier can be combined with an EDFA booster or inline amplifier to produce a more uniform power profile along the length of fiber.

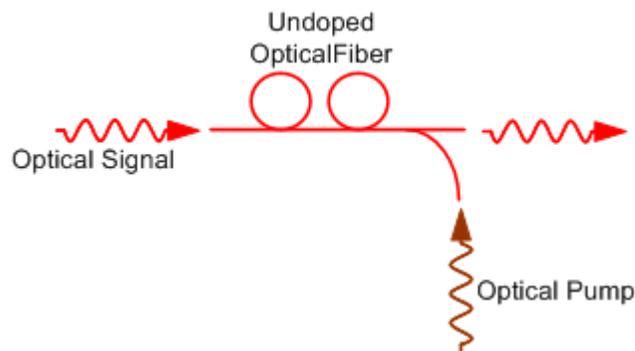


Figure 10.4. A fiber Raman optical amplifier.

EDFA Configurations

The configuration of a co-propagating EDFA is shown in **Figure 10.5**. The optical pump is combined with the optical signal into the erbium-doped fiber with a wavelength division multiplexer (WDM). A demultiplexer removes residual pump light from the fiber at the other end of the doped fiber. An in-line optical filter provides additional insurance that the pump light does not reach the output of the optical amplifier and is typically combined with an optical isolator to prevent reflected light from other portions of the optical system from entering the amplifier and causing instabilities.

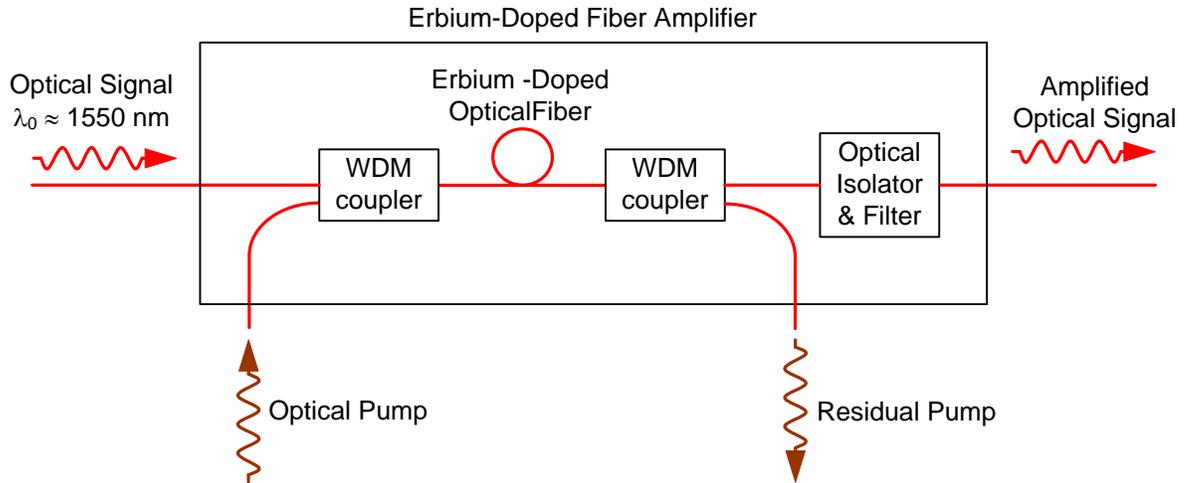


Figure 10.5. An EDFA for which the optical signal and optical pump are co-propagating.

An EDFA with a counter-propagating pump is pictured in **Figure 10.6**. The co-propagating geometry produces an amplifier with less noise and less output power. The counter-propagating geometry typically produces greater amplification at the cost of increased noise. Combining the co- and counter-propagating geometries in a bi-directional configuration strikes a compromise but then requires two pump sources.

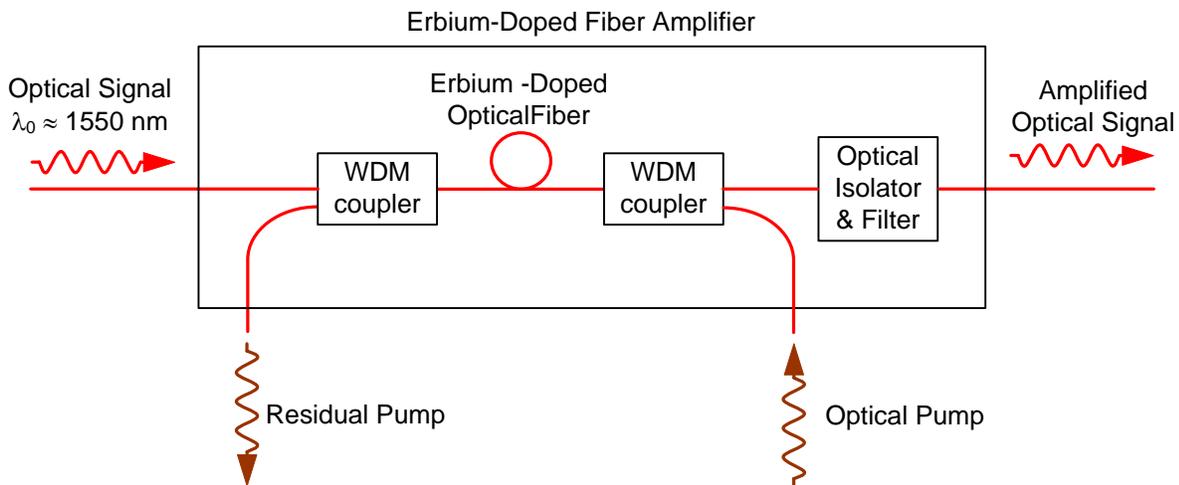


Figure 10.6. An EDFA for which the optical signal and optical pump are counter-propagating.

10.2 EDFA Properties

In this section we will discuss key characteristics of an erbium-doped fiber amplifier, currently the most important optical amplifier for optical communications. The characteristics of erbium-doped fiber amplifiers are summarized in Table 1.

Table 1. Typical values for characteristics of EDFAs.

Center Wavelength	1.55 μm
Bandwidth	30-40 nm
Gain	30-45 dB
Pump Power	20-100 mW
Pump Wavelength	980 nm, 1480 nm
3 dB Saturation Power	5-10 dBm
Polarization Sensitivity	No
WDM Crosstalk	No
Noise Figure	4-6 dB

Wavelength, Bandwidth, Pumping Power

The gain for an optical amplifier is defined by the equation

$$G \equiv \frac{P_{out}}{P_{in}}, \tag{Equation 10.1}$$

where P_{in} is the optical signal power at the input of the optical amplifier and P_{out} is the power at the output. The gain for an erbium-doped fiber amplifier is shown in **Figure 10.7**. The gain curve is centered about 1.55 μm – a fortunate circumstance as this wavelength corresponds to a minimum for optical attenuation in optical fiber. The curves show that an EDFA amplifies light over a bandwidth of approximately 30 to 40 nm. The curves also show pump powers of approximately 20 to 100 mW are required for the amplifier to have significant gain.

