CHAPTER 8

LIGHT AMPLIFIERS

8.1 INTRODUCTION

As the optical signal travels in a fiber waveguide, it suffers attenuation (loss of power). For very long fiber spans, the optical signal may be so attenuated that it becomes too weak to excite reliably the (receiving) photodetector, whereupon the signal may be detected at an expected low bit error rate ($\sim 10^{-9}$ to $\sim 10^{-11}$).

To reach destinations that are hundreds of kilometers away, the optical power level of the signal must be periodically conditioned. Optical amplifiers are key devices that reconstitute the attenuated optical signal, thus expanding the effective fiber span between the data source and the destination.

Some key characteristics of amplifiers are *gain, gain efficiency, gain bandwidth, gain saturation,* and *noise.* Optical amplifiers are also characterized by polarization sensitivity.

- *Gain* is the ratio of output power to input power (measured in dB).
- *Gain efficiency* is the gain as a function of input power (dB/mW).
- Bandwidth is a function of frequency, and as such *gain bandwidth* is the range of frequencies over which the amplifier is effective.
- *Gain saturation* is the maximum output power of the amplifier, beyond which it cannot increase despite the input power increase.
- *Noise* is an inherent characteristic of amplifiers. In electronic amplifiers noise is due to (random) spontaneous recombination of electron–hole pairs that produces an undesired signal added to the information signal to be amplified. In optical amplifiers, noise is due to spontaneous light emission of excited ions, which we will further explore.

- *Polarization sensitivity* is the gain dependence of optical amplifiers on the polarization of the signal.

In optical communications networks, there are two distinct types of amplification device: the *regenerator* and the *optical amplifier.*

8.2 REGENERATORS

A regenerator receives a modulated optical signal (at a high bit rate), transforms it to an electronic signal of the same bit rate, amplifies it, and then converts the electronic signal back to optical signal of the same modulation and bit rate.

Thus, a regenerator has three major components: an optical receiver, an electronic amplifier, and an optical transmitter (Figure 8.1). Additional functions, such as timing, error recovery, and pulse shaping may also be incorporated. Regenerators are classified as 2R or 3R amplifiers—2R if they amplify and reshape and 3R if they amplify, reshape, and retime. An all-optical amplifier is classified as a 1R (amplify-only) device.

Regenerators amplify a single wavelength and are maintenance intensive. In a multiwavelength system, an equal number of regenerators is needed. Thus, considering that in an optical link there are several regenerators (typically spaced every 40 km), in a multiwavelength fiber system the maintenance cost is significant.

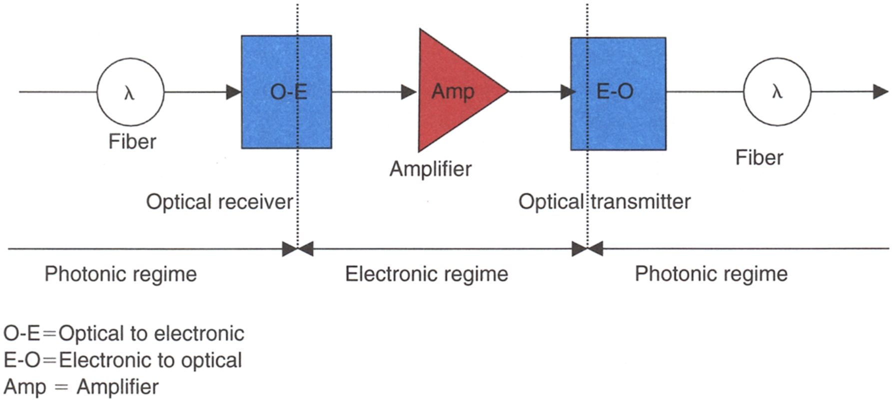

Figure 8.1 A regenerator consists of three major components: the optical receiver, the electronic amplifier, and the optical transmitter.

8.3 OPTICAL AMPLIFIERS

Optical amplifiers (OAs) are devices based on conventional laser principles. They receive one or more optical signals, each within a window of optical frequencies, and simultaneously amplify all wavelengths. That is, they coherently release more photons at each wavelength. This is a significant advantage of multiwavelength fiber systems over regenerators, because one device replaces many. OAs are 1R amplifiers (vs. 2R and 3R regenerators); that is, they only amplify directly an optical signal.

