Introduction to Optical Amplifiers

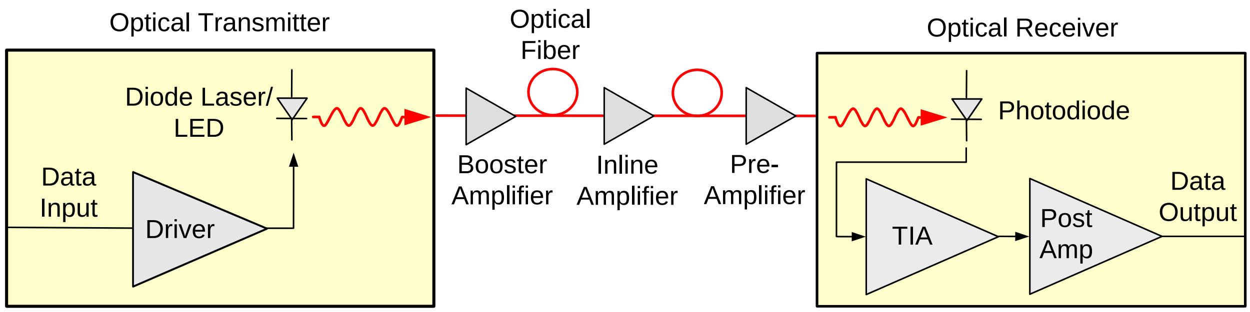

Figure 1. Optical amplifiers in a fiber optic data link.

Optical amplifiers are used extensively in fiber optic data links. Figure 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. The optical signal is attenuated 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 of an optical receiver.

Amplifier Types

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

Erbium-Doped Fiber Amplifiers

An erbium-doped fiber amplifier is illustrated in Figure 2.

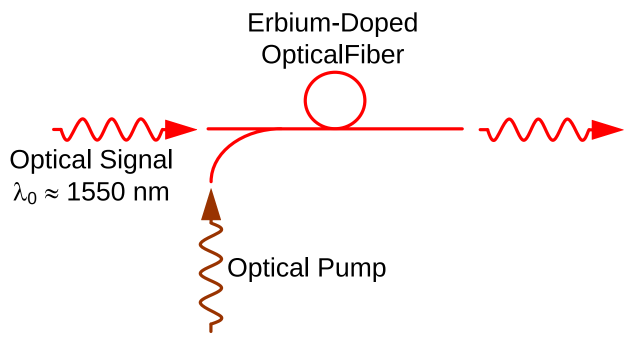

Figure 2. An erbium-doped fiber amplifier.

The amplifying 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. The erbium-doped glass optical gain medium amplifies light at wavelengths that are in the neighborhood of 1550 nm – the optical wavelengths that suffer minimum attenuation in optical fibers. Erbium-doped optical fiber amplifiers (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

A semiconductor optical amplifier is pictured in Figure 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 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 and lasing. A semiconductor optical amplifier (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 are networks where best performance is not required but cost is an important factor.

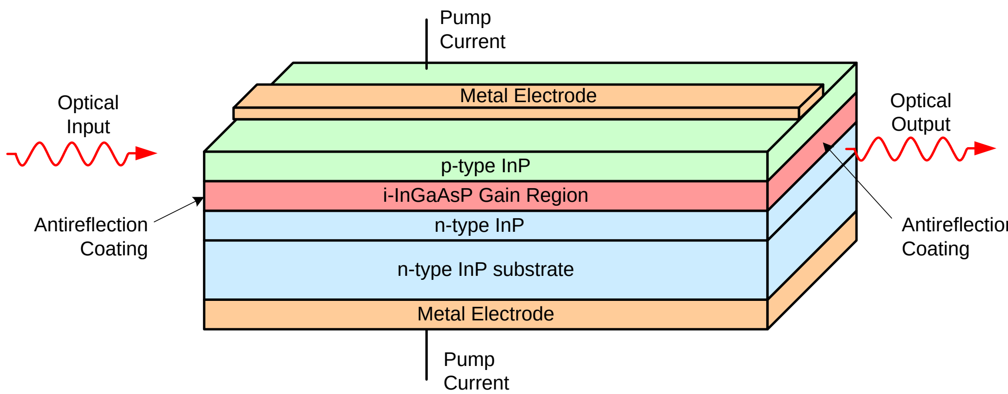

Figure 3. A semiconductor optical amplifier.