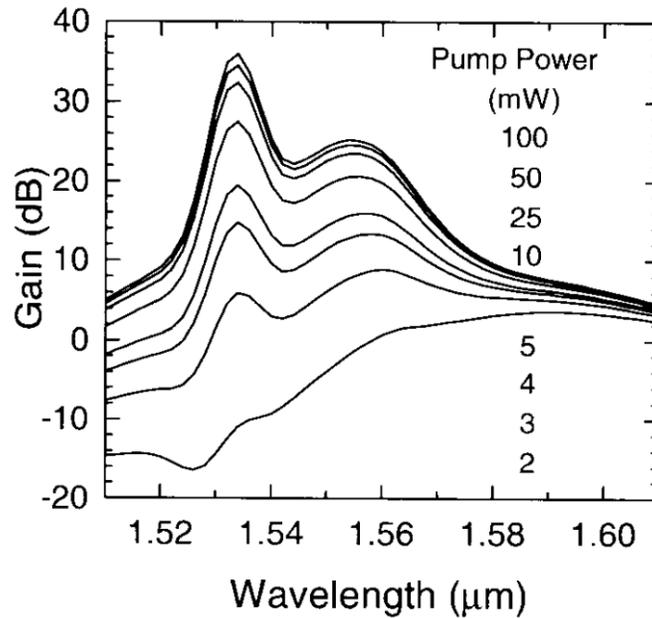


Figure 10.7. Gain for an erbium-doped fiber amplifier. The pump wavelength is 1480 nm, the fiber length is 30 meters, and the input signal power is -30 dBm. [From *Optical Amplifiers*, Mikhael N. Zervas and Gerlas van den Hoven, Chapter 5 in *Fiber Optics Communication Devices*, Norbert Grote and Herbert Venghaus, Editors, (Springer, Berlin, 2001) p. 169]

Pump Wavelength

Erbium-doped fiber amplifiers can be optically pumped at a variety of optical wavelengths for which the erbium ions have strong absorption. **Figure 10.8a** shows absorption peaks for erbium ions in glass fiber. EDFAs are most commonly pumped at 980 nm and 1480 nm. We illustrate how pumping works with the energy diagram of **Figure 10.8b**. A photon at 980 nm pumps an erbium ion from its ground state to an excited state labeled $4I_{11/2}$. The excited ion rapidly decays to a metastable (long lived, lifetime ~ 10 ms) upper amplification level labeled $4I_{3/2}$. During the amplification process, a photon with wavelength near 1550 nm stimulates the erbium ion back to the ground state producing a second photon.

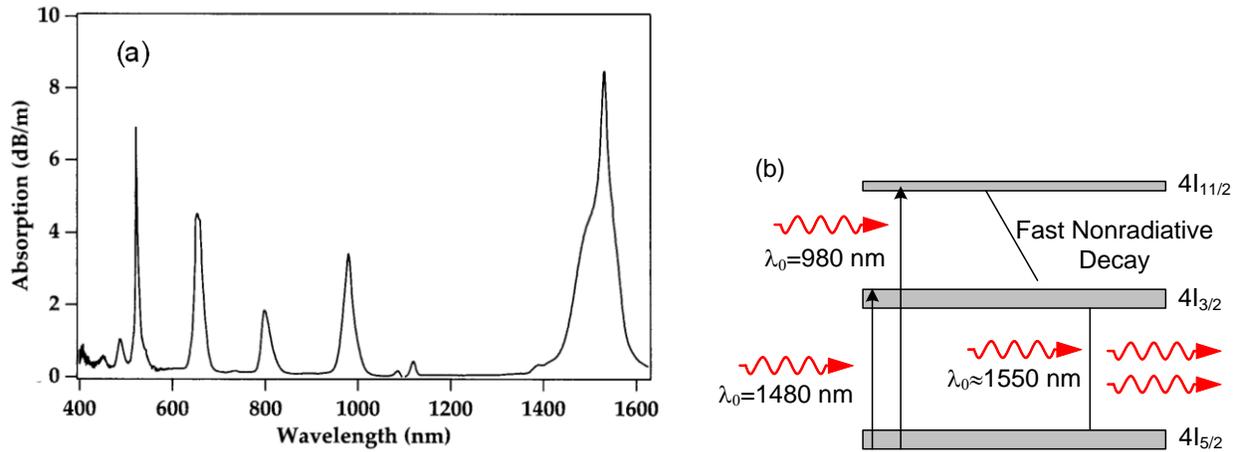


Figure 10.8. (a) Absorption for an erbium-doped glass fiber. The absorption in the region from 400 to 600 nm has been divided by 10. [from *Erbium-Doped Fiber Amplifiers: Fundamentals and Technology*, P. C. Becker, N. A. Olsson, and J. R. Simpson, (Academic Press San Diego, 1999), p. 112] (b) Optical transitions between energy levels that result in the absorption pictured in (a).

A 1480 nm photon excites an erbium ion from the ground level to the upper portion of the upper amplification level. The excited ion decays rapidly to the lower portion of this level. Then a photon with wavelength near 1550 stimulates a transition to the ground state, producing a second photon.

When choosing the wavelength for the pump, it is important to note that pumping with 1480 nm light is more efficient and gives higher gain. On the other hand, pumping with 980 nm light produces a less noisy amplifier.

Gain Saturation

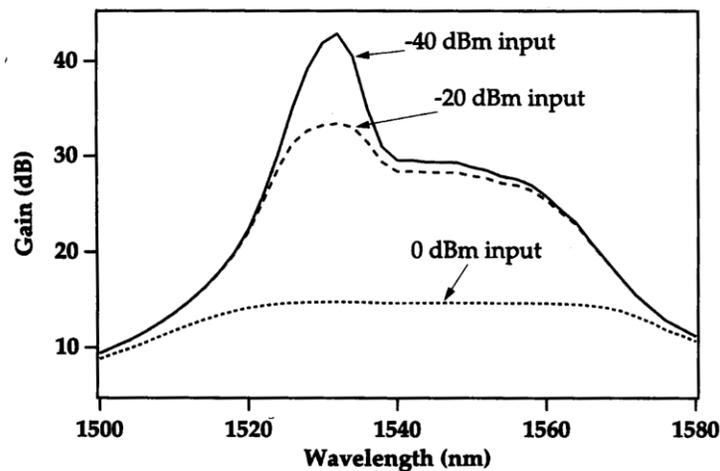


Figure 10.9. Simulated gain versus signal input level for an EDFA with 10 meters of optical fiber, pumped with 50 mW at 980 nm. [from *Erbium-Doped Fiber Amplifiers: Fundamentals and Technology*, P. C. Becker, N. A. Olsson, and J. R. Simpson, (Academic Press San Diego, 1999), p. 282]

The gain of an optical amplifier is not unlimited. This is intuitively obvious. Given a finite pump power, the power added to an optical signal certainly cannot exceed the pump power. As the power in the input signal is increased, there must be a power at which the amplifier gain decreases. We call this effect “gain saturation”. Gain saturation is exhibited in the curves shown in **Figure 10.9**. The input of -40 dBm (100 nW) is called a “small signal” input because the level is lower than what is required to saturate the amplifier gain.

