Complete Analysis of Erbium-Doped Fiber Amplifiers

Technical Paper

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Abstract

Optical amplifiers make the communication system transparent from the beginning to the end, in contrast to conventional repeater-type systems. This poses new challenges for the performance of all system components, including the optical amplifier. As a consequence, optical amplifiers need to be most thoroughly tested before their deployment.

This paper discusses methods and instruments for measuring EDFAs with respect to gain and noise figure, both in static and dynamic form, polarization dependence, polarization mode dispersion, wavelength division multiplex (WDM) characteristics and more. The influence of the source's spectral width on the amplifier's performance is also discussed.

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Contents

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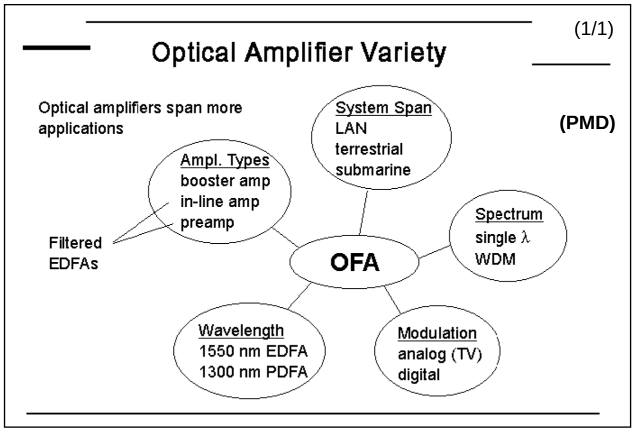
1. Introduction

It is interesting to see that optical fiber amplifiers (OFAs) are penetrating all lightwave communication markets and applications. As a consequence, many different types of OFAs are being developed and built today.

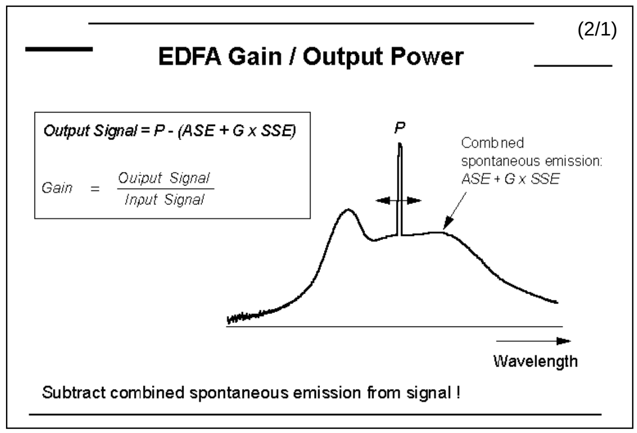


For example, a booster amplifier in a video distribution system, designed to drive the many fibers in parallel over a relatively short distance, differs substantially from an in-line amplifier in a submarine system, although their principle of operation is the same. Some of the tests for these amplifiers are common and well established today, e.g. gain, output power and noise figure. Other tests are more specific, for example measuring the wavelength-division-multiplex (WDM) characteristics or measuring the dynamic gain.
Needless to say, one test will not meet the system requirements for all these different amplifiers.
This paper discusses EDFA measurement techniques; both well established and more advanced techniques.

2. Gain Measurement

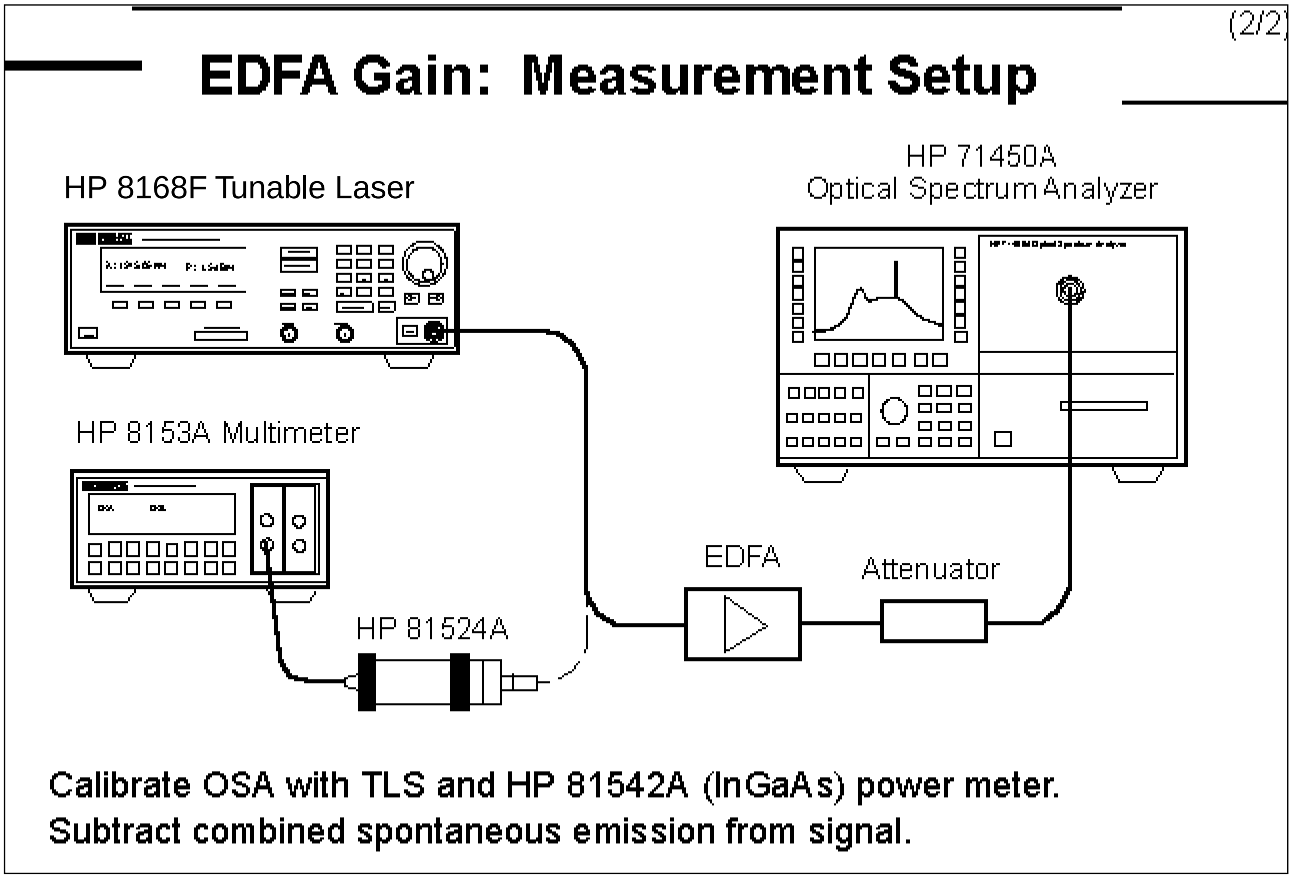
EDFA gain and signal output power are usually measured as a function of wavelength and input signal. Consequently, the tunable laser is the most important test equipment in optical amplifier (EDFA) testing, in particular because these amplifiers are the key elements in WDM systems.

