

# Erbium-Doped Fiber Amplifier Test System

The HP 81600 Series 200 EDFA test system combines various instruments with powerful software to characterize erbium-doped fiber amplifiers. The system is a turnkey solution with fully specified uncertainty.

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Erbium-doped amplifiers (EDFAs) are the latest state-of-the-art solution for amplifying optical signals in lightwave transmission systems (see Fig. 1). They are used as booster amplifiers on the transmitter side to get as much power as possible into the link, as inline amplifiers to overcome the loss of the fiber, and as preamplifiers at the receiver end to boost signals to the necessary receiver levels. EDFAs can be used in single-wavelength transmission systems, in wavelength division multiplexed (WDM) systems, and in soliton transmission systems. To use EDFAs in the various applications it is necessary to characterize the single amplifier as a component.

## Parameters and Measurement Techniques

The main parameters describing an EDFA are signal output power, total output power, gain, and noise figure.<sup>1</sup> All of these parameters are dependent on input power level and wavelength. To characterize these amplifiers fully it is necessary to measure their dependence on both input power and wavelength (see Fig. 2).

Signal output power is measured with an optical spectrum analyzer and the total output power is measured with a

power meter. The gain is the ratio of the signal output power of the amplifier to the signal input power.

Noise figure is defined as the ratio of the signal-to-noise ratio at the input to the signal-to-noise ratio at the output of the amplifier under the following conditions: shot-noise-limited photodetector, shot-noise-limited input signal, and optical bandwidth approaching zero. The main problem in measuring the noise figure is that sources used for generating variable input power and wavelength also generate a broad LED-like spectrum called source spontaneous emission (SSE). The SSE is amplified and adds to the output power. The amplifier output consists of amplified signal and amplified spontaneous emission (ASE). To measure only the signal and ASE contribution from the amplifier we have to eliminate the contribution from the SSE.

There are two principal methods<sup>2</sup> for measuring the exact noise level of the amplifier. The first is called the amplified spontaneous emission interpolation subtraction method. In this method the SSE level of the laser source is determined during the calibration and stored in a calibration file. With this calibration and the measured gain, the SSE  $\times$  gain

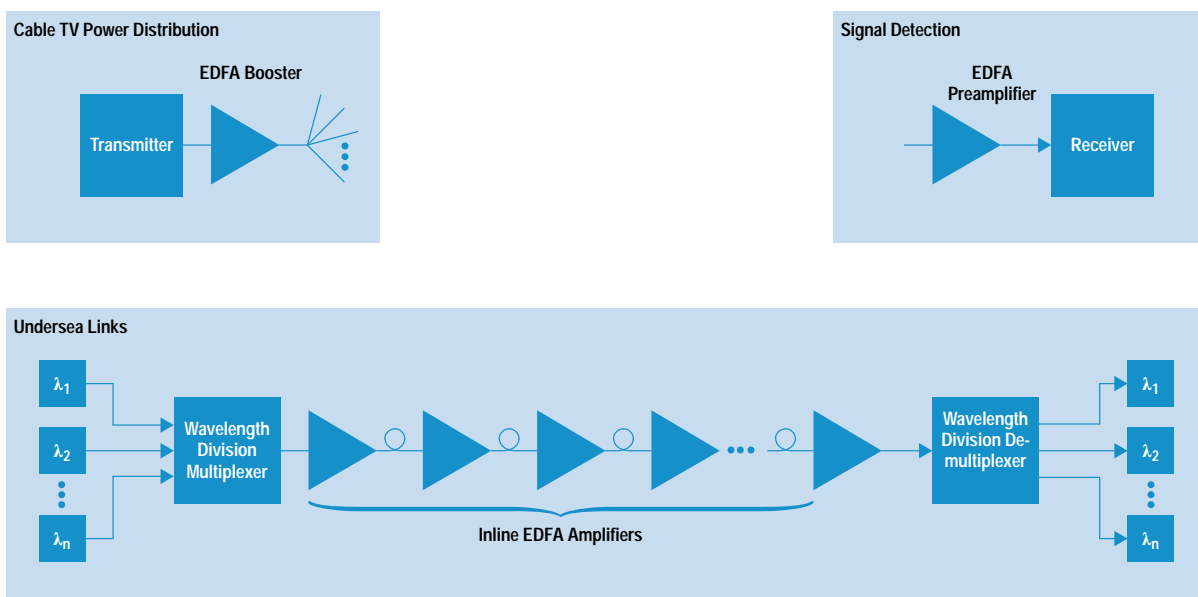


Fig. 1. Erbium-doped fiber amplifier (EDFA) applications in communication systems.