It is also common to indicate gain saturation in a semiconductor optical amplifier with a curve of gain versus optical output. We will derive an expression for this curve. First let us define a gain coefficient g for an amplifier with

$$\frac{dI(z)}{dz} \equiv \Gamma g(z) I(z), \quad (\text{Equation 10.2})$$

where z is distance along the length of the amplifier fiber, $I(z)$ is the optical intensity at position z , and Γ called the optical confinement factor, is the fraction of the optical signal that overlaps the optically active gain region. The gain coefficient is a property of the optically active region of the amplifier that does not depend on amplifier length.

Without going into the mechanism for gain saturation we will assume that g saturates according to

$$g(z) = \frac{g_0}{1 + \frac{I(z)}{I_{sat}}}, \quad (\text{Equation 10.3})$$

where g_0 is the unsaturated gain coefficient and I_{sat} is called the saturation intensity.

Now we can rewrite **Equation 10.2** to find

$$\frac{dI(z)}{dz} = \frac{\Gamma g_0}{1 + \frac{I(z)}{I_{sat}}} I(z). \quad (\text{Equation 10.4})$$

Integrating **Equation 10.2** from the input to the output of the amplifier gives

$$G = G_0 e^{-\left(\frac{G-1}{G}\right) \frac{I_{out}}{I_{sat}}}, \quad (\text{Equation 10.5})$$

where I_{out} is the optical intensity at the amplifier output and G_0 is the peak gain

$$G_0 = e^{\Gamma g_0 L}, \quad (\text{Equation 10.6})$$

where L is the length of the amplifier. G is usually large enough so that we can use the approximation

$$\frac{G-1}{G} \approx 1 \quad (\text{Equation 10.7})$$

and rewrite **Equation 10.5** as

$$G = G_0 e^{-\frac{I_{out}}{I_{sat}}}. \quad (\text{Equation 10.8})$$

Finally, since the optical intensity I is proportional to the optical power P , we can write

$$G = G_0 e^{-\frac{P_{out}}{P_{sat}}}. \quad (\text{Equation 10.9})$$

Equation 10.9 is plotted in **Figure 10.10** with $G_0 = 40$ dB and $P_{sat} = 5$ mW. In manufacturers' literature, the saturation power is often stated as the optical power at which G has decreased by 3 dB. For the plot of **Figure 10.10**, the 3 dB saturation power is 7 mW = 8.5 dBm.

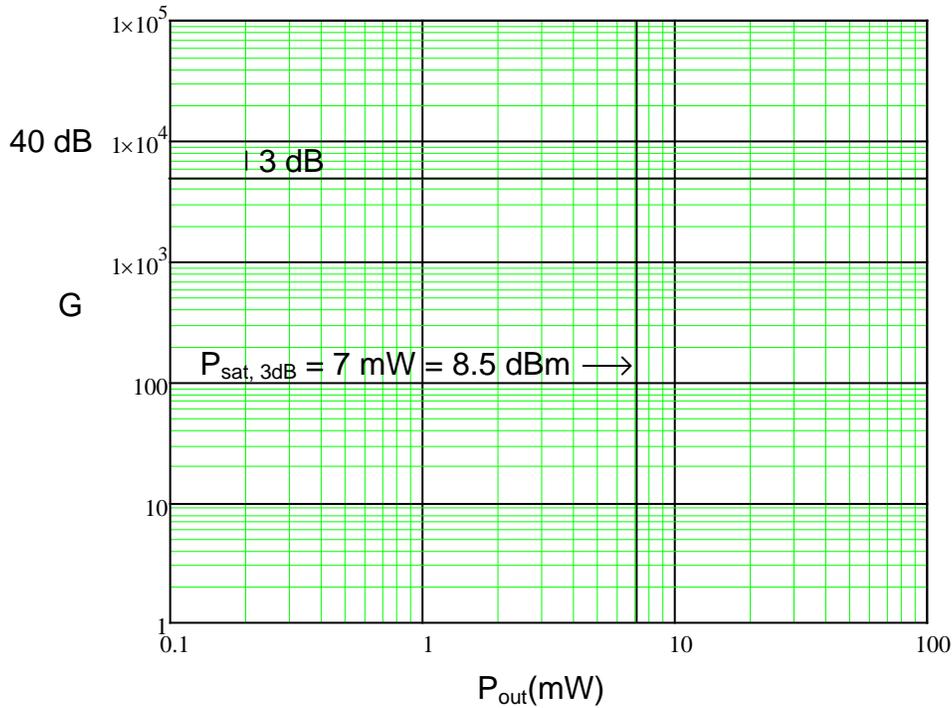


Figure 10.10. Gain as a function of amplifier output.

Polarization Sensitivity and WDM Crosstalk

It is desirable that the gain for an optical amplifier not depend on the polarization of the input signal. Polarization sensitivity can complicate an optical communication system by introducing an unpredictable variation in optical power. Preparing the amplifier input in a state of specified polarization can mitigate polarization sensitivity, but this comes at the cost of additional optical components. Erbium doped fiber amplifiers are not polarization sensitive.

Another highly desirable property of EDFAs is that they can amplify multiple signals simultaneously, without crosstalk between the signals, provided the signals are sufficiently separated in wavelength (**Figure 10.11**). This allows EDFAs to be used in wavelength division multiplexed (WDM) optical communication systems, where data is transmitted across a single optical fiber on multiple signals that are closely spaced in wavelength.

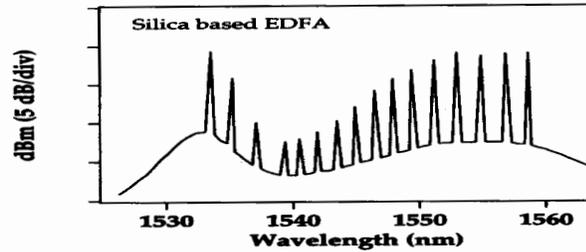


Figure 10.11. Simultaneous amplification of 16 optical signals by a chain of 4 EDFAs. [From *Erbium-Doped Fiber Amplifiers: Fundamentals and Technology*, P. C. Becker, N. A. Olsson, and J. R. Simpson, (Academic Press San Diego, 1999), p. 290; after B. Clesca et al. *Electron. Lett.* Vol. 30, pp. 586-587].

The property of erbium doped fibers that makes them suitable for WDM communications is the relatively slow response of the optical gain to variations in optical signal power. In general, it is possible for power fluctuations in a data stream to modulate an amplifier's gain so as to distort the data in a second stream. Fortunately, the data rates of typical optical communication signals are typically greater than a gigabit per second, and the gain of an EDFA responds only to the average power of the signal.

Amplifier Noise

The noise figure NF for an optical amplifier is defined as

$$NF \equiv \frac{SNR_{in}}{SNR_{out}}, \quad (\text{Equation 10.10})$$

where SNR_{in} and SNR_{out} are the signal-to-noise ratios at the amplifier input and output respectively. The primary source of optical amplifier noise is amplified spontaneous emission (ASE). All amplifiers add noise, and it can be shown that even the ideal optical amplifier has a noise figure of 3 dB. Typical values for EDFAs are 4 to 6 dB.

