Conclusion

Digital signal processors have been applied more and more in industrial motion control applications. Applying these processors together with a sophisticated control algorithm in an optical attenuator produces a system that provides overshoot-free, fast, and accurate positioning of the filter disk, even under noisy environmental conditions.

Acknowledgments

The authors would like to thank Wilfried Pless for project management, Michael Pott who was responsible for the design and implementation of the instrument firmware, and Rainer Eggert for the mechanical design of the optical attenuator. Special thanks to Joseph N. West at the Lightwave Operation of the HP Microwave Technology Division for his invaluable consulting and support regarding the filter drive system.

Reference

1. J.N. West, et al, "A High-Resolution Direct-Drive Diffraction Grating Rotation System," *Hewlett-Packard Journal,* Vol. 44, no. 6, December 1993, pp. 75-79.

Precision Reflectometer with Spurious-Free Enhanced Sensitivity

The HP 8504B precision reflectometer has an improved sensitivity of –80 dB at both 1300-nm and 1550-nm wavelengths. All spurious responses generated within the instrument itself have been significantly reduced. The instrument offers fiber-optic component designers and manufacturers the ability to pinpoint both large and small optical reflectances.

by David M. Braun, Dennis J. Derickson, Luis M. Fernandez, and Greg D. LeCheminant

A precision reflectometer is an effective tool for measuring the levels and locations of optical reflections in optical fiber systems.[1,2] The HP 8504B precision reflectometer (Fig. 1) uses an optical low-coherence reflectometry technique employing a Michelson interferometer with a low-coherence, broadband optical source to make spatially resolved measurements of optical reflections. One arm of the Michelson interferometer contains a translating mirror and in the other interferometer arm the device under test (DUT) is placed. When the optical path length to the mirror equals the optical path length to a reflecting surface in the DUT, the reflected signals add coherently, providing a calibrated reflectance response in the measurement trace. Measurements of reflecting surfaces within DUTs can be made in hundreds of milliseconds over distances as small as 1 mm or in tens of seconds over distances as wide as 400 mm, with a two-event spatial resolution of 25 μm at 1300 nm and 50 μm at 1550 nm.

Fig. 1. The HP 8504B precision reflectometer has enhanced –80-dB sensitivity with all spurious responses significantly reduced to greater than 65 dB below the largest reflection.

The HP 8504B precision reflectometer is an advancement of the HP 8504A, offering an improved sensitivity specification of –80 dB at both 1300-nm and 1550-nm wavelengths, with all spurious responses reduced to greater than 65 dB below the largest reflection. (A spurious response is a displayed signal that is generated within the instrument and not by the DUT.) Measurements of DUT reflections can now be made accurately across the entire measurement range without the need for interpretation of the measurement to eliminate instrument spurious responses.

A typical measurement application for a precision reflectometer is the analysis of low optical return loss in optical components and assemblies. Optical return loss is defined as the ratio of the incident optical power to the reflected optical power in units of dB. Optical assemblies often have many internal reflections, all of which contribute to the total return loss. Precision reflectometer measurements identify which physical optical interfaces within the component are causing the greatest optical reflections and therefore are limiting the return loss. Another measurement application uses the time delay measurement capability of the reflectometer to make accurate measurements of the positions or thicknesses of elements within packaged fiber pigtailed components, the differential time delay through birefringent material, and the group index.[3]

Reflectometer Design

The key to the improved performance of the HP 8504B is a low-coherence source optimized for precision reflectometer measurements. HP has developed a family of powerful edge-emitting light-emitting diode (EELED) sources specifically designed to improve instrument sensitivity while simultaneously reducing spurious responses. Sensitivity is determined in large part by the source optical power level. The output power from the EELED was improved by the use of a long gain region. In standard EELEDs, high output power is often accompanied by large internal reflections that cause spurious responses in measurements. By careful control of these internal reflections, high output power and low spurious responses were achieved simultaneously. The article on page 43 provides a detailed description of the diode source and of how the power was increased and the internal reflections reduced.