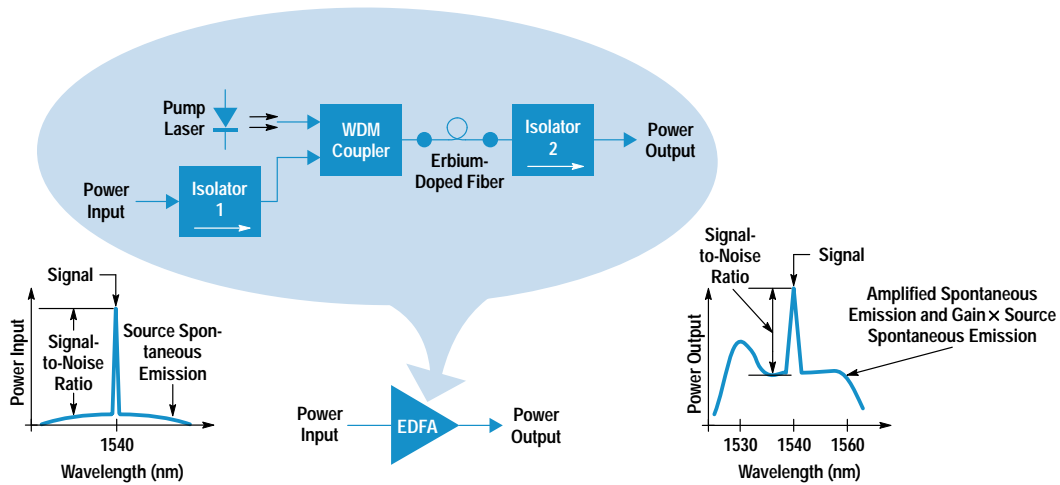


Fig. 2. Key components, optical signals, and measurement parameters for EDFA characterization.

contribution can be subtracted from the total spontaneous power level to obtain the ASE level of the amplifier itself.

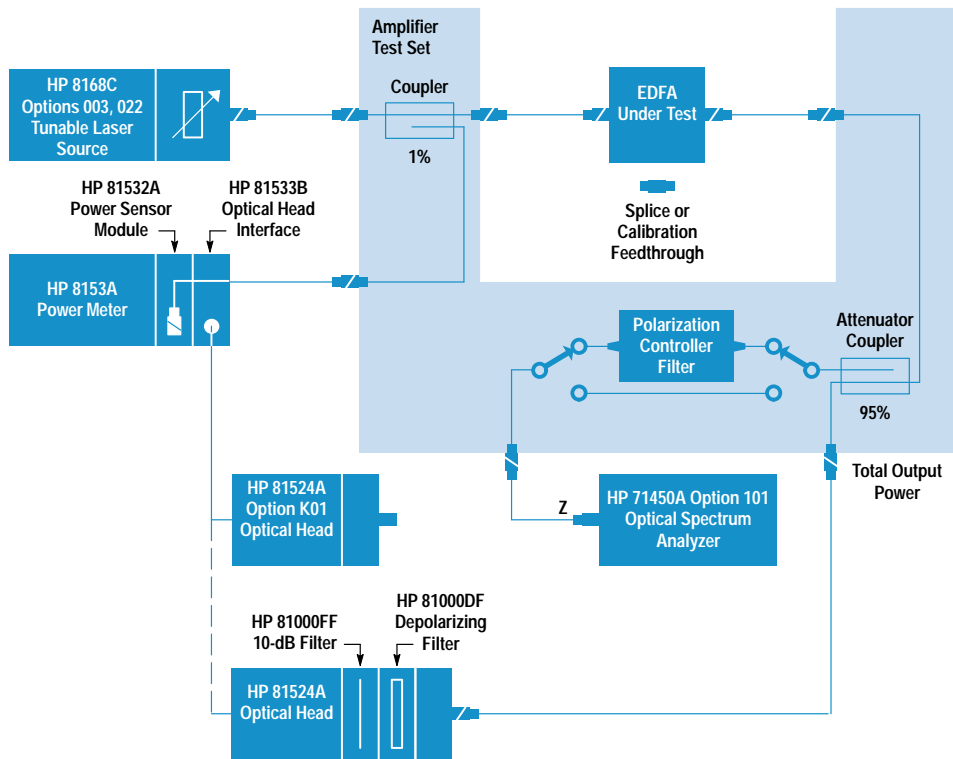
The second method is called the polarization extinction method. It depends on the fact that the signal and the SSE of the laser source have the same state of polarization because there is a polarizer at the output of the tunable laser signal source. The amplifier's ASE is unpolarized. This makes it possible to extinguish the amplified SSE contribution by blocking the signal and therefore also the SSE contribution after the amplifier. The extinction is accomplished with a polarization controller/filter.