10.3 EDFA as a Receiver Pre-Amplifier

In this section we consider the use of an erbium doped fiber amplifier as a pre-amplifier for an optical receiver in order to increase the sensitivity of the receiver. It is not obvious that the amplifier will indeed increase sensitivity because, as we noted in a previous section, optical

amplifiers always add noise and decrease signal to noise ratio at their output. Nevertheless, it turns out that an EDFA pre-amplifier will often increase receiver sensitivity. We illustrate this with calculations using typical values for amplifiers and receivers.

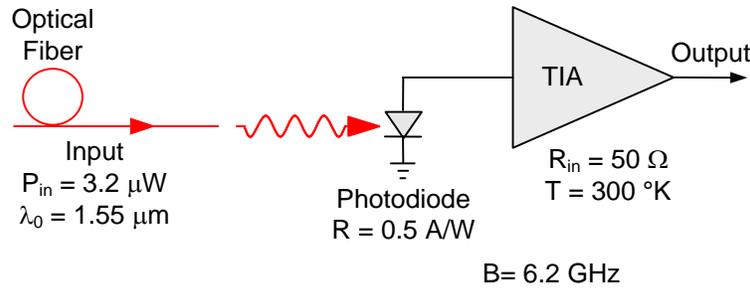


Figure 10.12. An optical receiver without an EDFA optical pre-amplifier.

First we calculate the signal to noise ratio for a receiver without an optical pre-amplifier as shown in **Figure 10.12**. The photodiode has a responsivity of 0.5 amps per watt. The photodiode is connected to a transimpedance amplifier (TIA) with an input impedance of 50 Ω. The electrical bandwidth B of the photodiode/TIA pair is 6.2 GHz. The TIA temperature is 300 K.

The mean square shot noise current for the optical input is

$$\begin{aligned} \langle i_{shot}^2 \rangle &= 2eI_s B \\ &= 2(1.6 \times 10^{-19})(3.2 \times 10^{-6} \times 0.5)6.2 \times 10^9 A^2, \quad (\text{Equation 10.11}) \\ &= 3.174 \times 10^{-15} A^2 \end{aligned}$$

while the mean square thermal noise from the input resistance of the TIA is

$$\begin{aligned} \langle i_{ther}^2 \rangle &= \frac{4kTB}{R_{in}} \quad (\text{Equation 10.12}) \\ &= \frac{4(1.38 \times 10^{-23})(300)(6.2 \times 10^9)}{50} = 2.053 \times 10^{-12} A^2 \end{aligned}$$

A comparison of these two noise contributions shows that thermal noise is dominant and that we can neglect shot noise in this calculation. The signal to noise ratio for the receiver without pre-amplification is then

$$SNR = \frac{(P_s R)^2}{\frac{4kTB}{R_{in}}} = \frac{(3.2 \mu W \times 0.5 A/W)^2}{4(1.38 \times 10^{-23})(300)(6.2 \times 10^9)} \quad (\text{Equation 10.13})$$

$$= \frac{2.56 \times 10^{-12} A^2}{2.053 \times 10^{-12} A^2} = 1.25$$

Next we redo the calculation with an EDFA as a pre-amplifier for the receiver as shown in **Figure 10.13**.

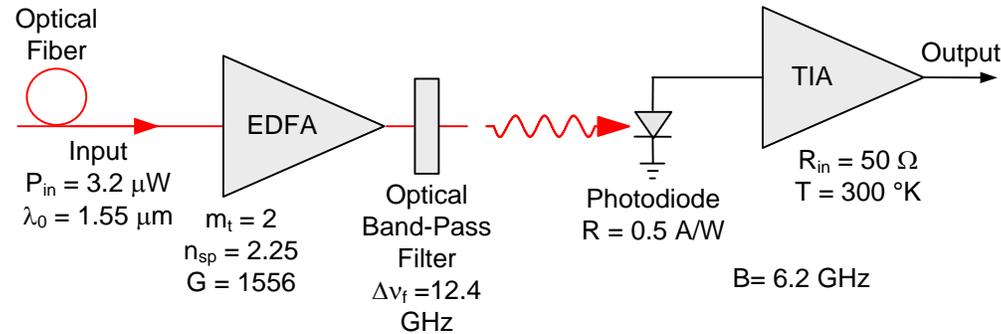


Figure 10.13. An optical receiver with an erbium-doped fiber pre-amplifier.

Two orthogonal optical polarizations can propagate in the amplifier so in noise calculations we include a factor $m_t = 2$. We also use a factor $n_{sp} = 2.25$, which is a measure of the completeness of the population inversion for the amplifier. The contribution of amplified spontaneous emission to noise is reduced with an optical band pass filter with a width of 12.4 GHz.

The amplified spontaneous emission (ASE) power is

$$P_{ASE} = m_t n_{sp} h\nu \Delta\nu_f$$

$$= (2)(2.25)(6.63 \times 10^{-34})(1.94 \times 10^{14})(1.24 \times 10^{10}) \quad (\text{Equation 10.14})$$

$$= 7.18 \times 10^{-9} W$$

and the corresponding ASE current is

$$I_{ASE} = R P_{ASE} = (0.5)(7.18 \times 10^{-9}) = 3.59 \times 10^{-9} A. \quad (\text{Equation 10.15})$$

Noise arises from a beating of the ASE with the optical signal, and the mean square beat noise current is

$$\begin{aligned} \langle i_{sig-spon}^2 \rangle &= 4(GI_s)(GI_{ASE}) \frac{B}{\Delta \nu_f} \\ &= 4(1556)(3.2 \times 10^{-6} \times 0.5)(1556)(3.59 \times 10^{-9}) \frac{6.2 \times 10^9}{1.24 \times 10^{10}} \\ &= 2.78 \times 10^{-8} A^2 \end{aligned}$$

(Equation 10.16)

Compare the beat noise current with the thermal noise current and note that beat noise is now dominant. The signal to noise with the pre-amplifier is

$$\begin{aligned} SNR &= \frac{(GP_s R)^2}{\langle i_{sig-spon}^2 \rangle} \\ &= \frac{(1556 \times 3.2 \mu W \times 0.5 A/W)^2}{2.78 \times 10^{-8} A^2} = 223 \end{aligned} \quad . \quad (Equation 10.17)$$

So, for this typical case, signal to noise is greatly improved with the use of an erbium-doped fiber pre-amplifier.

10.4 Optical Fiber Amplifier Design

The optical fiber amplifier (OFA) is the most important optical amplifier for optical communications. The OFA allows optical signals to be transmitted 1000's of kilometers in all-optical signal lines. Without OFAs, optical signals would need to be converted to electrical signals for amplification and then these amplified signals would subsequently be reconverted back to optical signals for transmission in the optical fiber lines. Such optical-electrical-optical (OEO) conversion is inefficient. Furthermore, the ability of an OFA to simultaneously amplify many optical signals, each with a different wavelength, has enabled the introduction of wavelength division multiplexing into fiber optic networks. In this section we consider some of the most important tools and considerations for the design of OFAs.

