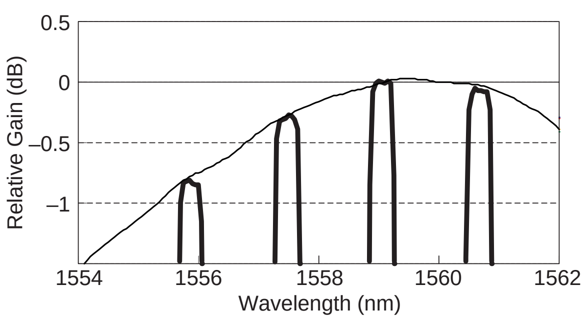
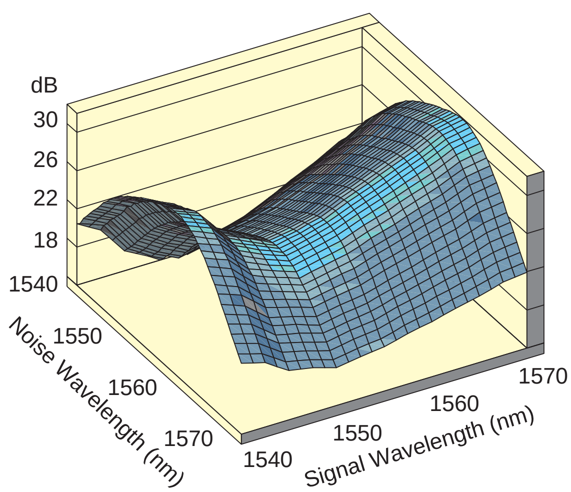
EDFA Noise Gain Profile and Noise Gain Peak Measurements

Product Note 71452-3



Agilent 71452B
Optical Spectrum Analyzer



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Introduction

This product note is part of a series of Optical Spectrum Analyzer documents. For an introduction to optical spectrum analysis and for basic information about characterizing optical amplifiers, see also:

[1] Optical Spectrum Analysis Basics, Agilent Application Note 1550-4 (Agilent literature number 5963-7145E)
[2] EDFA Testing with the Interpolation Technique, Agilent Product Note 71452-1 (Agilent literature number 5963-7146E)
[3] EDFA Testing with the Time Domain Extinction Technique Agilent Product Note 71452-2 (Agilent literature number 5963-7147E)
[4] D. Baney, J. Dupre, C. Hentschel: “Optical Fiber Amplifiers - Measurement of Gain and Noise Figure”, HP Lightwave Symposium 1993
[5] D. Baney: “Optical Power and Wavelength for Single Source Simulation of EDFA WDM Gain: Theoretical Basis”, Agilent Laboratories, Technical Report
[6] Pulsed or Time-Dependent Optical Spectra Measurements Agilent Product Note 71452-4 (Agilent literature number 5964-6416E)

The measurement methods described in this product note are based on the Time Domain Extinction (TDE) technique whose background is explained in [3] and [4]. Reference [5] discusses the physical background of the single saturating source.

Application Problems

In recent years, optical amplifiers have been commonly deployed in transcontinental, submarine and other state-of-the-art long distance connections. In addition, wavelength-division multiplexing (WDM) is at the horizon to boost the capacity of existing and future links. Both types of applications demand even more sophisticated optical amplifiers. This section discusses two typical cases where the application requires a comprehensive optimization of optical amplifiers.

Longhaul Applications

Typically undersea links consist of sections of singlemode fibers with Erbium doped fiber amplifiers (EDFAs) between them (Figure 1). Installing the amplifiers in series without any signal regeneration offers a substantial improvement on the overall performance but it also introduces new risks: assuming that each amplifier has characteristics similar to all other ones, then any amplifier imperfection is repeated and thus multiplied by the number of stages.

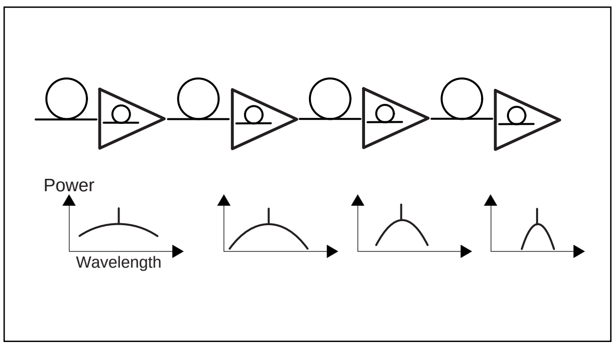

Figure 1. Typical longhaul system

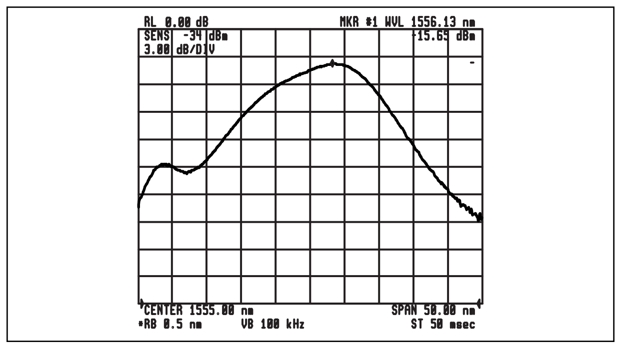

Figure 2. Noise gain of an EDFA

One aspect among many others is how noise builds up through the link. Each amplifier adds noise to the signal, which in turn, is further amplified. Noise is spread over a wavelength range while the signal appears at one wavelength only. How each amplifier amplifies noise strongly depends on wavelength, and there is a risk that some region of the noise is amplified more than the signal. Let us assume that the EDFA has GS gain at the signal wavelength λ_S, and it amplifies noise by $g_N(\lambda)$ (Figure 2). This function has a maximum at λ_N. If λ_N is different than λ_S, then it is possible that $g_N(\lambda_N)$ is greater than G_S. In other words, the noise at λ_N is amplified more than the signal at λ_S (Figure 3).

The difference may be very small. However, it multiplies by the number of cascaded amplifiers until it can have a significant impact on the signal-to-noise ratio (Figure 4). The technique described in this product note allows you to measure $g_N(\lambda)$, thereby optimizing your amplifiers for best performance in longhaul systems.