### EDFA Test System

The HP 81600 Series 200 EDFA test system is shown in Fig. 3. Fig. 4 is its block diagram. The tunable laser source with built-in attenuator<sup>3</sup> provides the input power levels over the required wavelength range. To guarantee the absolute power level at the input of the EDFA, the power is monitored by means of a coupler and a calibrated power meter.<sup>4</sup> At the output of the EDFA the total output power is measured with a 5% tap and a power meter. Because of the high output power of the EDFA it is necessary to insert attenuators in front of the power meter heads. The coupler for the power



Fig. 3. HP 81600 Series 200 EDFA test system.



**Fig. 4.** Block diagram of the HP 81600 Series 200 EDFA test system.

meter acts as an attenuator for the optical spectrum analyzer. The coupler is followed by a switch and the polarization controller/filter arrangement. This makes it possible to measure the signal directly or via the polarization controller/filter with the polarization extinction method. The optical spectrum analyzer acts as a wavelength-selective power measurement device.

### Amplifier Test Set

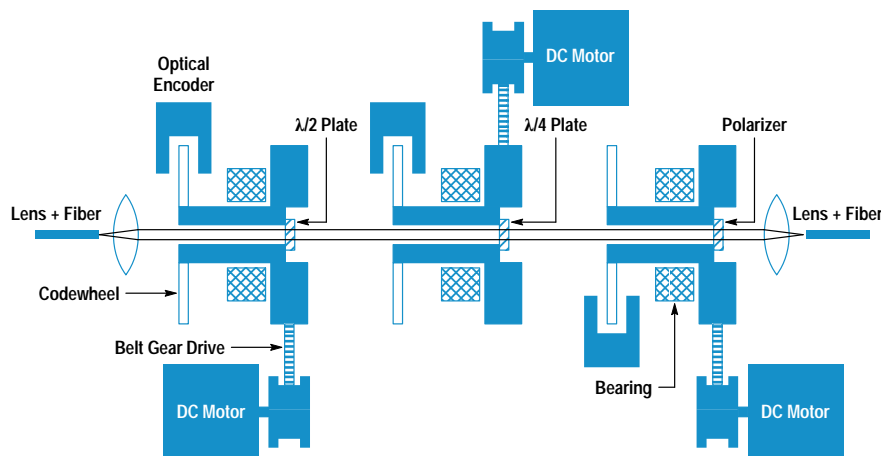
A specially developed instrument for this test system is the amplifier test set. The amplifier test set consists of couplers for monitoring the input and output power of the EDFA and a polarization controller/filter. The switches are used to select between gain measurement on the straight path and ASE measurement on the polarization controller/filter path.

The optical design of the polarization controller/filter is based on two retardation plates—one quarter-wave and one half-wave plate—and a linear dichroic polarizer (see Fig. 5). These parts are mounted on rotatable hollow shafts so that

the collimated light beam can pass through the shafts and through the center of the optical codewheel. The whole assembly—optical parts and encoder—is driven by a dc motor coupled with a belt gear drive. With this design any incoming state of polarization can be transformed into any other state by rotating the retardation plates to defined angular positions. A polarizer is added at the output so that linear states of polarization can be extinguished.