Rare Earth Optical Amplifiers

Perhaps the most common and prolific of optical amplifier designs are based on the use of rare-earth doped optical fibers as the active amplifying medium. In this case, silicate optical fibers

are doped with rare-earth constituents whose energy levels provide the basis for the population inversion and gain necessary for amplification of optical signals.

Erbium-Doped Fiber Amplifiers

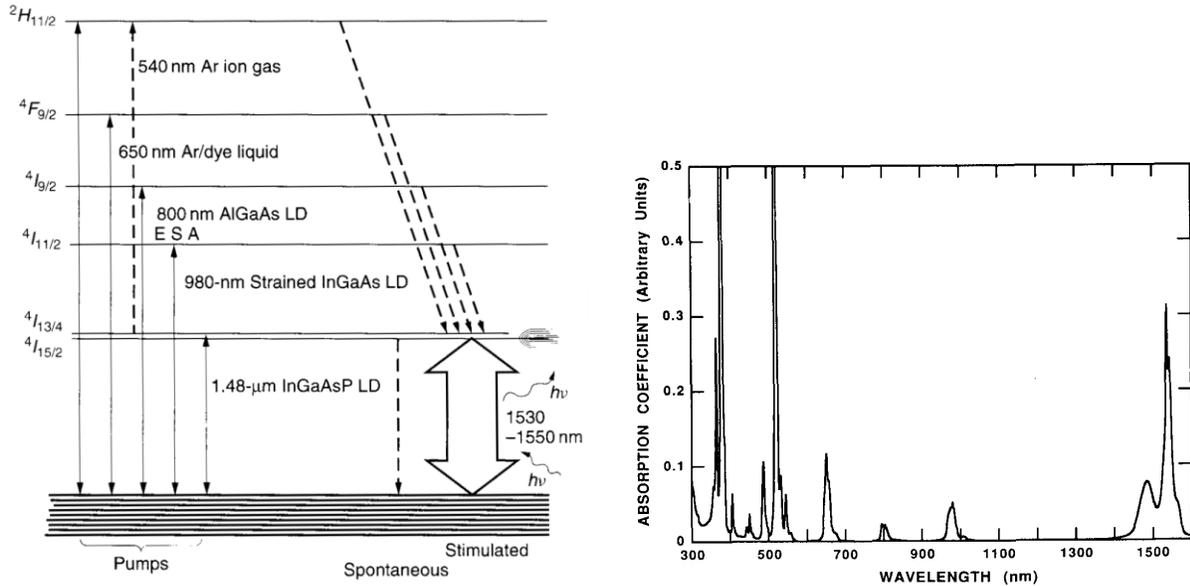


Figure 10.14. *Optical pumping lines for a number of possible pump sources for erbium-doped glass. The peaks of the strong absorption lines at 380 nm and 520 nm are 1.5 and 1.0 respectively. [(Left) From Elements of Photonics, Volume II, Keigo Iizuka (Wiley-Interscience, New York, 2002); (Right) From “Erbium-Doped Glasses for Fiber Amplifiers at 1500 nm,” William J. Miniscalco, Journal of Lightwave Technology, Vol. 9. No. 2, pp. 234-250 (1991)]*

As illustrated in **Figure 10.14**, optical amplification in erbium-doped glass takes place by stimulated emission from an electronic level labeled $4I_{15/2}$ to a ground level. An erbium-doped fiber amplifier (EDFA) is particularly suited for amplification in the optical C band from 1530 to 1565 nm. Optical pumping takes place by means of optical absorption at absorption lines located at 1480 nm, 980 nm, 800 nm, 650 nm, and 540 nm. The most commonly used pumping lines are 1480 nm and 980 nm. Pumping at 1480 nm produces the highest optical gain, while pumping at 980 nm results in an optical amplifier with the smallest amount of noise.

Rate Equations for Erbium-Doped Fiber Amplifiers

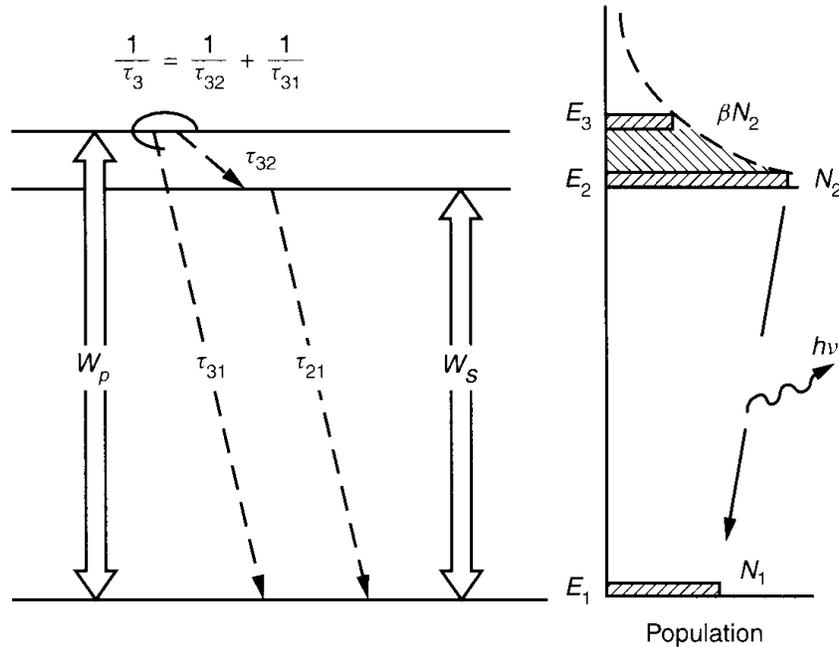


Figure 10.15. A three level model for erbium in glass. [From *Elements of Photonics, Volume II*, Keigo Iizuka (Wiley-Interscience, New York, 2002).

The most important energy levels for erbium in glass are shown in **Figure 10.15**. The figure shows optical pumping through the absorption line at 1480 nm, but the rate equations derived here apply equally to pumping schemes involving higher lying levels. The optical pump promotes erbium ions from the ground level (Level 1) to an excited level (Level 3) at a rate W_p . Erbium ions promoted to Level 3 equilibrate between Levels 2 and 3 by a rapid, nonradiative transfer from Level 3 to Level 2 with a time constant τ_{32} . Ions also leave Level 3 by spontaneous emission to the ground level with a time constant τ_{31} . Stimulated emission (which produces optical gain) takes place with a rate W_s by means of electronic transitions from Level 2 to Level 1. Level 2 is also de-occupied by spontaneous emission to the ground level with a time constant τ_{21} .

