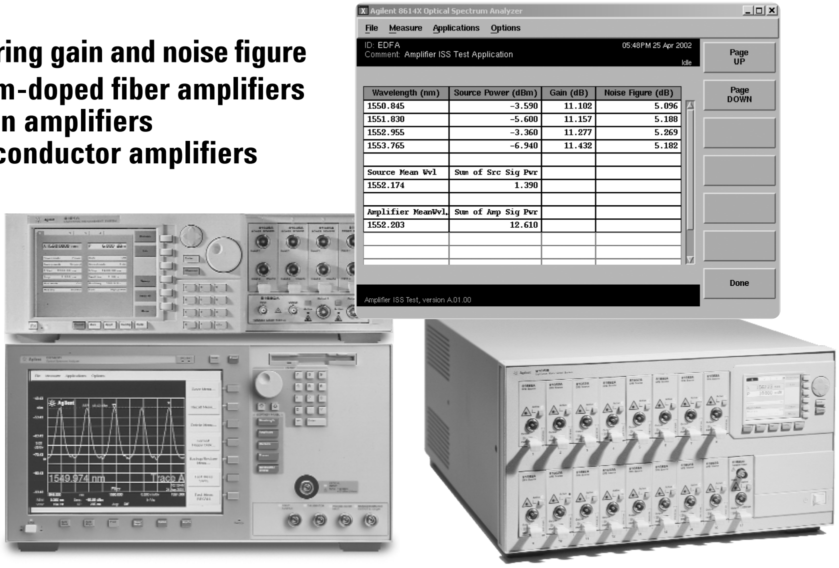
Optical Amplifier Testing with the Interpolated Source-Subtraction and Time-Domain Extinction Techniques

Application Note 1550-10

Measuring gain and noise figure
- **Erbium-doped fiber amplifiers**
- **Raman amplifiers**
- **Semiconductor amplifiers**



ID: EDFA

Comment: Amplifier ISS Test Application

05:48PM 25 Apr 2002

Idle

Wavelength (nm)	Source Power (dBm)	Gain (dB)	Noise Figure (dB)
1550.845	-3.590	11.102	5.096
1551.830	-5.600	11.157	5.188
1552.955	-3.360	11.277	5.269
1553.765	-6.940	11.432	5.182
Source Mean Wvl	Sum of Src Sig Pwr		
1552.174	1.390		
Amplifier MeanWvl.	Sum of Amp Sig Pwr		
1552.203	12.610		

Amplifier ISS Test, version A.01.00

Agilent Technologies

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Introduction

There is no component more ubiquitous in the fiber-optic network then the optical amplifier. The erbium-doped fiber amplifier (EDFA), along with dense wavelength-division multiplexing (DWDM), enabled high-capacity transmission in the submarine and long-haul terrestrial network. As depicted in Figure 1, the applications of optical amplifiers extend from submarine and long-haul terrestrial networks through the metropolitan (metro) networks. Metro application of optical amplifiers will become pervasive as DWDM expands into the metro networks. While the need for amplification to make up for fiber loss in metro is less significant because of the shorter lengths involved, the use of cross-connect switches and other signal routing devices require amplification to overcome insertion loss. Amplifiers in the metro segment will be required to carry fewer channels and in some cases, only a single channel. The reduced performance requirements open the door to lower-cost EDFA designs and alternative technologies such as the semiconductor optical amplifier (SOA) and the erbium-doped waveguide amplifier (EDWA).

Distributed Raman amplification (DRA) will be used in the submarine and long-haul terrestrial segments to accommodate an upgrade to 40 GB/s without shortening repeater spacing. Often DRA is used in conjunction with EDFAs to increase the reach or capacity of a link. However, all-Raman amplified spans are also currently operational and may become more common.

The need for optical amplification at various wavelengths, power levels, and costs has driven the research behind a multiplicity of fiber-based and non-fiber-based technologies. The International Electrotechnical Commission (IEC) [1] has developed a family tree (Figure 2) to classify the various amplifier types, many of which are still in research. First there is the division between the fiber-based designs (OFA) and waveguide designs (OWGA). The OFA designs are further classified by the dopant and then by the glass host. For example the erbium-doped fiber amplifier can be constructed by doping silica, fluoride, or tellurite glass fiber with erbium. The commonly known EDFA is more correctly an EDSFA (erbium-doped silica fiber amplifier. The two common OWGA devices are the semiconductor optical amplifier (SOA) and the erbium-doped waveguide amplifier (EDWA).

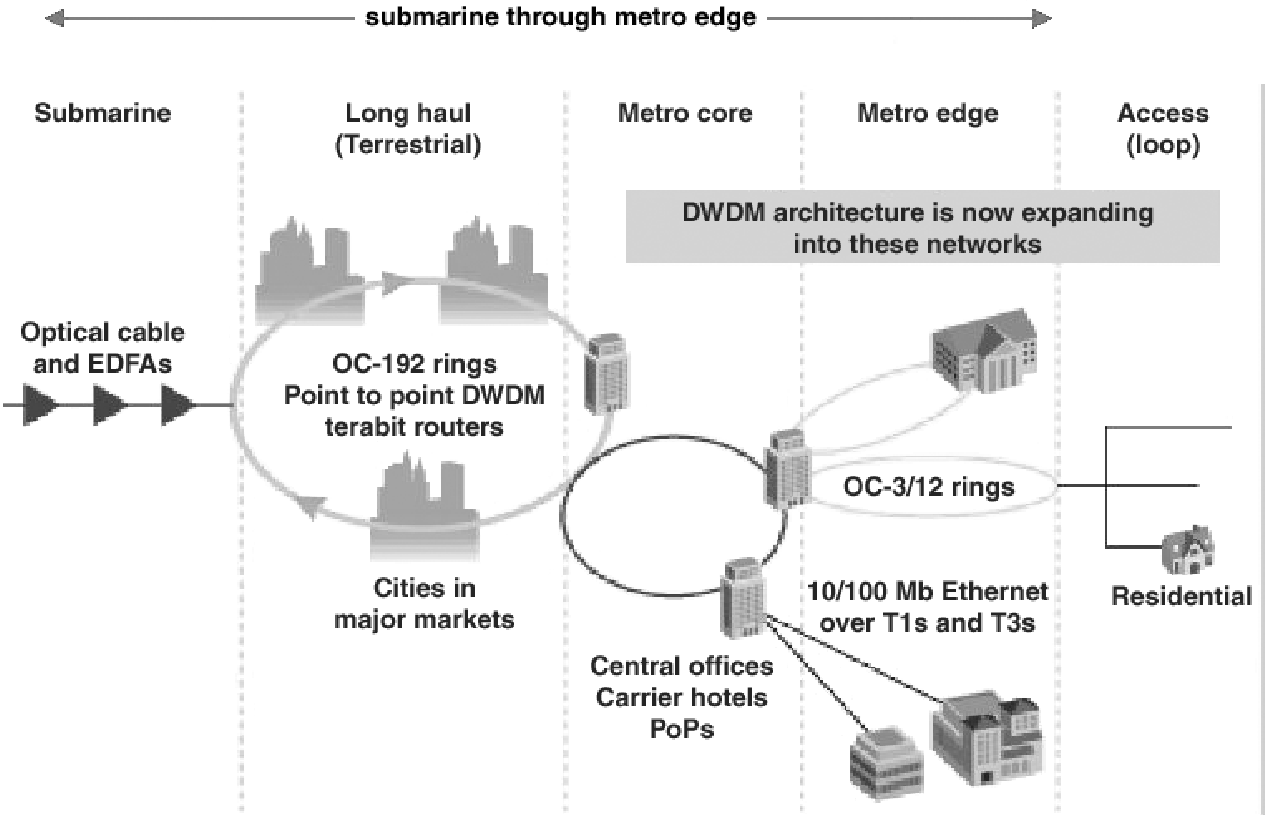


Figure 1. Optical amplifiers are used throughout the optical network - from submarine through metro edge.

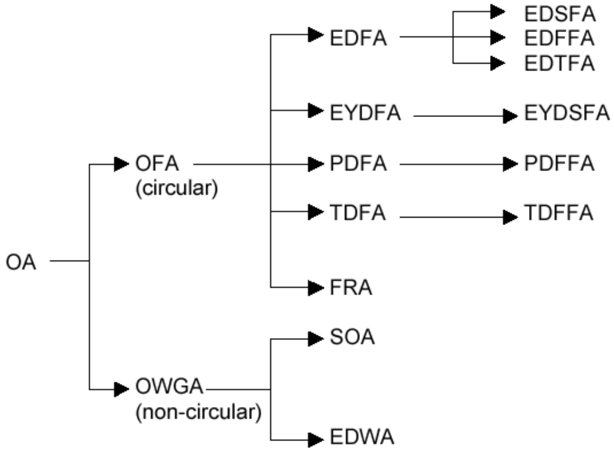


Figure 2. A variety of optical amplifier technologies have evolved.

The wavelength coverage obtainable with the various amplifier types depends on the dopant in the case of the doped-fiber designs. The fiber Raman amplifier (FRA), more commonly referred to as simply the Raman amplifier, is capable of amplification over the full range of single-mode optical fiber from 1280 to 1650 nm. The pump wavelength must be chosen for a particular band. The semiconductor optical amplifier can also be designed for operating bands in the 1280 to 1650 nm region.

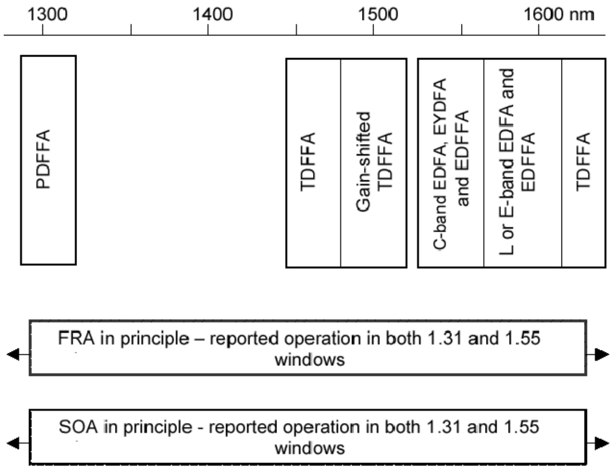


Figure 3. The suitability of a particular amplifier technology is dependent upon the required wavelength range.

Refer to Appendix E for the full names of the amplifier types abbreviated in Figures 2 and 3.

Erbium-doped fiber amplifier

The EDFA is based on optical fiber that has a small concentration of erbium atoms in the core. Pumping is provided by coupling laser light of the appropriate wavelength into this erbium-doped fiber. The erbium absorbs the pump light and can then reemit the energy as light in the C-band and less strongly in the longer-wavelength L-band. Signal light is also coupled into the fiber. It stimulates the erbium to emit at exactly the same wavelength, thus amplifying the signal. Many wavelengths within the gain band can be amplified at the same time!

Because the erbium can also emit light without stimulation from a signal, the amplifier also produces broadband spontaneous emission that is not related to the signals and can then be further amplified. This amplified spontaneous emission (ASE) mixes with the signal causing noise.

Figure 4 shows a very basic scheme for an amplifier; a complete EDFA may have considerably more complexity.

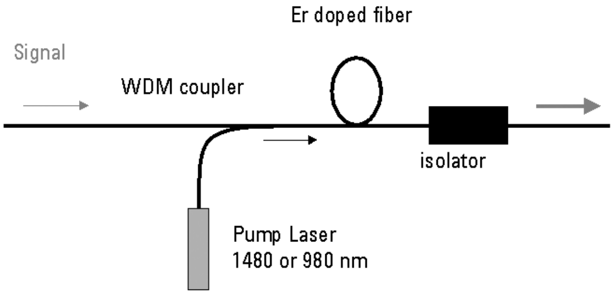


Figure 4. The generic EDFA has a very simple structure.

A more typical amplifier as shown in Figure 5 is more complex. Isolators are included to avoid the amplification of reflected light and the possibility of a resonant cavity.

Tap couplers with photodiodes are included to monitor the input, output, and reflected optical power levels. This information can be used as feedback for adjusting the pump laser power and initiating an automatic pump shutdown if the output fiber is broken or disconnected.

There may be two or more stages of amplification, with additional functionality between the stages, such as gain flattening or dispersion compensation.

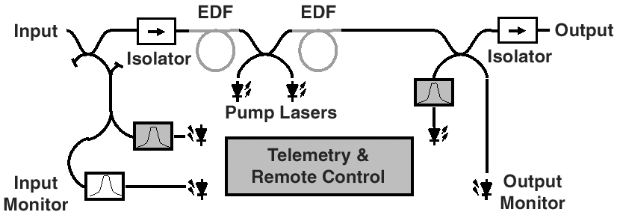


Figure 5. The EDFA becomes more complex to cope with the demands of the optical network.