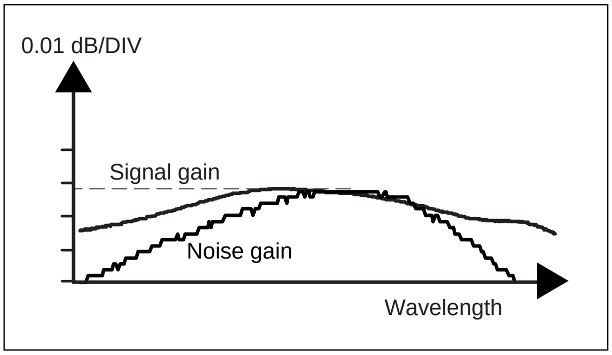

Figure 3. Gain difference of one amplifier

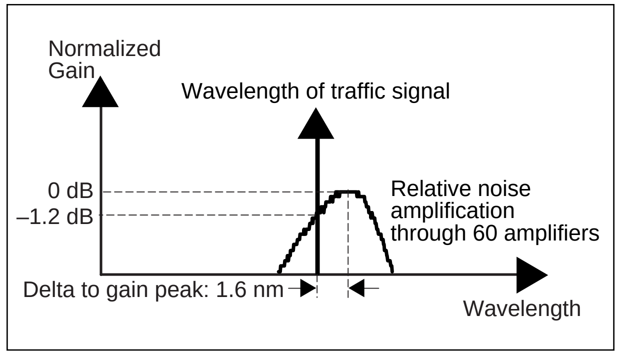

Figure 4. SNR degradation after N stages

WDM applications

Wavelength-division multiplexing (WDM) is a technique at the horizon in order to increase the capacity of existing and future fiberoptic links. It transmits several optical carriers (signals at different wave-lengths) at the same time while each one is modulated independently from all others. Optical amplifiers such as EDFAs are used here as well in order to optimize the distance between the transmitter and the receiver (Figure 5).

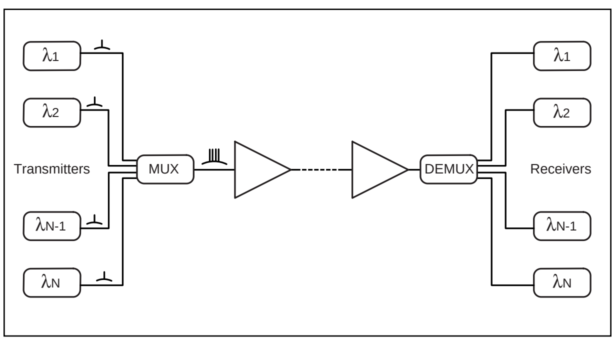

Figure 5. WDM with EDFA

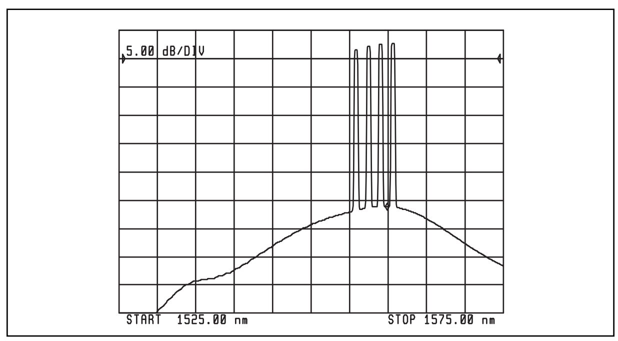

Figure 6. Output spectrum of the EDFA

Ideally the amplifier in such a system has to amplify all channels with equal gain. However, amplifiers have slightly different gains for different channels. Figure 6 shows the output spectrum of an EDFA when four equally strong input signals have been applied at the same time. The output power levels are different because the gain of the amplifier depends on the wavelength of the signals. In order to have the same signal-to-noise ratio (SNR) for all channels, pre-emphasis, filtering, gain flattening, or other techniques must be applied in the system. For all these techniques it is necessary to know the gain that the amplifier provides for each channel.

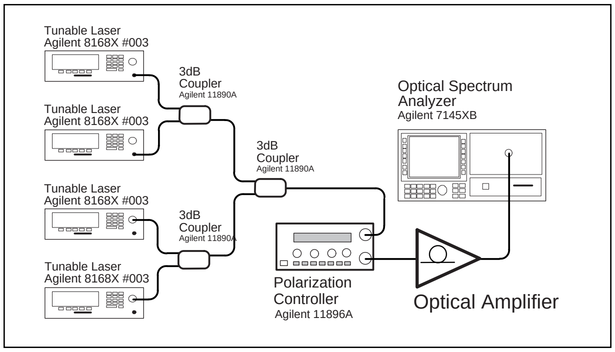

Figure 7. Most flexible WDM test setup

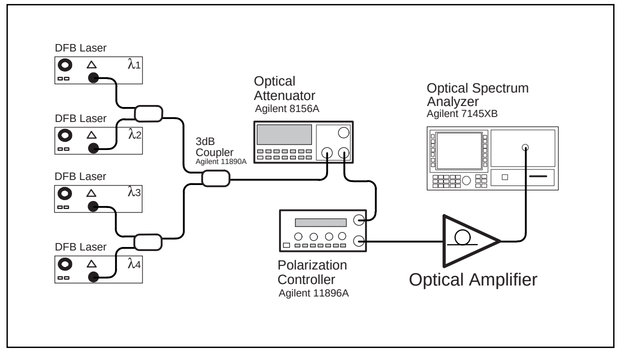

Figure 8. WDM test setup using Distributed Feedback Lasers (DFBs)

Characterizing an EDFA with many laser signals at the input allows you to measure channel gain very accurately. The most flexible test setup uses one tunable laser source (TLS) for each WDM channel (Figure 7). Less expensive is a setup using lasers with fixed wavelengths (Figure 8).

Fortunately, it is possible to calculate the gain for each channel from the noise gain functions $g_N(\lambda)$ which can be obtained by using a special LED and a tunable laser (Figure 9).

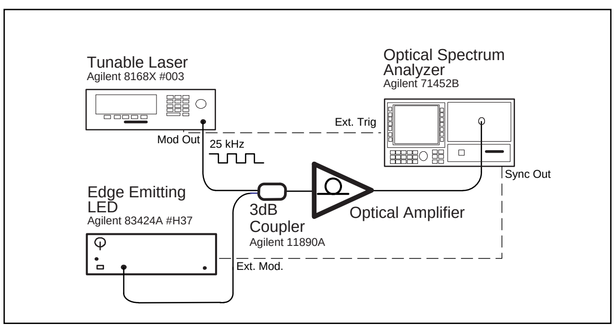

Figure 9. EELED test setup

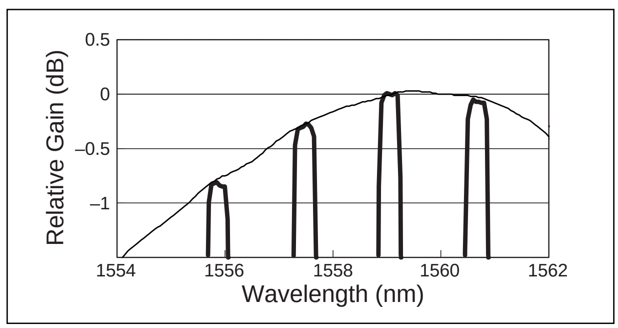

Figure 10. Channel gain versus noise gain

The noise gain is correlated with the channel gain. Figure 10 shows the combined results of both a four channel measurement (using Figure 7 setup), and a noise gain trace (using Figure 9 setup). All measurements have been normalized to the amplitude of channel #3 as shown in Figure 10.