Using the relation $\tau_3 = (1/\tau_{32} + 1/\tau_{31})^{-1}$ for the lifetime of erbium ions in Level 3, we have the following equations for the N_1 , N_2 , and N_3 – the population densities for the three erbium levels:

$$\begin{aligned} \frac{dN_3}{dt} &= W_p (N_1 - N_3) - \frac{N_3}{\tau_3} \\ \frac{dN_2}{dt} &= \frac{N_3}{\tau_{32}} - \frac{N_2}{\tau_{21}} - W_s (N_2 - N_1) \\ \frac{dN_1}{dt} &= -W_p (N_1 - N_3) + \frac{N_2}{\tau_{21}} + W_s (N_2 - N_1) \end{aligned} \quad , \quad (\text{Equation 10.18})$$

where the pumping and stimulated emission rates are given by

$$W_p = \sigma_p \frac{I_p}{h\nu_p} \text{ and } W_s = \sigma_s \frac{I}{h\nu}, \quad (\text{Equation 10.19})$$

and σ_p is the absorption cross section for the optical pump, σ_s is the emission cross section for the optical signal to be amplified, I_p is the pump intensity, I is the signal intensity, $h\nu_p$ is the energy of pump photons, and $h\nu$ is the energy of signal photons.

The pumping and emission cross sections depend on wavelength. The wavelength of the pump is usually taken to coincide with the peak of an absorption line. On the other hand, the emission cross section depends on the wavelength of the optical signal to be amplified. **Figure 10.16** shows the emission cross section for erbium in various glass hosts.

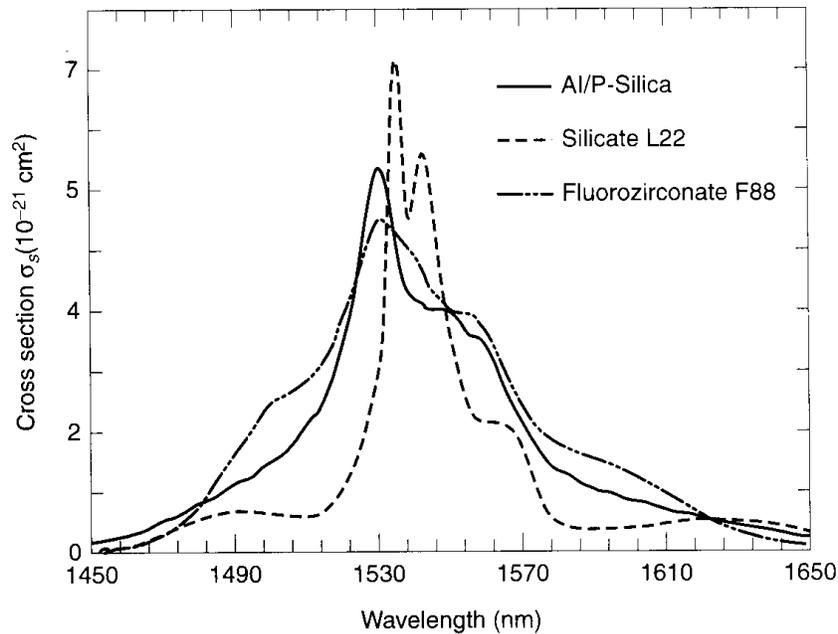


Figure 10.16. The emission cross section for erbium in various glass hosts. [From “Erbium-Doped Glasses for Fiber Amplifiers at 1500 nm,” William J. Miniscalco, *Journal of Lightwave Technology*, Vol. 9, No. 2, pp. 234-250 (1991)]

Finally, we also note that the energy levels E_2 and E_3 are closely spaced and strongly coupled by fast thermal processes so that the fractional relation

$$\beta \equiv \frac{N_3}{N_2} = e^{-(\Delta E/kT)} = 0.38 \quad (\text{Equation 10.20})$$

is always maintained at room temperature.

For steady state conditions we have

$$\frac{dN_1}{dt} = \frac{dN_2}{dt} = \frac{dN_3}{dt} = 0, \quad (\text{Equation 10.20b})$$

and the rate equations become

$$0 = W_p (N_1 - N_3) - \frac{N_3}{\tau_3} \quad (\text{Equation 10.21})$$

$$0 = \frac{N_3}{\tau_{32}} - \frac{N_2}{\tau_{21}} - W_s (N_2 - N_1)$$

$$0 = -W_p (N_1 - N_3) + \frac{N_2}{\tau_{21}} + W_s (N_2 - N_1)$$

The first rate equation gives

$$W_p (N_1 - N_3) = \frac{N_3}{\tau_3} \quad (\text{Equation 10.22})$$

which leads to the approximation

$$W_p (N_1 - N_3) = \frac{N_3}{\tau_{32}} \quad (\text{Equation 10.23})$$

Because $\tau_{31} \gg \tau_{32}$.

Using **Equation 10.23** in **Equation 10.22** gives

$$0 = W_p (N_1 - N_3) - \frac{N_2}{\tau_{21}} - W_s (N_2 - N_1). \quad (\text{Equation 10.24})$$

Next we eliminate N_3 using $N_3 = \beta N_2$ to find

$$\frac{N_2 - N_1}{N} = \frac{(1 - \beta) W_p \tau - 1}{(1 + \beta) W_p \tau + 1 + 2W_s \tau}, \quad (\text{Equation 10.25})$$

where $N = N_1 + N_2$ and $\tau \equiv \tau_{21}$. The population difference $(N_2 - N_1)/N$ on the left-hand side of **Equation 10.25** represents the extent to which there is a population inversion between Levels 1 and 2. A value for $(N_2 - N_1)/N$ of zero means there is no inversion at all, while $(N_2 - N_1)/N = 1$ means there is a complete population inversion. **Figure 10.17** shows how the population

difference and gain depend on the normalized pumping rate $W_p\tau$, the emission rate $W_s\tau$, and the N_3/N_2 population ratio β .

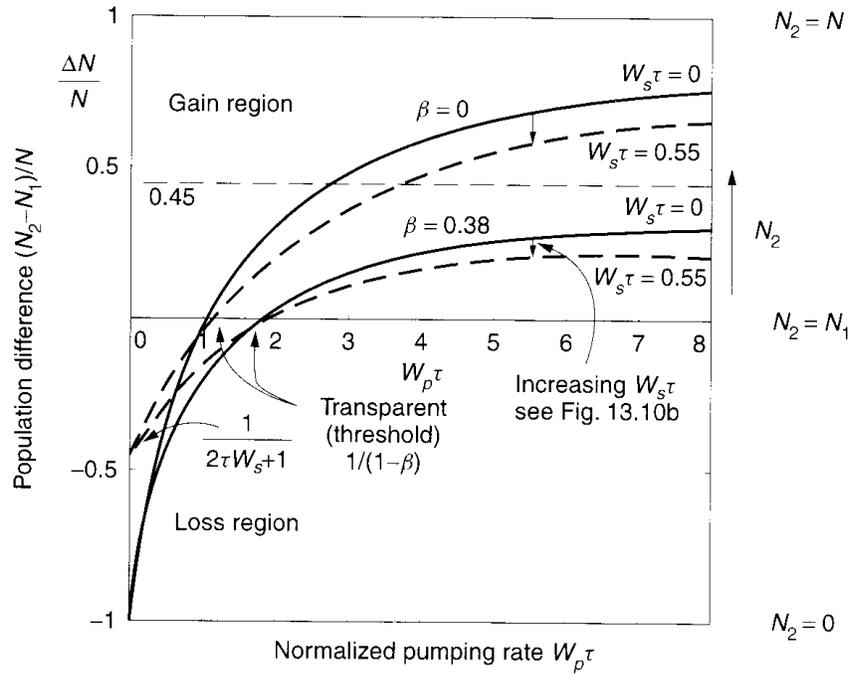


Figure 10.17. Population inversion versus pumping rate. [From *Elements of Photonics, Volume II*, Keigo Iizuka (Wiley-Interscience, New York, 2002)]

The theoretical curves for population inversion in **Figure 10.17** agree, qualitatively, quite well with the experimental curves for amplifier gain pictured in **Figure 10.18**.