Fiber Raman Amplifiers

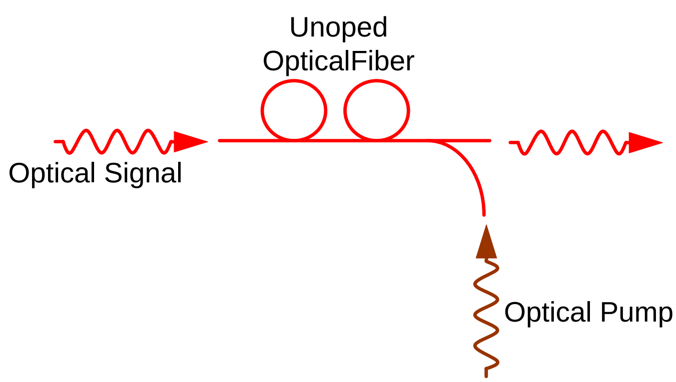

Figure 4. A fiber Raman optical ampflier.

A fiber Raman amplifier is pictured in Figure 4. The gain medium is undoped optical fiber. Power is transferred to the optical signal by a nonlinear optical process known as the Raman effect. Power to supply the optical gain is supplied by an optical pump. The wavelengths that experience optical gain are determined by the wavelength of the optical pump, so the Raman amplifier can me tailored to amplify a given optical wavelength by proper selection of the pump wavelength. The optical gain in a Raman amplifier 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.

EDFA Configurations

The configuration of a co-propagating EDFA is shown in Figure 5. The optical pump is combined with the optical signal into the erbium-doped fiber with a wavelength division multiplexer. A second multiplexer removes residual pump light from the fiber. An in-line optical filter provides additional insurance that pump light does not reach the output of the optical amplifier. An optical isolator is used to prevent reflected light from other portions of the optical system from entering the amplifier.

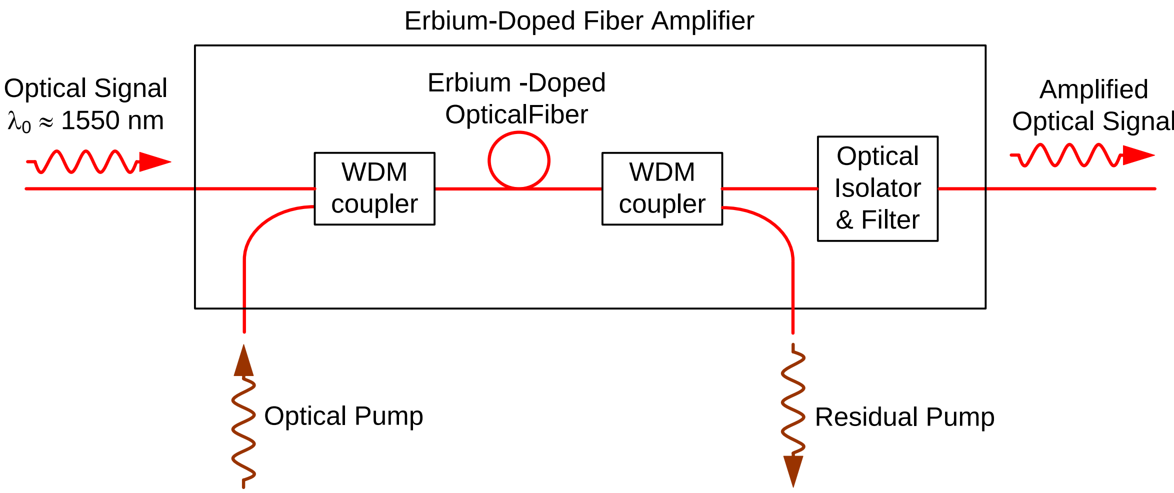

Figure 5. An EDFA for which the optical signal and optical pump are co-propagating.

An EDFA with a counter propagating pump is pictured in Figure 6. The co-propagating geometry produces an amplifier with less noise and less output power. The counter propagating geometry produces a noisier amplifier with high output power. A compromise can be made by combining the co- and counter-propagating geometries in a bi-directional configuration.