Raman Amplifier

The simplified diagram of a Raman amplifier (Figure 6) is similar to that of the EDFA but the principle is quite different. The active fiber is the same silica-based glass fiber that is used for transmission. In fact, it is most common that the same fiber used for transmission provides the Raman gain in response to pump energy. The pump light interacts with the material and a portion of the pump energy is shifted approximately 13 THz lower in frequency. The shift in photon energy corresponds to the energy of a vibrational excitation of the medium. A photon of pump light is replaced by a photon with longer wavelength, while an atomic vibration in the medium is created whose energy makes up the difference between the two photons.

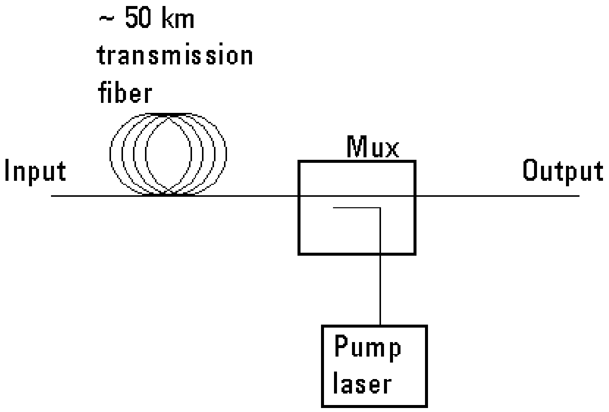


Figure 6. The distributed Raman amplifier utilizes standard transmission fiber as the gain medium.

The Raman effect is demonstrated by pumping 25 km of single-mode fiber at 1455 nm. The output spectrum is shown in Figure 7. A portion of the pump signal is shifted 13 THz down in frequency (approximately 100 nm up in wavelength). Without a signal in the Raman-shifted range, there is a band of ASE of about 20-nm in width. Raman amplification takes place when a signal in the shifted wavelength range passes through the fiber. The signal stimulates stronger Raman-shifted emission of light at the signal wavelength. To broaden the amplification region, multi-wavelength (WDM) pumping can be used. A 100-nm operating band with very flat gain characteristics has been demonstrated [2].

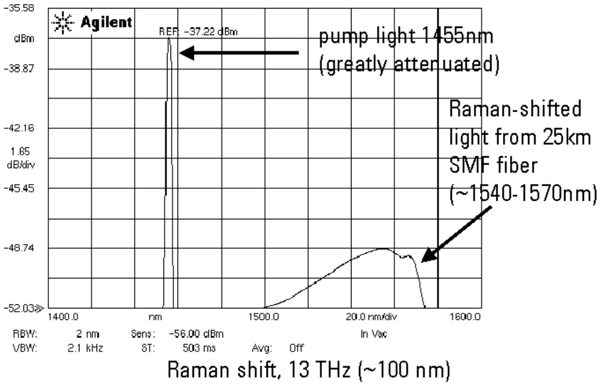


Figure 7. The Raman effect shifts some light to longer wavelengths.

Semiconductor optical amplifier

While the EDFA is currently the prevalent amplifier type and Raman is emerging to provide better performance, the semiconductor optical amplifier (SOA) continues to progress as a potentially more compact and lower cost alternative. The SOA also has applications in optical switching and as a non-linear device in applications such as wavelength conversion. The SOA may also be applied in the 1310-nm window where doped-fiber amplifiers have not yet proven to be viable.

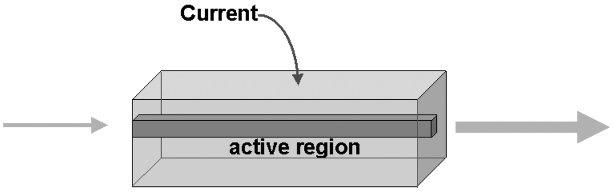


Figure 8. In a semiconductor amplifier, gain occurs in semiconductor waveguide.

The simplest construction of an SOA (Figure 8) is a semiconductor laser, operated below threshold, with low facet reflectivity. Such a device can be compact in size, have low power consumption and be readily integrated with other optical components.

Erbium-doped waveguide amplifier

Another amplifier type that is suitable for integration is the erbium-doped waveguide amplifier (EDWA). An example of such a device is shown in Figure 9. Like the EDFA, erbium-doped silica glass is the active medium. The difference is that the erbium-doped material is a planar waveguide deposited on a silica substrate. Pump laser, input and output isolators, and other components are integrated in a hybrid form. It is convenient to integrate waveguide devices like couplers, splitters, and AWG filters in the same structure.

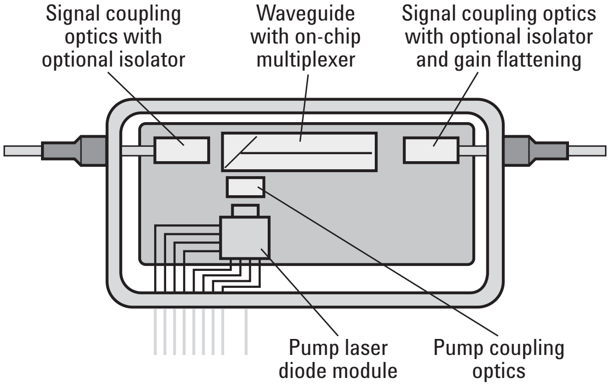


Figure 9. An erbium-doped waveguide amplifier (EDWA) uses the same principle as the EDFA but with an erbium-doped planar waveguide.

Optical amplifier gain and noise figure definitions

The IEC has defined gain and noise figure parameters for the general case of an optical amplifier used in a multichannel (WDM) application [3]. A typical configuration of an OA in a multichannel application is shown in Figure 10. At the transmitting side n signals, coming from n optical transmitters, T_{x1}, T_{x2}, . . . T_{xn}, each with a unique wavelength, λ_1, λ_2, . . . λ_n, respectively, are combined by an optical multiplexer (OM). At the receiving side the n signals at λ_1, λ_2, . . . λ_n, are separated with an optical demultiplexer (OD) and routed to separate optical receivers, R_{x1}, R_{x2}, . . . R_{xn}, respectively. To characterize the OA in this multi-channel application an input reference plane and an output reference plane are defined at the OA input and output ports, respectively.

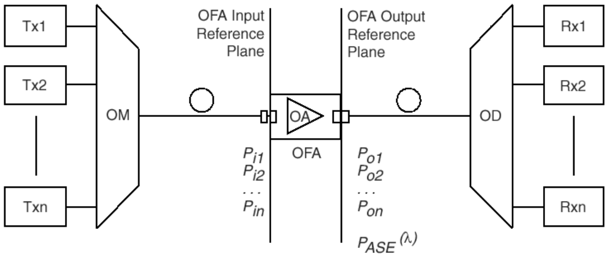
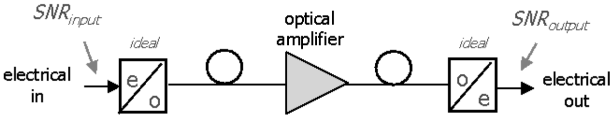


Figure 10. Optical amplifier gain and noise parameters are defined for multichannel (WDM) stimulus.

At the input reference plane, n input signals at the n wavelengths are considered, each with a unique power level, P_{i1}, P_{i2}, . . . P_{in}, respectively. At the output reference plane, n output signals at the n wavelengths, resulting from the optical amplification of the corresponding n input signals, are considered, each with power level P_{o1}, P_{o2}, . . . P_{on}, respectively. Moreover, the amplified spontaneous emission (ASE) with a noise power spectral density, $P_{ASE}(\lambda)$, is also to be considered at the OA output port.

Often called *total noise figure*, the basic definition of optical amplifier noise figure is defined in electrical quantities as shown in Figure 11 [4][5]. It is explicitly defined as:

> *The decrease of the signal-to-noise ratio (SNR), at the output of an optical detector with unitary quantum efficiency, due to the propagation of a shot-noise-limited signal through the OA, expressed in dB.*



$$F_{total} = \frac{SNR_{input}}{SNR_{output}}$$

Figure 11. Total noise factor is defined in terms of electrical signal-to-noise ratios.

Noise factor is the linear representation of noise figure and is related to noise figure as follows:

Noise figure (*NF*) = 10log(*F*) where *F* is the noise factor

The noise factor as shown in Figure 11 may be broken down into multiple contributions as indicated in Figure 12. Each of these contributions can be expressed by a partial noise factor [6]:

a) Signal shot noise factor, $F_{shot,sig}$, from shot noise from amplified input signal;
b) ASE shot noise factor, $F_{shot,ase}$, from shot noise from amplified spontaneous emission;
c) Signal-spontaneous noise factor, $F_{sig\text{-}sp}$, from signal beating with ASE;
d) Spontaneous-spontaneous noise factor, $F_{sp\text{-}sp}$, from ASE beating with itself;
e) Noise factor from multiple path interference (MPI), F_{mpi} .

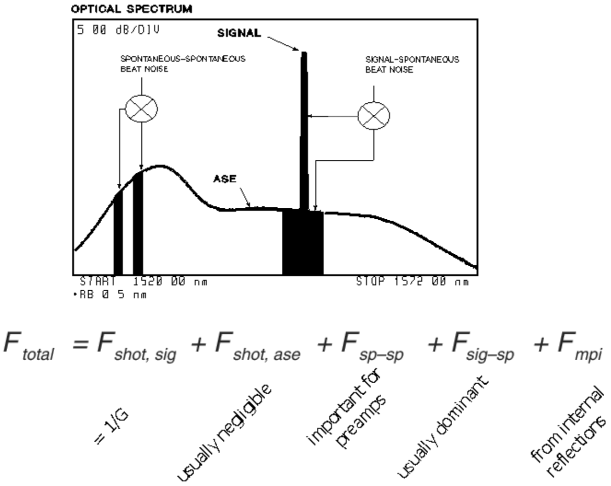


Figure 12. Total noise factor can be subdivided into components caused by various sources of noise.

For most amplifier types, the signal-spontaneous beat noise contribution, $F_{sig\text{-}sp}$, is dominant. It can be derived from measurements of ASE with an optical spectrum analyzer. From measured ASE it is calculated as follows:

$$F_{sig\text{-}sp} = 2\,\frac{\rho_{ase,p}}{G\,h\,\nu_{sig}} \qquad (1)$$

where:

$\rho_{ase,p}$ = the optical power density of spontaneous emission, in the same polarization state as the output signal, at the signal wavelength, in W/Hz;
h = Planck's constant;
ν_{sig} = c/λ_{sig} = optical signal frequency in Hz

It is important to note that it is the component of ASE in the same state-of-polarization as the signal that contributes to $F_{sig\text{-}sp}$. However, it is usually assumed that ASE is unpolarized so equation (1) becomes:

$$F_{sig\text{-}sp} = \frac{\rho_{ase}}{GhP_{sig}} \qquad (2)$$

where:

ρ_{ase} = the optical power density of spontaneous emission

The term due to signal shot noise, $F_{shot,sig}$, is equal to 1/G. The spontaneous-spontaneous noise factor is:

$$F_{sp\text{-}sp} = \frac{\rho_{ase}^2\,B_{sp\text{-}sp}}{2\,h\,\nu_{sig}\,G^2\,P_{in}} \qquad (3)$$

where:

$B_{sp\text{-}sp}$ = equivalent optical bandwidth of the ASE

The noise factor due to multipath interference, F_{mpi}, is generated by the beating between the output signal and one or more doubly reflected replicas of the output signal. Two or more reflection points inside the OFA are necessary to generate MPI noise. MPI noise cannot be derived from the ASE as measured on an optical spectrum analyzer. It must be measured after a broadband optical-to-electrical conversion on an electrical spectrum analyzer.

The definitions of gain and noise figure is somewhat complicated for distributed amplification, the most common is distributed Raman amplification, DRA. In discrete amplifiers, the gain is simply the increase in intensity between the input and the output. When the gain is distributed in a long transmission fiber, there is substantial attenuation associated with the fiber between the "input" and "output". This attenuation often exceeds the gain due to the Raman pumping, leading to a net negative gain for the distributed amplifier. Thus it is convenient and common to determine the "effective gain" by comparing the signal intensity with pumping to the intensity through the fiber with the pump turned off. This is sometimes also called "on/off gain".

The noise figure for a distributed amplifier is also dependent on the way that the input signal is defined. If the input signal is defined as that level at the output of the unpumped fiber, the noise figure will be significantly lower, in fact it may be negative which is not possible in a discrete amplifier. Referring to Figure 13, the effective gain and noise figure of a distributed amplifier are defined as the gain and noise figure of an equivalent discrete amplifier (that is producing identical output signal power) placed at the output of the unpumped transmission fiber.

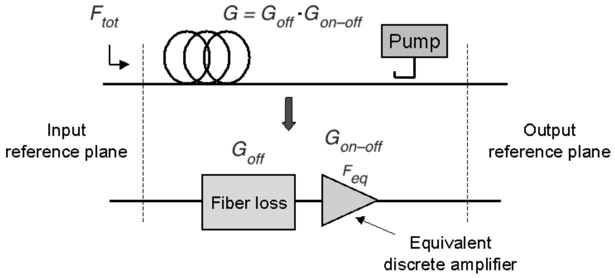


Figure 13. For a distributed amplifier, the gain and noise figure of an equivalent discrete amplifier following the fiber loss are defined.