The optical input power controls the EDFA saturation state and gain. Gains of 50 dB are achieved with modern amplifiers. In deep saturation (at high input power), this gain will drop to 10 dB or less.



At low input power, the total output power is mostly amplified spontaneous emission (ASE). The amplified signal is small. Therefore, an optical spectrum analyzer (OSA) must be used to extract the signal. Even then, the measured signal may contain some power from the ASE and the amplified source spontaneous emission (amplified SSE). Therefore, measuring and subtracting both noise powers is advisable.

Furthermore, optical spectrum analyzers are not designed to measure absolute optical power accurately. Therefore it is also recommended that the OSA is calibrated using a tunable laser and an accurate power meter such as the InGaAs large-area HP 81524A optical head.



A frequent requirement in testing optical amplifiers is high input power, for example 0 dBm. Such power levels are necessary to obtain large signal-to-noise ratios required in analog systems. The new HP 8168F tunable laser generates +8 dBm signal power when no attenuator is included, or +7 dBm with an attenuator.

2.1 Polarization dependent gain (PDG)

The polarization state of optical signals traveling on a long fiber is subject to continuous and sudden environmental changes. It is therefore statistical in nature. When the link consists of a number of concatenated amplifiers, then these statistics may lead to changes in received power level and even system failure. This is due to the fact that it is difficult to build optical amplifiers with PDGs of less than 0.1 dB. In any case, testing the polarization dependence of optical amplifiers is gaining importance. Two methods, polarization scanning and the Mueller / Stokes method are commonly used, see figure 2/3:

(2/3)

Polarization Dependent Gain

2 Methods:

- **Polarization Scanning:**
  Apply all polarization states, determine min / max.
  Difficulties: polarization dependence of test equipment.
- **Mueller / Stokes Method:**
  Apply defined polarization states.
  Calculate polarization dependence.
  Difficulties: needs a calibration step;
  more complicated calculation;
  wavelength dependence of plates.
  Advantage: faster, potentially better accuracy.

  used in EDFA test system

A power meter with low polarization dependence is needed in both cases !

The HP 81600 EDFA test system makes use of the Mueller method because the test system already includes a waveplate-type polarization controller. Its polarization dependent insertion loss, specified as ±0.03 dB can be cancelled out with this method. The method is described in [1].

Typical causes of PDG in optical amplifiers are:

a) the input and output isolators, producing polarization dependent loss (PDL);

b) polarization holeburning (PHB) in the active fiber; PHB reduces the gain ***and*** the ASE in the signal's state of polarization [2]. This effect depends on the degree of saturation and on the relative orientation of the signal and the pump; typical PDGs caused by PHB are on the order of 0.1 - 0.2 dBp-p. PHB is detrimental in lightwave communication systems because it tends to build up ASE in the state of polarization which is orthogonal to the signal.

The ”passive“ PDL of the isolators can be measured with either of the two methods mentioned above. The ”active“ PDG can be measured by adding a small probe signal to the saturating signal and changing the probe's orientation with respect to the orientation of the saturating signal. Measuring the amplified probe signal is possible either by modulating the probe signal and using frequency selective detection, or by adding a small wavelength offset to the probe to make it accessible to an optical spectrum analyzer.

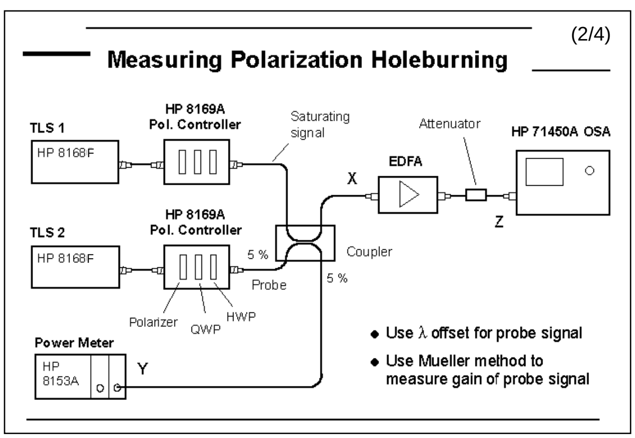


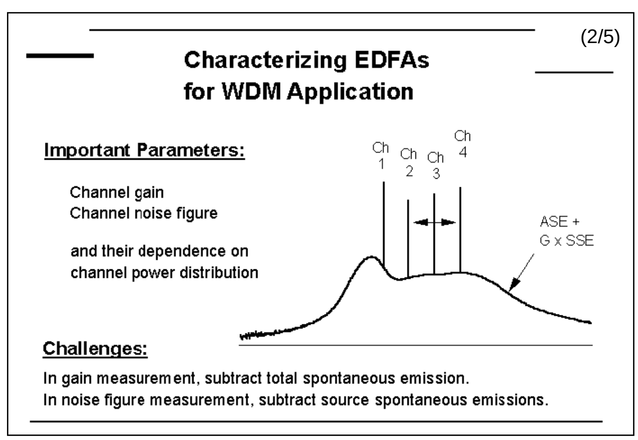
Figure 2/4 shows a measurement setup for polarization holeburning using two tunable laser sources, two polarization controllers to set the polarization states of both the saturating signal and the probe, and an optical spectrum analyzer. The best way of using this setup is analyzing the polarization dependent probe gain with the Mueller method mentioned previously.

Notice that, in addition to polarization holeburning, the probe signal experiences the same polarization dependent loss (PDL) as the saturating signal. Therefore measuring the PDL at low input power levels, e.g. at -30 dBm, and determining the gain variation from polarization holeburing is recommended, e.g. as a function of input power level, from the difference to the PDL.