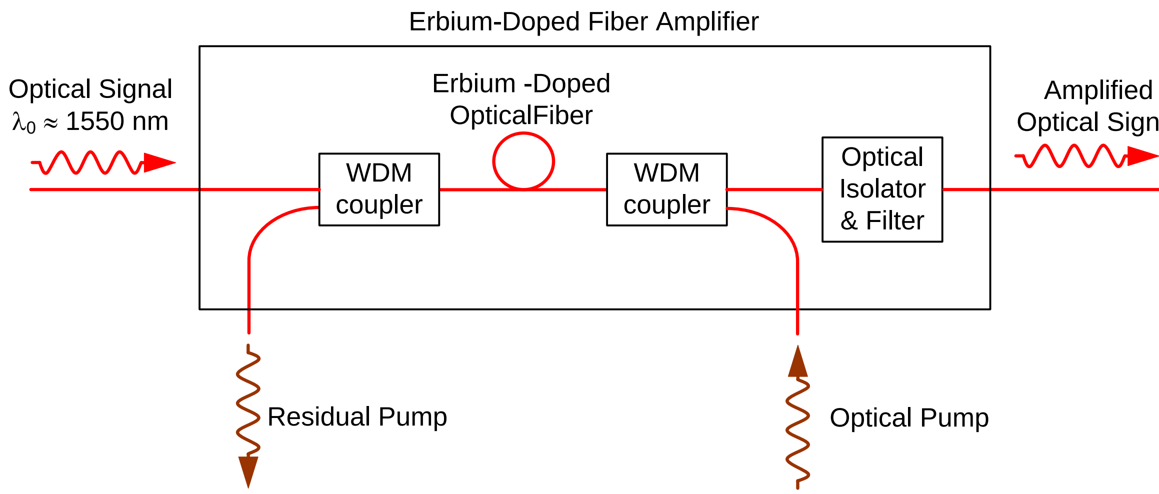

Figure 6. An EDFA for which the optical signal and optical pump are counter-propagating.

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 are summarized in Table 1 at the end of the section.

Wavelength, Bandwidth, Pumping Power

The gain for an optical amplifier is defined by the equation

$$G \equiv \frac{P_{out}}{P_{in}},$$

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 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 a significant gain.

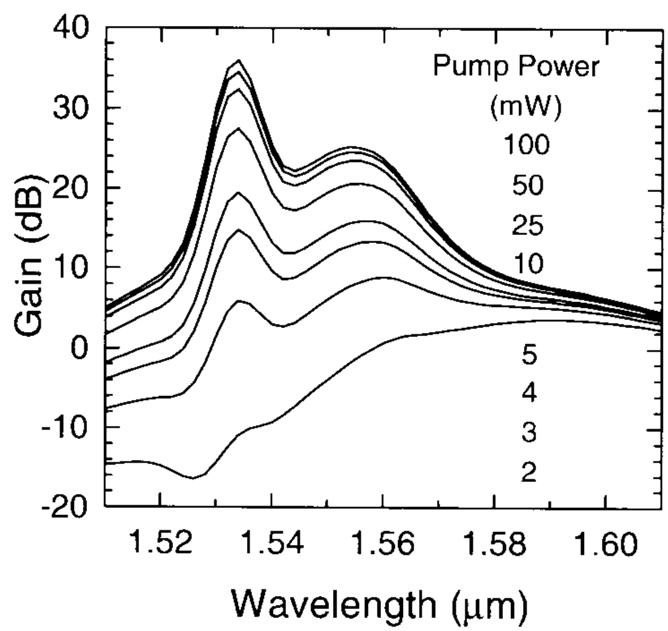

Figure 7. Gain for an erbium-doped fiber amplifier. The pump wavelength is 1480 nm, the fiber length is 30 meters, and the input signal power is -30 dBm. [From *Optical Amplifiers*, Mikhael N. Zervas and Gerlas van den Hoven, Chapter 5 in *Fiber Optics Communication Devices*, Norbert Grote and Herbert 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 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 in with the energy diagram of Figure 8b. A photon at 980 nm pumps an erbium ion from its ground state to an excited state that is 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 while producing a second photon.

