

# Testing Erbium-Doped Fiber Amplifiers

James R. Stimple

EDFAs can overcome losses in long fiber-optic links independent of the digital bit rate, and can amplify multiple signals in a wavelength-division multiplexed (WDM) system architecture. As more and more EDFAs are deployed, designers add new features, creating a need for more sophisticated testing. This paper provides a brief survey of the tests required to characterize EDFAs.

**A** small child in California calls her grandmother in Germany. To her, the call seems effortless and Grandma sounds as if she is right there. A teenager in Arkansas is surfing the Net to find out about the latest in skateboard parks for a trip planned for the upcoming summer. A retired auto worker in Japan checks e-mail to see if a message from an old coworker has arrived confirming their upcoming fishing trip. These common, everyday events are only possible because of the vast deployment of capacity on the global communications network.

Fiber-optics technology is the heart of this “information superhighway” which spans the globe. Its tremendous capacity for carrying information in digital form is revolutionizing the way people live and work. Linked with cellular phone systems and computers around the world, this network provides access to incomprehensible amounts of information and vast connectivity. The most recent element adding to the success of these systems is the fiber-optic amplifier.

## Erbium-Doped Fiber Amplifiers

The development of erbium-doped fiber amplifier (EDFA) technology has greatly changed the design methodology of fiber-optic system designers. Traditional fiber-optic systems used regenerative repeaters to boost the signals, as shown in **Figure 1a**. When the length of the link exceeded the practical single-span passive limit, these regenerative repeaters detected the signal and retransmitted it with a laser, restoring the signal level as well as the signal

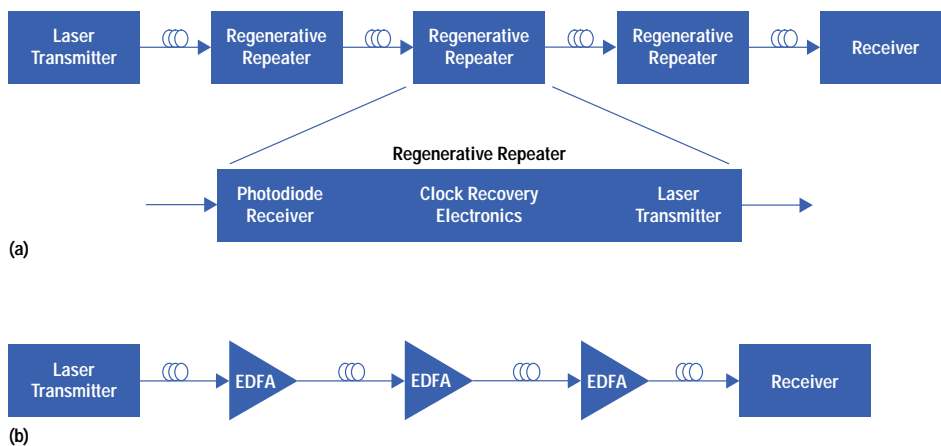


**James R. Stimple**

Jim Stimple is a project manager for erbium-doped fiber amplifier systems at the HP Lightwave Division. He has worked for HP since 1978. He received his BSEE degree from Northwestern University in Evanston, Illinois in 1974.

**Figure 1**

(a) Lightwave system with regenerative repeaters. Gain is provided by the electronics and each regenerative repeater is matched to the data rate of the system. (b) Lightwave system with erbium-doped fiber amplifiers (EDFAs). The amplifiers boost the signal independent of the data rate and allow multiple wavelengths.



fidelity. Although these regenerative repeater systems worked well, they were very expensive, and once installed, the capacity of the link was fixed.

With the development of EDFAs, the link losses could be overcome by amplification as shown in **Figure 1b**. Unlike the regenerative repeater systems, these “transparent” amplified systems are independent of the digital bit rate. This feature allows an upgrade path to higher bit rates as solutions to other limiting factors such as chromatic and polarization-mode dispersion become available. EDFAs are also able to amplify multiple signals in a wavelength-division multiplexed (WDM) system architecture, adding another dimension to the capacity equation.