Noise Gain Measurements

Explanation of terms

The expression *SIGNAL GAIN* means the gain provided by the optical amplifier to a large signal such as the traffic signal driving it into saturation. This signal mainly determines the operating point of the amplifier. In contrast, *NOISE GAIN* is the gain of a small signal while a large signal is driving the amplifier into saturation. The small signal should have little or no impact on the amplifier's operating point. The expression *PROFILE* stands for "as a function of wavelength." For instance, the noise gain can be a simple figure (expressed in dB) for one given wavelength, while the noise gain profile describes how the noise gain is dependent on wavelength. The maximum of this function is called the *NOISE GAIN PEAK*.

CHANNEL GAIN is the gain of one signal out of several in a WDM system. The channel gain usually is different for different wavelengths (channels). *GAIN TILT* describes the gain change versus wavelength, i.e., the derivative (dB/nm) of the gain profile. Another expression often used is *GAIN FLATNESS* which is basically the same as gain tilt. Gain flatness describes a desired property of the amplifier (i.e. a "flat", wavelength independent gain) while gain tilt describes the observed property.

Measurement setup and timing

The noise gain (as discussed above being a possible problem in longhaul systems) already gives a hint on how to measure it: the setup in Figure 9 uses a tunable laser source to drive the amplifier into saturation, and it uses an edge emitting LED (EELED) as a noise source which is the stimulus for the measurement. The advantage of using an EELED as a probe signal is its high power density and incoherence, so the amplified EELED spectrum simply adds to the incoherent amplified spontaneous emission (ASE) power. The power density must be high enough, so that its amplified spectrum at least exceeds the ASE level of the amplifier. However, it has to be small enough to avoid impacting the amplifier's operation point. This point is defined only by the signal from the tunable laser which drives the amplifier into saturation.

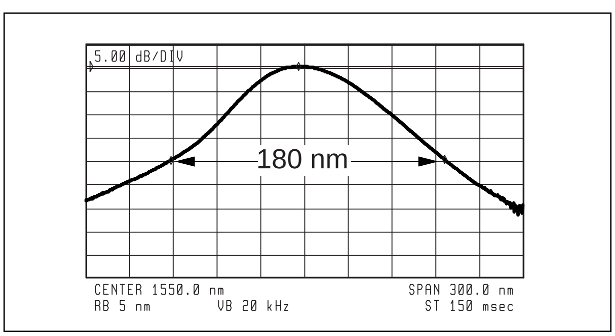

Figure 11. EELED spectrum

Requirements for the probe signal

- Wavelength range covered is larger than wavelength of interest
- Power density (µW / nm) depends little on wavelength
- Total power has neglegible impact on the saturation condition
- Amplified probe power is at least as high as the ASE power
- Light is incoherent and not very polarized

Figure 12. Noise source requirements

Before any measurement, the optical amplifier in Figure 9 is replaced by a through adapter. A built-in user program ("EDFA_NG") of the Agilent 7145XB helps to adjust the average TLS power, as it characterizes and stores the EELED spectrum for further normalization purposes. The EELED is very stable, so it must be characterized typically only once or twice per day. The built-in program also controls the EELED by sending a pulse to it from the "sync" output. In order to measure the amplifier's ASE spectrum, the EELED is not turned on at all. In this case the ASE is measured with the TDE method as described in [3]. However, for the noise gain measure-ment it is pulsed as shown in Figure 13. To minimize the impact on the operating point of an EDFA, only a short pulse is provided.

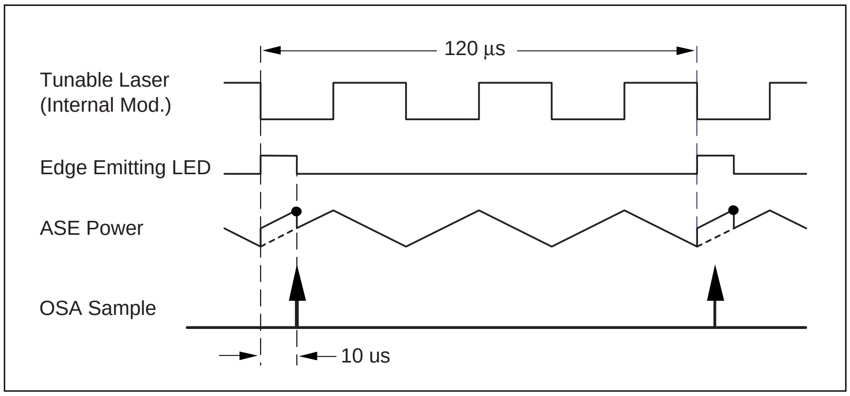

Figure 13. Timing diagram

The EELED turns on at the falling edge of the laser signal until the OSA has taken a data sample. In this mode, the trace on the OSA screen consists of the amplified EELED plus the amplifier ASE power (Trace B in Figure 14). As mentioned before, the ASE is measured (Trace A) when the OSA completely omits pulsing the EELED. These two traces plus the EELED spectrum are the raw data from which the noise gain is calculated.

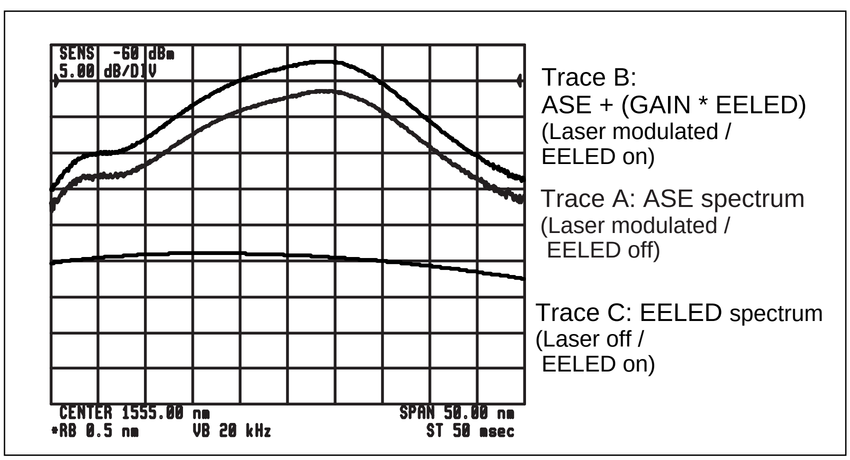

Figure 14. Raw data traces

The raw data traces consist of

Trace C = EELED
Trace B = ASE + (Gain x EELED)
Trace A = ASE

Therefore, the gain can be calculated as

$$\text{Gain} = \frac{\textit{Trace B} - \textit{Trace A}}{\textit{Trace C}}$$

Because of the time domain extinction, Traces A, B, C and the calculated gain consist of 800 points. They represent amplitude (or gain) at all wavelengths in the measurement range. Figure 15 shows the results as displayed by the built-in program of Agilent's 7145XB optical spectrum analyzers.

