any periodic filter can be used as an interleaver by matching its period to the desired channel spacing. For example, a fiber-based Mach-Zehnder interferometer is a common choice. These devices are now commercially available, and interleaving is becoming a popular approach toward realizing high channel count multiplexers and demultiplexers.

3.4 Optical Amplifiers

In an optical communication system, the optical signals from the transmitter are attenuated by the optical fiber as they propagate through it. Other optical components, such as multiplexers and couplers, also add loss. After some distance, the cumulative loss of signal strength causes the signal to become too weak to be detected. Before this happens, the signal strength has to be restored. Prior to the advent of optical amplifiers over the last decade, the only option was to regenerate the signal, that is, receive the signal and retransmit it. This process is accomplished by *regenerators*. A regenerator converts the optical signal to an electrical signal, cleans it up, and converts it back into an optical signal for onward transmission.

Optical amplifiers offer several advantages over regenerators. On one hand, regenerators are specific to the bit rate and modulation format used by the communication system. On the other hand, optical amplifiers are insensitive to the bit rate or signal formats. Thus a system using optical amplifiers can be more easily upgraded, for example, to a higher bit rate, without replacing the amplifiers. In contrast, in a system using regenerators, such an upgrade would require all the regenerators to be replaced. Furthermore, optical amplifiers have fairly large gain bandwidths, and as a consequence, a single amplifier can simultaneously amplify several WDM signals. In contrast, we would need a regenerator for each wavelength. Thus optical amplifiers have become essential components in high-performance optical communication systems.

Amplifiers, however, are not perfect devices. They introduce additional noise, and this noise accumulates as the signal passes through multiple amplifiers along its path due to the analog nature of the amplifier. The spectral shape of the gain, the output power, and the transient behavior of the amplifier are also important considerations for system applications. Ideally, we would like to have a sufficiently high output power to meet the needs of the network application. We would also like the gain to be flat over the operating wavelength range and to be insensitive to variations in input power of the signal. We will study the impact of optical amplifiers on the physical layer design of the system in Chapters 4 and 5. Here we explore their principle of operation.

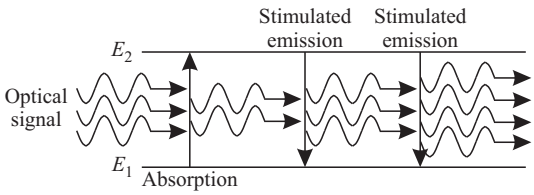

Figure 3.33 Stimulated emission and absorption in an atomic system with two energy levels.

We will consider three different types of amplifiers: *erbium-doped fiber amplifiers, Raman amplifiers,* and *semiconductor optical amplifiers.*

3.4.1 Stimulated Emission

In all the amplifiers we consider, the key physical phenomenon behind signal amplification is *stimulated emission* of radiation by atoms in the presence of an electromagnetic field. (This is not true of fiber Raman or fiber Brillouin amplifiers, which make use of fiber nonlinearities, but we do not treat these here.) This field is an optical signal in the case of optical amplifiers. Stimulated emission is the principle underlying the operation of lasers as well; we will study lasers in Section 3.5.1.

According to the principles of quantum mechanics, any physical system (for example, an atom) is found in one of a discrete number of energy levels. Accordingly, consider an atom and two of its energy levels, E_1 and E_2, with $E_2 > E_1$. An electromagnetic field whose frequency f_c satisfies $hf_c = E_2 - E_1$ induces transitions of atoms between the energy levels E_1 and E_2. Here, h is Planck's constant (6.63×10^{-34} J s). This process is depicted in Figure 3.33. Both kinds of transitions, $E_1 \rightarrow E_2$ and $E_2 \rightarrow E_1$, occur. $E_1 \rightarrow E_2$ transitions are accompanied by *absorption* of photons from the incident electromagnetic field. $E_2 \rightarrow E_1$ transitions are accompanied by the *emission* of photons of energy hf_c, the same energy as that of the incident photons. This emission process is termed *stimulated emission* to distinguish it from another kind of emission called *spontaneous emission*, which we will discuss later. Thus if stimulated emission were to dominate over absorption—that is, the incident signal causes more $E_2 \rightarrow E_1$ transitions than $E_1 \rightarrow E_2$ transitions—we would have a net increase in the number of photons of energy hf_c and an amplification of the signal. Otherwise, the signal will be attenuated.

It follows from the theory of quantum mechanics that the rate of the $E_1 \rightarrow E_2$ transitions per atom *equals* the rate of the $E_2 \rightarrow E_1$ transitions *per atom*. Let this common rate be denoted by r. If the populations (number of atoms) in the energy levels E_1 and E_2 are N_1 and N_2, respectively, we have a net increase in power (energy per unit time) of $(N_2 - N_1)rhf_c$. Clearly, for amplification to occur, this must be positive, that is, $N_2 > N_1$. This condition is known as *population inversion*. The reason for this term is that, at thermal equilibrium, lower energy levels are more highly populated, that is, $N_2 < N_1$. Therefore, at thermal equilibrium, we have only absorption of the input signal. In order for amplification to occur, we must *invert* the relationship between the populations of levels E_1 and E_2 that prevails under thermal equilibrium.

Population inversion can be achieved by supplying additional energy in a suitable form to pump the electrons to the higher energy level. This additional energy can be in optical or electrical form.

3.4.2 Spontaneous Emission

Before describing the operation of the different types of amplifiers, it is important to understand the impact of spontaneous emission. Consider again the atomic system with the two energy levels discussed earlier. Independent of any external radiation that may be present, atoms in energy level E_2 transit to the lower energy level E_1, emitting a photon of energy hf_c. The spontaneous emission rate per atom from level E_2 to level E_1 is a characteristic of the system, and its reciprocal, denoted by τ_{21}, is called the *spontaneous emission lifetime*. Thus, if there are N_2 atoms in level E_2, the rate of spontaneous emission is N_2/τ_{21}, and the spontaneous emission power is $hf_c N_2/\tau_{21}$.

The spontaneous emission process does not contribute to the gain of the amplifier (to first order). Although the emitted photons have the same energy hf_c as the incident optical signal, they are emitted in random directions, polarizations, and phase. This is unlike the stimulated emission process, where the emitted photons not only have the same energy as the incident photons but also the same direction of propagation, phase, and polarization. This phenomenon is usually described by saying that the stimulated emission process is *coherent*, whereas the spontaneous emission process is *incoherent*.

Spontaneous emission has a deleterious effect on the system. The amplifier treats spontaneous emission radiation as another electromagnetic field at the frequency hf_c, and the spontaneous emission also gets amplified, in addition to the incident optical signal. This *amplified spontaneous emission* (ASE) appears as noise at the output of the amplifier. The implications of ASE for the design of optical communication

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

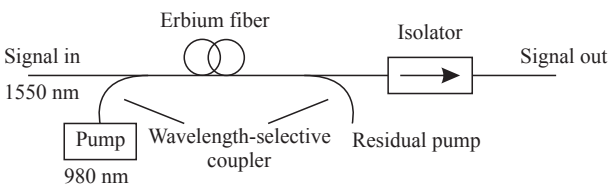

Figure 3.34 An erbium-doped fiber amplifier.