Many point-to-point terrestrial links are being upgraded from regenerative repeaters to amplified links because of the high cost of laying more fibers in the ground. In many cases, adding sections of dispersion-compensating fiber with each amplifier can allow upgrades in bit rate as well as the possibility of WDM. Amplified systems will soon use WDM not only for increased capacity, but as a means for information routing, eliminating the need for expensive high-speed demultiplexing and remultiplexing at each optical node.

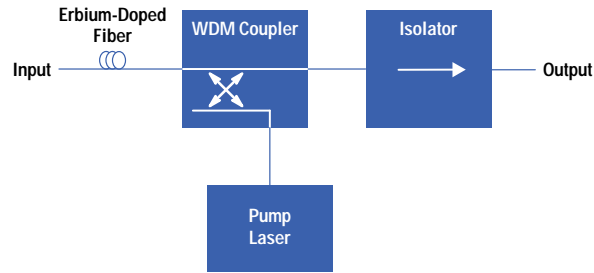
To date, the major emphasis of EDFAs has been in the high-capacity portions of the network, but as the cost of EDFAs comes down, they will also be deployed in the subscriber loop. Here the emphasis will be on WDM to allow single users high-speed access to the network. Thus, the EDFA is rapidly becoming the workhorse of the system of fibers that spans our globe.

#### How the EDFA Works

**Figure 2** shows the simplest block diagram of an EDFA. The erbium-doped fiber is a silica-based fiber waveguide with a high concentration of erbium atoms. The presence of the erbium provides for ionic transitions leading to photon emission in the 1530-to-1570-nanometer wavelength range. Pump lasers at one or more of the absorption wavelengths (typically 1480 nm or 980 nm) provide the excitation for the emission process. The fiber length is typically around 70 meters and amplifier small-signal gains of 35 dB are common.

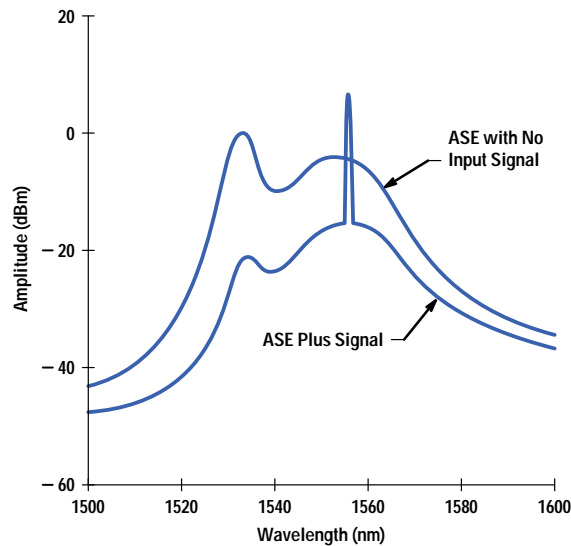
**Figure 2** shows the pump laser in the counterpropagating configuration, in which the pump energy travels in the direction opposite to the signal. Amplifiers can be pumped in the copropagating direction by placing the WDM on the input side. Many amplifiers have both copropagating and counterpropagating pumps for redundancy.

**Figure 2**  
EDFA block diagram.



Without an input signal, the EDFA is a source of spontaneously emitted photons. The wavelength spectrum of this spontaneous emission process is determined by the statistical distribution of the energy bands in the erbium atoms. Spontaneous emission photons are of random phase, random direction, and random states of polarization. As these spontaneous photons travel along the fiber, they can replicate through the process of stimulated emission. This process creates a second photon of the same wavelength, phase, polarization, and direction as the first. The total output spectrum originating from spontaneous emission photons of the EDFA is called the *amplified spontaneous emission* (ASE) and is shown in **Figure 3**.

**Figure 3**  
EDFA output spectrum measured by an optical spectrum analyzer.



With a laser signal applied at the amplifier input, many of the would-be spontaneous emission photons from both the forward and reverse directions in the fiber are stimulated by photons from the laser. This not only provides the required amplification, but reduces the ASE as shown in **Figure 3**.