The quantum yield Q, is a measure of the efficiency of a photon at a given wavelength for a given reaction and for a given period of time. This is defined by:

$$Q = \frac{\text{number of transformed molecules}}{\text{number of absorbed photons}}$$

However, the number of absorbed photons $\mathbf{I_a}$ is not directly proportional to the optical density (**OD**) at the excitation wavelength but it is connected by the equation:

$$\mathbf{I_a} = k(1 - 10^{-\mathbf{OD}}),$$

where k is constant proportional to the incident intensity.

There are two types of OA: the semiconductor optical laser type amplifier (SOA) and the fiber-type amplifier [erbium-doped (EDFA) or praseodymium-doped (PDFA)]. In addition, there are other amplifying devices that depend on the nonlinear properties of optical materials, such as Raman and Brillouin scattering. Optical amplifiers require electrical or optical energy to excite (pump up) the state of electron–hole pairs. Energy is typically provided by injecting electrical current (in SOA) or optical light in the UV range (in EDFA).

To reduce optical signal losses at the couplings, antireflective (AR) coatings are used at the optical fiber–device interface (Figure 8.2).

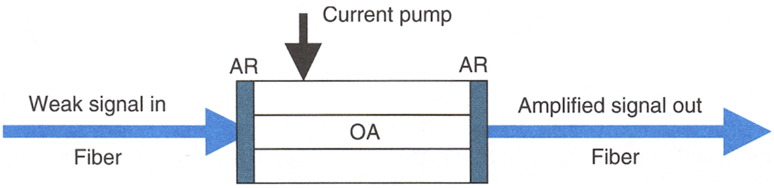

Figure 8.2 An optical amplifier (OA) is based on conventional laser principles.

Amplifiers are characterized by gain, bandwidth, gain over the bandwidth, maximum output power, dynamic range, cross-talk, noise figure, output saturation power, physical size, and so on. The output saturation power is defined as the output power level at which the gain has dropped by 3 dB.

OAs, based on their structure, are distinguished as follows:

- Traveling wave laser amplifiers
- Fabry–Perot laser amplifiers
- Injection current distributed-feedback (DFB) laser amplifiers
- Stimulated Raman
- Stimulated Brillouin
- EDFA
- PDFA

Each structure has advantages and disadvantages depending on the application.

8.4 SEMICONDUCTOR OPTICAL AMPLIFIERS

The most important advantage of SOAs is that they are made with InGaAsP and are thus small, compact, and able to be integrated with other semiconductor and optical components. The SOA salient characteristics are as follows.

- They are polarization dependent, and thus require a polarization-maintaining fiber (polarization sensitivity in the range 0.5–2 dB).
- They have relatively high gain (20 dB).
- Their output saturation power is in the range of 5–10 dBm.
- They have a large bandwidth.
- They operate at the wavelength regions of 0.8, 1.3, and 1.5 μm.
- They are compact semiconductors easily integrable with other devices, which can also be used as wavelength converter.
- Several SOAs may be integrated into an array.

Because of nonlinear phenomena (four-wave mixing), however, SOAs have a high noise figure and high cross-talk level.

8.5 ERBIUM-DOPED FIBER AMPLIFIERS

One attractive fiber-optic amplifier (FOA) in optical communications systems, and particularly in DWDM systems, is the EDFA. The EDFA is a fiber segment a few meters long heavily doped with the rare earth element erbium (and also co-doped with Al and Ge). The erbium ions may be excited by a number of optical frequencies—514, 532, 667, 800, 980, and 1480 nm. The shortest wavelength, 514 nm, excites erbium ions to the highest possible energy level. From this level, it may drop to one of four intermediate metastable levels, radiating phonons (the acoustical quantum equivalent of photons). From the lowest metastable level, it finally drops to the initial (ground) level, emitting photons around 1550 nm in wavelength. Similar activity takes place with the remaining wavelengths, although the number of metastable levels decreases as the wavelength becomes longer. Finally, the longest wavelength, 1480 nm, excites ions to the lowest metastable level, from which it drops directly to the ground level. Figure 8.3 illustrates the two lowest and most important energy excitations and spontaneous emission for erbium; erbium has more energy levels, which for simplicity are not shown.