In the polarization extinction method the polarization controller/filter is used as a polarization analyzer to determine the input state of polarization. Based on this measurement, the retardation plates are rotated to calculated angular positions, which change the signal and the amplified SSE to a linear state perpendicular to the pass direction of the polarizer. This causes the signal and the amplified SSE to be extinguished.

The amplifier test set contributes to the overall system uncertainty. Therefore, the couplers, switches, and polarization



**Fig. 5.** Polarization controller/filter.

controller/filter were designed or selected for lowest polarization dependent loss. In addition, the switches were selected for very good repeatability and high return loss. The polarization controller/filter was also designed for low rotation dependent loss. Finally, an intelligent algorithm and optimized speed of the polarization controller/filter reduce the total measurement time.

Before starting a measurement, it is necessary to run a calibration. The first calibration step is to measure the coupling ratio of the coupler before the DUT with the help of the two power meter heads. The second step is to calibrate the optical spectrum analyzer and the power meter in conjunction with the attenuators and the losses of the paths. A feed-through is used to connect the test system's input and output ports. The calibration is verified by measuring the feed-through. In this case the gain is well-known (0 dB) and the output power must be the same as the input power.

### EDFA Test System Uncertainty

Major efforts went into understanding, characterizing and, wherever possible, correcting the actual and potential sources of error in the HP 81600 Series 200 EDFA test system. This task is complex because the test system and measurement tasks are complex. All measurement tasks start with the calibration of the system, in which optical power traceability to PTB and NIST is ensured.<sup>4</sup> Optical power traceability is important in conjunction with the signal power, total power, and ASE measurements, the latter being used to calculate the noise figure. For the gain measurement, it is important that the power scale be linear. This parameter is also traceable to PTB through a chain of scale comparisons. Finally, wavelength traceability is ensured through comparisons to specific gas lamps and lasers, which can be considered natural physical constants.

A careful uncertainty analysis was carried out for each of four parameters: signal power, total power, gain, and noise figure. In each case, the entire process of calculation was analyzed. For example, the gain is defined as the ratio of signal output power to signal input power. Signal input power is measured by means of the input coupler and the HP 8153A optical power meter with the HP 81532A power sensor module. This measurement relies on the accuracy of the input calibration and the performance of the equipment involved. Signal output power is measured with the amplifier test set and an optical spectrum analyzer. This measurement relies on the accuracy of the output calibration and on the performance of the equipment.

As an example, the following represents a summary of the uncertainty analysis for the determination of noise figure. This analysis is the most complicated because the noise figure  $F$  is a function of the ASE power density  $\rho_{ase}$  and the gain  $G$ :

$$F = \frac{1}{G} + \frac{\rho_{ase}}{h\nu G}$$

where  $h$  is Planck's constant and  $\nu$  is the optical frequency. Analyzing this equation for the origin of the numeric values and the performance of the instruments involved leads to the following list of partial uncertainties for the noise figure:

- Polarization dependence of the amplifier test set and the optical spectrum analyzer

- Small errors in the optical spectrum analyzer scale fidelity
- Drift effects in the amplifier test set
- Uncertainty attributable to the input connector pair (the output connector pair cancels out because it influences the gain and the ASE in the same way)
- Calibration uncertainty of the HP 81524A optical head
- Finite accuracy of the cancellation of the source's spontaneous emission in determining the ASE level
- Loss uncertainty of the path through the polarization controller
- Uncertainty of the optical spectrum analyzer's resolution bandwidth
- Uncertainty of the input power measurement resulting from the polarization dependence of the input coupler and the HP 81532A power sensor module.