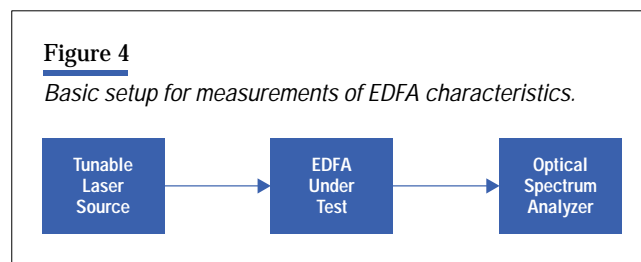
The parametric nature of the amplification provides a nonlinear gain characteristic. EDFAs are generally operated in the compression region. This is highly desirable for long communication links because the amplifiers provide natural leveling of the signal. An additional feature of EDFAs is their long time constants for the absorption and emission processes. These are typically from 100 to 500 microseconds. Since the lasers are modulated with 2.5-gigabit/second data or higher, there is virtually no distortion of the information being transmitted. This attribute also proves highly desirable in a WDM system because it eliminates the possibility of cross-modulation products in the amplifier, which would be devastating to the system integrity.

#### Testing EDFAs

As more and more EDFAs are deployed, designers are adding new features to the basic design. Amplifiers are basically custom designed to meet the particular application requirements. As the complexity of these amplifiers evolves, so does the need for more sophisticated testing. At Hewlett-Packard Laboratories and the HP Böblingen Instrument and Light-wave Divisions, significant efforts are ongoing in test method research and the development of test and measurement systems for EDFAs.

#### Basic Gain and Noise Figure

The basic measurement requirements for an EDFA are simply gain and noise figure. How much amplification does it provide and how much degradation of the signal-to-noise ratio might be caused by the amplifier in a given application? The diagram in **Figure 4** shows the basic measurement setup. The source is generally a tunable laser to allow a variety of wavelengths and powers for the input signal. The receiver is an optical spectrum analyzer to provide wavelength selection (resolution) of the output signal and ASE.



The amplifier's nonlinearity complicates the measurements, since the gain is a function of the input signal level and wavelength. The noise figure measurement is further complicated by the fact that the source has a spontaneous emission spectrum of its own in addition to the dominant laser spectral line.

To accurately measure the gain characteristics of the amplifier, one must first specify the wavelength and power of the input signal. Usually the power and wavelength are both a range of desired values. Measuring the output signal level under each of these conditions will give the gain. The gain  $G$  in each case is simply the output signal power divided by the input signal power. For low signal levels, it is important to subtract the spontaneous emission from the measured output signal to obtain the true output signal power.

The noise figure is calculated from an additional measurement of the output ASE and the equation:

$$NF = ASE/h\nu G + 1/G,$$

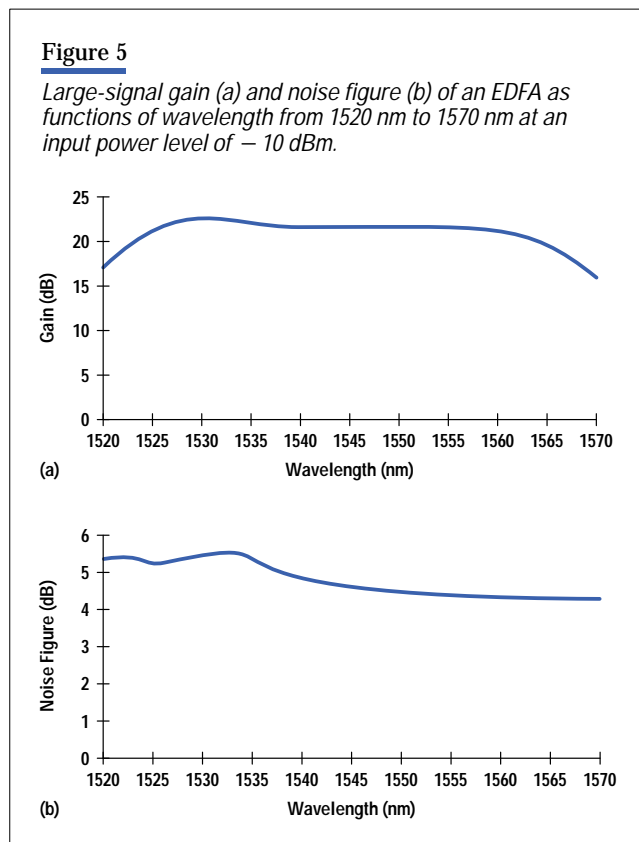
where ASE is expressed in watts/Hz,  $h$  is Planck's constant, and  $\nu$  is the optical frequency in hertz.