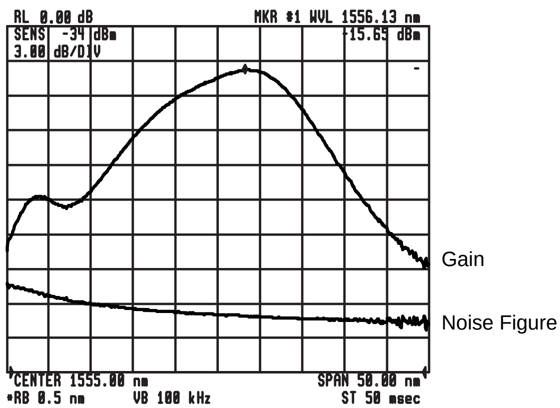

Figure 15. Noise gain profile

The program also calculates the noise figure of a small signal (such as the EELED signal) as a function of wavelength:

$$NF = \frac{N_{OUT}}{h\nu B_w G} + \frac{1}{G}$$

$N_{OUT} = N_{ASE}$:	ASE noise measured (Trace A in Figure 14)
h:	Plank's constant
ν:	Optical frequency
B_w:	Optical bandwidth
G:	Noise gain (upper trace in Figure 15)

The measurement of the raw data (Traces B and A) and the calculations take less than one minute. It is therefore an easy and convenient way in R&D and production to characterize the noise gain of an optical amplifier, and its speed allows quick characterization for a variety of saturation conditions.

A more general concern is how the noise gain profile depends also on the large saturating signal. Figure 15 shows the gain only for one wavelength setting of the TLS. If the measurement is repeated for a range of TLS wavelengths then the noise gain can be shown as a function of both the wavelength of the noise and the wavelength of the saturating TLS signal (Figure 16). The saddle plot was obtained by measuring 25 noise gain profiles. For each one, the TLS has been set to a different wavelength, and the resulting trace is transferred to a personal computer (see appendix). Finally, all traces are imported to a spreadsheet in order to plot the data.

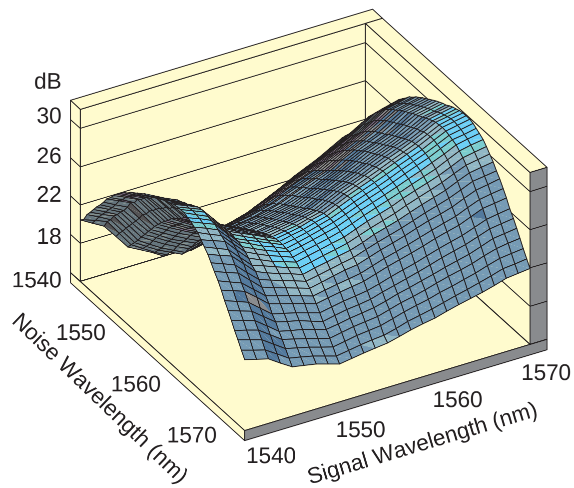

Figure 16. Noise gain as a function of noise wavelength and saturation wavelength

The noise gain profile depends on the input power level as well. Figure 17 shows a set of measurements where the laser wavelength is kept constant, but the power is modified. It can be seen that the gain shape and the wavelength of the maximum gain changes with input power. It is therefore essential to choose the right input wave-length and the right saturation power before conclusions can be made from the noise gain results.

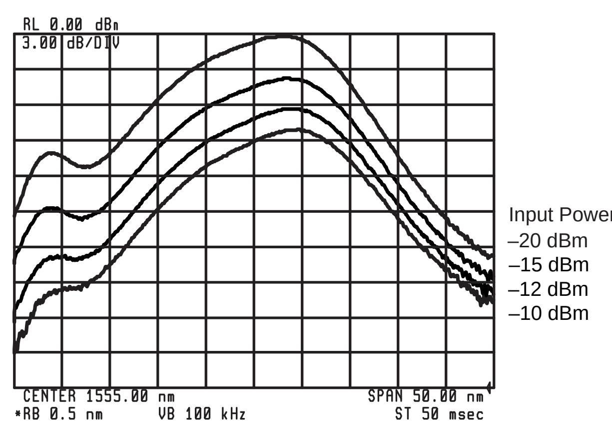

Figure 17. Noise gain as a function of input power

Determination of Measurement Accuracy

The gain and noise figure measurement uncertainties for a particular measurement can be calculated based on the measurement technique and the specifications of the equipment used. In this section, the significant uncertainty terms are described and values determined using the noise gain profile technique. This analysis assumes that the EDFA ASE relaxation time constant is 400 µs or greater, allowing the TDE technique to be used effectively. Two example uncertainties are made: one to determine the absolute uncertainty of the noise gain and the small signal noise figure (NF), and another to determine the accuracy of the shape of the gain and NF profiles. The shape uncertainty looks at the relative change only. It is valid for a small wavelength range (< 5 nm) and amplitude range (< 1 dB) only.

The examples are based on the use of the "EDFA_NG" program of an Agilent 71452B Optical Spectrum Analyzer (which has been calibrated, see [2]), and an Agilent 8168X Tunable Laser Source modulated internally with 25 kHz. The EELED Agilent 83424A #H37 provides –40 dBm/nm at the input of the amplifier. The amplifier under test is driven into a saturation, where it has a noise gain of 20 dB and a small signal noise Figure of 4 dB.

Measurements should be made after the tunable laser and the optical spectrum analyzer have been allowed to warm up for one hour and the auto-align routine has been run on the OSA.

Noise gain is calculated as the ratio of the output power (P_{OUT}) to the input power (P_{in}). For these examples:

$$G = \frac{P_{OUT}}{P_{IN}} = \frac{10\ \mu W/nm}{100\ nW/nm} = 100$$

An uncertainty of a given magnitude affecting the measurement of either P_{OUT} or P_{IN}, but not both, will result in a gain uncertainty of the same magnitude. For example, a 2% error in the measurement of only P_{OUT} will result in a 2% error in the calculated gain. As a result, the gain uncertainty can be determined directly from the individual uncertainties for the measurements of P_{OUT} and P_{IN}. Because this is a relative measurement, those uncertainties that affect both measurements equally will cancel out and have no effect on the gain uncertainty.