The two most convenient excitation wavelengths are 980 and 1480 nm. When a 980-nm or 1480-nm source propagates through an EDFA fiber, erbium ions are excited and stimulated emission takes place, releasing photonic energy in the wavelength range of 1520–1620 nm. EDFAs that perform best within the C-band are known as C-band EDFAs and those in the L-band as L-band EDFAs (see also Table 3.1). When EDFA ions are excited by a 980-nm source, after approximately 1 μs the excited ions fall into the metastable energy level from which, if triggered, they drop to the ground energy level and emit light at the wavelength of the triggering photon.

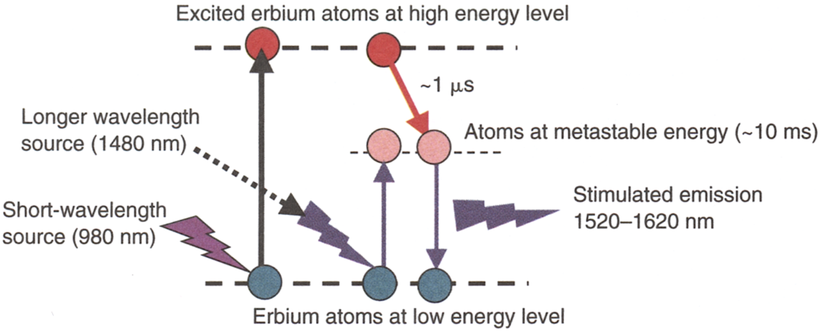

Figure 8.3 Principles of spontaneous emission of erbium; only the two lowest levels are shown.

If they are not triggered, after approximately 10 ms (known as the *spontaneous lifetime*), they spontaneously drop from the metastable level emitting light in the range around 1550 nm (Figure 8.3). In communications, the bit rate is very high (Gb/s) and the bit period is very short (ps), compared with the long lifetime (ms); thus there is no intersymbol interference. However, at the absence of fast bits, the spontaneous emission adds to noise.

The EDFA amplifier consists of a coupling device, an erbium-doped fiber, and two isolators (one per EDFA end) (Figure 8.4). The fiber carrying the signal is connected via the isolator that suppresses light reflections into the incoming fiber. The isolator at the output of the EDFA suppresses the reflections by the outgoing fiber (Figure 8.4). The EDFA is stimulated by a higher optical frequency (in the UV range) laser source, known as the *pump*. Laser light from the pump (980 or 1480 nm or both) is also coupled in the EDFA. The pump excites the fiber additives that directly amplify the optical signal passing through at a wavelength in the 1550-nm region.

The pump laser is specifically designed for EDFA applications. Pump lasers are enclosed in a small package (approximately 20 × 15 × 8 mm^3) with a connectorized single-mode fiber pigtail that can be coupled with the EDFA (fiber). Typical pumps have a wavelength of 980 or 1480 nm and an output power from under 100 mW to about 250 mW. In multimode fiber (EDFA), pumping can be done through the cladding (known as cladding pumping) using inexpensive 1-W diode (LED) pumps.

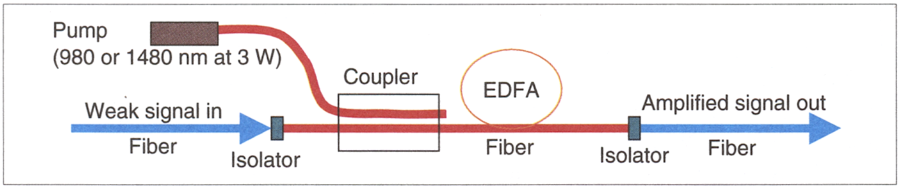

Figure 8.4 An EDFA amplifier consists of an erbium-doped silica fiber, an optical pump, a coupler, and isolators at both ends.

8.5.1 Advantages of EFDAs

- A high power transfer efficiency from pump to signal ($> 50\%$).
- Directly and simultaneously amplify a wide wavelength region (in the region of 1550 nm) at an output power as high as +37 dBm, with a relatively flat gain (> 20 dB), which is suitable to WDM systems.
- Saturation output is greater than 1 mW (10–25 dBm).
- Gain time constant is long (> 100 ms) to overcome patterning effects and intermodulation distortions (low noise).
- Large dynamic range (> 80 nm).
- Low noise figure.
- They are transparent to optical modulation format.
- Polarization independent (thus reducing coupling loss to transmission fiber).
- Suitable for long-haul applications.
- Modified EDFAs can also operate in the L-band.