The ASE measurement is difficult because the spontaneous emission spectrum of the laser is amplified and can add to the ASE of the amplifier. Elimination of this effect can be accomplished in one of three ways:

- **Interpolation source subtraction.** The level of spontaneous emission at the signal wavelength is interpolated (averaged) from measurements on either side of the signal and is subtracted from the signal.
- **Polarization extinction.** This technique uses the fact that the signal from the laser and its spontaneous emissions are polarized and the ASE in the EDFA is not polarized. By placing a polarizer in front of the optical spectrum analyzer and adjusting the polarization to null out the signal, the spontaneous emission of the tunable laser source is extinguished from the measurement, leaving ASE/2 received at the optical spectrum analyzer.
- **Time-domain extinction.** This is similar to polarization extinction in that the effects of the source are eliminated rather than subtracted. This method uses the fact that the EDFA recovery has a long time constant. Modulating the tunable laser source on and off rapidly compared to the recovery time and measuring the ASE when the tunable laser source is off provides the extinction of source spontaneous emission.

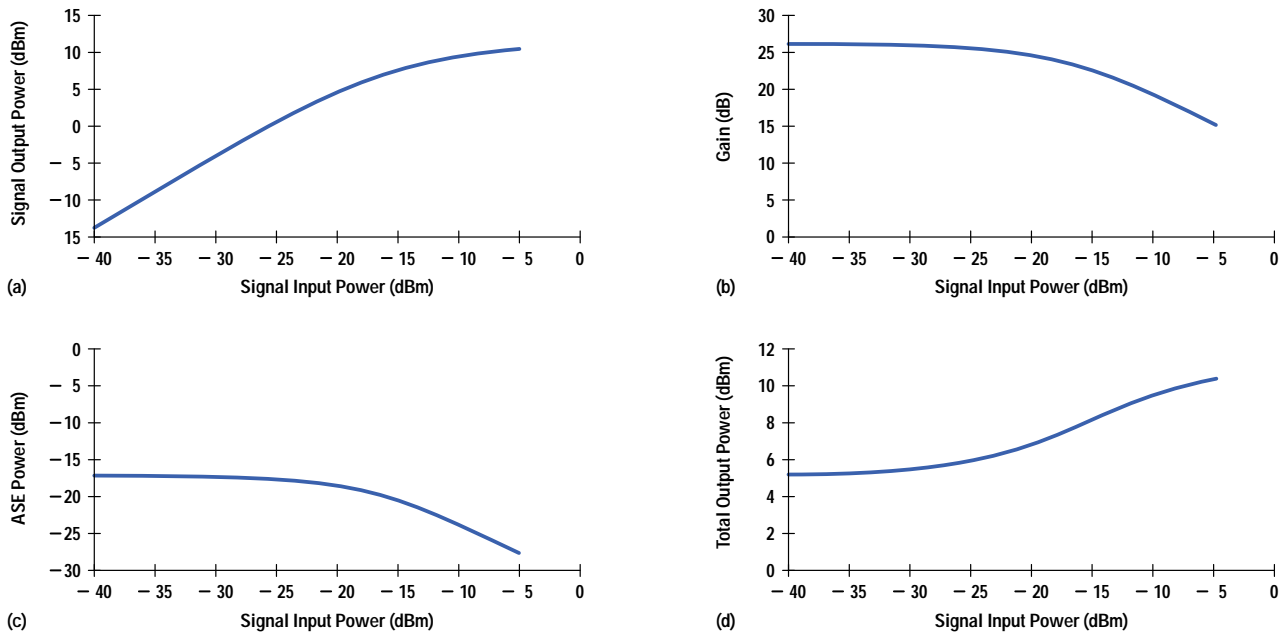
Other measurements that are generally included along with the gain and noise figure are the output signal power (required for gain), the integrated ASE, and the total output power (signal plus the integrated ASE).