Small signal noise figure is calculated based on the amplifier gain (G), the amplified spontaneous emission produced by the amplifier (N_{ASE}), and the emission produced by the EELED (N_{EELED}). When the EELED is not pulsed, the value of N_{ASE} is equal to the amplifier's output noise level ($N_{OUT} = N_{ASE}$). Therefore,

$$NF = \frac{N_{out}}{h \times \upsilon \times B_w \times G} + \frac{1}{G} = A + C$$

For simplicity, the terms on the right hand side of the equation will be referred to as A and C in this analysis. The impact of an error in the measurement of G or N_{OUT} on the overall noise figure error depends on the relative magnitude of the term (A or C) that it affects and how that error mechanism affects the other measurements.

In the example using an EELED with a power density of –40 dBm/nm (after the coupler), the EELED noise in the optical analyzer's 1 nm resolution bandwidth is 100 nW. At 1550 nm, hv (Plank's constant multiplied by the laser frequency) is equal to 1.28 $*10^{-19}$ Ws, and B_W is equal to 124.8 GHz (for the resolution bandwidth RBW = 1 nm). With a noise Figure of 2.512 (4.0 dB), N_{ASE} is equal to 4.00 µW (= N_{OUT}). Solving the noise Figure equation for the measurement yields:

$$NF \frac{4.00\,\mu W}{1.28 \times 10^{-19}\, Ws \times 124.8\, GHz \times 100} + \frac{1}{100} = 2.502 + 0.01$$

In this case, the noise figure calculation is dominated by the A-term (2.502), which contains the measured values of N_{OUT} and G. An uncertainty of a given magnitude in the measurement of either N_{OUT} or G will result in a noise figure uncertainty of a similar magnitude. For example, a 2% error in the measurement of N_{OUT} will result in a (2.502/2.512) * 2% error in the calculated noise figure (assuming this error mechanism does not affect the other terms). In a case such as this with large gain, a simplified approximation of the measurement uncertainty could be made by assuming that all the errors are a result of the A-term, and that the C-term is insignificant.

Sources of Measurement Uncertainty

This analysis takes the conservative approach of treating all of the individual measurement uncertainties as systematic — that is, uniform probability distribution within the specified limits. An error contribution is determined for each of the uncertainty terms described below. The total uncertainties are then calculated using the following equation:

$$uncertainty = 2\sqrt{\sum \frac{U^2}{3}}$$

where "*U*" is the uncertainty of each individual term. All uncertainties are expressed as peak values. An uncertainty of ±0.04 dB will be written as 0.04 dB.

Connector uncertainty

When a fiber connection is made, either with a connector or splice, there is an amplitude uncertainty associated with it. Three connections contribute to the gain uncertainty. They are the coupler-to-OSA connection during the source measurement (P_{EELED}), the coupler-to-EDFA, and EDFA-to-optical spectrum analyzer connections during the noise profile measurement (P_{OUT}).

In order to determine the connector uncertainty in the noise figure measurement, the noise figure equation can be rewritten expanding the definition of gain:

$$NF = \frac{N_{out} \times N_{EELED}}{P_{out} \times h \times \upsilon \times B_w} + \frac{1}{G}$$

The ratio N_{OUT}/P_{OUT} in the A-term will not be affected by connector uncertainties because the two terms are measured with the same connections. As a result, the A-term has the connector uncertainties associated with the absolute measurement of the input signal only. The input measurement contains two connector uncertainties: the source-to-OSA connection during the calibration, and the source-to-EDFA connection during the amplifier test. Because the noise figure is much greater than $1/G$, the A-term is much greater than the C-term and the noise figure uncertainty can be approximated using two connector uncertainties.

With Connectors: If good quality physical-contact, fiber-optic connectors are used and maintained to have 35 dB minimum return loss and 0.25 dB maximum mismatch uncertainty, the contribution to the gain uncertainty is 3 x 0.25 dB, and the contribution to the noise figure uncertainty is 2 x 0.25 dB.

With Fusion Splices: Assuming a maximum mismatch uncertainty of 0.05 dB per connection, the contribution to the gain uncertainty is 3 x 0.05 dB, and the contribution to the noise figure uncertainty is 2 x 0.05 dB.

The connector or splice uncertainty is zero for the shape analysis because there is no connector change during a trace.

Source stability

Gain is calculated as the difference between two power measurements. Any change in the source power level between these measurements will directly affect the measurement accuracy. The 15 minutes stability specification for the Agilent 83424A #H37 Edge Emitting LED is 0.02 dB, and this will be used for the gain measurement uncertainty.

During a sweep the power change of both the EELED and the ASE is very small. This contribution is negligible for the shape uncertainty.

OSA absolute amplitude accuracy

The measurement of the input and output noise levels are absolute amplitude measurements. The gain calculation is based on a relative measurement, and this term is not a factor in the gain uncertainty.

The absolute amplitude accuracy (see [2]) contains two error terms: the power meter transfer accuracy (0.1 dB) and the uncertainty of the OSA connection made during the calibration. The connection uncertainty has already been taken into account and does not need to be included again.

The power meter transfer accuracy affects the A-term. For the single wavelength and swept wavelength examples, this term is 0.1 dB * A/NF = 0.1 dB * (2.502/2.512) = 0.10 dB.

The shape is a relative term. Therefore, the absolute accuracy does not contribute to the uncertainty.

OSA digital resolution

The signal processing inside the OSA finally calculates the amplitude in dBm. The result is reported with two digits after the decimal point. This 0.01 dB resolution has an impact only on the shape uncertainty.

OSA polarization sensitivity

The optical power from the EELED is less than 40% polarized. The amplified spontaneous emission produced by the EDFA is not significantly polarized. The Agilent 71452B Optical Spectrum Analyzer provides a polarization sensitivity of 0.05 dB from 1542 nm to 1562 nm. Because the gain calculation involves two measurements of polarized signals, the gain uncertainty term is 2 * (0.05 dB * 40%) = 2 * 0.02 dB in worst case. This is also the contribution of the gain uncertainty to the noise figure measurement.

OSA scale fidelity

Scale fidelity reflects the accuracy with which the optical spectrum analyzer can be used to make relative amplitude measurements. The gain calculation is based on a relative measurement, and the absolute noise-level measurements can be considered as relative measurements with the calibration source. The optical spectrum analyzer's scale fidelity specification is 0.05 dB because the built-in noise gain profile locks the amplitude range to one transimpedance only. The contribution to the gain uncertainty and to the noise figure uncertainty is 0.05 dB.