Test methods for measuring the noise figure of optical amplifiers can be classified as *electrical* and *optical*. The electrical methods analyze the electrical noise at the output of a broadband optical to electrical converter and are suitable to measure the total noise figure as defined in Figure 11. One such technique, the RIN subtraction method, as shown in Figure 14, makes a measurement of relative intensity noise (RIN) on a lightwave signal analyzer. Total noise figure may be calculated by:

$$F = (RIN_{out} - RIN_{source})\, P_{in}/2h\nu + 1/G \qquad (4)$$

Measuring total noise figure in this manner is important when multi-path interference (MPI) noise is significant as it can be on a Raman amplifier. In this application note, however, only optical methods are described in detail.

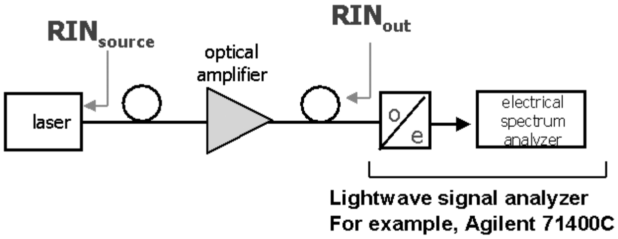


Figure 14. Total noise figure can be derived from relative intensity noise (RIN) measurements at the input and output of an optical amplifier.

The optical methods, using an optical spectrum analyzer, measure ASE and calculate signal-spontaneous noise figure, $F_{sig\text{-}sp}$, as described in equation (2). The particular method of extracting the ASE is what distinguishes the various optical methods. The challenge is to extract an accurate value of ASE at each DWDM channel in the presence of the multiple signals. As shown in Figure 15, this is a complex signal environment. In the magnified view, within the circles, are the values of ASE at each channel that are desired to calculate per-channel noise figure. Direct measurement of the noise at these wavelengths is not possible because of the presence of the signals at the same wavelengths. Estimation methods using interpolation and time-domain extinction are described in this application note.

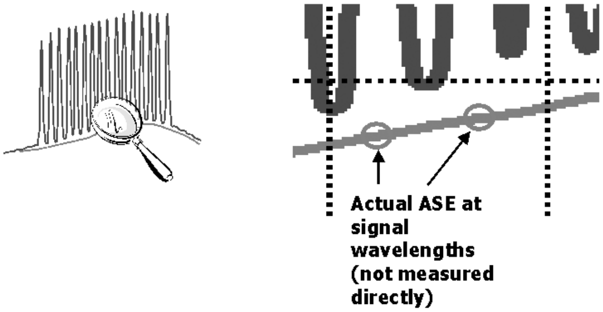


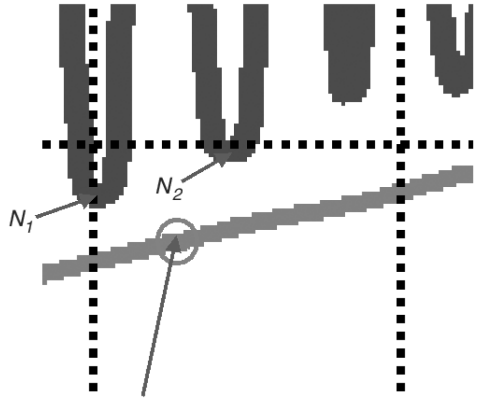
Figure 15. Signal-spontaneous noise figures can be calculated from an estimate of amplified spontaneous emission (ASE) at each channel wavelength.

Because of the saturation properties of optical amplifiers, it is necessary to test amplifiers intended for DWDM applications with a source that has multiple channels. It is not required however to test an amplifier with the ultimate number of channels that may be used. For example, an amplifier intended for a 100 channel C-band system can be adequately tested with, perhaps, 20 lasers spaced uniformly. Appendix A provides some guidance on determining the number of required lasers.

The Interpolated Source-Subtraction (ISS) Method

Description

This method is called *interpolated source subtraction* (ISS) because ASE at each channel is obtained by interpolating from measurement mode at a small wavelength offset around each channel. It is the simplest to implement in that it only requires a laser source and an optical spectrum analyzer (OSA). It is also a flexible method because it is applicable to all types of amplifiers including doped-fiber, SOA and Raman. Like all OSA-based methods, ISS measures gain and signal-spontaneous noise figure. A complication in implementing ISS is that the laser sources used to stimulate the optical amplifier have spontaneous emission. Like a signal, the spontaneous emission is amplified by the optical amplifier and appears at the output along with the ASE. Since it is only the ASE that needs to be measured, the source spontaneous emission must be subtracted from the measured noise at each channel. As shown in Figure 16, the values of noise, N_1 and N_2, are measured for a particular channel. The ASE is calculated by interpolating N_1 and N_2 and subtracting the source noise contribution. In this illustration, straight-line or linear interpolation is used. Higher-order curve fitting may also be used to improve accuracy.



$$ASE = \frac{N_1 + N_2}{2} - \text{Gain X source noise}$$

Figure 16. The simplest way to determine ASE is by interpolating between channels and subtracting the source noise contribution.

A simplified setup for ISS is shown in Figure 17. While optical amplifiers designed for single-wavelength operation require only single-wavelength stimulus, WDM amplifiers require multi-wavelength stimulus as shown. A light from a number of fixed-tuned lasers (typically DFB laser) is combined and routed to the input of the amplifier-under-test. The output goes to the OSA. A bypass path is required to measure the source characteristics.

As will be shown in a later section, a practical configuration usually requires accessories such as an optical power meter, variable optical attenuator, and often, optical switches.

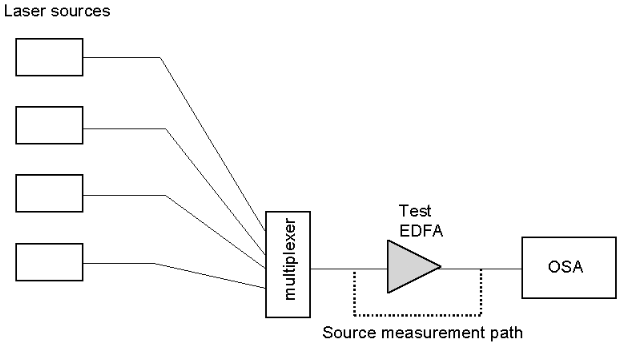


Figure 17. The interpolated source subtraction (ISS) method requires a multichannel source and an OSA.

Interpolation error

There are two predominant error sources in making measurements with the ISS method: interpolation error and source noise subtraction error. Interpolation error can occur if the ASE vs. wavelength has a curvature and straight-line interpolation is used as illustrated in Figure 18. As shown, straight-line interpolation will provide a value for ASE that is lower than the actual value at the signal wavelength. Using quadratic or higher order curve fitting reduces this problem.

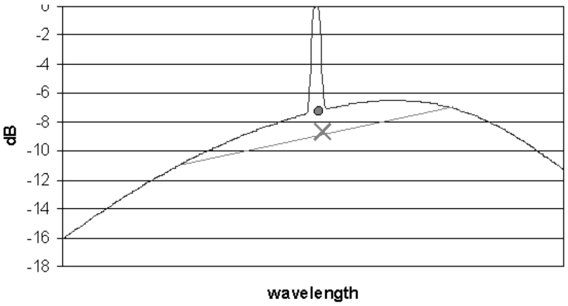


Figure 18. Curvature in the ASE characteristic will cause an error when using straight-line interpolation.

Error due to source spontaneous emission

A second error source for noise figure measurement with the ISS method is caused by the spontaneous emission of the laser sources. Considering the equation in Figure 16, if the two terms are similar in value, small measurement uncertainties translate to large uncertainty in the ASE calculation. Figure 19 shows that the value of the uncertainty in noise figure increases dramatically with total source spontaneous power spectral density. This particular chart is for noise figure of 5 dB and assumes a noise measurement uncertainty of 0.05 dB.

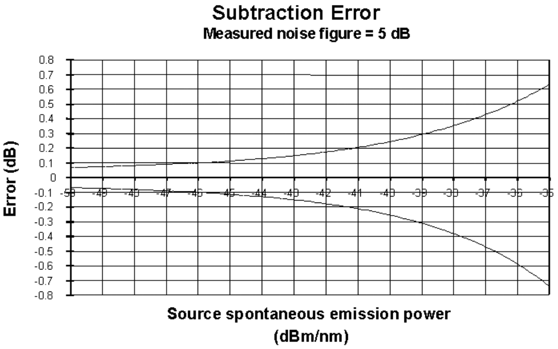


Figure 19. Error due to source noise subtraction increases with source spontaneous emission power level.

A calculation of the error due to source spontaneous emission from which this chart is derived is given in Appendix B.

The effect of multiplexer type

There are two types of multiplexers used for combining the laser outputs for multichannel sources. The selection will have a large impact on the uncertainty due to source spontaneous emission power. The *broadband* multiplexer uses fused silica fiber couplers or planar waveguide couplers and the insertion loss for each channel is given by:

$$L_{bb} = 10\ \mathbf{log}\ (1/N) \div R_{bb} \qquad \text{dB} \qquad (5)$$

where N is the number of inputs and R_{bb} is the excess insertion loss. A typical value for R_{bb} is 0.5 dB. The total power, P_T, from the combining of N sources, with each channel having an identical output power P_s in dBm, is

$$P_T = P_S - R_{bb} \qquad \text{dBm} \qquad (6)$$

Source spontaneous emission passes through the multiplexer with its spectral characteristics unmodified. At the combined output, the total signal to spontaneous noise ratio will be approximately equal to that of the individual lasers, but the OSNR of individual channels will be reduced on average by 10 log (1/N) dB because the overlapping SSE contributions add together.

The second type of multiplexer is the *wavelength-selective multiplexer* which uses fiber Bragg grating, array waveguide, or dielectric filter technology. Unlike the broadband device, the insertion loss for each channel is not inversely proportionally to N but is given by:

$$R_{WS} \qquad \text{dB} \qquad (7)$$

where R_{ws} is the residual insertion loss and has a typical value of 6 dB. Thus, the total power, P_T, from the combining of N sources, with each channel having an identical output power P_s in dBm, is:

$$P_T = P_S + 10\ \mathbf{log}\ (N) - R_{WS} \qquad \text{dBm} \qquad (8)$$

Because the wavelength-selective multiplexer presents a bandpass filter characteristic to each channel, it filters the spontaneous emission from all sources. The output signal to spontaneous noise ratio is significantly improved on the combined output signal.

Two examples of multichannel source spectra are shown below. Figure 20 is the spectrum of eight DFB lasers combined with a broadband multiplexer. Figure 21 is from sixteen DFB lasers combined with a wavelength selective source.

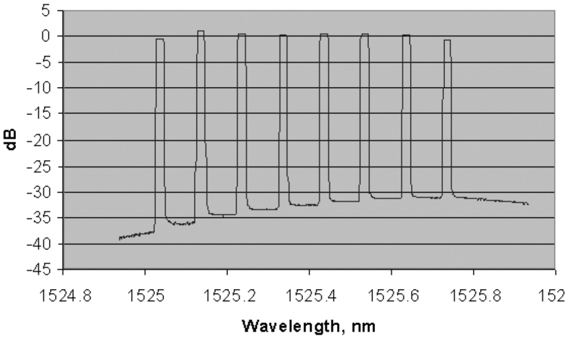


Figure 20. With a broadband multiplexer, spontaneous emission from individual laser sources is additive producing a higher noise level as shown in this spectral plot.

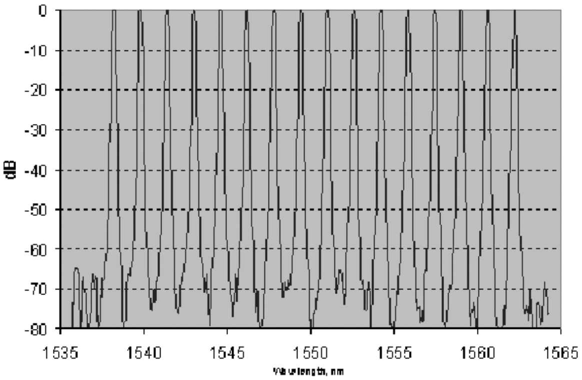


Figure 21. With a wavelength selective multiplexer, the spontaneous emission is significantly reduced.

The broadband multiplexed source provides a minimum of 31 dB/nm spontaneous emission ratio on a per channel basis. It can provide up to –6 dBm total input power to a test OA before ISS subtraction error is excessive (>0.1 dB).

The wavelength-selective multiplexed source provides a minimum of 60 dB/nm spontaneous emission ratio on a per channel basis. It can provide up to +16 dBm total input power to a test OA before the subtraction error is excessive.

