systems are discussed in Chapters 4 and 5. In addition, in some amplifier designs, the ASE can be large enough to *saturate* the amplifier. Saturation effects are explored in Chapter 5.

3.4.3 Erbium-Doped Fiber Amplifiers

An erbium-doped fiber amplifier (EDFA) is shown in Figure 3.34. It consists of a length of silica fiber whose core is doped with ionized atoms (ions), Er^{3+}, of the rare earth element erbium. This fiber is pumped using a pump signal from a laser, typically at a wavelength of 980 nm or 1480 nm. In order to combine the output of the pump laser with the input signal, the doped fiber is preceded by a wavelength-selective coupler.

At the output, another wavelength-selective coupler may be used if needed to separate the amplified signal from any remaining pump signal power. Usually, an isolator is used at the input and/or output of any amplifier to prevent reflections into the amplifier. We will see in Section 3.5 that reflections can convert the amplifier into a laser, making it unusable as an amplifier.

A combination of several factors has made the EDFA the amplifier of choice in today's optical communication systems: (1) the availability of compact and reliable high-power semiconductor pump lasers, (2) the fact that it is an all-fiber device, making it polarization independent and easy to couple light in and out of it, (3) the simplicity of the device, and (4) the fact that it introduces no crosstalk when amplifying WDM signals. This last aspect is discussed later in the context of semiconductor optical amplifiers.

Principle of Operation

Three of the energy levels of erbium ions in silica glass are shown in Figure 3.35 and are labeled E_1, E_2, and E_3 in order of increasing energy. Several other levels in Er^{3+} are not shown. Each energy level that appears as a discrete line in an isolated

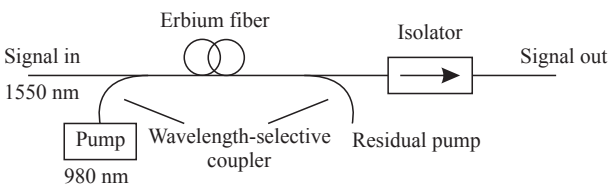

Figure 3.34 An erbium-doped fiber amplifier.

ion of erbium is split into multiple energy levels when these ions are introduced into silica glass. This process is termed *Stark splitting*. Moreover, glass is not a crystal and thus does not have a regular structure. Thus the Stark splitting levels introduced are slightly different for individual erbium ions, depending on the local surroundings seen by those ions. Macroscopically, that is, when viewed as a collection of ions, this has the effect of spreading each discrete energy level of an erbium ion into a continuous *energy band*. This spreading of energy levels is a useful characteristic for optical amplifiers since they increase the frequency or wavelength range of the signals that can be amplified. Within each energy band, the erbium ions are distributed in the various levels within that band in a nonuniform manner by a process known as *thermalization*. It is due to this thermalization process that an amplifier is capable of amplifying several wavelengths simultaneously. Note that Stark splitting denotes the phenomenon by which the energy levels of free erbium ions are split into a number of levels, or into an energy band, when the ion is introduced into silica glass. Thermalization refers to the process by which the erbium ions are distributed within the various (split) levels constituting an energy band.

Recall from our discussion of the two-energy-level atomic system that only an optical signal at the frequency f_c satisfying $hf_c = E_2 - E_1$ could be amplified in that

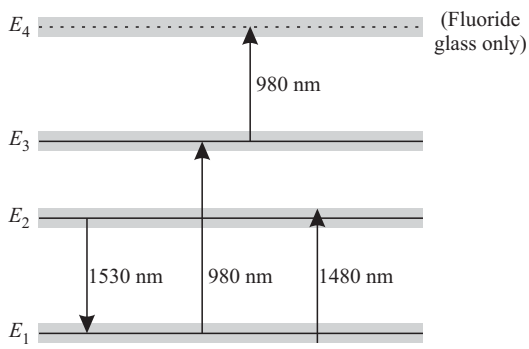

Figure 3.35 Three energy levels E_1, E_2, and E_3 of Er^{3+} ions in silica glass. The fourth energy level, E_4, is present in fluoride glass but not in silica glass. The energy levels are spread into bands by the Stark splitting process. The difference between the energy levels is labeled with the wavelength in nm of the photon corresponding to it. The upward arrows indicate wavelengths at which the amplifier can be pumped to excite the ions into the higher energy level. The 980 nm transition corresponds to the band gap between the E_1 and E_3 levels. The 1480 nm transition corresponds to the gap between the bottom of the E_1 band to the top of the E_2 band. The downward transition represents the wavelength of photons emitted due to spontaneous and stimulated emission.