Because the shape uncertainty analysis has been limited to a small range, the estimated nonlinearity is only a tenth of the (large signal) specification of the OSA.

OSA resolution bandwidth accuracy

The measured spontaneous emission levels are a function of the optical spectrum analyzer's resolution bandwidth. This bandwidth is taken into account in the calculation of noise figure and, as a result, the accuracy with which the resolution bandwidth is known affects the noise figure accuracy. The actual bandwidth of the 0.5 nm resolution bandwidth filter is known to within 3%, which corresponds to a 0.13 dB uncertainty in the noise measurements.

The resolution bandwidth uncertainty is constant for all trace points and does not contribute to the shape error.

OSA internal etalons

Internal etalons in the optical spectrum analyzer can cause an amplitude uncertainty when measuring narrow linewidth laser sources. At the time when data samples are taken, the TLS modulation is in its "off" state. The measurement of a broadband signal, such as the amplified spontaneous emission or the light from the EELED, is not affected by this mechanism. Therefore this source for measurement errors can be ignored.

Source modulation stability

The 100% on-off modulation of the EELED may cause small power changes which are further reduced by video averaging. The contribution for both the gain to the noise figure uncertainty is less than 0.02 dB.

OSA trigger delay

The OSA trigger delay is 10 µs with 1 µs resolution, and the ASE relaxation constant is 400 µs or greater. In the worst case, digitizing results in a one-half count error. Therefore, the relative error in measuring the triangle waveform is:

$$\frac{1 + (10\ \mu s + 0.5\ \mu s)/400\ \mu s}{1 + (10\ \mu s - 0.5\ \mu s)/400\ \mu s} = 1.002442 \text{ or } 0.0106 \text{ dB}$$

OSA pulse recovery

The photodetector in the OSA receives the complete modulated signal, whose pulse amplitude is 3 dB higher than the average output power of the amplifier. With the falling edge of the square wave, the electronics have to recover within microseconds from this high power level and settle precisely to the ASE power which may be one thousand times weaker than the pulse. The measurement error due to recovery tails at ten microseconds after a 30 dB power drop is less than ±0.2 dB.

Calculation of Total Measurement Uncertainties

The following table summarizes the error terms calculated for the example measurements in the previous section and shows the total measurement uncertainties.

Table 1. Noise Gain Profile Measurement Uncertainties

	Absolute Measurement		Shape (relative change)	
	Gain	NF	Gain	NF
Splice Uncertainty	3 x 0.05 (splice) 3 x 0.25 (conn.)	2 x 0.05 (splice) 2 x 0.25 (conn.)	0.000	0.000
Source Stability	0.020	0.020	0.000	0.000
Modulation Stability	2 x 0.010	2 x 0.010	0.000	0.000
OSA Trigger Delay	n/a	0.011	n/a	0.000
OSA Pulse Recovery	n/a	0.200	n/a	0.020
OSA Absolute Accuracy	n/a	0.100	n/a	0.000
OSA Digital Resolution	2 x 0.01	2 x 0.01	2 x 0.01	2 x 0.01
OSA Polarization Sensitivity	2 x 0.02	2 x 0.02	2 x 0.02	2 x 0.02
OSA Scale Fidelity	0.050	0.05 (Gain) 0.05 (N_{OUT})	0.005	0.005 (Gain) 0.005 (N_{OUT})
OSA RBW Accuracy	n/a	0.128	n/a	0.000
Total Uncertainty **With Splices** **With Connectors**	 ±0.12 dB ±0.51 dB	 ±0.32 dB ±0.51 dB	 ±0.037 dB ±0.037 dB	 ±0.044 dB ±0.044 dB

Performing Measurements

Agilent offers an OSA program (which is standard in the Agilent 71452B and optional for the Agilent 71450B/71451B) to automate most of the noise gain measurement. It supports both the recommended Agilent setup (by using the AUTO mode, see below) and a setup which uses a noise source other than Agilent's (MANUAL mode).

This section discusses in detail how to perform the measurements using Agilent's EELED. Consult the manual "EDFA Noise Gain Profile Personality" (Agilent literature number 70952-90006) when using other noise sources.

To describe keystrokes of the OSA, it uses this style for Front-panel keys and this one for Softkeys . For other instruments, the style TLS Key is used.

1. Set up the Instruments
   Connect the output of the TLS to one input of the 3 dB coupler and the EELED to the other input. Connect the output with the OSA using patchcords and a through adapter (i.e., replace the amplifier by a feedthrough). Select the desired WAVELENGTH at the TLS[1], select –10 dBm OUTPUT POWER (for the OSA auto alignment) with modulation turned off (OUTPUT POWER , MOD/CW), and activate the TLS output.

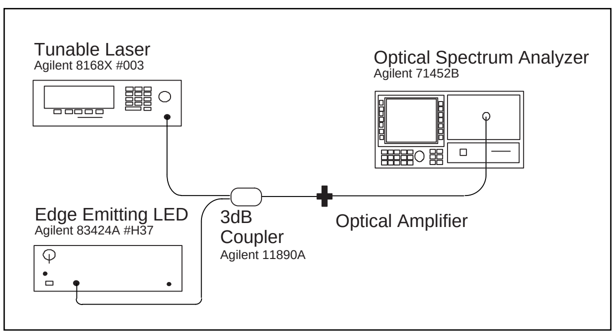

Figure 18. Instrument setup

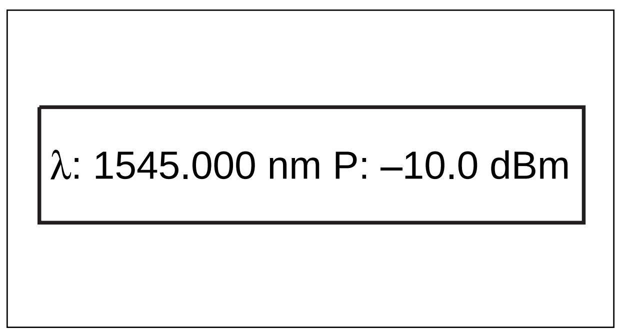

Figure 19. TLS screen

Set up the OSA by hitting INSTR PRESET , AUTO ALIGN , and AUTO MEAS . If desired, adjust the wavelength range (START , STOP). Automatic alignment is essential for accurate results, and it should be run every day (or if the OSA has been moved or exposed to vibration or mechanical shock).

Agilent also suggests calibrating the OSA with a power meter traceable to a national standard. See the OSA manuals or [2] for details.

[1] The TLS shows the wavelength in vacuum. Around 1550 nm, the OSA displays typically 0.5 nm less because it measures the wavelength in air.