The Time-Domain Extinction (TDE) Method

Description

The time-domain extinction (TDE) method, used exclusively for EDFAs and EDWAs, takes advantage of the fact that the meta-stable energy level of the erbium ions has a time constant of several hundred microseconds or more. As shown in Figure 22 where the input signal is pulse modulated at a 1-kHz rate, immediately after the input signal is turned off, the ASE level remains at the same level as it was in the presence of the input signal. It then exponentially increases to its signal-off value. The slow time dynamics of the EDFA are the basis of the TDE and other pulsed source methods [7]. Making ASE measurements when the source is pulsed off, solves one of major problems with ISS: the source spontaneous emission is also pulsed off so that it is not additive with the ASE.

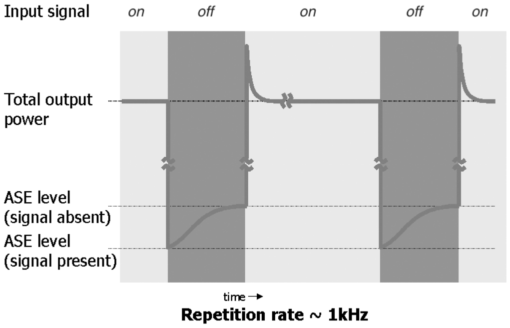
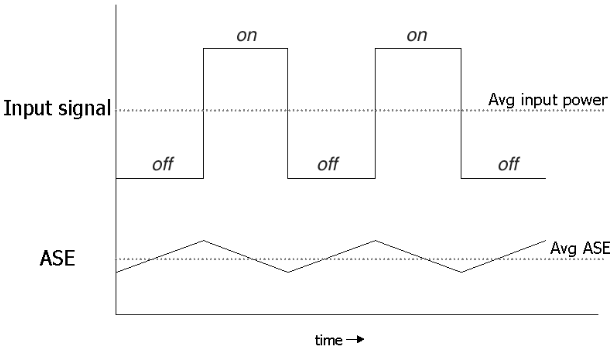


Figure 22. TDE takes advantage of slow time dynamics of the EDFA.

At faster pulse rates the shape of the ASE vs. time waveform becomes triangular as the pulse width becomes small compared to the relaxation time of the erbium ions. It is important that the value of ASE used in the noise figure equation corresponds to the average value of input power. Referring to Figure 23, it is shown that the average value of ASE corresponds to the average value of input power.



The correct ASE for noise figure calculation is the average ASE

Figure 23. At higher repetition rate, ASE waveform is triangular in response to square-wave excitation.

Measuring the average ASE during the signal off period is accomplished by either external optical gating with acousto-optic modulators (AOMs) or with electrical gating in the OSA. In either case it is important to sample the ASE waveform in order to capture the average value of the ASE which is at the center of the off period. As shown in Figure 24, the acousto-optic modulator gating window is typically wide compared to the off period while the OSA gating window is narrow. Accurate timing to sample the ASE waveform is crucial for accurate measurements.

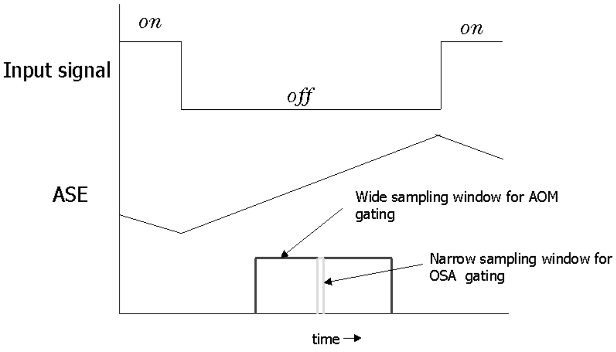


Figure 24. Pulse methods sample ASE in the signal-off period.

To implement TDE with AOMs, a configuration like that in Figure 25 is used. The sources are combined and pulse-modulated with an input AOM. At the output of the amplifier-under-test, a second AOM gates the optical signal in opposite phase to that of the input AOM. The pulsed modulation source supplies the necessary in-phase and out-of-phase drive to the modulators. Controlling the duty cycle and timing to the output AOM is particularly important in order to accurately gate the ASE for measurement on the OSA. Patch cords and the EDFA itself have time delays that must be taken into account in AOM timing.

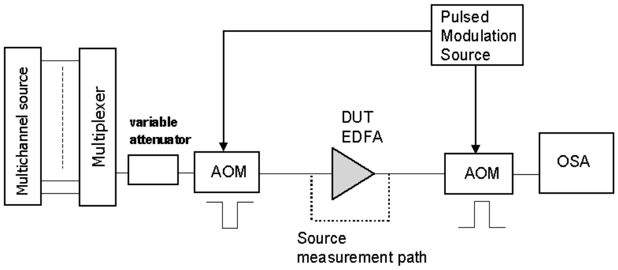


Figure 25. TDE test setup using acousto-optic modulators (AOMs).

A second TDE method with a somewhat simpler configuration is shown in Figure 26. The sources are synchronously modulated with an internal square wave generator. A trigger signal from the sources is applied to the OSA and provides the timing reference for the sampling of data in the OSA. A trigger delay is entered in the OSA so that data is taken at the proper point in the source off period. For example, when modulating at 100 kHz, the off period is equal to 5 µs. Ideally the trigger delay is set to half that value or 2.5 µs so that data is taken half way through the off period. In practice, the optimal delay will vary from the ideal value due to time delays in the optical path and in the instrumentation.

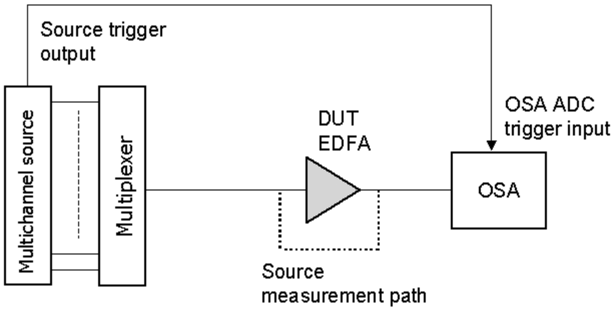


Figure 26. TDE implemented with direct source modulation and OSA electrical gating.

Selecting the modulation frequency

The TDE methods are limited to amplifiers with slow time dynamics like the EDFA. They are unsuitable for SOAs or Raman amplifiers. Even for EDFAs, care must be taken to select a modulation frequency sufficiently high so that the waveshapes are linear as in Figure 23.

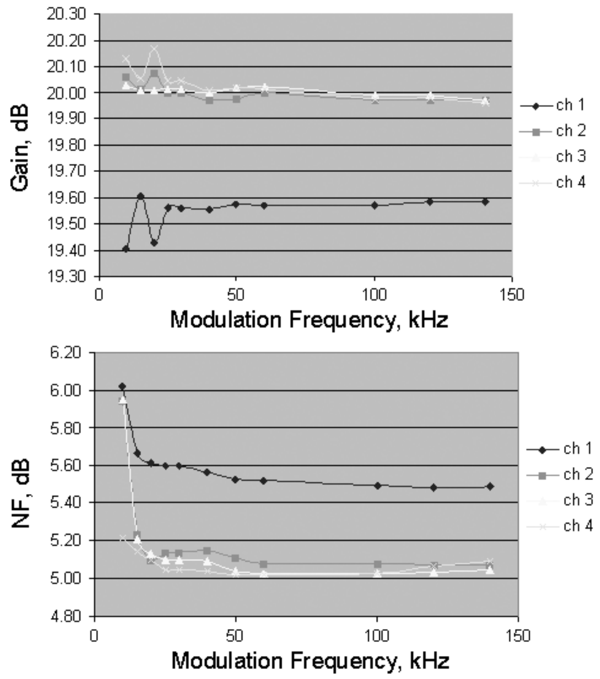


Figure 27. Measured gain and noise figure are constant at modulation frequencies above approximately 50 kHz

For most EDFAs without active automatic gain or level control (AGC/ALC) circuits, a modulation frequency of 65-kHz is sufficiently high. For amplifiers with such control loops, modulation frequencies in excess of several MHz may be required. A dual 980nm-pumped EDFA with a four-laser WDM source was measured with TDE vs. modulation rate. The results in Figure 27, show very small deviation in gain or noise figure above a modulation rate of about 50 kHz.

Because the gain recovery time constant is shorter than the ASE recovery time constant (refer to Figure 22), it is simple to evaluate gain response vs. modulation frequency. An optical source with variable modulation frequency is applied to the optical amplifier. The average output power of the optical amplifier is measured on an optical power meter. As the modulation frequency is increased, the power meter reading asymptotically approaches a final value. At low modulation frequencies there is an increasing error due to nonlinear gain recovery of the optical amplifier. If applying this procedure, do not modulate below 10-kHz because the resulting transients may cause damage to the EDFA or the setup.

The effect of imperfect extinction

While TDE implemented with OSA gating (Figure 26) is a very simple setup, the extinction obtainable is not sufficient to completely extinguish the signal. In this case, interpolation is also utilized. The benefit of TDE in this case is to extinguish the source spontaneous emission to improve accuracy. Figure 28 shows the input and output spectra with imperfect extinction. While there is some signal feedthrough, the source spontaneous emission has been reduced well below the measured ASE level.

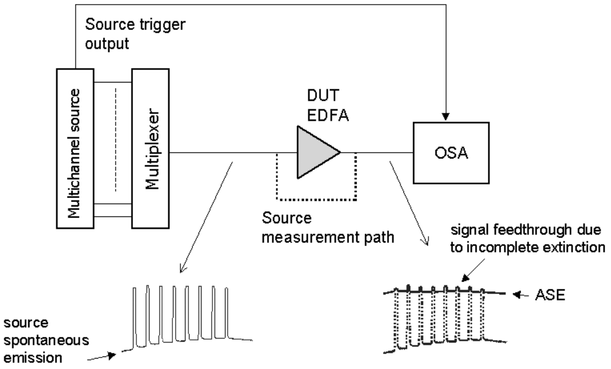


Figure 28. With imperfect extinction, signal feedthrough can occur but source noise is still sufficiently reduced.

Making ISS Measurements with the 8614xB OSA

Setting the parameters in the ISS application

The equipment setup for making measurements with the 8614xB OSA using the ISS method is shown in Figure 29. The source consists of one or more lasers, typically DFBs, that are combined with a multiplexer. See page 10 for a discussion of the differences between broadband and wavelength selective multiplexers. A variable optical attenuator follows the multiplexer for varying the total input power to the optical amplifier. The OSA is connected to the output of the amplifier.

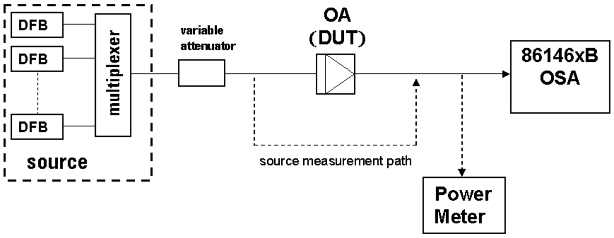


Figure 29. Equipment arrangement for an ISS test with manual source measurement.

In order to measure the signal and noise power of the laser source, that is, it is necessary to provide a measurement path that bypasses the OA. This may be done manually with a patch cord as indicated in Figure 29 or in a more-automated manner using optical switches as shown in Figure 30. It is also required to calibrate the absolute power of the source to an accuracy that is only achievable with an optical power meter.

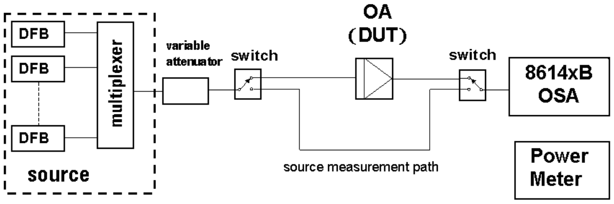


Figure 30. Equipment arrangement for an ISS test with source/DUT switching.

From the 8614xB's application menu, first select Amplifier Test & , then Interpolation (ISS) Test as indicated in Figure 31. Next enter the Measurement Setup & (Figure 32). The Measurement Setup window as shown in Figure 33 allows entry of all the parameters necessary to perform an ISS measurement.

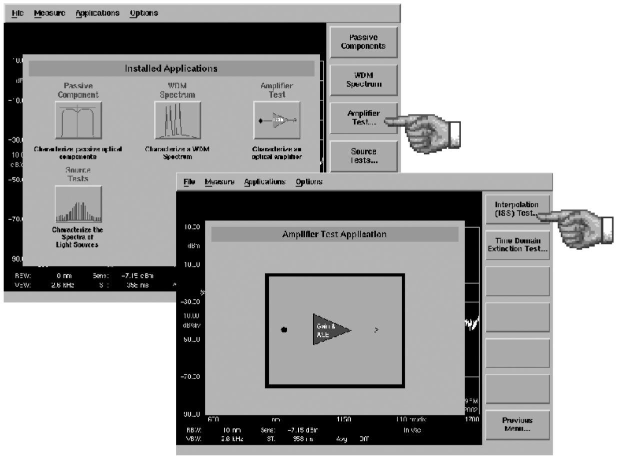


Figure 31. Enter the ISS application by pressing *Amplifier Test* then *Interpolation (ISS)* Test.