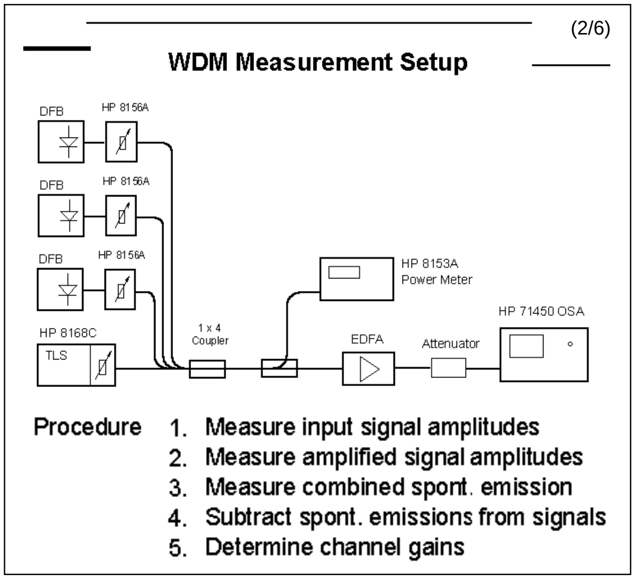
2.2 WDM Gain

WDM is considered to be one of the most powerful methods of increasing the transmission capacity of an optical fiber system. It is a clear alternative to using extremely high-frequency modulation and detection, and it makes use of the thousands of gigahertz of electrical bandwidth offered by the fiber. Note that the 40 nm typical optical bandwidth offered by an EDFA corresponds with 5000 GHz electrical bandwidth. Of course, today's WDM system designs don't fully exploit these capabilities; even WDM systems don't usually occupy more than 50 gigahertz bandwidth.

An optical amplifier can amplify all of the optical carriers in parallel. However, the gain for an individual channel depends on the power and wavelength of all channels, because all channels together set the amplifier's operating point (compression state). That makes WDM characterization somewhat complicated. Various combinations of channel powers should be applied to obtain complete WDM characteristics.



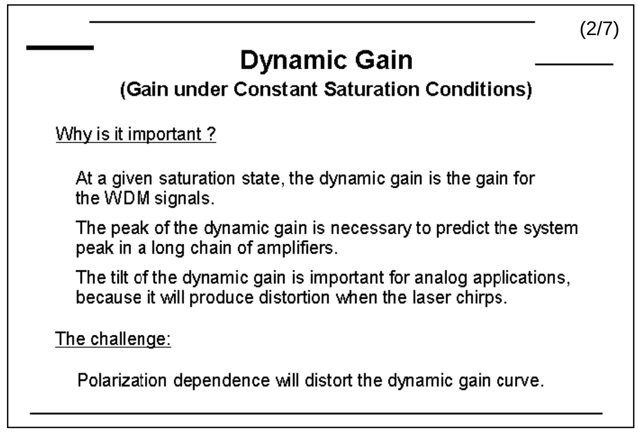
In determining the channel gains, it may be necessary to measure and subtract the ASE and the combined spontaneous emissions of all sources, $\sum$ (G x SSE), when the signals are not much larger than the spontaneous emissions.



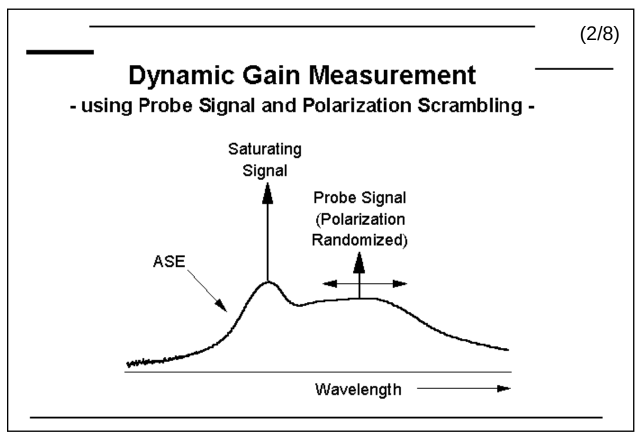
Channel ASE measurement, for the purpose of noise figure determination, should be done on the basis of measuring the spontaneous emissions of all sources and multiplying them by the individual channel gains. This can be considered as an extension of the ASE interpolation technique; see the noise figure discussion below.

2.3 Dynamic Gain

Normally, the gain of an optical amplifier is measured by applying a tunable laser signal with wavelength independent input power. Depending on the signal wavelength, the saturation state (compression) changes. In contrast, the dynamic gain is measured under constant saturation conditions, for example by saturating the amplifier with one strong signal and measuring the gain with a small probe signal. The dynamic gain is important for the reasons mentioned in figure 2/7.