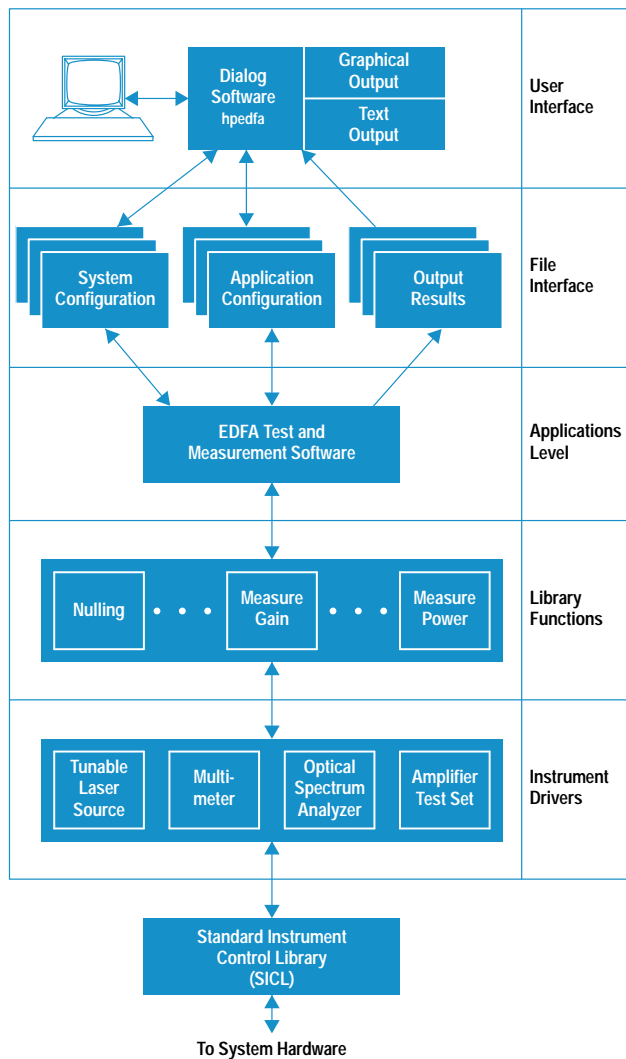
Table I shows a summary of the uncertainty analysis for the HP 81600 Series 200 EDFA test system in conjunction with the polarization extinction technique. Also shown are the total uncertainties, which are obtained by root-sum-squaring. They serve as the basis for the test system specifications.

**Table I**  
**Uncertainty Summary for HP 81600 Series 200 EDFA Test System**

Uncertainty	Output Signal (dB)	Gain (dB)	Noise Figure (dB)
Gain Compression by SSE	±0.10	±0.10	
Optical Spectrum Analyzer Polarization Dependence	±0.10	±0.10	±0.05
Test Set Polarization Dependence	±0.07	±0.07	±0.07
Optical Spectrum Analyzer Scale Fidelity	±0.05	±0.10	±0.10
Drift of Test Set	±0.10	±0.10	±0.10
Output Connector Pair	±0.25	±0.25	
Input Connector Pair		±0.25	±0.25
Power Meter Scale	±0.11	±0.11	±0.10
Input Power		±0.05	±0.10
SSE Cancellation			±0.10
Polarization Controller/Filter Path Loss			±0.07
Optical Spectrum Analyzer Resolution Bandwidth			±0.10
Total Uncertainty: Connectors	±0.39	±0.48	±0.39
Splices	±0.27	±0.24	±0.25

### Software

Testing an EDFA device in production requires software that is easy to use, since EDFA measurement methods are quite new and the software will be used by people who may not know all of the details of the test process. On the other hand, software flexibility was an important design goal to allow extensions for additional measurement methods and integration into existing customer processes and databases.



**Fig. 6.** EDFA test system software overview.

The EDFA test system software runs on an HP 745i workstation under the HP-UX\* 9.01 operating system, and is implemented mostly in the C programming language. Fig. 6 shows an overview of the software structure. On the lower level, there is a set of drivers for the different instruments, along with some modules for accessing configuration information and help texts. They supply an easy and portable access to the instrument hardware shown in Fig. 2.

The communication layer for the instrument drivers is based on the SICL (Standard Instrument Control Library). Using the SICL, data can be written to and read from instruments with commands similar to those for reading and writing files in C. All calls to the SICL are handled through a control module called *inst\_drv* (Fig. 7). Its purpose is to allow the logging of traffic going to and from the instruments and to support some basic functionality like detecting the presence of an instrument on the HP-IB (IEEE 488, IEC 625). It also supplies central error handling facilities.

For each instrument type there is a separate driver module. Each module can control several instruments of the same type at once, and keeps track of the internal instrument states to save execution time. The driver modules check

parameters before passing them to the instruments, and support instrument error checking.

To speed up measurements where multiple instruments are involved, the drivers act asynchronously. For example, both channels of the HP 8153A optical power meter can fetch data while the HP 70950 optical spectrum analyzer is making a swept measurement. Additional commands are available to synchronize the instruments and make sure everything is settled before a measurement is taken.