2. Set up the Saturation Condition
Connect the modulation output of the TLS with the trigger input of the OSA, and connect the sync output of the OSA with the modulation input[2] of the EELED (the electrical ports of the OSA and the EELED are located at the back).

Activate the internal modulation of the TLS at 25 kHz (OUTPUT POWER , MOD/CW , Freq), then enter a TLS OUTPUT POWER which is about 7 dB higher than the desired average input power at the amplifier (the modulation has 50% duty cycle which causes the average power to be only one-half of the displayed CW power, and the coupler including the connectors typically has 4 dB loss).

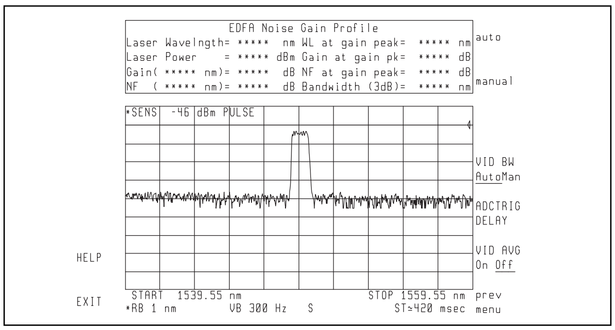

Figure 20. OSA screen

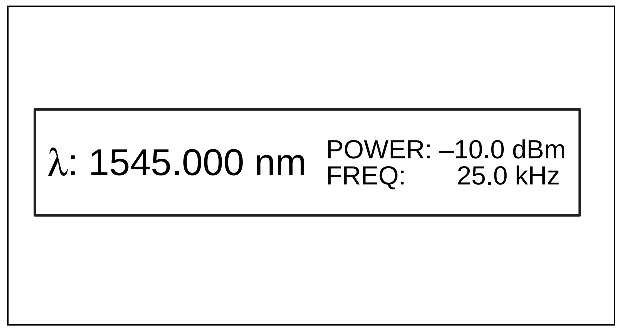

Figure 21. TLS screen

Start the OSA program for noise gain measurements by pressing USER , EDFA_NG , then setup , auto , ADJUST LASER . During this mode, the OSA seeks the wavelength of the laser signal which still can be changed (if necessary). Pressing ZOOM saves the measured wavelength, and it zooms into a small window around that wavelength. Now change the output power of the TLS until the OSA measures the desired power for saturation. Hit DONE when ready.

3. Characterize the EELED
The EELED is controlled by the OSA which itself gets its sync pulses from the TLS. When pressing MEASURE EELED , the OSA sends pulses to the EELED during the break of the TLS pulse, and it samples the EELED power as a function of wavelength. This process runs for several seconds automatically.

The EELED spectrum is very stable, which allows you to skip this step if the measurement has to be repeated (for example, for different saturation conditions).

[2] The Agilent 83424A #H37 EELED is constantly on if nothing is connected to the modulation input. When connected to the OSA sync output, then it is on only when the OSA sends a TTL pulse (e.g., in the ADC trigger mode).

4. Characterize the Amplifier
   Disable the TLS output and insert the optical amplifier as shown in Figure 9. For best accuracy, do not disconnect patchcords from either the TLS, EELED, OSA, or the coupler, and minimize any fiber movement.

   Activate the TLS again and press MEASURE EDFA . As soon as the OSA has taken a trace, it calculates all values and updates the result table above the grid.

5. The regular MARKER function can be used to measure the noise gain and the small signal noise figure anywhere on the trace. Furthermore, the vertical scale can be changed with MENU, Amptd , dB/DIV , and with REF LVL (reference level) or MKR TO REF (marker to reference level). Press USER to return to the built-in EDFA test program.

6. For further processing of the data, capture the screen traces (see appendix) into a text file. Then import it into a spreadsheet or math program and apply the desired operations.

7. To repeat the measurement for the same amplifier at a different input power or wavelength (or for a different amplifier), start again at point 2. To leave the program, press EXIT .

Appendix

WDM Saturation Spreadsheet

For a good correlation between the noise gain profile and actual channel gains, it is essential that the optical amplifier is driven into a very similar saturation condition.

The saturation condition during the noise gain profile is (almost) the same to the one in the WDM application if the amount of stimulated emissions amplifying the input spectrum is the same:

$$P_{OUT(WDM)} = \sum P_{OUT(i)} = P_{OUT(NG)} \qquad \text{(Equation 1)}$$

$P_{OUT(WDM)}$: Total power of all WDM channels at the output of the EDFA

$P_{OUT(i)}$: Output power of WDM channel i

$P_{OUT(NG)}$: Output power during the noise gain measurement

In an EDFA test procedure, typically only the power levels P_i at the input of the EDFA are given. Therefore, we have to express equation 1 as:

$$\sum P_i \times G_i = P_s \times G_s \qquad \text{(Equation 2)}$$

P_i: Input power of channel i

G_i: Gain provided for channel i

P_s: Saturating input power during the noise gain profile measurement

G_s: Noise gain measured at the saturating wavelength

The noise gain setup in Figure 18 allows you to adjust the saturating power P_s (and its wavelength). However, neither G_i nor G_s are known. Therefore, we have to use an approximation strategy. For the first iteration, the saturating power P_s is simply the sum of all WDM input powers, and we use the weighted average wavelength:

$$P_{s1} = \sum P_i \qquad \text{(Equation 3)}$$

$$\lambda s = \frac{\sum P_i \times \lambda_i}{\sum P_i} \qquad \text{(Equation 4)}$$

With these values at the EDFA input, we measure the amplifier's noise gain profile and determine the small signal gains at all wavelengths λ_i and at λ_s. Then we can calculate the left and the right side of equation 2. If the results are not equal, then the saturating condition caused by P_s is not equal to the one in the WDM environment. To correct this, we have to adjust P_s accordingly:

$$P_{s2} = \frac{1}{G_{s1}} \times \sum P_i \times G_{i1} \qquad \text{(Equation 5)}$$

P_{s2}: Saturating input power for iteration 2
G_{s1}: Noise gain at λ_s measured in iteration 1
G_{i1}: Noise gain at λ_i measured in iteration 1

We now repeat the noise gain profile measurement with P_{s2}, and we calculate equation 2 again. Typically this time both sides of the equations result in close values. For an even better convergence, we can repeat the iteration a third or even a fourth time.

The spreadsheet below is an example of a WDM application using four channels. It can be easily adapted to other numbers of channels by inserting more columns.