case. If these levels are spread into bands, all frequencies that correspond to the energy difference between some energy in the E_2 band and some energy in the E_1 band can be amplified. In the case of erbium ions in silica glass, the set of frequencies that can be amplified by stimulated emission from the E_2 band to the E_1 band corresponds to the wavelength range 1525–1570 nm, a bandwidth of 50 nm, with a peak around 1532 nm. By a lucky coincidence, this is exactly one of the low-attenuation windows of standard optical fiber that optical communication systems use.

Denote ionic population in level E_i by N_i, $i = 1, 2, 3$. In thermal equilibrium, $N_1 > N_2 > N_3$. The population inversion condition for stimulated emission from E_2 to E_1 is $N_2 > N_1$ and can be achieved by a combination of absorption and spontaneous emission as follows. The energy difference between the E_1 and E_3 levels corresponds to a wavelength of 980 nm. So if optical power at 980 nm—called the *pump power*—is injected into the amplifier, it will cause transitions from E_1 to E_3 and vice versa. Since $N_1 > N_3$, there will be a net absorption of the 980 nm power. This process is called *pumping*.

The ions that have been raised to level E_3 by this process will quickly transit to level E_2 by the spontaneous emission process. The lifetime for this process, τ_{32}, is about 1 μs. Atoms from level E_2 will also transit to level E_1 by the spontaneous emission process, but the lifetime for this process, τ_{21}, is about 10 ms, which is much larger than the E_3 to E_2 lifetime. Moreover, if the pump power is sufficiently large, ions that transit to the E_1 level are rapidly raised again to the E_3 level only to transit to the E_2 level again. The net effect is that most of the ions are found in level E_2, and thus we have population inversion between the E_2 and E_1 levels. Therefore, if simultaneously a signal in the 1525–1570 nm band is injected into the fiber, it will be amplified by stimulated emission from the E_2 to the E_1 level.

Several levels other than E_3 are higher than E_2 and, in principle, can be used for pumping the amplifier. But the pumping process is more efficient, that is, uses less pump power for a given gain, at 980 nm than these other wavelengths. Another possible choice for the pump wavelength is 1480 nm. This choice corresponds to absorption from the bottom sublevel of the E_1 band to the top sublevel of the E_2 band itself. Pumping at 1480 nm is not as efficient as 980 nm pumping. Moreover, the degree of population inversion that can be achieved by 1480 nm pumping is lower. The higher the population inversion, the lower the noise figure of the amplifier. Thus 980 nm pumping is preferred to realize low-noise amplifiers. However, higher-power pump lasers are available at 1480 nm, compared to 980 nm, and thus 1480 nm pumps find applications in amplifiers designed to yield high output powers. Another advantage of the 1480 nm pump is that the pump power can also propagate with low loss in the silica fiber that is used to carry the signals. Therefore, the pump laser can be located remotely from the amplifier itself. This feature is used in some systems to avoid placing any active components in the middle of the link.