The measurement application is built on top of this driver structure. It contains different algorithms for testing EDFAs, one of which is active at a time. Currently, the following measurement functions are integrated:

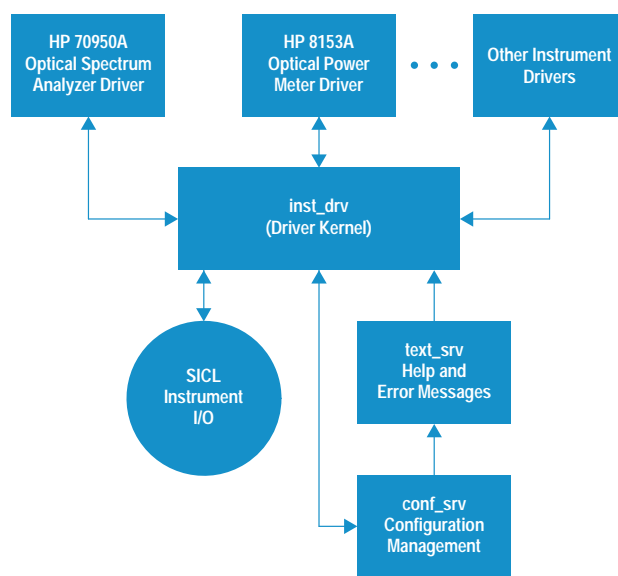
- Perform an input calibration of the test system
- Perform an output calibration of the test system
- Verify the calibration
- Measure an EDFA using the polarization extinction method
- Measure an EDFA using the amplified spontaneous emission method
- Perform a self-test.

While the measurement proceeds, intermediate results are checked against limits set up for the device by the operator, and against certain fixed system limits (to detect improper connections, etc.).

A C language interface allows customized extensions, such as controlling additional parameters (e.g., the EDFA pump current) or performing additional measurements (e.g., reading a voltmeter).

All results of the calibration and measurement steps are stored in a single file, along with information about the EDFA device, the test conditions, and the overall result (pass or fail). This file is organized in a structured ASCII format and allows easy extraction of all important test results for use in analysis programs and databases.

For user-friendly parameter input and measurement control, a sophisticated user interface was designed. Written with a



**Fig. 7.** Instrument driver overview.

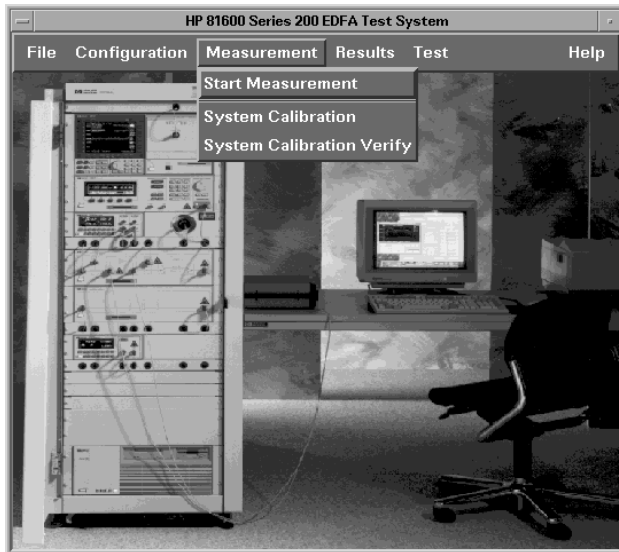


Fig. 8. Main window of the EDFA test system user interface.

user interface builder, along with some C code, it is based on X11/Motif (Fig. 8).

The user is guided through the setup and calibration of the test system by easy-to-use menus and dialog boxes. Different calibration setups for specific wavelength ranges can be entered, as well as test conditions with limits appropriate for certain EDFAs (Fig. 9).