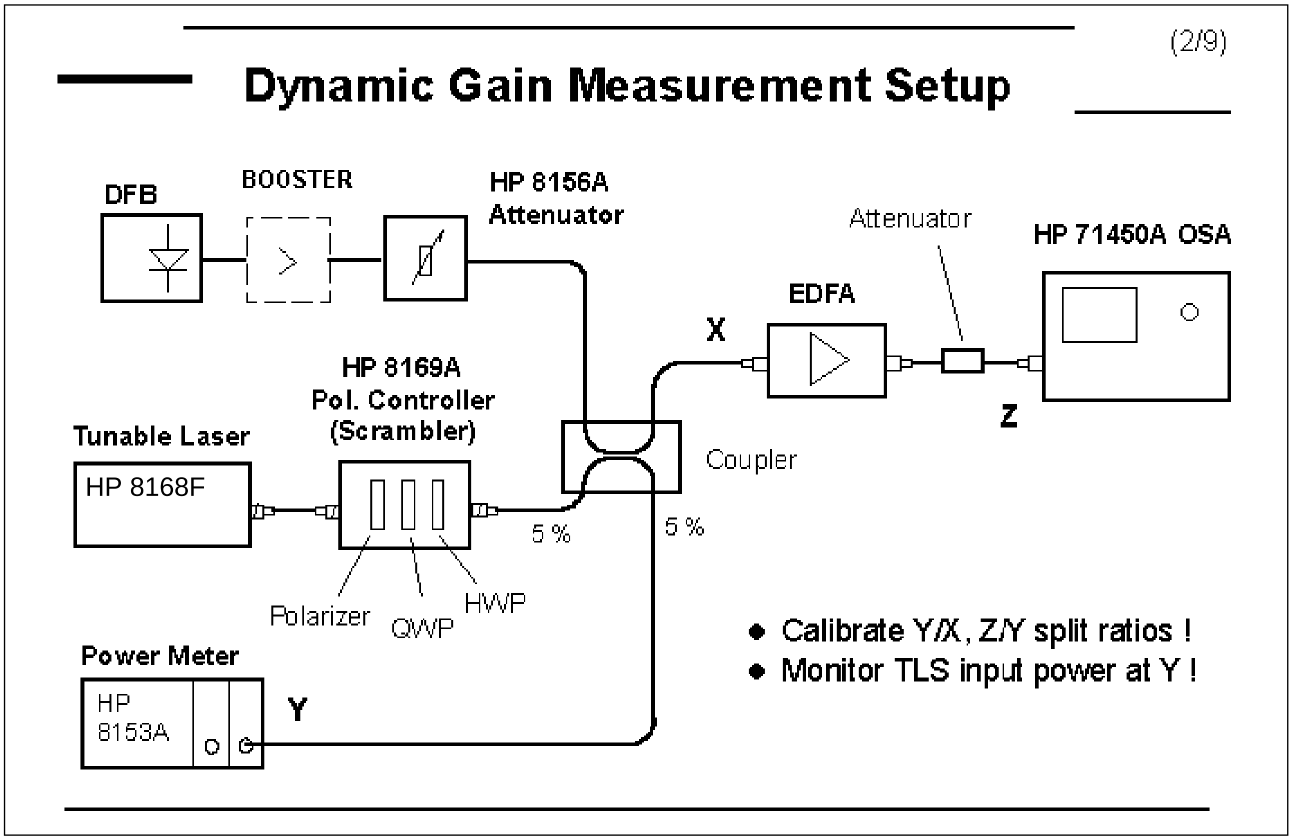


In dynamic gain measurements, it is very important to obtain the precise shape of the gain curve. This shape can easily be distorted by the amplifier's polarization dependence, given the fact that the input polarization state will be wavelength dependent. Therefore, it is highly recommended that you either use an unpolarized probe, such as an LED, or randomize the polarization state.



The HP 8169A polarization controller is well suited for polarization scrambling [3]. An isolator is not needed in this case because the HP 8168F tunable laser source has a built-in isolator.

Figure 2/9 shows the measurement setup. Note the similarity with the setup for polarization holeburning. The major difference is that in this setup the polarization controller is used for scrambling instead of polarization control.



The measurement should start by calibrating the wavelength-dependent power split ratios Y/X (using the two power meter channels) and Z/Y. The results of this calibration are then used to calculate correct signal gains. During the measurement of the test device, the actual input power can be monitored at point Y by momentarily disabling the DFB with the HP 8156A optical attenuator. It is assumed that the polarization controller is continuously scrambling during all these measurements.

The probe signal should be 20 dB lower than the saturating signal so that scanning the probe signal does not influence the saturation state. In preparation for calculating the dynamic gain, it is also advisable to measure the spontaneous emission (ASE + G x SSE) by switching the probe signal off. Then the combined spontaneous emission power can be subtracted from the measured probe signal, to obtain correct signal amplitudes.

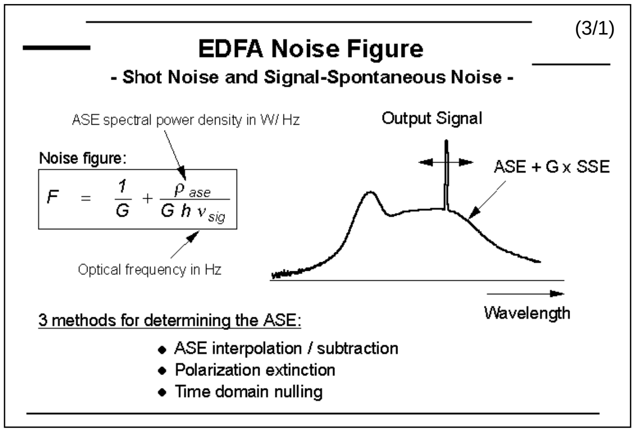
3. Noise Figure

The noise figure of an optical amplifier is particularly important for analog systems. The signal-to-noise ratios of analog systems are often so demanding that noise figures of less than 5 dB must be measured reliably. Another important purpose of the noise figure is to characterize the amount of ASE produced by the amplifier, because the ASE tends to accumulate in the communcation system.

In principle, the noise figure of an optical amplifier can be measured electrically or optically. Electrical noise figure measurements are often thought of as being closer to reality. However, they are complicated and usually suffer from a lack of accuracy. Because of their better accuracy and closeness to optical performance, optical measurements are often preferred by EDFA manufacturers.

3.1 Signal-Spontaneous Noise / Shot Noise

Figure 3/1 shows the most important contributions to the noise figure, the signal-spontaneous contribution and the shot noise contribution.



The optical methods are based on calculating the noise figure from precisely measured gain and ASE [4]. How can the ASE be measured accurately? Two circumstances make ASE measurements complicated:

a) the ASE at the signal wavelength is obscured by the signal itself, and
b) the spontaneous emission near the signal wavelength includes both ASE and amplified SSE.

To solve these problems, at least three techniques have been invented for precise ASE and noise figure measurement.

(3/2)

Noise Figure
Measurement Techniques

ASE interpolation / SSE subtraction:
- Measure SSE and gain.
- Measure and interpolate combined sp. emission: ASE + G x SSE.
- Subtract G x SSE.

Polarization extinction (signal and SSE must be polarized):
- Extinguish amplified SSE using polarization controller.
- Measure and interpolate ASE.

Time domain extinction:
- Switch off signal, so that only ASE remains.
- Measure ASE quickly before amplifier recovers.

The HP 8168F tunable laser is compatible with all of these methods, because:

a) for the polarization extinction technique, the TLS output signal ***and*** the SSE are completely polarized;
b) for the time-domain extinction technique, the TLS has internal and external modulation capability.

All of these methods challenge the performance of both the tunable laser and the optical spectrum analyzer, as shown in figure 3/3.

(3/3)

Accurate NF Measurement

What is important ?