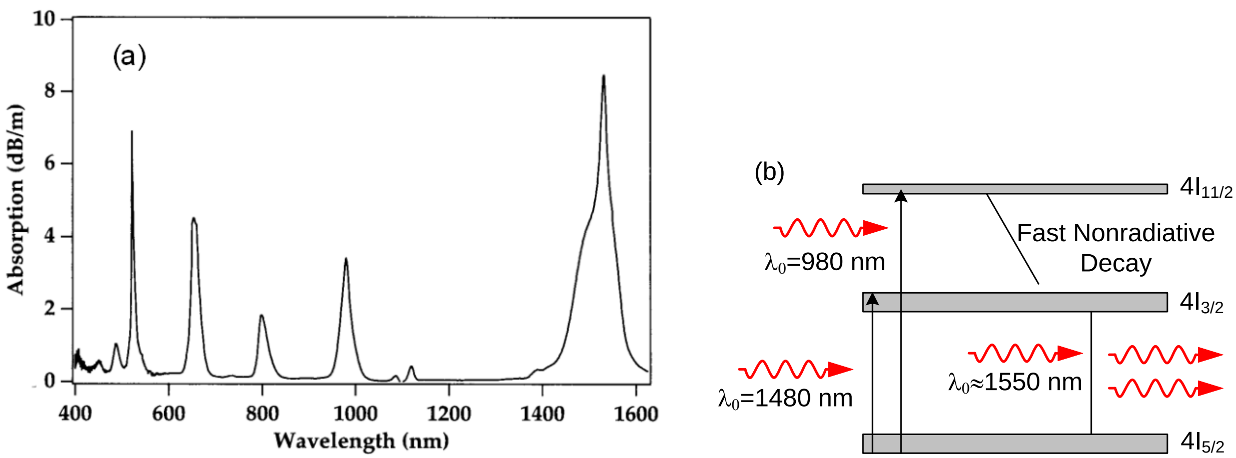

Figure 8. (a) Absorption for an erbium-doped glass fiber. The absorption in the region from 400 to 600 nm has been divided by 10. [from *Erbium-Doped Fiber Amplifiers: Fundamentals and Technology*, P. C. Becker, N. A. Olsson, and J. R. Simpson, (Academic Press San Diego, 1999), p. 112] (b) Optical transitions 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

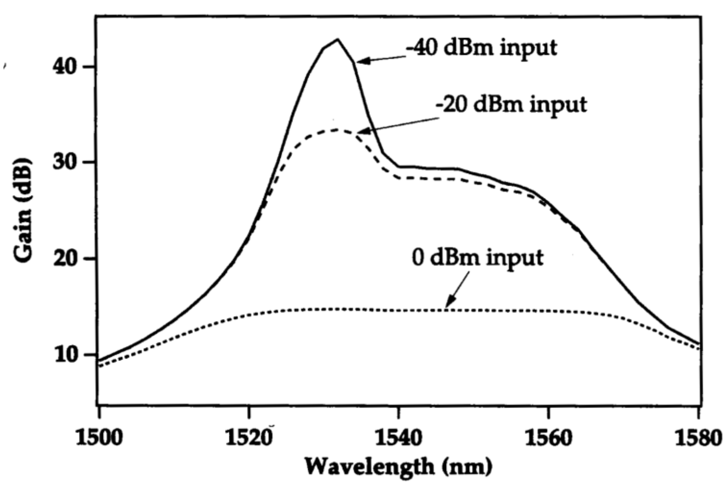

Figure 9. Simulated gain versus signal input level for an EDFA with 10 meters of optical fiber, pumped with 50 mW at 980 nm. [from *Erbium-Doped Fiber Amplifiers: Fundamentals and Technology*, P. C. Becker, N. A. Olsson, and J. R. Simpson, (Academic Press San Diego, 1999), p. 282]

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 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

$$\frac{dI(z)}{dz} \equiv \Gamma g(z) I(z), \qquad \text{Eq. 1}$$

where z is distance along the length of the amplifier, 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 optical 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

$$g(z) = \frac{\Gamma g_0}{1 + \frac{I(z)}{I_{sat}}},$$

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

Now we can rewrite Equation 1 to find

$$\frac{dI(z)}{dz} = \frac{\Gamma g_0}{1 + \frac{I(z)}{I_{sat}}} I(z). \qquad \text{Eq. 2}$$

Integrating Equation 2 from the input to the output of the amplifier gives

$$G = G_0 e^{-\frac{G-1}{G}\frac{I_{out}}{I_{sat}}}, \qquad \text{Eq. 3}$$

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

$$G_0 = e^{-g_0 L},$$

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

$$\frac{G-1}{G} \approx 1$$

and rewrite Equation 3 as

$$G = G_0 e^{-\frac{I_{out}}{I_{sat}}}.$$

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

$$G = G_0 e^{-\frac{P_{out}}{P_{sat}}}. \qquad \text{Eq. 4}$$

Equation 4 is plotted in Figure 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, the 3 dB saturation power is 7 mW = 8.5 dBm.