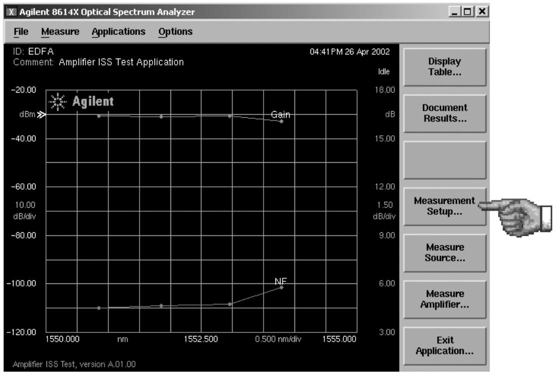
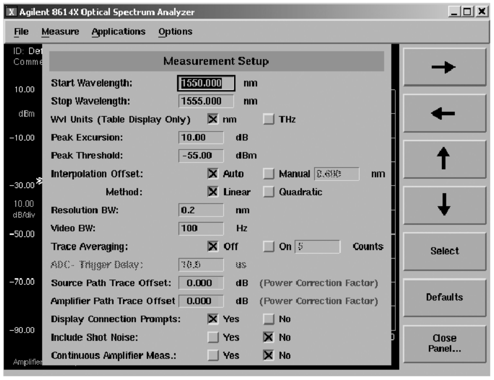


Figure 32. Press *Measurement Setup* for the setup panel.



Measurement Setup

Start Wavelength: 1550.000 nm
Stop Wavelength: 1555.000 nm
Wvl Units (Table Display Only) ☒ nm ☐ THz
Peak Excursion: 10.00 dB
Peak Threshold: -55.00 dBm
Interpolation Offset: ☒ Auto ☐ Manual 0.600 nm
Method: ☒ Linear ☐ Quadratic
Resolution BW: 0.2 nm
Video BW: 100 Hz
Trace Averaging: ☒ Off ☐ On 5 Counts
ADC- Trigger Delay: 10.5 us
Source Path Trace Offset: 0.000 dB (Power Correction Factor)
Amplifier Path Trace Offset 0.000 dB (Power Correction Factor)
Display Connection Prompts: ☒ Yes ☐ No
Include Shot Noise: ☐ Yes ☒ No
Continuous Amplifier Meas.: ☐ Yes ☒ No

Figure 33. The ISS *Measurement Setup* panel.

Calibrating optical power at the defined reference plane

Note particularly the *Source Path Trace Offset* and *Amplifier Path Trace Offset* parameters. The values inserted here are the calibration factors for the source path and amplifier path and establish a precise power calibration at a defined reference point at the input of the optical amplifier. Determining these values is simplified by making an amplifier measurement but with a clear fiber substituting for the actual amplifier. For the manual source measurement setup of Figure 29, follow this procedure:

1. Connect the equipment as in Figure 34.
2. Connect the source output and OSA input fibers at the reference plane.
3. Measure the source path using the OSA Amplifier Test application Measure Source function.
4. Without changing the setup, perform the Measure Amplifier function in the Amplifier Test application. This step is necessary to have the source data appear in the Display Table.
5. Record the source mean wavelength and sum of source signal power values from the Display Table. See Figure 36.
6. Connect the source to the power meter as in Figure 34. Set the power meter wavelength parameter to the source mean wavelength value from the Display Table. See Figure 36.
7. Measure the power and record the value.
8. Calculate the difference between the power meter reading and the application reading using:
   Offset = Power Meter Reading - Application Sum of Source Signal Power.
9. Enter the calculated value into the Measurement Setup dialog box as Source Path Trace Offset and Amplifier Path Trace Offset. For a standard measurement setup, the offsets in the source and amplifier paths will be the same.
10. To verify the offset is correct, repeat Measure Source and Measure Amplifier. The source total power should read the same as measured by the power meter in Step 6. The gain should be 0.0 dB ±0.05 dB for each channel.

After measuring and verifying the path offsets, you can connect the amplifier under test as in Figure 29.

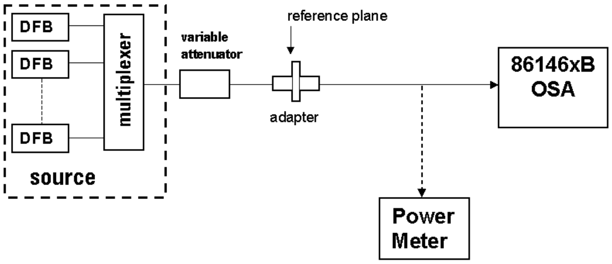


Figure 34. Source calibration requires a connection first to the OSA, then to a power meter.

More complex measurement setups can provide an alternative path for measuring the source. When this is the case, the offsets in the source and amplifier paths will be different. This second procedure accounts for these additional losses in a sample test configuration using switches. Use this procedure:

1. Connect the source output and receiver input fibers as shown in Figure 35.
2. Set switches to the source path (S) positions.
3. Measure the source path with the Measure Source function.
4. Without changing the setup, measure the source path with the Measure Amplifier function.
5. From the Display Table, record the Source Mean Wavelength and Sum of Source Signal Power. See Figure 36.
6. Set the switches to the amplifier path (A) positions.
7. Measure the amplifier path with the Measure Amplifier function.
8. From the Display Table, record the Sum of Amplifier Signal Power. See Figure 36.
9. Connect the power meter to the adapter at the reference plane as shown in Figure 35. Set the power meter wavelength parameter to the source mean wavelength value.
10. Measure the power and record the value.
11. Calculate the difference between the power meter reading and the application source reading using:
    Source Path Offset = Power Meter Reading - Application Sum of Source Signal Power.
12. Enter the calculated value into the Measurement Setup dialog box as the Source Path Trace Offset.
13. Calculate the difference between the power meter reading and the application amplifier reading using:
    Amplifier Path Offset = Power Meter Reading - Application Sum of Amplifier Signal Power.
14. Enter the calculated value into the Measurement Setup dialog box as the Amplifier Path Trace Offset.

15. To verify the offsets are correct, repeat Measure Source and Measure Amplifier with the corresponding switch positions. The source and amplifier total power should read the same as measured by the power meter in Step 10. The gain should be 0.0 dB ±0.05 dB for each channel.
16. After measuring and verifying the path offsets, you can connect the amplifier under test as in Figure 30.

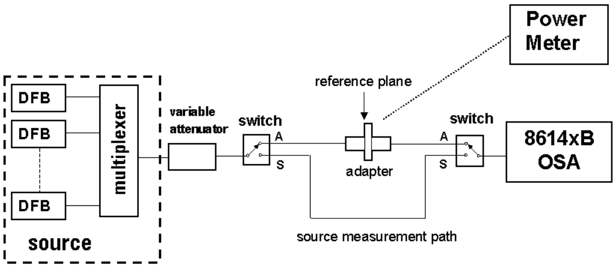
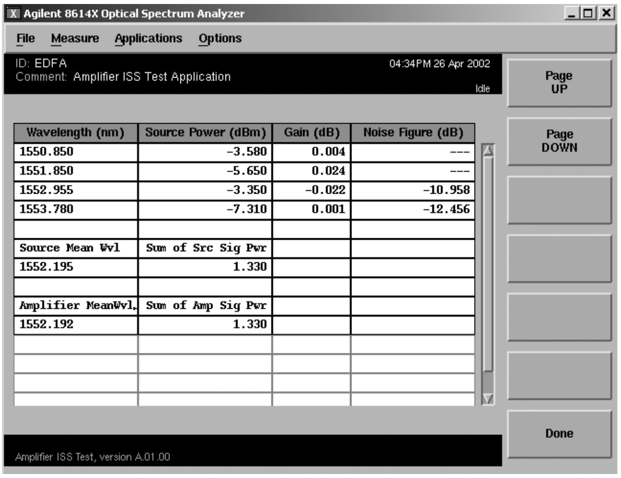


Figure 35. With optical switches, it is necessary to calibrate source and DUT paths.



ID: EDFA
Comment: Amplifier ISS Test Application
04:34PM 26 Apr 2002
Idle

Wavelength (nm)	Source Power (dBm)	Gain (dB)	Noise Figure (dB)
1550.850	-3.580	0.004	---
1551.850	-5.650	0.024	---
1552.955	-3.350	-0.022	-10.958
1553.780	-7.310	0.001	-12.456
Source Mean Wvl	Sum of Src Sig Pwr		
1552.195	1.330		
Amplifier MeanWvl.	Sum of Amp Sig Pwr		
1552.192	1.330		

Amplifier ISS Test, version A.01.00

Figure 36. A measurement of the source path facilitates source calibration.

Measurement example - An EDFA

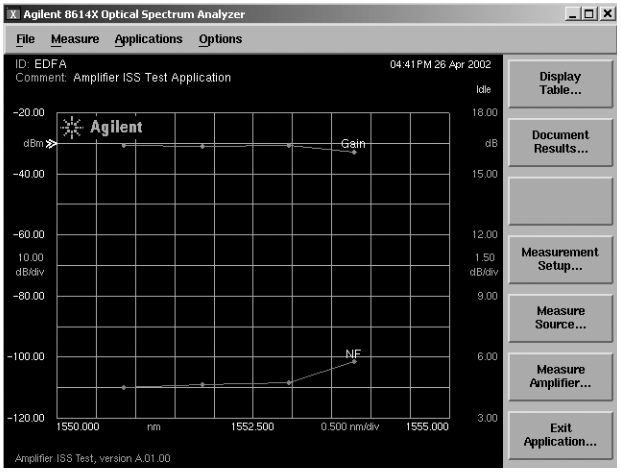
After the path offsets are calculated as described in the previous section, an actual amplifier measurement can be made. Here is the procedure:

1. From the *Interpolation ISS Test* menu, select *Measure Source...*.
2. Note that the *Measure Amplifier...* softkey is disabled until the source measurement is completed.
3. The system prompts you to connect the source to the OSA.
4. The display connection prompts can be turned off in the measurement setup dialog box, in which case *Measure Source...* will immediately initiate the measurement.
5. Press *Continue* to initiate the measurement.
6. *Measure Source...* is replaced with *Stop Source Measurement...* while the measurement is in progress.
7. The progress of the measurement is noted on the status panel:
   - An initial sweep is taken to set references, indicated by Source *Initial Sweep...*
   - A second sweep measures the peak of the signal, indicated by Source *Peak Sweep....*
   - A third sweep measures the noise level, indicated by Source *Noise Sweep....*
8. When the measurement is complete, the *Measure Amplifier...* softkey is enabled. The progress status label reads *Idle*.
9. Connect the amplifier between the source and the OSA.
10. Press *Measure Amplifier...* to begin the amplifier measurement process.
11. The system prompts you to install the device to be tested.
12. The display connection prompts can be turned off in the measurement setup dialog box, in which case *Measure Amplifier...* will immediately initiate the measurement.
13. Press *Continue* to initiate the measurement. The *Measure Source...* softkey is disabled. *Measure Amplifier...* is replaced with *Stop Amp Measurement...* while the measurement is in progress. The progress of the measurement is noted on the status panel:
    - An initial sweep is taken to set references, indicated by *Amplifier Initial Sweep....*
    - A second sweep measures the peak of the signal, indicated by *Amplifier Peak Sweep....*
    - A third sweep measures the noise level, indicated by *Amplifier Noise Sweep....*
14. After all the data is received, the application calculates the measurement results. The progress label reads *Calculating Results....*
15. When the measurement is complete, the progress status label reads Idle.
16. The measurement results will be displayed graphically. The points indicating the amplifier gain and noise figure are displayed relative to the dB scale on the right side of the graph.

NOTE: If Continuous Amplifier Measurement mode is selected in the measurement setup dialog box, the measurement will continue to update the points on the display and in the Display Table at the end of each measurement.

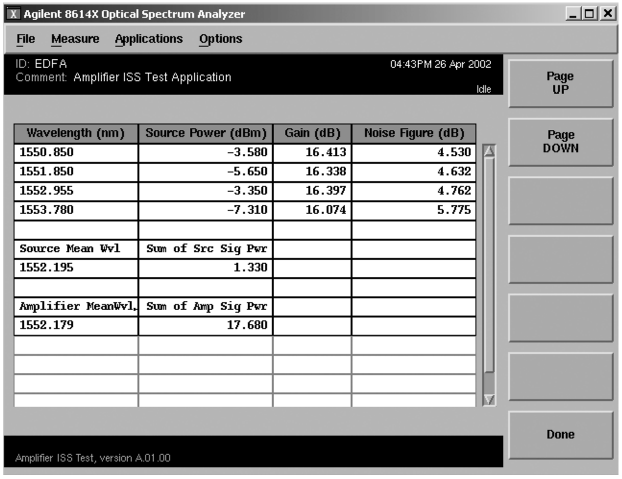
The Display Graph and Display Table for an example EDFA measurement using a four-channel source are shown in Figures 37 and 38. The Display Table... softkey is enabled when an amplifier measurement is complete and valid data is available.