**Figure 5** shows a number of measurements using the HP 83465A EDFA test system on a Fitel ErFA1313 amplifier. **Figures 5a and 5b** show the large-signal gain and noise figure as functions of wavelength from 1520 nm to 1570 nm at an input power level of  $-10$  dBm. The graphs in **Figure 6** show the effect of varying the input power level at a single wavelength of 1550 nm. **Figure 6a** demonstrates the amplifier saturation by showing the asymptotic limit of the output signal power as the input is increased. **Figure 6b** shows the same effect on the gain, where there is a gradual decrease in the gain from its small-signal (linear) value. **Figure 6c** shows a decrease in the ASE power with increasing signal level,



**Figure 6**

Effects of varying the input power level at a single wavelength of 1550 nm. (a) Signal output power, showing amplifier saturation, the asymptotic limit of the output signal power as the input level is increased. (b) The gain shows the same effect. (c) The ASE power decreases with increasing signal level, indicating a better signal-to-noise ratio. (d) The total output power shows a relatively small change (3 to 5 dB) as the signal input power changes over a very large range (35 dB).



indicating a better signal-to-noise ratio. **Figure 6d** shows the relatively small change (3 to 5 dB) in the total output power as the signal input power changes over a very large range (35 dB). This is because the energy for the signal amplification comes from the same source (the pump laser) as the ASE in the unsaturated case.

#### Small-Signal Gain

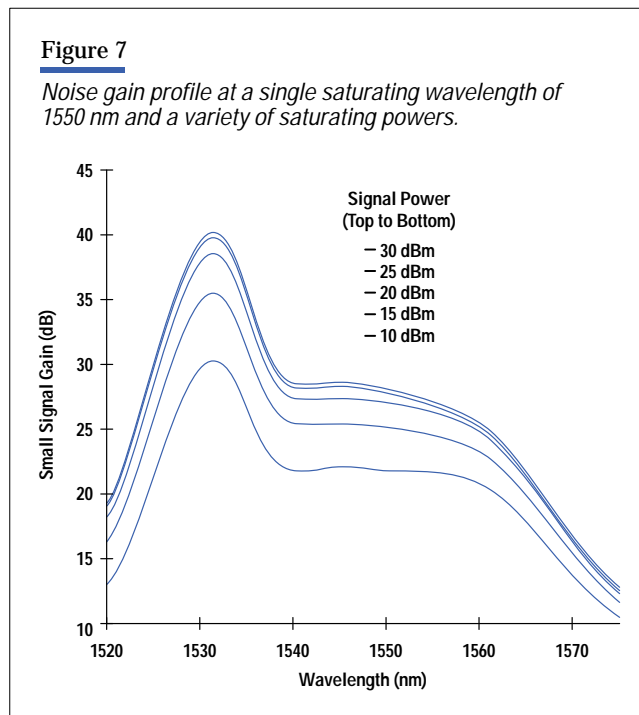
Because the EDFA is nonlinear, a simple measurement of the large-signal saturating laser gain may not completely characterize the amplifier. If one were to take a small-signal probe laser and measure the gain at various wavelengths in the presence of the saturating laser, this would give the small-signal gain  $g(\lambda)$ . This small-signal gain can also be measured with a spontaneous emission source instead of the probe laser. In this case  $g(\lambda)$  is called the *noise gain profile*.

In the case of a single-channel system,  $g(\lambda)$  gives the wavelength of the gain peak, which tells the designer the best operating wavelength to avoid a buildup of ASE. In the case of a WDM system,  $g(\lambda)$  tells the user how the multiple laser channels will share the available gain of the amplifier. It can also be used to characterize an effect called *spectral hole burning*, which is a depletion of gain over a narrow wavelength range caused by a large saturating laser. By measuring  $g(\lambda)$  at a matrix of pump currents, saturating wavelengths, and input powers, a very complete model of the EDFA can be obtained that will predict its behavior in virtually any system environment.

**Figure 7** shows a measurement of the noise gain profile at a single saturating wavelength of 1550 nm and a variety of saturating powers. Note the difference between  $g(\lambda)$  at -10 dBm shown in **Figure 7** and the large-signal gain variation with wavelength shown in **Figure 5a**. **Figure 5a** is much flatter because of the change in saturation level as the signal wavelength is tuned.

**Figure 7**

Noise gain profile at a single saturating wavelength of 1550 nm and a variety of saturating powers.