8.5.2 Disadvantages of EFDAs

- EDFAs are not small devices (fibers are kilometers long) and cannot be integrated with other semiconductor devices.
- EDFAs exhibit amplified spontaneous light emission (ASE). That is, even if no incoming signal is present, there is always some output signal as a result of some excited ions in the fiber; this output is termed *spontaneous noise.*
- There is cross-talk.
- There is gain saturation.

EDFAs have found applications in long-haul as well as in wavelength division multiplexing (WDM) transport systems. Gain in excess of 50 dB, a wide bandwidth of 80 μm, and very low noise characteristics have been demonstrated. A fiber span (hundreds of kilometers long) consists of fiber segments (tens of kilometers each). Optical amplifiers are placed at the interconnecting points to restore the attenuated optical signal. Thus, there may be several EDFAs along the fiber span (typically up to 8). However, three issues become important: gain flatness (all wavelengths at the EDFA output should have the same optical power), dynamic gain, and low noise.

All wavelengths are not amplified through EDFAs in the same way; that is, the gain is not exactly flat. This issue is addressed with gain-flattening optical filters, passive in-line filters with low insertion loss, low dispersion, and stable performance over a wide range of temperatures.

The power pumped into an EDFA is shared by all wavelengths. The more wavelengths, the less power per wavelength, and vice versa. This has an undesirable effect in optical add–drop multiplexing (OADM) WDM with EDFAs. As wavelengths are dropped by an OADM and not added, EDFAs (in series with OADM) amplify fewer additional wavelengths, and as wavelengths are added by another OADM, they are amplified less. That is, the gain does not remain at the same level from one OADM to the next. This imbalance is addressed by engineering the WDM system and dynamic gain control.

Noise is addressed differently. It should be remembered that optical noise sources are cumulative and that the spontaneous emission of EDFAs introduces noise that degrades the S/N ratio. Thus when engineering a fiber-optic path, one may be tempted to try to overcome this by launching a strong optical signal into the fiber. However, near the zero-dispersion wavelength region, four-wave mixing could become dominant and could degrade the S/N ratio.

The selection of power (per channel) launched into the fiber becomes a puzzle: amplifier noise restricts the minimum power of the signal, and four-wave mixing limits the maximum power per channel launched into the fiber. This implies the need to select a power level that lies between a lower and an upper limit. To determine the power level, many other parameters must be taken into account so that the required quality of signal is maintained. Some of these parameters are:

- Fiber length between amplifiers (km)
- Fiber attenuation (loss) per kilometer
- Number of amplifiers in the optical path
- Amplifier parameters (gain, noise, chromatic dispersion, bandwidth)
- Number of channels (wavelengths) per fiber
- Channel width and spacing
- Receiver (detector) specifications
- Transmitter specifications
- Polarization issues
- Optical component losses and noise (connectors, other devices)
- Quality of signal (bit error rate, S/N)
- Signal modulation method and bit rate
- Other design parameters

8.6 PRASEODYMIUM-DOPED FIBER AMPLIFIERS

PDFAs have a high gain (~30 dB) and a high saturation power (20 dBm), and they are suitable in the region of 1280–1340 nm, where EDFAs are not. However, PDFAs require a nonsilica fiber (fluoride) that is not very common, and a high-power (up to 300 mW) pump laser at 1017 nm (not the popular 980 or 1480 nm). Thus, PDFA technology is not yet popular or well developed. An alternative to this is fibers that contain elements such as gallium and lanthanium (gallium-lanthanium-sulfide and gallium-lanthanium iodine).

8.7 STIMULATED RAMAN AND STIMULATED BRILLOUIN SCATTERING AMPLIFIERS

Stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) amplifiers are nondoped fiber amplifiers, as already described in Sections 3.21.1 and 3.20.2, that employ high-power pump lasers to take advantage of the nonlinear properties of the fiber.

Raman amplifiers have their pump near the receiver, and the pump light travels in opposite direction toward the source. Thus, the pump is strongest at the receiver and weakest at the source. This arrangement has an important advantage: the pump power is where it is most needed (at remote distances from the source) and less needed (in the vicinity of the source). Consequently, the signal is amplified where it is weakest and less where it is strongest. In addition, four-wave mixing effects are minimized.

Another configuration features two pumps, one at the transmitting side and one at the receiving side, with each pump at different wavelengths (to meet a simultaneous C- and L-band amplification). However, this arrangement is still experimental and certain nonlinearity issues (FWM, polarization), signal/pump interactions, increased optical signal to noise ratio (OSNR), and Rayleigh reflection (which may incude a lasing effect) need be resolved.