At the end of the table, after all channels present have been measured, the table will display values of source mean wavelength, sum of source signal power, amplifier mean wavelength, and sum of amplifier signal power.



ID: EDFA
Comment: Amplifier ISS Test Application
04:41PM 26 Apr 2002
Idle
Amplifier ISS Test, version A.01.00

Figure 37. An ISS gain and NF result graph.



ID: EDFA
Comment: Amplifier ISS Test Application
04:43PM 26 Apr 2002
Idle

Wavelength (nm)	Source Power (dBm)	Gain (dB)	Noise Figure (dB)
1550.850	-3.580	16.413	4.530
1551.850	-5.650	16.338	4.632
1552.955	-3.350	16.397	4.762
1553.780	-7.310	16.074	5.775
Source Mean Wvl	Sum of Src Sig Pwr		
1552.195	1.330		
Amplifier MeanWvl.	Sum of Amp Sig Pwr		
1552.179	17.680		

Amplifier ISS Test, version A.01.00

Figure 38. An ISS gain and NF result in tabular form.

Measurement example - Raman amplifier

A Raman amplifier consisting of 25-km of SMF-28 fiber and counter-directionally pumped with a 1455-nm pump unit was measured with the setup of Figure 39.

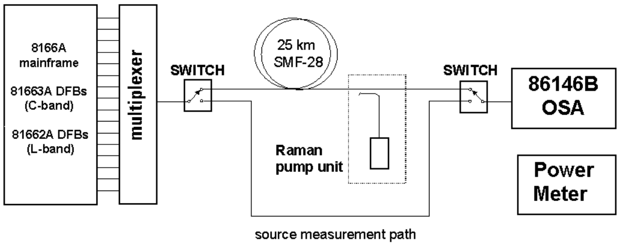


Figure 39. Setup for a Raman amplifier measurement.

As discussed in a prior section (see Figure 13), the gain and noise figure of a distributed Raman amplifier can be defined and measured conventionally or by considering the effective (On/Off) gain and noise figure. The conventional gain is measured in the same manner as the EDFA. The source is measured by bypassing the amplifier. For the On/Off gain measurement, the source is measured with the 25-km spool of SMF-28 fiber in place but with the pump turned off. The results for the two gain definitions are plotted in Figure 40. Note that the conventional gain, considering the amplifier as a discrete device, is negative while the On/Off gain is positive. The difference between the two curves is the unpumped insertion loss of the SMF-28 fiber.

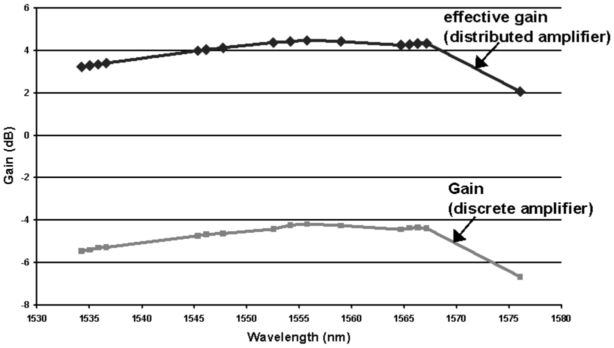


Figure 40. Effective (On/Off) gain and gain measurement on a Raman amplifier.

Conventional noise figure and effective noise figure are also measured by simply measuring the source either with or without the SMF-28 fiber in place. The results are shown in Figure 41. The conventional noise figure is positive as one might expect. The effective noise figure is negative - a situation that cannot occur in a discrete amplifier. As with gain, the difference between the two curves equals the insertion loss of the unpumped fiber.

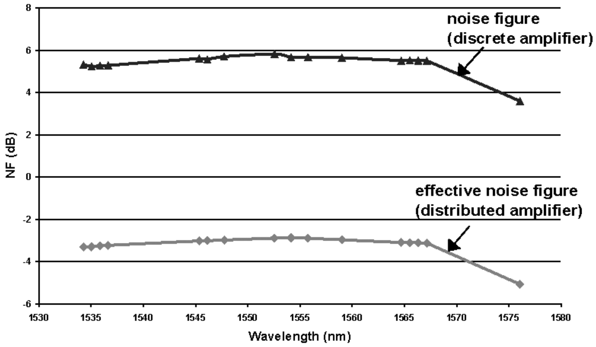


Figure 41. Noise figure and effective noise figure measurement on a Raman amplifier.

Making TDE Measurements with the 86146B OSA and the Lightwave Multichannel System Family of Laser Sources

The setup for making measurements with the TDE method is shown in Figure 42. The Lightwave Multichannel system consists of an 8166B mainframe and a number of laser plug-ins. The plug-ins may be the 81662A/81663A DFB lasers or the 81689A/B and 81649A compact tunable lasers. The 8166B mainframe can accommodate 17 plug-in modules. Alternatively, the 8164B mainframe, with space for four modules and a swept-wavelength tunable laser, can be used.

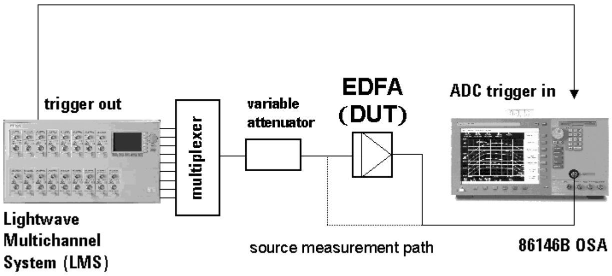


Figure 42. Equipment arrangement for a TDE measurement.

Setting the optical source for synchronous pulse modulation

To use TDE, it is necessary to setup synchronous source modulation on the 8166B Lightwave Multi-channel system and plug-in modules, or the 8164B Lightwave Measurement system and plug-in modules. Any of the plug-in modules including DFB lasers, tunable lasers, or compact tunable lasers can be configured for synchronous square-wave modulation. The internal modulation source from one of the lasers is used to trigger all of the lasers from synchronous modulation.

The modulation frequency may be from 20 kHz to 200 kHz. The 81662A and 81663A DFB modules may be modulated up to 100 kHz. A setting of 65 kHz is a good initial setting for most erbium-doped fiber amplifiers.

For synchronized modulation of two or more laser modules in the same mainframe, the setup is as follows:

1. Choose the “master” laser and set as follows:
    - Menu > Modulation Source > Internal
    - Menu > Modulation frequency > desired value
    - Menu > Output trigger mode > Modulation
2. Set all “slave” modules:
    - Menu > Modulation Source > Backplane (DFB modules require firmware version 4.0 or higher)
    - Menu > Output trigger mode > disabled (important)
3. To pass the master trigger to the slaves, set up the mainframe through the Config button under the screen:
    - Config > Trigger > Feedback (or Loopback)

Note: The master laser must always be turned on, if one or more slaves are on. Otherwise, it causes an error due to the missing trigger.

If an additional mainframe is used, a BNC cable can connect its input trigger to the master mainframe. Then this mainframe’s trigger configuration should be left on default and all modules set to modulate on the backplane. Finally, as indicated on Figure 42, a BNC cable is required from the Source Trigger Out to the OSA ADC Trigger.

Setting the parameters in the TDE application

From the 86146B’s application menu, first select *Amplifier Test ...*, then *Time Domain Extinction Test ...* as indicated in Figure 43. Next enter the Measurement Setup & (Figure 44). The Measurement Setup window allows entry of all the parameters necessary to perform a TDE measurement.

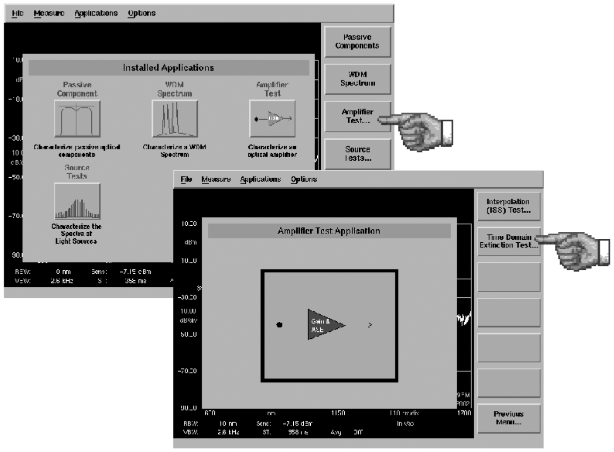
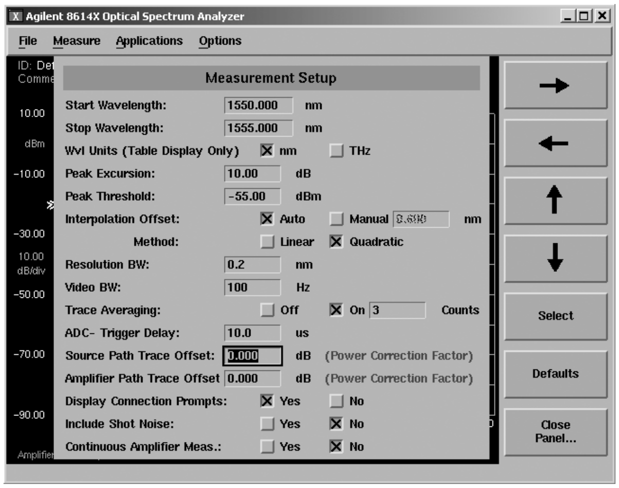


Figure 43. Enter the TDE application by pressing Amplifier Test then Time-Domain Extinction Test.



Measurement Setup

Start Wavelength: 1550.000 nm
Stop Wavelength: 1555.000 nm
Wvl Units (Table Display Only) ☒ nm ☐ THz
Peak Excursion: 10.00 dB
Peak Threshold: -55.00 dBm
Interpolation Offset: ☒ Auto ☐ Manual 0.600 nm
Method: ☐ Linear ☒ Quadratic
Resolution BW: 0.2 nm
Video BW: 100 Hz
Trace Averaging: ☐ Off ☒ On 3 Counts
ADC- Trigger Delay: 10.0 us
Source Path Trace Offset: 0.000 dB (Power Correction Factor)
Amplifier Path Trace Offset 0.000 dB (Power Correction Factor)
Display Connection Prompts: ☒ Yes ☐ No
Include Shot Noise: ☐ Yes ☒ No
Continuous Amplifier Meas.: ☐ Yes ☒ No

Figure 44. The TDE Measurement Setup panel.

NOTE: It is recommended to check and, if necessary, to readjust the DFB wavelengths, when modulated, usng the OSA.

Calibrating optical power at the defined reference plane

The first step in making a measurement is to determine the Source Path and Amplifier Path Trace Offsets and enter them into the table. Follow the identical procedure for the ISS method on p. 14. The values inserted here are the calibration factors for the source path and amplifier path and establish a precise power calibration at a defined reference point at the input of the optical amplifier.

After the path offsets, we can proceed with the amplifier measurement. The procedure consists of three parts: measuring the source, enabling the Optimal Display Search, and making the amplifier measurement.

The Measure Source step must be repeated if there is any change in the measurement parameters or the source wavelength and power. Source data will be lost when exiting the application and must be remeasured. Here is the procedure:

Measuring the source

1. From the TDE Test menu, select *Measure Source....* Note that the *Measure Amplifier...* softkey is disabled until the source measurement is completed.
2. When prompted, connect the source to the OSA. The display connection prompts can be turned off in the measurement setup dialog box; in which case *Measure Source...* will immediately initiate the measurement.
3. Press *Continue* to initiate the measurement. *Measure Source...* is replaced with Stop Source Measurement... while the measurement is in progress. The progress of the measurement is noted on the status panel:

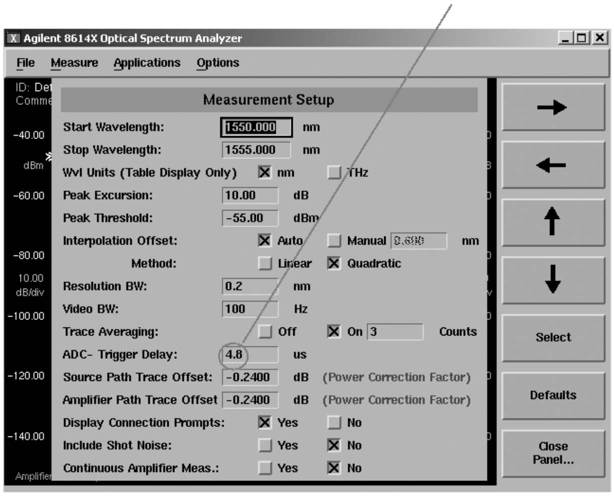
- An initial sweep is taken to set references, indicated by “Source Initial Sweep...”.
- A second sweep measures the peak of the signal, indicated by “Source Peak Sweep...”.
- When the measurement is complete, the Measure Amplifier... softkey is enabled. The progress status label reads “Idle”.

Using the Optimal Delay Search function

With the amplifier connected, press *Optimal Delay Search* on the TDE application menu.