Where fiber connections have to be made in the calibration and measurement process, a graphic is brought up on the screen showing the necessary steps and connections. All

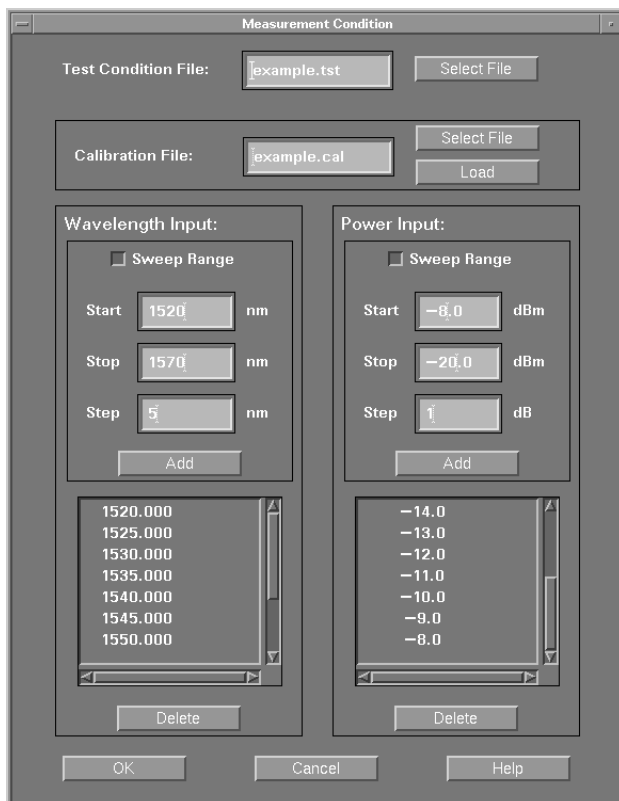


Fig. 9. Test condition input panel.

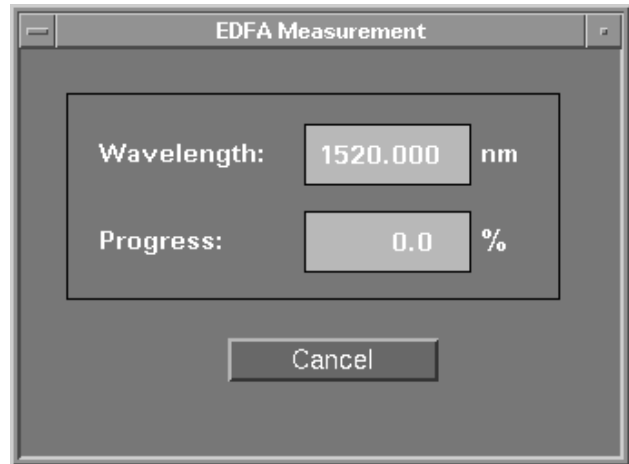


Fig. 10. Progress status window.

numeric data is checked for correctness immediately after it is entered. Before a measurement starts, the calibration is matched against the needs of the requested test.

The progress of a running calibration or test is shown with an information box on the screen (Fig. 10). Meanwhile, the program stays fully usable for entering new test setup data, or for reviewing the results of previous measurements.

Result data can be examined in textual form. A table showing input parameters and results can be viewed and printed. A graphical output system is included so that the user can review the data graphically and create graphs for EDFA device documentation.

A menu (Fig. 11) allows the user to choose an X-Y plot of any result parameter against any input parameter (including user-specified parameters). Fig. 12 shows such a plot. A single graph can have up to eight traces. The graph can be interactively scaled and zoomed, and markers can be placed either freely or bound to measurement points. The X-Y values of each measurement point can be read out with a single mouse click.

The graphics system also provides hard-copy functionality and allows the merging of different graphs on a specified number of pages, thus enabling the output of a user-defined data sheet which can be printed out automatically after each test is completed. Supported printers are the HP LaserJet series and the DeskJet series, the latter allowing color printouts.