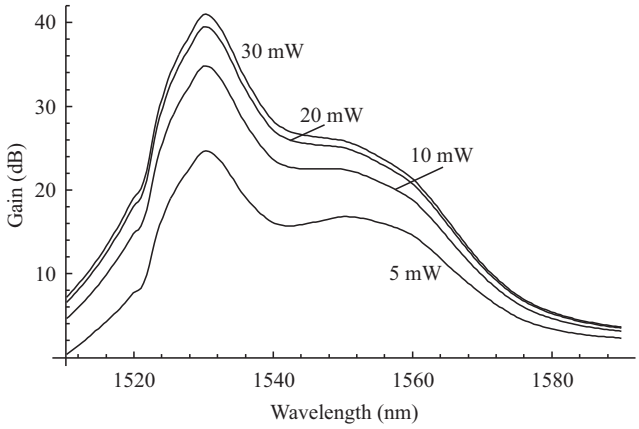

Figure 3.36 The gain of a typical EDFA as a function of the wavelength for four different values of the pump power, obtained through simulations. The length of the doped fiber is taken to be 15 m and 980 nm pumping is assumed.

Gain Flatness

Since the population levels at the various levels within a band are different, the gain of an EDFA becomes a function of the wavelength. In Figure 3.36, we plot the gain of a typical EDFA as a function of the wavelength for different values of the pump power. When such an EDFA is used in a WDM communication system, different WDM channels undergo different degrees of amplification. This is a critical issue, particularly in WDM systems with cascaded amplifiers, and is discussed in Section 5.5.2.

One way to improve the flatness of the amplifier gain profile is to use fluoride glass fiber instead of silica fiber, doped with erbium [Cle94]. Such amplifiers are called erbium-doped fluoride fiber amplifiers (EDFFAs). The fluoride glass produces a naturally flatter gain spectrum compared to silica glass. However, there are a few drawbacks to using fluoride glass. The noise performance of EDFFAs is poorer than EDFAs. One reason is that they must be pumped at 1480 nm and cannot be pumped at 980 nm. This is because fluoride glass has an additional higher energy level E_4 above the E_3 level, as shown in Figure 3.35, with the difference in energies between these two levels corresponding to 980 nm. This causes the 980 nm pump power to be absorbed for transitions from the E_3 to E_4 level, which does not produce useful gain. This phenomenon is called *excited state absorption*.

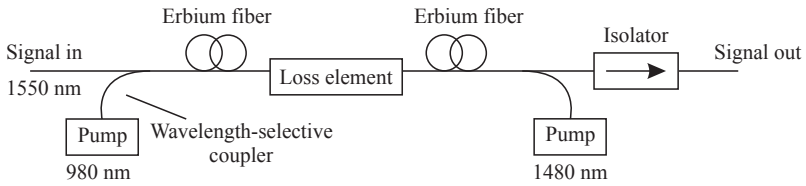

Figure 3.37 A two-stage erbium-doped fiber amplifier with a loss element inserted between the first and second stage.

In addition to this drawback, fluoride fiber itself is difficult to handle. It is brittle, difficult to splice with conventional fiber, and susceptible to moisture. Nevertheless, EDFFAs are now commercially available devices.

Another approach to flatten the EDFA gain is to use a filter inside the amplifier. The EDFA has a relatively high gain at 1532 nm, which can be reduced by using a notch filter in that wavelength region inside the amplifier. Some of the filters described in Section 3.3 can be used for this purpose. Long-period fiber gratings and dielectric thin-film filters are currently the leading candidates for this application.

Multistage Designs

In practice, most amplifiers deployed in real systems are more complicated than the simple structure shown in Figure 3.34. Figure 3.37 shows a more commonly used two-stage design. The two stages are optimized differently. The first stage is designed to provide high gain and low noise, and the second stage is designed to produce high output power. As we will see in Problem 4.5 in Chapter 4, the noise performance of the whole amplifier is determined primarily by the first stage. Thus this combination produces a high-performance amplifier with low noise and high output power. Another important consideration in the design is to provide redundancy in the event of the failure of a pump, the only active component of the amplifier. The amplifier shown in the figure uses two pumps and can be designed so that the failure of one pump has only a small impact on the system performance. Another feature of the two-stage design that we will address in Problem 4.5 is that a loss element can be placed between the two stages with negligible impact on the performance. This loss element may be a gain-flattening filter, a simple optical add/drop multiplexer, or a dispersion compensation module used to compensate for accumulated dispersion along the link.