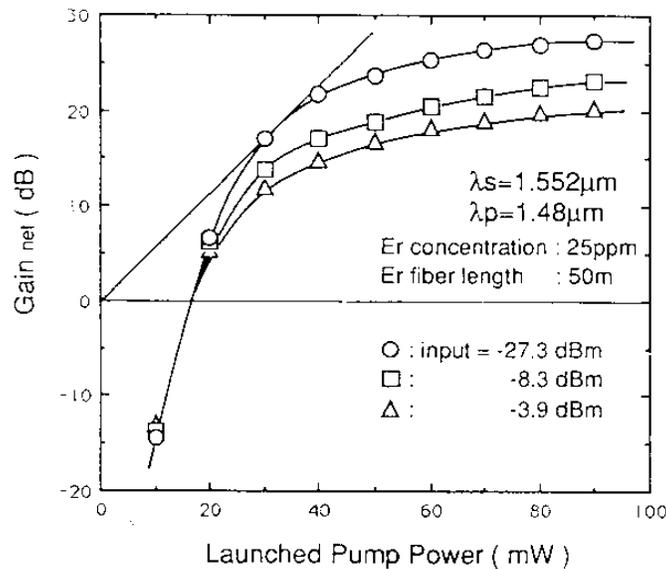


Figure 10.18. Amplifier gain versus optical pump power. [From “Trunk and Distribution Network Application of Erbium-Doped Fiber Amplifier,” K. Nakagawa, S. Nishi, K. Aida, and E. Yoneda, *Journal of Lightwave Technology*, Vol. 9, No. 2, pp. 198-208 (1991)]

We can see in **Figures 10.17 and 10.18** that the population difference and gain decrease with the stimulated emission rate W_s . This is also predicted by the rate equations as is evident by inspection of **Equation 10.25**, which can be rewritten to put it into a standard form for saturating systems:

$$\frac{N_2 - N_1}{N} = \frac{\Delta N_{\max}}{N} \frac{1}{1 + \frac{I}{I_{\text{sat}}}}, \quad (\text{Equation 10.26})$$

where

$$\Delta N_{\max} = N \frac{(1 - \beta)W_p\tau - 1}{(1 + \beta)W_p\tau + 1}, \quad I_{\text{sat}} = \frac{h\nu}{\sigma_s} \frac{1}{2} \left((1 + \beta)W_p + \frac{1}{\tau} \right), \quad (\text{Equation 10.27})$$

and I is the intensity of the amplified optical signal. **Equation 10.26** is plotted in **Figure 10.19**. Note that the saturation intensity is the value for which the population fraction has decreased by $\frac{1}{2}$.

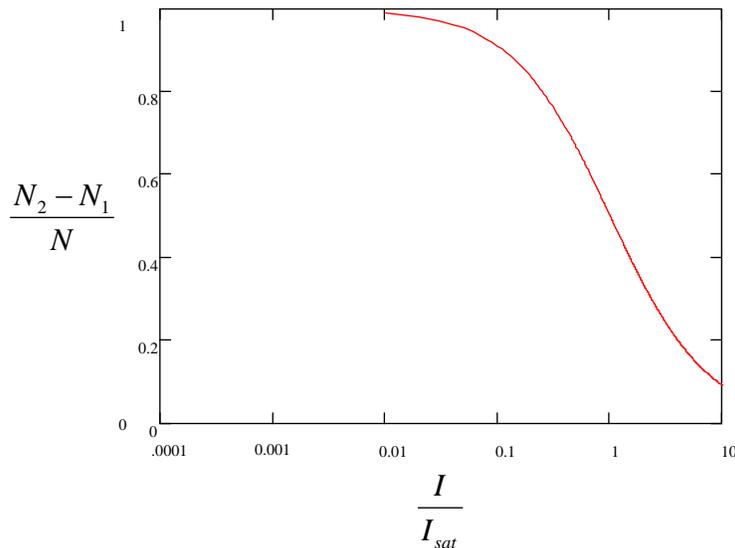


Figure 10.19. Population fraction versus signal intensity.

Praseodymium-Doped Optical Amplifiers

Optical fibers also carry optical signals near 1.3 μm - the approximate wavelength for minimum chromatic dispersion (and thus minimum pulse spreading) in optical fiber. Optical amplifiers have been developed for these wavelengths by doping ZBLAN fiber with praseodymium ions (ZBLAN stands for $\text{ZrF}_4\text{-BaF}_2\text{-LaF}_3\text{-AlF}_3\text{-NaF}$). Praseodymium-doped fiber amplifiers are optically pumped at a wavelength of 1.01 μm . There is less of a need for optical amplifiers for this application because fiber links that operate at wavelengths near 1.3 μm are shorter in length and optical amplification may not be necessary.

10.5 Raman Amplifiers

Raman amplifiers are currently used in optical communication systems to augment the amplification of erbium doped fiber amplifiers. An EDFA is typically used at the beginning of a fiber span, while a Raman amplifier is located at the other end. The combination results in a signal of reasonable intensity at the end of the span, without a very high intensity at the beginning of the span that could induce detrimental nonlinear optical distortion of optical signals. Unlike the amplification of an EDFA, Raman amplification is distributed over a considerable length of optical fiber.

Stimulated Raman Amplification

Stimulated Raman amplification is illustrated in **Figure 10.20**. A weak optical signal with wavelength λ_s and a stronger optical pump with wavelength λ_p propagate in a Raman gain medium. The medium of interest for optical communications is optical fiber. Through a nonlinear optical interaction, power is transferred from the pump light to the signal, amplifying the signal.

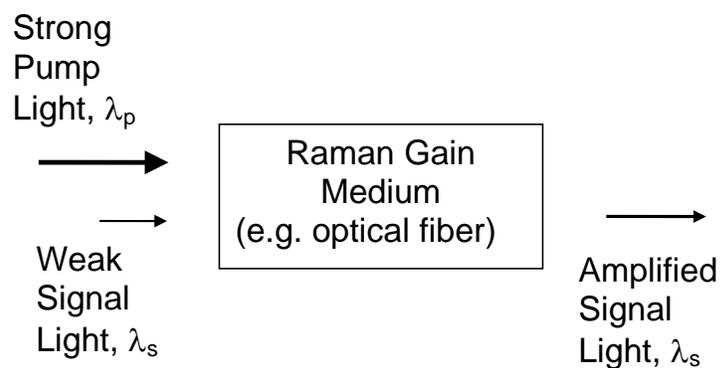


Figure 10.20. *Raman Amplification*

Linear and Nonlinear Optics

The relationship between the “E” and “D” fields in electromagnetism is

$D = \epsilon_0 E + P$, where P is the induced polarization in an optical medium. The expression describes the way in which an optical medium interacts with an electromagnetic wave to modify

the propagation of the wave. In linear and isotropic optical media, the polarization is linearly proportional to the E field and in the same direction, so we can write

$$P = \varepsilon_0 \chi^1 E, \quad (\text{Equation 10.28})$$

where χ^1 is a constant known as the linear susceptibility. In a medium that obeys **Equation 10.28**, the optical properties of the medium (e.g. refractive index and absorption coefficient) do not depend on light intensity.