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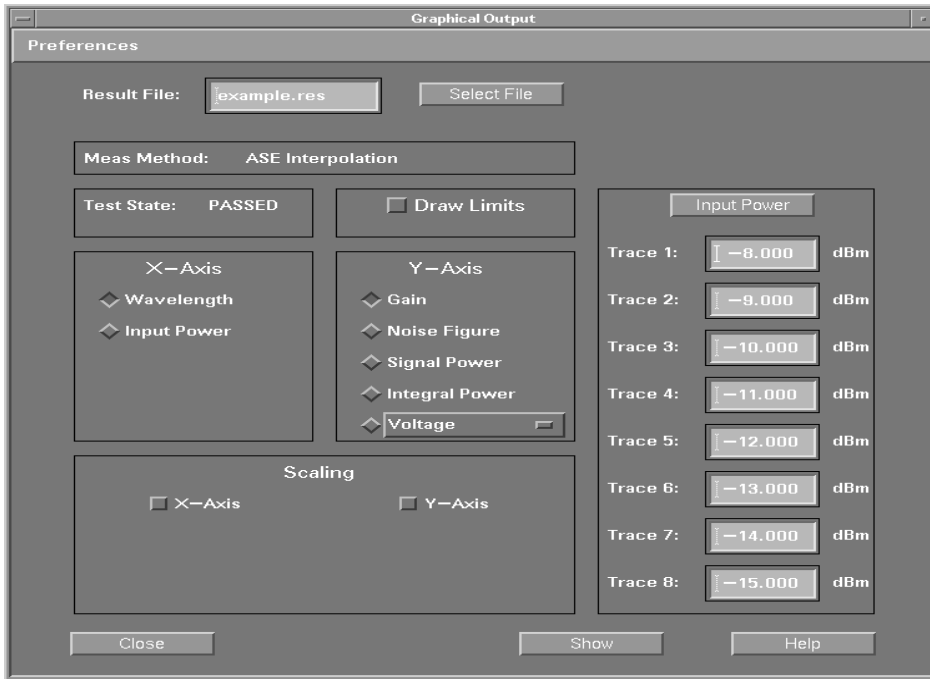


Fig. 11. Graphical output window.

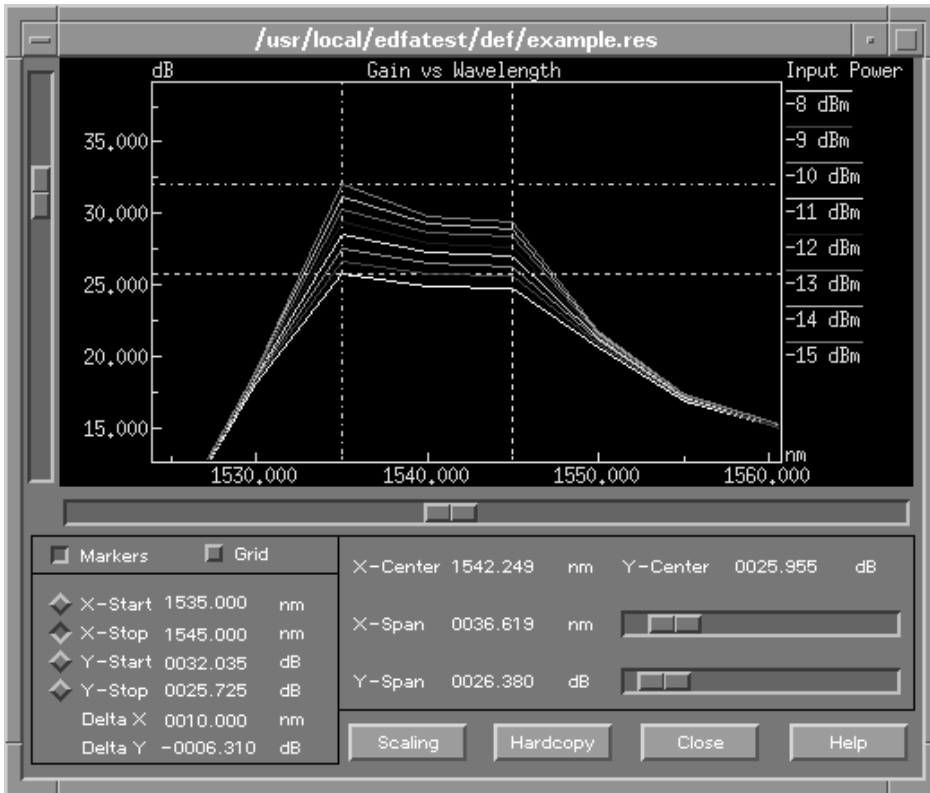


Fig. 12. X-Y parameter plot with markers.

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### References

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4. *Hewlett-Packard Journal*, Vol. 42, no. 1, February 1991, pp. 58-83.

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