Tunable laser source:	HP 8168F (New)
High power	+7 dBm with attenuator
Low source spontaneous emission	-55 dB/nm
Power stability, repeatability	< 0.03 dB
Coherence control	yes
Optical spectrum analyzer	HP 71450A, Option 101:
Low polarization dependence	±0.05 dB (1542 - 1562 nm)
Good linearity	±0.05 dB
Calibrated resolution bandwidth	±0.13 dB
Calibration against power meter	use HP 81524A optical head

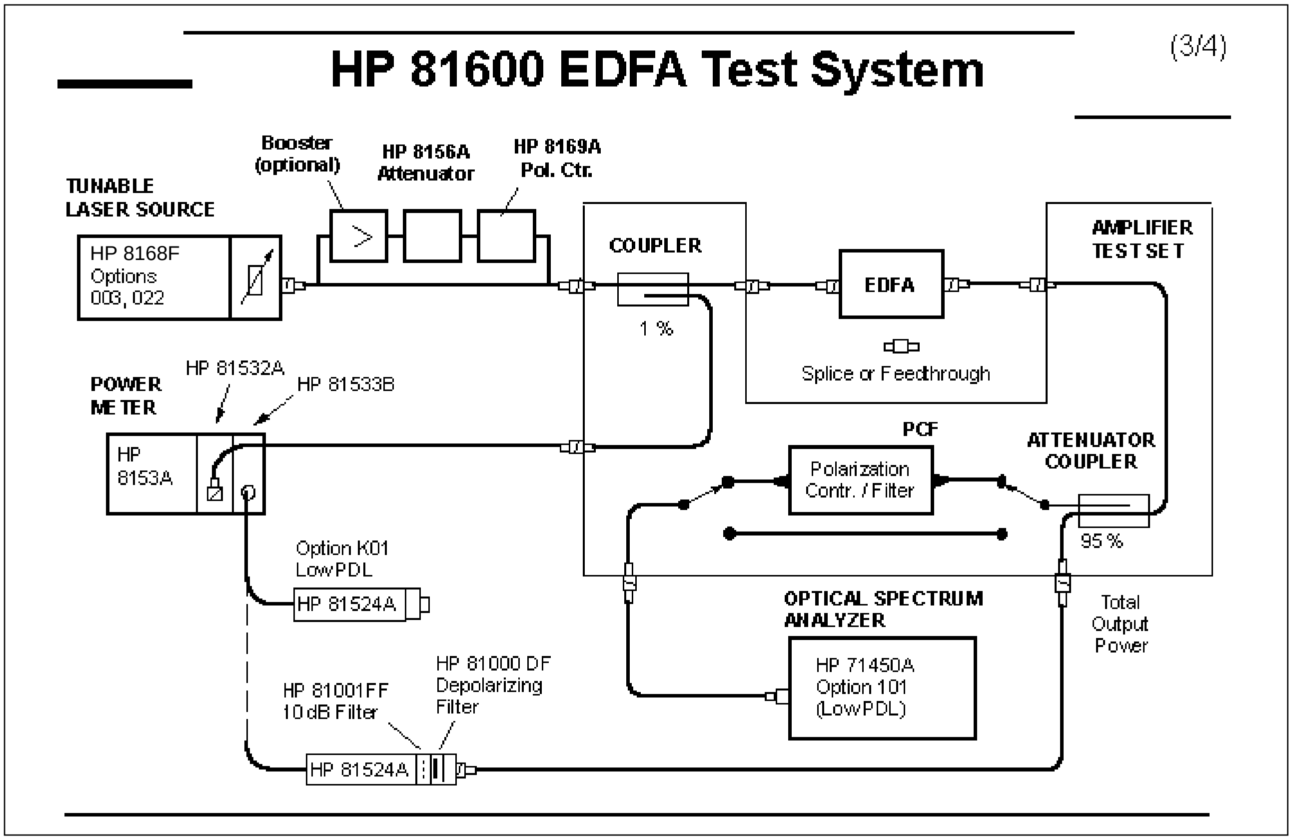
Low SSE is particularly important for EDFA noise figure testing. In this situation, high accuracy is obtained when the amplified SSE is at least smaller than the ASE. Depending on the noise figure test method, SSE filtering, extinction or subtraction accomplishes this condition.

HP offers a turn-key solution to EDFA testing: the HP 81600 EDFA test system was specifically built to meet the EDFA production needs. A block diagram of the test system is shown in figure 3/4.

dependent gain and polarization mode dispersion. More measurement features are currently being worked on.

3.2 Total Noise Figure

Until now, we have mainly discussed the signal-spontaneous noise contribution to the total noise figure. In practical applications, there may other important noise contributions: noise from spontaneous-spontaneous (sp-sp) mixing and optical

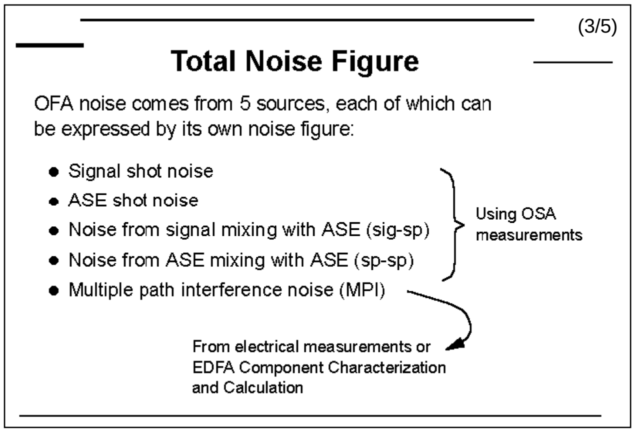


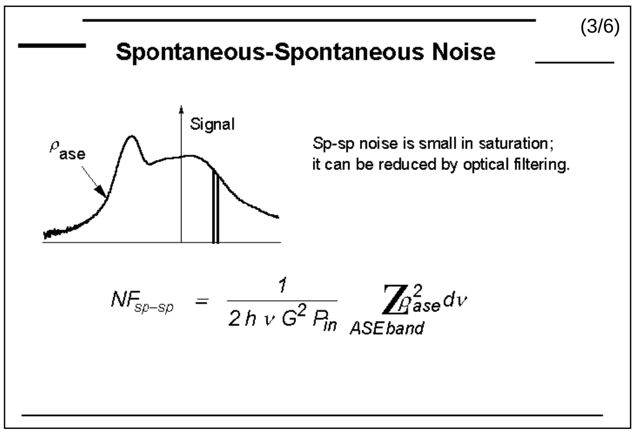
On the input side, a coupler continuously monitors the input power. On the output side, the amplified signal and ASE are routed to an optical power meter (for total power measurements) and an optical spectrum analyzer (for gain and ASE measurements). All power and loss calibrations are based on a high performance large-area power meter with an InGaAs detector (HP 81524A).