A suitable fiber for Raman amplification is the DCF.

The most important feature of Raman amplifiers is nonresonance and a wide bandwidth range that can extend over the complete useful spectrum from 1300 nm to 1600^+ nm (500 optical channels at 100-GHz spacing), with no restriction to gain over bandwidth thus enabling a multiterabit transmission technology, also referred to as *Raman supercontinuum.* On the negative side, Raman amplification requires very long fibers (in the order of several kilometers) and pump lasers with high optical power (>1 W). Thermal management issues as well as safety issues are yet to be resolved.

8.8 CLASSIFICATION OF OPTICAL FIBER AMPLIFIERS

Optical fiber amplifiers (OFAs) are classified in electronic amplifiers, electronic systems, and wireless systems as *power amplifiers, preamplifiers,* and *line amplifiers.*

Optical fiber amplifiers should be applied properly to minimize several factors that may affect the integrity of the channel and the transmitted signal in response to nonlinearities, polarization, and other effects. ITU-T has recommended parameter limits as well as applications of optical fiber amplifiers in G.662 and G.663.

8.8.1 Power Amplifiers

An OFA capable of increasing the optical power of the modulated photonic source (i.e., the optical transmitted signal) is called an *optical power amplifier.* An optical power amplifier acts like a booster. It is placed right after the source, and thus may also be integrated with it. It receives a large signal (from the laser source) with a large signal-to-noise ratio and boosts its power to levels about −10 dBm or higher.

8.8.2 Preamplifiers

An OFA with very low noise that is able to increase a highly attenuated signal to a level that can be detected reliably by an optical detector is called an optical preamplifier. A preamplifier is placed directly before the detector and may be integrated with it.

8.8.3 Line Amplifiers

An OFA with low noise, able to amplify an attenuated signal so that it can travel an additional length of fiber, is called an optical line amplifier. Therefore, the line amplifier must have large gain and very low noise and should not add noise to the already received attenuated signal.

8.8.4 Amplifier Standards

The following ITU standards deal with optical amplifiers:

(In-) line amplifier	G.662
Booster amplifier	G.662
Erbium-doped fiber amplifier	G.662
Optical amplifier device	G.662
Optical amplifier subsystem	G.662
Optical amplifier	G.662
Optical fiber amplifier	G.662
Optical return loss	G.957
Optically amplified receiver	G.662
Optically amplified transmitter	G.662
Preamplifier	G.662
Remotely pumped amplifier	G.973

8.9 WAVELENGTH CONVERTERS

Wavelength conversion enables optical channels to be relocated, adding to the flexibility and efficiency of multiwavelength systems. Wavelength conversion may be achieved by employing the nonlinear properties of certain heterojunction semiconductors.

SOAs are also used as wavelength-converting devices. Their basic structure consists of an active layer (erbium-doped waveguide) sandwiched between a p-layer InP and an n-layer InP (Figure 8.5). Various methods have been explored that are based on *cross-gain modulation, four-wave mixing, dispersion-shifted fiber,* and other *interferometric* techniques.

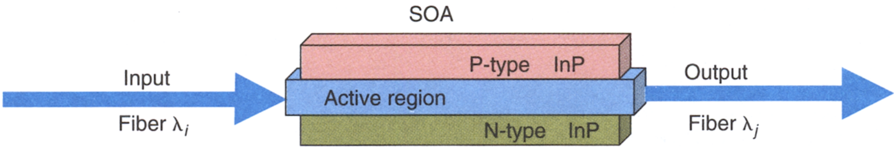

Figure 8.5 Semiconductor optical amplifiers may be used as wavelength converting devices.

8.9.1 Cross-Gain Modulation

Gain saturation in an optical amplifier occurs when high optical power is injected in the active region and the carrier concentration is depleted through stimulated emission. Then, the optical gain is reduced.

Based on this, consider two wavelengths injected in the active region of an optical amplifier. Wavelength λ_1 is modulated with binary data and wavelength λ_2, the target, is continuous (not modulated) (Figure 8.6).

When the input bit in λ_1 is a logic one (i.e., high power) depletion occurs, it blocks λ_2. When the bit in λ_1 is a logic zero (no power) depletion does not occur, and λ_2 is at high power (logic one). Thus, a transfer of inverted data from λ_1 to λ_2 takes place. This method is known as cross-gain modulation.