	A	B	C	D	E	F	G	H
1	WDM Application Data							
2		Channel	#	1	2	3	4	
3		Wavelenth	nm	1555.0	1557.0	1559.0	1561.0	
4		Input Power	dBm	-20.00	-20.00	-20.00	-20.00	
5			mW	0.0100	0.0100	0.0100	0.0100	0.0400
6				15.55	15.57	15.59	15.61	1558
7								
8	Wavelength for saturation:			1558.0				
9	Power to start with:			-13.98				
10								
11	Channel			1	2	3	4	Sat. Src.
12		Sat. Pwr.		Measured Gain (dB)				
13	Iteration #1	-13.98	dBm	20.92	22.08	22.83	22.35	22.42
14				1.236	1.614	1.919	1.718	8.12
15	Iteration #2	-14.30		21.07	22.31	22.94	22.49	22.56
16				1.279	1.702	1.968	1.774	8.28
17	Iteration #3	-14.28						
18								
19	Iteration #4							
20								
21								

Figure 22. Spreadsheet to calculate the saturating input power

Spreadsheet instructions:

1. Start your favorite spreadsheet program and enter the text as shown above (cells A1, B2..B4, C2..C5, D2..G2, A8..A9, A11..H12, A13, A15, A17, A19 and C13). Draw lines if desired.

2. Enter the wavelength (nm) of the WDM channels in cells D3..G3, and their power levels (dBm) in cells D4..G4. To convert these values to linear, enter the formula “10^(D4/10)” in cell D5, then copy this cell to E5..G5. The formula “@SUM(D5..G5)” in H5 computes the total power.

3. Enter the formula “+D3*D5” in cell D6, then copy this cell to E6..G6. Compute the weighted wavelength in cell H6 by the formula “@SUM(D6..G6)/H5”, and show the result with “+H6” in cell D8.

4. Cell D9 displays the total power using the formula “10*@LOG(H5)”, which is the starting point for the iteration. Therefore, cell B13 contains “+D9”.

5. Now make a noise gain profile measurement with the wavelength shown in cell D8 and the power shown in cell B13. Then use a marker on the OSA screen to read the gain at the wavelength shown in cells D3..G3 and in D8. Enter these values into the cells D13..G13 and into H13.

   DO NOT disconnect a fiber or change the setup. This can cause a poor convergence of the iterations due to connector repeatability issues. The EELED from Agilent is stable enough to make a couple of iterations.

6. The next line now calculates the output power of each channel if the input signals shown in row 5 experience the gains just measured. Enter the formula “+D$5*10^(D13/10)” into cell D14, then copy this cell to E14..G14. Enter the formula “10*@LOG(@SUM(D14..G14))” into cell H14 in order to calculate the total output power (expressed in dBm). The formula “+H14-H13” in cell B15 divides the total power by the gain (expressed in dB) seen at the saturating wavelength.

7. Make another noise gain profile measurement with the power shown in cell B15. Again, use an OSA marker to read the gain at the wavelength shown in cells D3..G3 and in D8. Enter these values into the cells D15..G15 and into H15. Copy the formulas in cells D14..H14 to cells D16..H16, and copy the formula in cell B15 to B17.

8. If the difference between cell B15 and B17 is still significant, then repeat the previous step until it converges. Copy the formulas during that step appropriately.

Transferring Trace Data to a PC

Agilent provides a program called OSACapture[3] that obtains trace data or screen graphics from any Agilent 7145XX Optical Spectrum Analyzer. The trace data is stored in an ASCII table along with additional information to identify the measurement. It can be imported easily into all major spreadsheets and other programs. Furthermore, a graphics copy of the OSA screen can be saved into a variety of graphics file formats for use in reports and other documentation. OSACapture requires a PC running DOS 5.0 (or higher), and an IEEE 488 interface card (such as the Agilent 82335B/I or the National AT-GPIB/TNT).

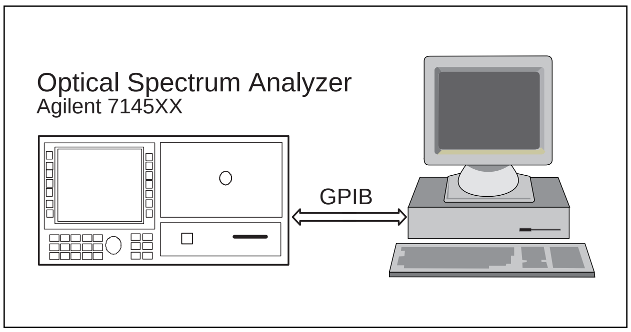

Figure 23. OSA Capture setup

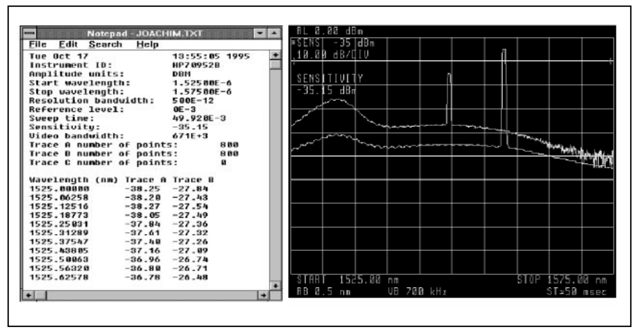

Figure 24. OSA Capture examples

If you prefer to write your own application program (for example, to automate an entire series of measurements), then the following Agilent BASIC extract may be useful. It shows two different methods to read trace data from the OSA into a computer. For details, consult with the Agilent 7145X programmer's guide and your computer language manuals.

```
...
70   DIM A$[6000]        ! a looooong string
80   REAL B(1:800)       ! default trace has 800 points
90   Osa=723             ! IEEE 488 bus address
...
180  ! define response format
190  OUTPUT Osa;"AUNITS DBM;TDF P;"  ! unit = dBm, ASCII data
...
210  ! read trace A into an ASCII string
220  OUTPUT Osa;"TRA?"
230  ENTER Osa;A$
240  PRINT A$
...
260  ! read trace B into an array of numbers (type REAL)
270  OUTPUT Osa;"TRB?"
280  ENTER Osa;B(*)
290  PRINT B(*)
...
```

[3] Available at no charge. Call the AUTOFAX number (707) 577-3770, request document 450 and enter your fax number (outside the USA and Canada, add the country codes to the phone numbers).

“AUNITS DBM;” selects the physical unit dBm. “TDF P;” sets the output format to ASCII numbers, and “TRA?;” returns Trace A as a series of N values separated by commas. Use “TRB?;” or “TRC?;” for Trace B or C, respectively. The default for N (trace length) is 800. The wavelength of the data point i (i=1,2, 3, .. N) can be calculated as START + SPAN * (i-1)/N. See also “STARTWL?;”, “STOPWL?;”, “SP?;”, “TRDSP TRA,?;” and “TRDEF TRA,?;” in the Programmer’s Guide manual of the Agilent 7145X family of optical spectrum analyzers.

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