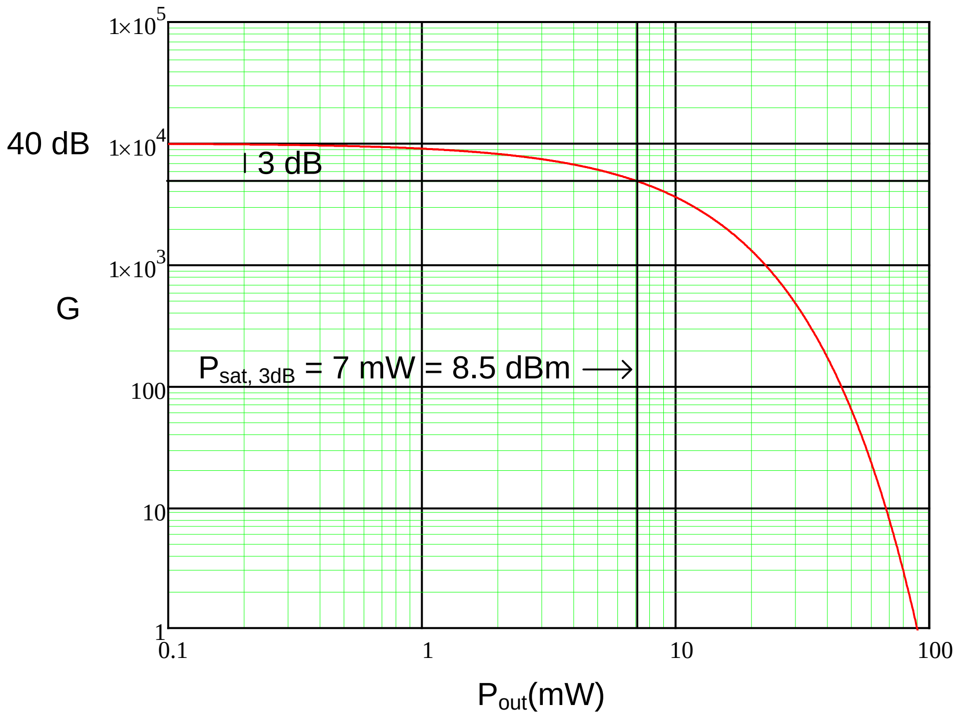

Figure 10. Gain as a function of amplifier output.

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. Polarization sensitivity can be mitigated by preparing amplifier input in a state of specified polarization, 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 separated in wavelength (Figure 11). This allows

EDFAs to be used in wavelength division multiplexed (WDM) optical communication systems, where data is transmitted down a single optical fiber on multiple signals that are closely spaced in wavelength.

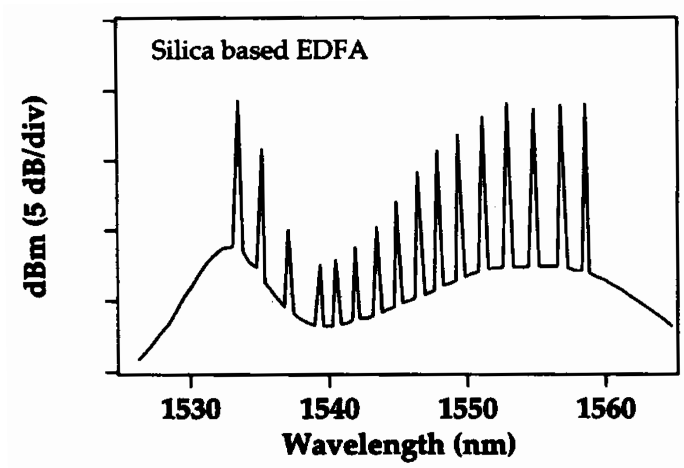

Figure 11. Simultaneous amplification of 16 optical signals by a chain of 4 EDFAs. [From *Erbium-Doped Fiber Amplifiers: Fundamentals and Technology*, P. C. Becker, N. A. Olsson, and J. R. Simpson, (Academic Press San Diego, 1999), p. 290; after B. Clesca et al. Electron. Lett. Vol. 30, pp. 586-587]

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. It 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

$$NF \equiv \frac{SNR_{in}}{SNR_{out}},$$

where SNR_{in} and SNR_{out} are the signal-to-noise ratios at the amplifier input and output respectively. The origin of optical amplifier noise is amplified spontaneous emission. 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.

Summary

The characteristics of erbium-doped fiber amplifiers are summarized in Table 1.

Table 1. Typical values for characteristics of EDFAs.

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

An 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.