In addition to measuring the noise figure with both the ASE interpolation and the polarization extinction method, the system can also measure gain, signal output power, total output power, polarization

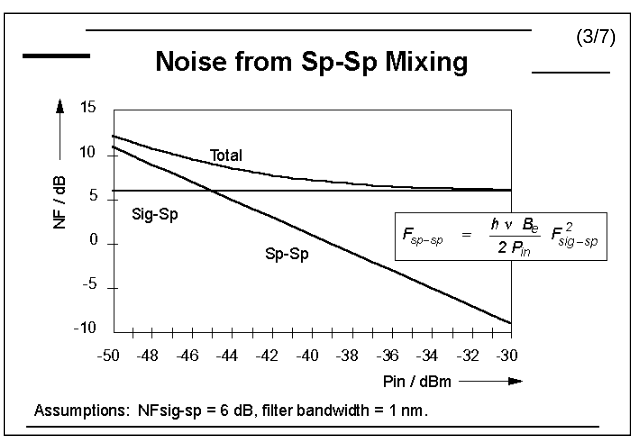
interference noise caused by multiple path interference (MPI) in the amplifier. Figure 3/5 provides an overview of all noise sources contributing to the ”total“ noise figure.

Today’s EDFAs are frequently used as in-line amplifiers and pre-amplifiers. These amplifiers operate with input power levels down to -45 dBm. For such low power levels, the effect from spontaneous-spontaneous mixing cannot be ignored. Figure 3/6 illustrates the effect and gives a formula for the noise figure contribution from sp-sp mixing in an unfiltered amplifier.



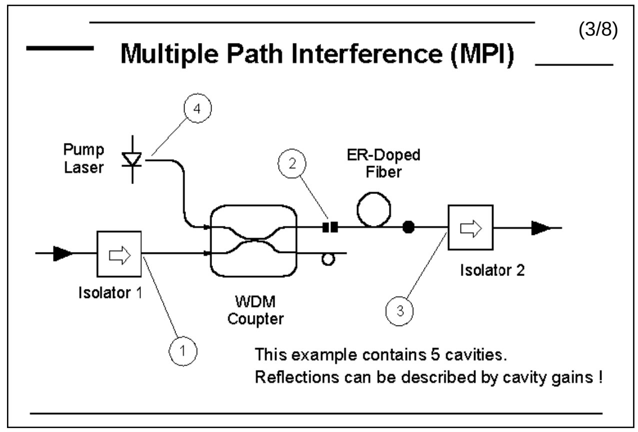


Mathematical calculation shows that sp-sp mixing can be substantial. Therefore, most in-line amplifiers and pre-amplifiers use optical filtering to reduce the magnitude of the integral. Figure 3/7 shows a numeric example for the influence from sp-sp mixing when a filter with 1 nm bandwidth is used. Note that the noise figure (NF) contribution from spontaneous-spontaneous mixing can be calculated using the signal-spontaneous NF.

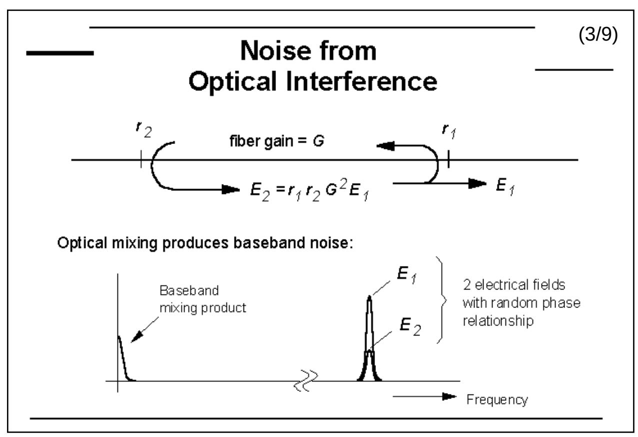


It is obvious that even narrow bandwidth filters cannot completely eliminate the influence of sp-sp mixing, particularly at low input powers.

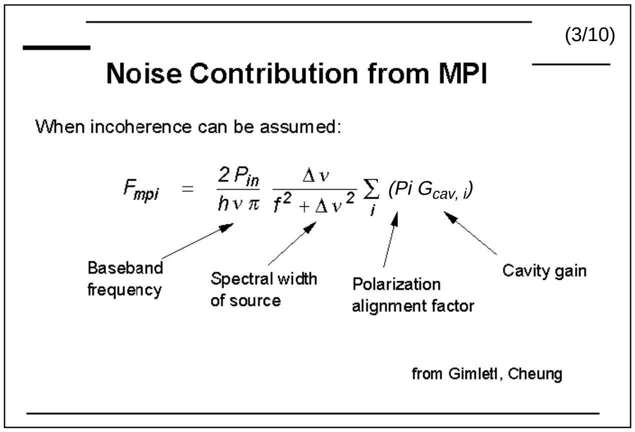
Another serious effect is noise from multiple path interference. Figure 3/8 shows possible reflection points in an optical amplifier.



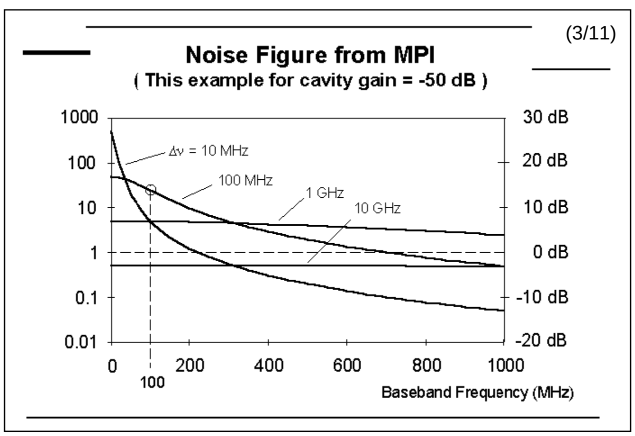
Baseband noise is created by mixing (coherent or incoherent mixing) between the direct and the doubly reflected light. An example with two reflection points which are separated by an amplifying fiber is shown in figure 3/9.