#### Polarization Effects

The polarization of the laser light always creates challenges in lightwave measurements. Since most systems use standard circularly symmetric fibers, the polarization of the signals is not preserved. In measuring the gains previously mentioned, it is desirable to measure the *unpolarized* gains. Since the lasers used to saturate the amplifier are polarized, this can be accomplished using a technique called *polarization randomizing*. Varying the state of polarization with time and averaging the measurements over a sufficiently long time window yields a measurement that converges to the unpolarized gain.

In addition to the average gains, a user may want to know the magnitude of the changes in gain and noise figure resulting from changes in the state of polarization of either the saturating signal or the probe signal. These effects are of great importance in systems with many cascaded amplifiers. This variation is measured by simply recording the maximum and minimum gains over the time window.

#### Return Loss and Isolation

Since the EDFA has the potential for gain in both directions, many systems require splicing the amplifiers into the system or the use of high-return-loss angled connectors. Verification of the input and output return loss and the reverse isolation is another test requirement for EDFAs.

Return loss is measured using a fused fiber coupler with good directivity. This separates a sample of the forward propagating wave from the reverse propagating wave.

Isolation is simply a gain measurement in the reverse direction. However, since the gain is nonlinear, the simplest way to make this measurement is to measure reverse gain at low saturation (without a forward propagating wave) and correct the gain for the ratio of the saturated and unsaturated small-signal gains.

In addition, small reflections inside the EDFA can cause multipath interference. This is most apparent in cable TV applications of EDFAs. Verification of the absence of amplifier internal reflections is a very complicated procedure beyond the scope of this paper.

## Monitors

Many EDFAs have features called monitors, which are simply optical signal-level taps. They detect the level of light at the input, at the output, and at the output in the reverse direction. These monitors are used for fault detection and signal-level monitoring and control. A complete measurement system will characterize and verify the operation of these features. A digital voltmeter is used as the sensing apparatus and the tunable laser source power and wavelength are varied as total output power measurements are made by the optical spectrum analyzer.

## Device Setup

In many cases the test system provides the interfaces to the EDFA pumps by means of a laser diode controller. These lasers are mounted on a thermoelectric cooler system with a thermistor as the temperature sensing element. The controller regulates the laser temperature by closing the control loop to maintain the thermistor resistance constant. The controller also supplies the laser with bias current. Sometimes there is a monitor photodiode on the back facet of the laser to monitor the laser power. In this case the laser power can be leveled by monitoring the photocurrent and controlling the laser current.

## Parametric Measurements

When the test system is used to set up the amplifier, the system operator is able to make parametric measurements. For example, the gain and noise figure can be measured as a function of pump laser current or pump laser temperature. This is very important for determining the optimum parameters for best amplifier performance. Optimization is becoming more important in the case of amplifiers used for WDM applications since the management of signal-to-noise ratio is more critical because of the lower power of each channel.

A good example of optimization is in the case of an amplifier with a built-in filter to equalize or flatten the naturally rounded peak of the gain. Since the gain slope changes with both pump power and input drive level, for a fixed input drive level there is an optimum pump power for best gain flatness. The optimum pump power setting can be determined by making multiple small-signal gain measurements as a function of pump power setting. On a plot of gain slope (the derivative of small-signal gain) versus pump power, the optimum setting is the power where the slope is zero.

## Conclusion

As the market for EDFAs matures, the designs are becoming more complex. Along with this complexity comes the need for sophisticated test methods that are fast and accurate, yet able to verify all of the features of the product for utmost reliability. By supplying test systems, tools for research, and consulting for the latest in measurement techniques, HP test and measurement groups are doing their part to ensure that the manufacturers of EDFAs have the testing capacity to meet their rapidly increasing demand.

## Bibliography

1. C.R. Giles and E. Desurvire, "Modeling Erbium-Doped Fiber Amplifiers," *Journal of Lightwave Technology*, Vol. 9, no. 2, February 1991.
2. D.M. Baney and J. Stimple, "WDM EDFA Gain Characterization with a Reduced Set of Saturating Channels," *IEEE Photonics Letters*, Vol. 8, no. 12, December 1996, pp. 1615-1617.
3. H. Chou and J. Stimple, "Inhomogeneous Gain Saturation of Erbium-Doped Fiber Amplifiers," *Conference on Optical Amplifiers and their Applications Technical Digest*, 1995, paper Th E1-1.

---

---

[▶ Go to Journal Home Page](#)