This routine will search for the optimal trigger delay for the source modulation rate. The optimal delay sets the ASE measurement point to the midpoint of the source *Off* period.

In to the Measurement Setup window, please note that a value for the ADC trigger delay has been automatically entered. See Figure 45.


ADC trigger delay set by optimal delay search routine

Measurement Setup

Start Wavelength: 1550.000 nm
Stop Wavelength: 1555.000 nm
Wvl Units (Table Display Only) ☒ nm ☐ THz
Peak Excursion: 10.00 dB
Peak Threshold: -55.00 dBm
Interpolation Offset: ☒ Auto ☐ Manual 0.600 nm
Method: ☐ Linear ☒ Quadratic
Resolution BW: 0.2 nm
Video BW: 100 Hz
Trace Averaging: ☐ Off ☒ On 3 Counts
ADC- Trigger Delay: 4.8 us
Source Path Trace Offset: -0.2400 dB (Power Correction Factor)
Amplifier Path Trace Offset -0.2400 dB (Power Correction Factor)
Display Connection Prompts: ☒ Yes ☐ No
Include Shot Noise: ☐ Yes ☒ No
Continuous Amplifier Meas.: ☐ Yes ☒ No

Figure 45. Use the Optimal Delay Search routine to automatically set the ADC-Trigger delay.

Occasionally, the Optimal Delay Search will not be able to find an optimal setting. In this case, enter the ADC trigger delay manually. The value should be 25% of the modulation period plus 0.8 ms.

For a 65 kHz modulation rate, the period is 15.4 ms. The appropriate trigger delay is:

$$0.25 \times 15.4 \text{ ms} + 0.8 \text{ ms} = 4.6 \text{ ms}.$$

Measuring the amplifier

Connect the amplifier between the source and the OSA. The system measures the peak and noise power for the wavelengths measured in Measuring the Source and creates/updates the Display Table. Here is the procedure:

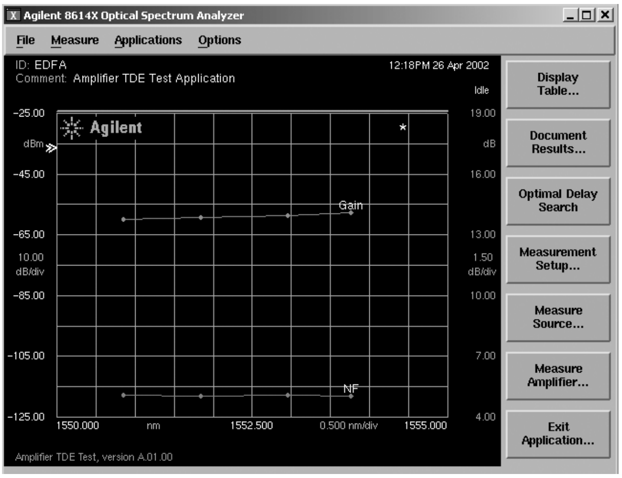
1. Press *Measure Amplifier...* to begin the process. The system prompts you to connect the device to be tested. The display connection prompts can be turned off in the measurement setup dialog box, in which case *Measure Amplifier...* will immediately initiate the measurement.
2. Press *Continue* to initiate the measurement. The *Measure Source...* softkey is disabled. *Measure Amplifier...* is replaced with *Stop Amp Measurement...* while the measurement is in progress.
3. The progress of the measurement is noted on the status panel:
   - An initial sweep is taken to set references, indicated by *Amplifier Initial Sweep....*
   - A second sweep measures the peak of the signal, indicated by *Amplifier Peak Sweep....*
   - A third sweep measures the noise level, indicated by *Amplifier Noise Sweep....*
   - After all the data is received, the application calculates the measurement results. The progress label reads *Calculating Results....*
   - When the measurement is complete, the progress status label reads *Idle*.

The measurement results will be displayed graphically as shown in Figure 46. The points indicating the amplifier gain and noise figure are displayed relative to the dB scale on the right side of the graph. Negative noise figure values will not be displayed.

NOTE: If Continuous Amplifier Measurement mode is selected in the measurement setup dialog box, the measurement will continue to update the points on the display and in the Display Table at the end of each measurement.

The *Display Table*... softkey is enabled when an amplifier measurement is complete and valid data is available. The results are displayed in a table similar to the one shown below. The Page Up and Page Down keys display previous and next pages of data if available. An example display table is shown in Figure 47.

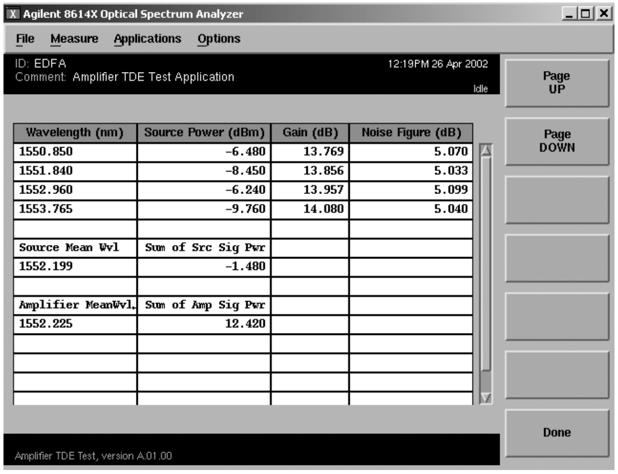
At the end of the table, after all channels present have been measured, the table will display values of source mean wavelength, sum of source signal power, amplifier mean wavelength, and sum of amplifier signal power.



ID: EDFA
Comment: Amplifier TDE Test Application

Amplifier TDE Test, version A.01.00

Figure 46. A TDE gain and NF result graph.



ID: EDFA
Comment: Amplifier TDE Test Application

Wavelength (nm)	Source Power (dBm)	Gain (dB)	Noise Figure (dB)
1550.850	-6.480	13.769	5.070
1551.840	-8.450	13.856	5.033
1552.960	-6.240	13.957	5.099
1553.765	-9.760	14.080	5.040
Source Mean Wvl	Sum of Src Sig Pwr		
1552.199	-1.480		
Amplifier MeanWvl.	Sum of Amp Sig Pwr		
1552.225	12.420		

Amplifier TDE Test, version A.01.00

Figure 47. A TDE gain and NF result in tabular form.

Polarization Effects in Erbium-doped Fiber Amplifiers

The basic model of an EDFA useful for understanding polarization effects is shown in Figure 48. It includes passive linear components with PDL (polarization dependent loss) on the input and output. In general these are not correlated, meaning that they add as vectors and there is no attempt to align their phase. The non-linear gain element (EDF) links the two with a variable gain depending on input drive level. This non-linear characteristic of the EDF produces interesting results when the polarization of multiple sources is varied. For this analysis, it is assumed that the EDF itself has no PDL. This is usually a good approximation unless the fiber cross-section is significantly elliptical.

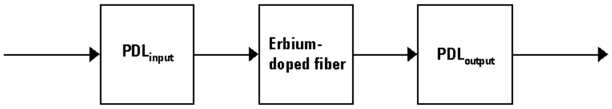


Figure 48. For analyzing polarization dependencies, an EDFA can be modeled as an input passive component, the active fiber, and an output passive component.

A generic polarization measurement setup is shown in Figure 49. The signal laser is used for measuring the large signal parameters of the amplifiers, while the probe laser is used to measure the small signal parameters. In order for the probe to measure the small signal parameters, its presence must have negligible effect on the inversion level of the amplifier. To achieve this requirement, the probe signal level at the output of the amplifier must be small compared to the total output power of the amplifier. If the signal laser is present, it is usually sufficient to set the probe power small compared to the signal power at the input of the EDFA.

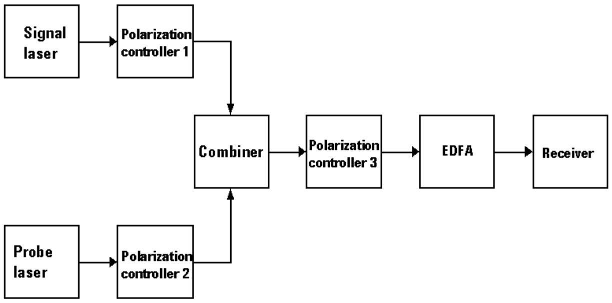


Figure 49. An equipment setup for isolating the various forms of polarization dependence.

Polarization Dependent Loss, PDL

For small signals propagating through the system (either in the presence of a saturating signal or not), the effect of changes in amplitude of the signal does not effect the unpolarized gain (or loss) of the system. In this case, the measurement of the small signal amplitude at the output of the system is equivalent to a PDL measurement of passive components. The purpose of the signal laser is to set the operating point (gain) of the amplifier. The resultant variation is determined by the vector combination of all of the PDL elements in the path. For the model shown in Figure 48 this becomes:

$$PDL = PDL_{in} \; (+) \; PDL_{out} \qquad (9)$$

where (+) indicates a vector sum of the two elements. PDL is measured by moving polarization controller #2 with #1 and #3 fixed. The saturating laser may be on or off for this measurement, however if the magnitude of the saturating laser is too large, the effects of PHB (discussed later) will also be present.

Polarization Dependent Gain, PDG (large signal)

This term is defined as the output amplitude variation of the saturating signal as a function of its SOP (state-of-polarization). PDG takes into account the high degree of non-linearity in the large signal gain of the EDFA. When the amplifier is in saturation, there is very little change in output amplitude as a function of input amplitude as observed at high input power levels in Figure 49. The derivative (slope of the log {signal output power} versus log {signal input power}) of this curve (dP_{out} / dP_{in}) is a function which is unity at low input power and approaches zero at high saturation levels. As a result, the effect of the input PDL is reduced.

The effect of gain saturation on the output amplitude variation adds a suppression factor to the PDL_{in} component:

$$PDG \text{ (large signal)} = (\{dP_{out} / dP_{in}\} * PDL_{in}) \; (+) \; PDL_{out} \qquad (10)$$

This measurement is made with no probe laser and by varying the polarization of the saturating laser with polarization controller #1.

Polarization Dependent Gain, PDG (small signal)

This term is defined as the variation in gain of a small signal of constant SOP in the amplifier versus SOP of the saturating laser. Under high levels of saturation, this term is dominated by the gain variation from the input PDL and the PHB (polarization hole burning) in the EDF.

$$PDG \text{ (small signal)} = (dP_{out}/dP_{in} - 1) * PDL_{in} \; (+) \; PHB \qquad (11)$$

This measurement is made by varying polarization controller #1 (#2 and #3 fixed).

Polarization Hole Burning, PHB

This term is a measure of the PHB effect in the fiber itself [13]. It can be isolated from other PDL effects by making two probe gain measurements, one with the polarization of the probe aligned with the saturating laser (g[s]) and one with the polarization of the probe orthogonal to the saturating laser (g[p]). In this case either polarization controller #1 or #2 can be used to align the saturating and probe laser states of polarization. Controller #3 would be used as a randomizer to converge the gain on the average (unpolarized) small signal gain.

$$\mathrm{PHB} = g[p] - g[s] \qquad (12)$$

Measuring PDG (large signal)

The ISS or TDE procedures can be used to measure large signal PDG by inserting a polarization controller such as the Agilent 11896A before the amplifier-under-test as shown in Figure 50. The 11896A can provide randomized states of polarization using the following procedure:

- Set to AUTOSCAN
- Set scan rate to the highest rate (8)
- Allow to scan for a few seconds
- Set to MANUAL for a randomized polarization state.
- Repeat this procedure to obtain another random polarization state.

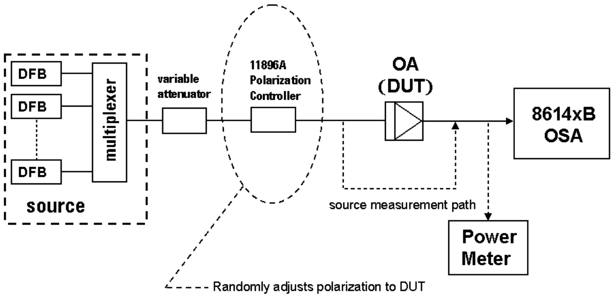


Figure 50. An equipment setup to randomize source polarization or to measure large signal PDG.

To measure PDG, make consecutive measurements of gain using the ISS or TDE routines with random polarization states obtained by the procedure above. Collect the maximum and minimum values of gain for each channel wavelength. The difference is the PDG.

This measurement was made for a four-channel source and the results are shown in Figure 51. The PDG varies from 0.10 dB peak-to-peak (channel 4) to 0.20 peak-to-peak (channel 1).

Averaging the polarization state

Often, it is required to average the polarization state of the source in order to obtain a repeatable average value of gain and noise figure. The test configuration of Figure 50 may also be used for this purpose with the 11896A set to AUTOSCAN. To obtain an average over multiple polarization states, use the trace averaging function in the ISS or TDE Measurement Setup window. Set trace averaging to 10 counts to obtain an average gain and noise figure over 10 polarization states.