Each of the cavities between two reflection points can be described by its own cavity gain. On this basis, the partial noise figure caused by incoherent mixing can be expressed by the formula in figure 3/10. This formula was developed on the basis of [5].



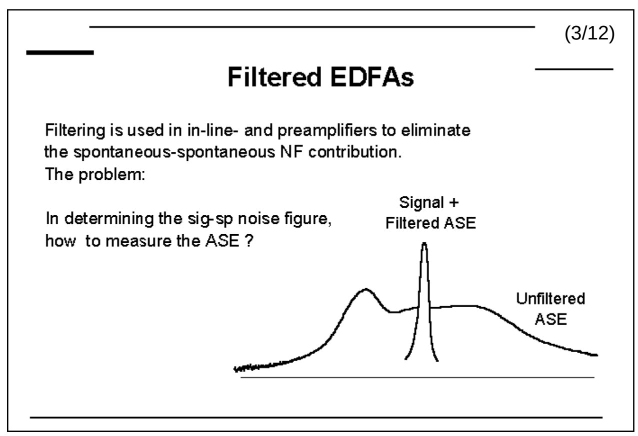
For two reflections of -25 dB each, the cavity gain is -50 dB. The resulting contribution to the noise figure is shown in figure 3/11. It is obvious that very large noise figures can be produced by optical interference and that they depend strongly on the source linewidth. The integral, however, is a device-typical number, which, in many cases is a only weak function of the input power. HP proposed calling the integral (the area under the MPI-curve) the ”figure of merit“ for the reflection characteristics of the amplifier [6].



The influence of optical interference on the noise figure can either be calculated, using known reflectivities and gains, or directly measured by replacing the optical spectrum analyzer with a combination of fast O/E converter and electrical spectrum analyzer. One possibility is the HP 71400 lightwave signal analyzer. In electrical measurements, it is important that the source linewidth is neither too narrow nor too wide. A tunable laser cannot be used because its 100 kHz linewidth is too narrow for the characterization of the optical interference effects. A distributed feedback (DFB) laser is a good compromise.

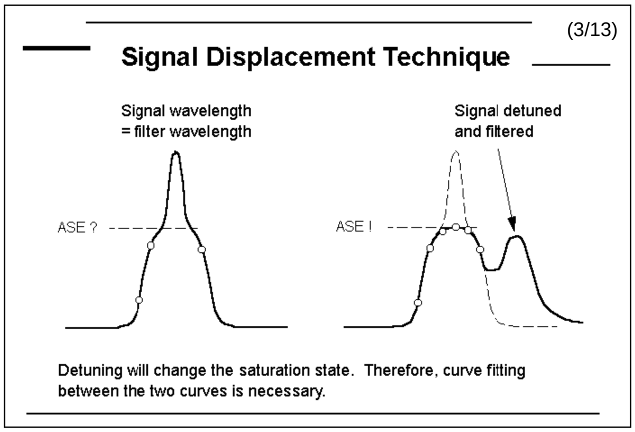
3.3 Noise Figure of Filtered EDFAs

In many optical amplifiers, the input power is relatively large, so the noise contribution from spontaneous-spontenous mixing can be disregarded. This is not the case for in-line amplifiers. They receive low input power which means that their ASE is large and, accordingly, their noise contribution from spontaneous-spontaneous mixing is large. Filtering is used to eliminate these noise contributions. Typical filter bandwidths are 1 nm or less. That means that ASE and signal can no longer be distinguished on the optical spectrum analyzer. The situation is depicted in figure 3/12. One possibility of extracting the ASE from the combined power is time-domain extinction. In this technique, the signal (and the SSE) is momentarily gated off so that access to the ASE is possible.



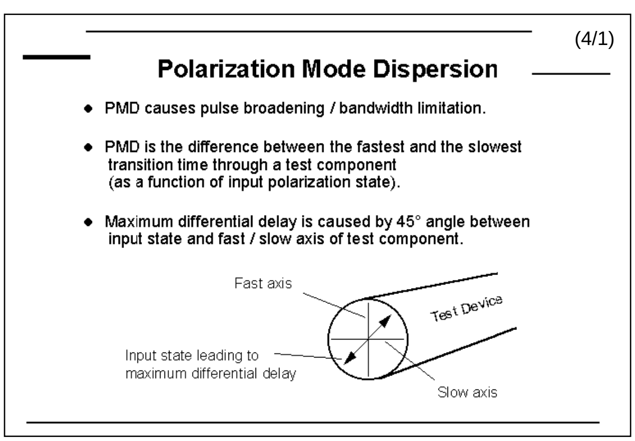
The HP 81600 EDFA test system uses a technique which was termed ”signal displacement“(see fig 3/13). In this technique, the signal is detuned, e.g. by 2 nm, to separate it from the filtered ASE. The output signal is filtered and thereby attenuated. The input signal, however, remains the same. Therefore, the operating point only changes slightly because of the change of input wavelength.

To correct for the change in saturation condition, the samples on the first curve are used to define the absolute level of the ASE samples. The second curve is used to complete the missing shape of the ASE curve. The peak ASE level is determined after stitching the two curves together.



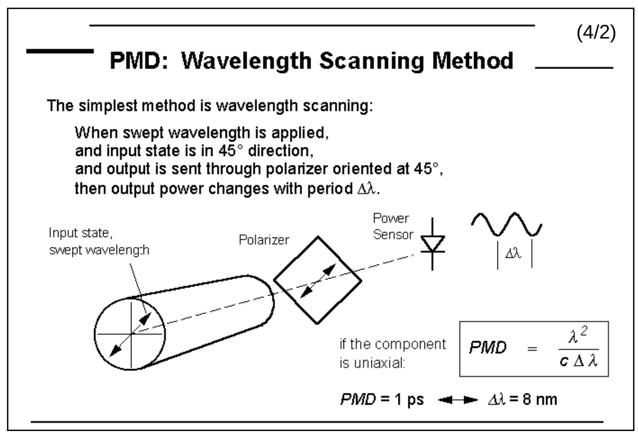
4. Polarization Mode Dispersion (PMD)

A serious effect in long distance communication is pulse broadening due to polarization mode dispersion, i.e. the change of transit time due to change in the polarization state input. This effect is statistical in nature. Each link component, e.g. optical fiber and optical amplifier, can be described by its own polarization mode dispersion (PMD). Fiber PMD is usually relatively small and varies with time and wavelength. Optical amplifier PMD is larger, e.g. 1 ps, and more deterministic. The need for testing PMD comes from the fact that the amplifiers often dominate the PMD of the whole system.