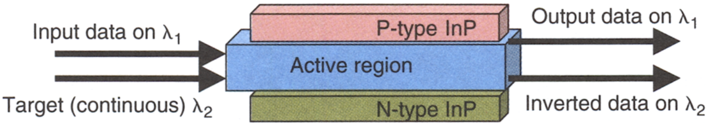

Figure 8.6 Cross-gain modulating devices transfer inverted data from one channel to another one having a different wavelength.

8.9.2 Four-Wave Mixing

We have described four-wave mixing (FWM) as an undesirable nonlinearity. However, FWM can also be taken advantage of to produce at will an additional wavelength. Consider that a modulated wavelength λ_1 is to be converted to another, λ_2. Then λ_1 and two more wavelengths are selected, such that when all three are injected in the fiber device, FWM will cause a fourth wavelength to be produced, λ_2, which is modulated as the λ_1. A pass-band filter that passes through only the new wavelength, λ_2, is placed in series to the FWM device.

8.9.3 Optical Frequency Shifter

Optical frequency shifters rely on the nonlinearity property of dispersion-shifted doped fibers, which produce a new wavelength when two wavelengths at high power and in close wavelength proximity interact (in the range of 1550 nm) as in FWM. Thus when a modulated wavelength λ_1, known as the *probe signal*, and also a continuous power wavelength λ_2, known as the *pump*, are launched into a 10-km dispersion-shifted fiber, a third modulated wavelength is generated (Figure 8.7). The new wavelength, λ_3, is at λ_2 shifted by an amount equal to the difference between the original wavelength of the signal and the pump. At the output of the dispersion-shifted fiber an interference filter (IF) eliminates the probe and the pump wavelengths and allows only the frequency-shifted wavelength, λ_3, to pass through (thus acting as a band-pass filter; Figure 8.8).

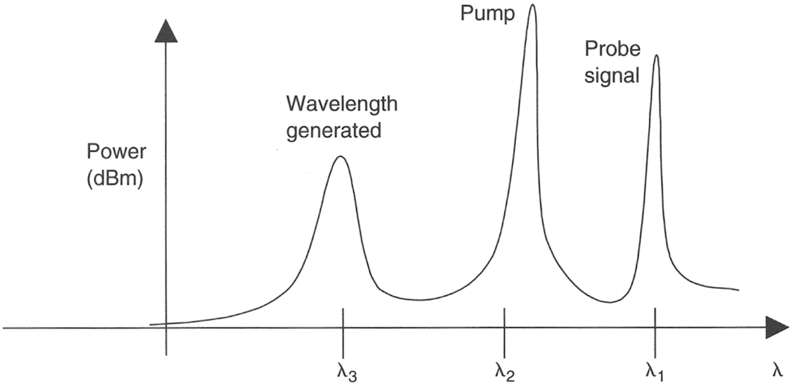

Figure 8.7 In dispersion-shifted doped fibers a third wavelength may be produced when two high-power wavelengths are in close wavelength proximity.

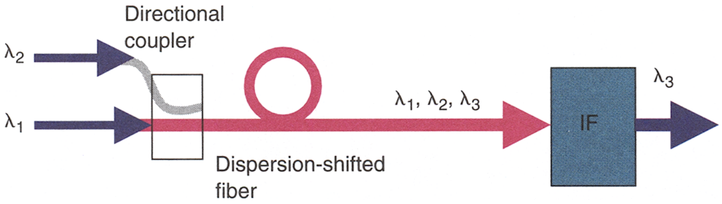

Figure 8.8 At the output of the dispersion-shifted fiber an interference filter (IF) eliminates the probe and the pump wavelengths.

EXERCISES

1. What is the main difference between a regenerator and an optical amplifier?
2. What is the difference between an SOA and an EDFA?
3. What is ASE? What is spontaneous noise?
4. For an EDFA to amplify a signal in the region of 1550 nm, a strong light source is required. What is the wavelength of this light source, and what is it called?
5. How are OFAs classified? Where are they placed with reference to a laser source?
6. What is a wavelength converter?
7. How can FWM be used constructively to convert one wavelength into another?
8. What is a wavelength shifter?
9. A wavelength fiber shifter requires two inputs, a probe signal and a pump source. Which is the continuous source and which is the modulated source?
10. What is required at the output of a wavelength fiber shifter to ensure that only the shifted frequency is passed?