When the light intensity is high, we often find that the relation between the optical polarization and the E field is nonlinear. An example of a nonlinear relationship is

$$P = \varepsilon_0 \chi^1 E + \varepsilon_0 \chi^3 E^3, \quad (\text{Equation 10.29})$$

where the constant χ^3 is called the third order susceptibility. **Equation 10.29** can be rewritten by factoring out an E to give

$$P = \varepsilon_0 (\chi^1 + \chi^3 E^2) E. \quad (\text{Equation 10.30})$$

The quantity in parentheses in **Equation 10.30** looks like a susceptibility that changes with light intensity. In fact, this relation describes a material with a refractive index and absorption coefficient that are intensity dependent.

Raman Amplification as a Nonlinear Optical Effect

Stimulated Raman amplification is described by a form of **Equation 10.30** in which the induced polarization depends on both the electric field of the optical pump and the optical signal:

$$P = \varepsilon_0 (\chi^1 + \chi^3 E_{pump}^2) E_{signal} \quad (\text{Equation 10.31})$$

The way to interpret **Equation 10.31** is that the pump changes the absorption coefficient for the medium – making the absorption negative – to produce optical gain at the signal frequency.

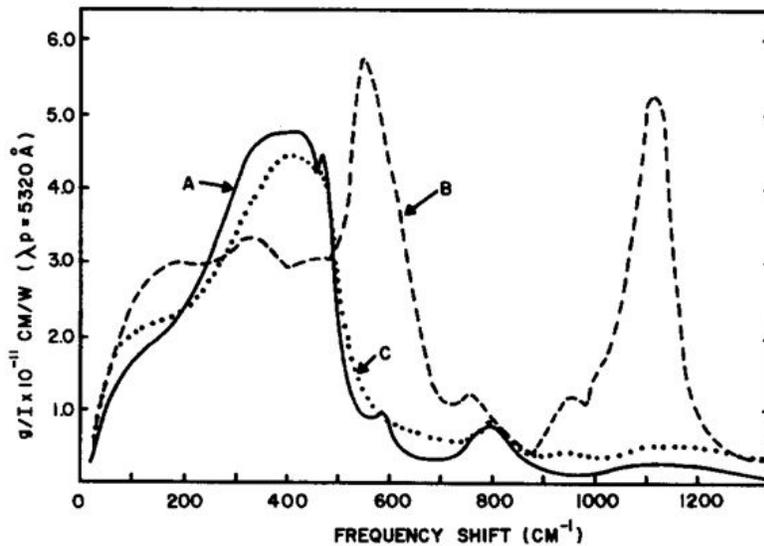


Figure 10.21. Raman gain for three undoped glasses. A- fused quartz, B- soda lime silicate (20:10:70), and C- pyrex. [From “Raman Oscillation in Glass Optical Waveguide,” R. H. Stolen, E. P. Stolen, and A. R. Tynes, *Applied Physics Letters*, Vol. 20, No. 2, pp. 62-64 (1972).

Experimentally measured Raman gain is shown in **Figure 10.21**. The horizontal axis is the separation, expressed as a frequency shift, between the pump wavelength (532 nm for these experiments) and the wavelength for which the optical gain was measured. A frequency shift of 400 cm⁻¹ corresponds to a wavelength separation of about 90 nm for wavelengths of approximately 1.5 μm. As a result, a Raman pump wavelength of approximately 1450 nm is used to amplify signals in the C band from 1530 to 1565 nm.

Use of Raman Amplification in Fiber Optic Data Links

Erbium-doped fiber amplifiers work very well for optical communication and Raman amplifiers will not replace them. However, network engineers use a combination of both types of amplifiers to increase the spacing between repeaters. The advantage of the combination is illustrated in **Figure 10.22**.

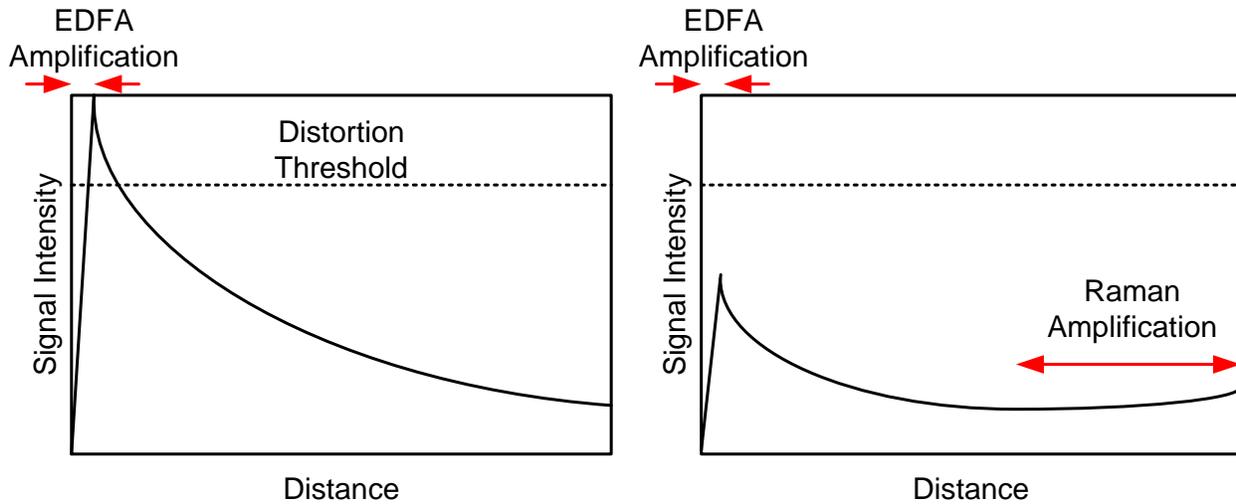


Figure 10.22. (Left) Amplification by EDFA alone. (Right) An EDFA combined with Raman amplification.

The left hand side of **Figure 10.22** illustrates optical amplification with an EDFA. The signal intensity decays exponentially with distance from the amplifier. If the distance to next amplifier is large, the initial signal amplification must be very large in order to produce a signal that can be detected or amplified at the end of the fiber span. In this case, the amplified signal may exceed the threshold for detrimental nonlinear optical effects, such as Stimulated Brillouin Scattering, that can distort the signal.

The right hand side of the **Figure 10.22** shows optical amplification with a combination of an EDFA and Raman amplification. Raman amplification maintains the signal level at the end of the fiber span, so that the signal level at the beginning of the span can be reduced below the distortion threshold. This technique makes possible fiber spans as long as 100's of kilometers.