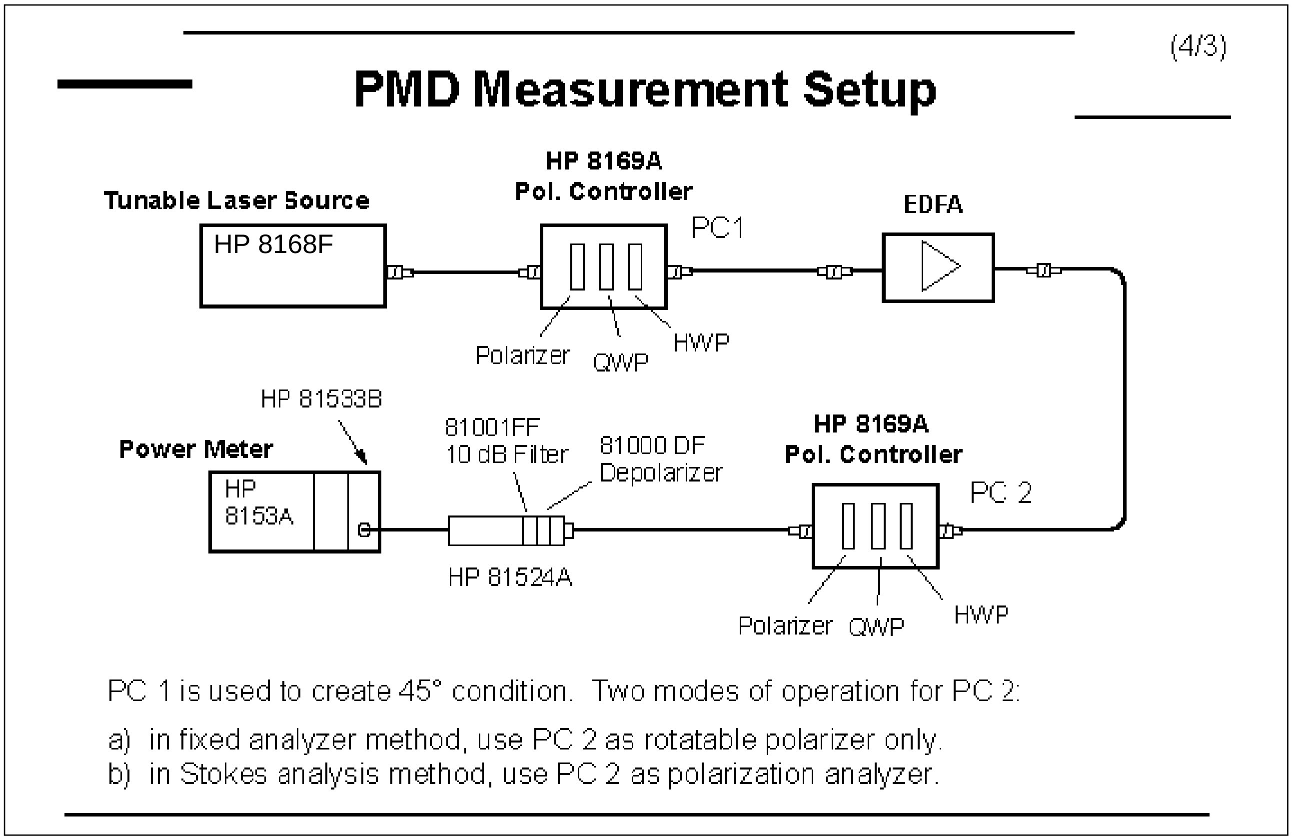


In the simplest case, the test component has one fast and one slow axis with no mode coupling between the axes (uniaxial component). In this case, the phase shift between the two axes is periodic with wavelength and can be detected by inserting a polarizer at the output of the test device.

In the wavelength scanning method (see figure 4/2) with a fixed analyzer, the differential delay can then be calculated from the wavelength period, Δì , of the detected power changes. Note that it is not necessary to maintain precise 45° launch conditions, because the period does not depend on the launch angle. Only the contrast (amplitude difference between maximum and minimum) depends on both input and output conditions. The contrast will go to zero if either the input state or the output polarizer is aligned with one of the device axes.



A practical setup for PMD measurement is shown in figure 4/3. One possibility for using this setup is wavelength scanning with a fixed analyzer. In this case, the first polarization controller is used to set the input state. The second polarization controller is only used as analyzer, e.g. by aligning the waveplate axes with the axis of the polarizer.



A second possibility for using the setup in figure 4/3 is the Mueller / Stokes analysis [7]. This method is more advisable when the test component contains more than one PMD producing element (multiaxial test component). The two isolators of a typical optical amplifier, both producing their own PMD, are a good example. In this case, the wavelength dependence may not go through complete cycles, and the analysis must be carried out on smaller sections of the cycle.

To accomplish this, a wavelength step, Δì , is applied to the test device, and the arc on the Poincaré sphere caused by this wavelength step is analyzed for different settings of the first polarization controller. The second polarization controller is used as a polarization analyzer, and the PMD is calculated by analyzing the measured Stokes vectors. This method is used in the HP 81600 EDFA test system.

The measured PMD value is inversely proportional to the wavelength step, see the formula in figure 4/2. This means that the smallest measurable PMD value depends on the wavelength range of the TLS (1450 - 1590 nm for the HP 8168F). In this situation, the smallest measurable PMD value is limited by an accuracy of approximately ±0.1 ps. The largest measurable PMD depends on the accuracy with which the TLS can generate a small wavelength step. The typical accuracy of a wavelength step generated by the HP 8168F is typically ±0.001 nm, resulting in good accuracy for PMD values up to approximately 2 ps.

Summary

The wide variety of optical amplifiers necessitates a large number of test methods which have to be well understood and selected for the specific type of amplifier. A number of these measurements were analyzed in this paper, particularly gain, noise figure and polarization mode dispersion. The modern derivatives of these methods also discussed were, for example polarization dependent gain, polarization holeburning, WDM measurements, dynamic gain and filtered EDFA measurements.

In most cases, the reasons for these measurements were pointed out, and the requirements for high accuracy were analyzed.

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Data subject to change

Hewlett-Packard Company
Printed in USA 03/96 (CT)
5965-0976E