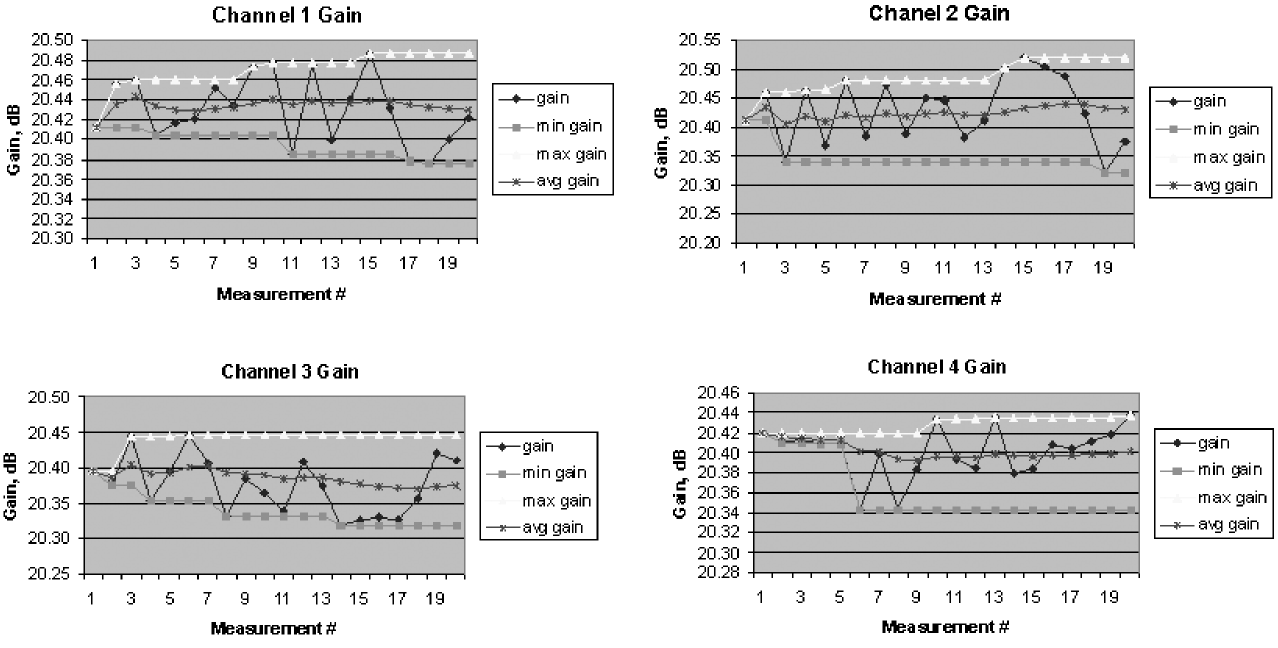


Figure 51. Four-channel PDG measurement results.

Appendix A: Determining the Number of Optical Sources to Prevent Error Due to Spectral Hole Burning

Setting the power level of a reduced set of lasers to replicate the effect of a larger set is based upon the homogeneous model [8]. As shown in Figure 52, the spectrum is divided into regions. The regions may be unequal in width and all the signals within each region are simulated by one larger signal in each region. However, when spectral hole burning (SHB) plays a role, the saturation wavelength is approximated as a weighted average of the ensemble of closely spaced channel powers.

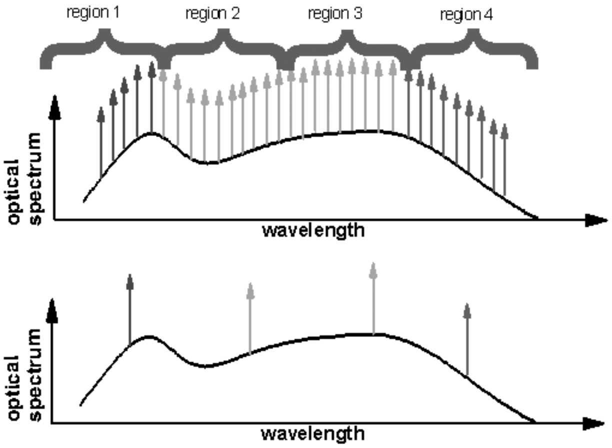


Figure 52. The number of saturating laser sources may be reduced by dividing the wavelength range into regions.

The reduction in the number of lasers is limited by spectral hole burning (SHB). As shown in Figure 53, SHB is a wavelength-localized depression in gain that is signal power dependent. SHB reduces the average ion population contributing to gain locally (in wavelength) in excess of the global reduction. For an amplifier that is to be used in a WDM environment, it is essential that the gain and noise figure that are measured include the SHB effect. If the spacing of the test lasers is too wide, the measured gain will be different than actually encountered in the WDM system. The gain depression has a width, called the spectral hole width, that is in the order if 3 to 8 nm. [9]. For good accuracy, the lasers must be positioned in wavelength so that their spacing is less than the spectral hole width.

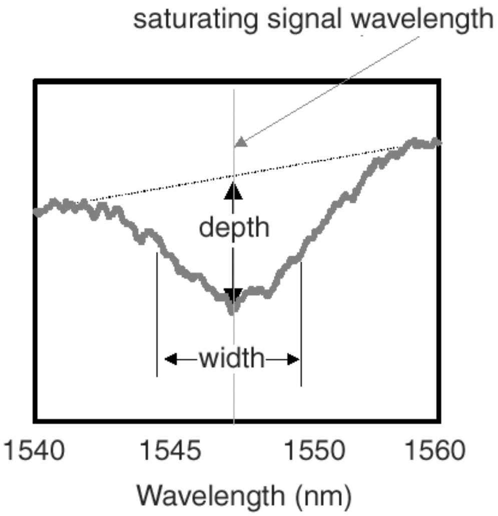


Figure 53. Spectral hole burning (SHB) is a localized depression in gain in the region of each saturating laser source.

A computer simulation that has been used to predict the error that will occur due to the effect of SHB suggest that 16 to 32 equally spaced lasers in the C-band are required to eliminate errors due to SHB [10]. Judicious wavelength placement (closer spacing in the 1535-nm region) could further reduce this number. For L-band designs, it has been reported that the localized gain depression caused by SHB is not a factor [11].

Both the measurement of spectral hole width and simulation studies suggest that wavelength spacing should be less than 200-GHz (approximately 1.6 nm) to eliminate gain error due to spectral hole burning. This spacing is necessary in the 1535-nm region where SHB is the strongest. Above this region, spacing may be wider. Experiments have also shown the number of saturating sources may be reduced by using nonuniform wavelength spacing. [12]

Appendix B: Calculation of ISS Error Due to Source Spontaneous Emission

The ISS method requires the subtraction of the amplified source spontaneous emission from the total noise measured on the OSA. This calculation is as follows:

$$P^{amp}_{ASE}(\lambda_S) = 10 \log \left[10^{\frac{P^{total}_{SE}(\lambda_S)}{10}} - G \text{ x } 10^{\frac{P_{SSE}(\lambda_S)}{10}} \right] \quad (13)$$

where P^{amp}_{ASE} is the ASE power generated in the amplifier, P^{total}_{SE} is the measured noise power, and P_{SSE} is the source spontaneous emission power.

Under certain conditions, the two terms within the brackets can be very close in value. A small measurement error in either term is magnified by the subtraction. The error is largest when measuring low values of noise figure at high input power levels.

The magnitude of this error may be calculated for specific values of measured noise figure, source spontaneous emission level, and the uncertainty on measuring the noise level. It is convenient in this analysis to reference noise values to the input of the amplifier to eliminate the gain term. The following are noise power levels referred to the input of the amplifier:

$$P^{amp}_{ASE} = \mathrm{NF}_{sig-sp} + 10 \, \mathbf{log} \, (h\nu B_o) \quad (14)$$

where NF_{sig-sp} is the signal spontaneous noise figure.

$$P^{amp}_{ASE} \, (linear) = 10^{P^{amp}_{ASE}/10} \quad (15)$$

In linear units: The total measured uncorrected noise in linear units is:

$$P^{total}_{SE} \, (linear) = 10^{P_{SE}/10} \quad (16)$$

The source spontaneous emission in linear units is:

$$P_{SSE} \, (linear) = 10^{P_{SE}/10} \quad (17)$$

For an uncertainty of α dB in measuring total noise and source spontaneous emission, the error in amplifier noise is calculated as follows:

$$+\,error = 10 \, \mathbf{log} \frac{10^{\alpha/10} P^{total}_{SE}(linear) - 10^{-\alpha/10} P_{SSE}(linear)}{P^{amp}_{ASE} \, (linear)} \text{ dB} \quad (18)$$

$$-\,error = 10 \, \mathbf{log} \frac{10^{\alpha/10} P^{total}_{SE}(linear) - 10^{-\alpha/10} P_{SSE}(linear)}{P^{amp}_{ASE} \, (linear)} \text{ dB} \quad (19)$$

Figure 19 is a plot of equations (18) and (19) for an a value of 0.05 dB.

Appendix C: Description of Quadratic Interpolation Algorithm

Straight-line or 2-point interpolation can result in large error in regions of high curvature on the gain curve as explained in Figure 18. A higher-order interpolation scheme is desired for a more accurate estimate. A good assumption is that the characteristic of ASE vs. wavelength is quadratic over small regions so a quadratic (or 4-point) interpolation method can be selected.

The geometry is depicted in Figure 54 in which the amplitude is assumed in log scale. The 2 points closest to the channel are distanced γ and η from the channel wavelength. The outer 2 points are at α and β from the channel wavelength. These variables are taken to be positive numbers. The corresponding quadratic curve is given by (20) where a, b, and C are constants.

$$y = ax2 + bx + C, \qquad (20)$$

The interpolation point C is given by

$$C = [\alpha\beta(\alpha+\beta)(\eta y_1 + \gamma y_2) - \gamma\eta(\gamma+\eta)(\beta y_3 + \alpha y_4)] / [(\alpha+\beta)(\gamma+\eta)(\alpha\beta-\gamma\eta)]. \qquad (21)$$

The interpolation offset may be set to Auto or Manual. If it is set to Auto, its value is:

$$\text{Interpolation Offset} = (0.5 * \text{RBW}) + 0.5 \text{ nm} \qquad (22)$$

where RBW is the resolution bandwidth in nanometers.

The parameters in (21), are set as follows:

$$\gamma = \eta = \text{interpolation offset}$$
$$\alpha = \beta = 1.5 * \text{interpolation offset}$$

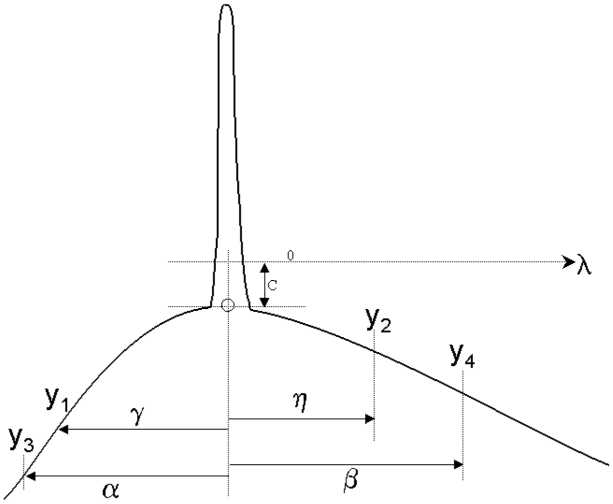


Figure 54. A quadratic interpolation algorithm is used to improve the accuracy over straight-line interpolation.

Appendix D: References

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Appendix E: List of Abbreviations

AOM	Acousto-optic modulator
ASE	Amplifier spontaneous emission
DRA	Distributed Raman amplifier
DWDM	Dense wavelength-division multiplexing
EDF	Erbium-doped fiber
EDFA	Erbium-doped fiber amplifier
EDFFA	Erbium-doped fluoride fiber amplifier
EDSFA	Erbium-doped silica fiber amplifier
EDTFA	Erbium-doped tellurite fiber amplifier
EDWA	Erbium-doped waveguide amplifier
EYDFA	Erbium ytterbium doped fiber amplifier
FRA	Fiber Raman amplifier
IEC	International electrotechnical commission
ISS	Interpolated source subtraction
MPI	Multiple path interference
OA	Optical amplifier
OFA	Optical fiber amplifier
OSA	Optical spectrum analyzer
OWGA	Optical waveguide amplifier
PDFA	Praseodymium-doped fiber amplifier
PDFFA	Praseodymium-doped fluoride fiber amplifier
PDG	Polarization dependent gain
PDL	Polarization dependent loss
PHB	Polarization hole burning
RBW	Resolution bandwidth
RIN	Relative intensity noise
SHB	Spectral hole burning
SNR	Signal-to-noise ratio (electrical)
SOA	Semiconductor optical amplifier
TDE	Time domain extinction
TDFA	Thulium-doped fiber amplifier
TDFFA	Thulium-doped fluoride fiber amplifier
WDM	Wavelength-division multiplexing

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