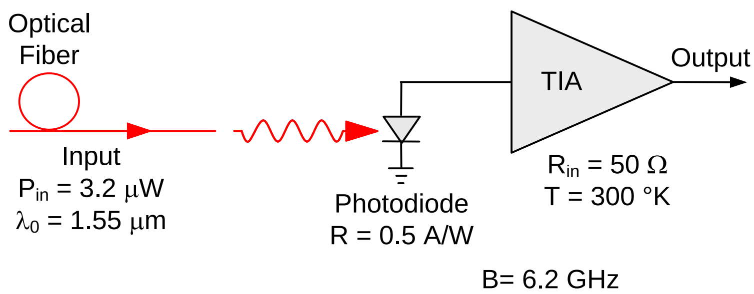

Figure 12. An optical receiver without an EDFA optical pre-amplifier.

First we calculate the signal to noise ratio for a receiver without an optical pre-amplifier as shown in Figure 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

$$\langle i_{shot}^2 \rangle = 2eI_sB$$
$$= 2\left(1.6\times10^{-19}\right)\left(3.2\times10^{-6}\times0.5\right)6.2\times10^{9}A^2\ ,$$
$$= 3.174\times10^{-15}A^2$$

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

$$\langle i_{ther}^2 \rangle = \frac{4kTB}{R_{in}}$$
$$= \frac{4\left(1.38\times10^{-23}\right)(300)\left(6.2\times10^{9}\right)}{50} = 2.053\times10^{-12}A^2 .$$

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

$$SNR = \frac{(P_sR)^2}{\frac{4kTB}{R_L}} = \frac{\left(3.2\mu W\times0.5A/W\right)^2}{\frac{4\left(1.38\times10^{-23}\right)(300)\left(6.2\times10^{9}\right)}{50}} .$$
$$= \frac{2.56\times10^{-12}A^2}{2.053\times10^{-12}A^2} = 1.25$$

Next we redo the calculation with an EDFA as a pre-amplifier for the receiver as shown in Figure 13.

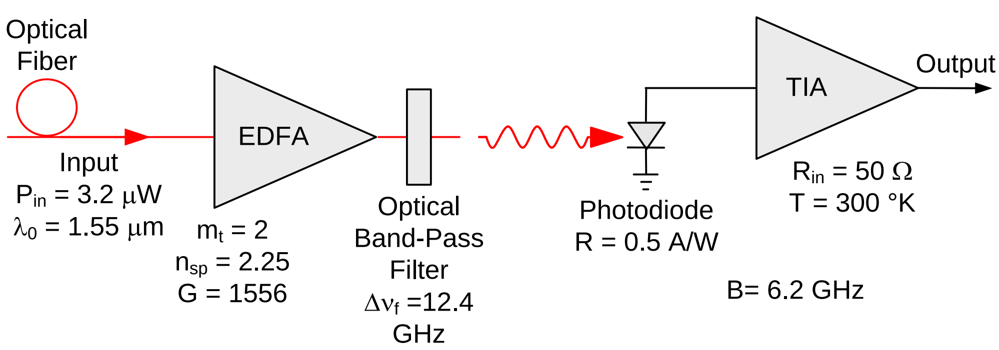

Figure 13. An optical receiver with an erbium-doped fiber pre-amplifier.

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

$$\begin{aligned} P_{ASE} &= m_t n_{sp} h\nu \Delta\nu_f \\ &= (2)(2.25)\left(6.63\times10^{-34}\right)\left(1.94\times10^{14}\right)\left(1.24\times10^{10}\right), \\ &= 7.18x10^{-9}W \end{aligned}$$

and the corresponding ASE current is

$$I_{ASE} = RP_{ASE} = (0.5)\left(7.18\times10^{-9}\right) = 3.59\times10^{-9}A.$$

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

$$\begin{aligned} \left\langle i^2_{sig-spon}\right\rangle &= 4GI_sGI_{ASE}\frac{B}{\Delta\nu_f} \\ &= 4(1556)\left(3.2\times10^{-6}\times0.5\right)(1556)\left(3.59\times10^{-9}\right)\frac{6.2\times10^9}{1.24\times10^{10}}. \\ &= 2.78\times10^{-8}A^2 \end{aligned}$$

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

$$SNR = \frac{\left(GP_sR\right)^2}{\left\langle i_{sig-spon}^2 \right\rangle}$$

$$= \frac{\left(1556 \times 3.2\mu W \times 0.5A/W\right)^2}{2.78 \times 10^{-8} A^2} = 223 \, .$$

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