Since all HP 8504B spurious responses were reduced, the need for the normal-sensitivity mode of the HP 8504A was eliminated. The instrument firmware was rewritten for one standard high-sensitivity mode, making the instrument easier to use and reducing factory calibration time and cost. This one mode of operation allows the simultaneous measurement of both large and small component reflections. Factory cost was an important consideration throughout the instrument redesign, resulting in a reduced manufacturing cost and a lower list price. All other important features of the HP 8504A have been retained in the HP 8504B.

Optical fiber communication systems continue to demand lower reflection levels. The improved performance of the HP 8504B addresses these increasing demands. The remainder of this article presents three measurement examples that illustrate different applications of the reflectometer.

Optical Connector Endface Characterization

Undesired reflections caused by contamination on connector endfaces are a serious concern for optical fiber systems. Contamination can decrease connector return loss and damage the endface.

Quantitative evaluation of endface cleanliness has been a difficult task. Visual inspection, surface interferometry, and surface profilometry are unable to give quantitative measurements of the small particles or films on connector endfaces. Because of its high sensitivity, the HP 8504B precision reflectometer can measure the small reflections caused by contaminants.

A setup for measuring endface cleanliness is shown in Fig. 2. The small reflections caused by contaminants were measured using a source wavelength of 1550 nm. The DUTs were custom ST connectors with endfaces polished to an 8° angle. When cleaned properly, these components can provide an optical return loss between 60 and 70 dB. Although there are multiple reflection sites in the test setup, the HP 8504B was set to examine only the connector endface of interest. The ability to distinguish between the reflection from the angled connector and the reflections from the other connectors and the ability to measure the reflection from the angled connector very accurately made the HP 8504B an excellent choice for this measurement application.

This measurement technique was used to measure the effectiveness of various cleaning processes on our manufacturing line. An optical test system began producing inconsistent results that seemed to be related to changes in the swab material used in the cleaning procedure. An evaluation was conducted examining the three materials commonly used in cleaning connectors: "lint-free" cotton, polyurethane foam, and polyester. Approximately twenty connectors were cleaned with propanol, rubbed with "lint-free" cotton swabs, and blown dry with filtered dry compressed nitrogen. Then the optical return loss was measured with the HP 8504B. The same group of connectors was cleaned again, this time using polyurethane foam swabs. The return loss was then measured again. This procedure gave a performance comparison between "lint-free" cotton swabs and polyurethane foam swabs. This process was repeated with a different batch of cables, using the cotton and polyester swabs. The measurement results are shown in Fig. 3.

The contamination clearly increased with the polyurethane foam swabs as indicated by a decrease in optical return loss. The average return loss degraded from 59.5 dB when cleaned with cotton swabs to 50.7 dB when cleaned with polyurethane foam swabs. The variability of cleanliness, measured by the standard deviation of the reflection, also worsened dramatically from 1.7 dB when cleaned with the cotton swabs to 8.9 dB with polyurethane foam swabs. Visual examination under a microscope indicated some evidence that polyurethane foam swabs may have left a film on the connector endfaces.

The polyester swabs performed much better. Here the average return loss for the connectors cleaned with cotton swabs was 60.3 dB and actually improved slightly to 61.7 dB with

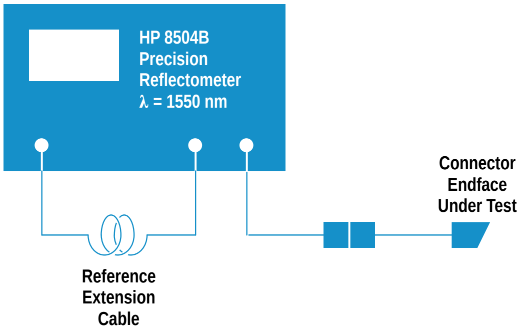

Fig. 2. Block diagram of a test setup for measurement of optical connector endface contamination. The system consists of an HP 8504B operating at 1550 nm with a single-mode fiber connected to the test port. The single-mode fiber is terminated with an ST connector that has been polished at an 8° bevel.

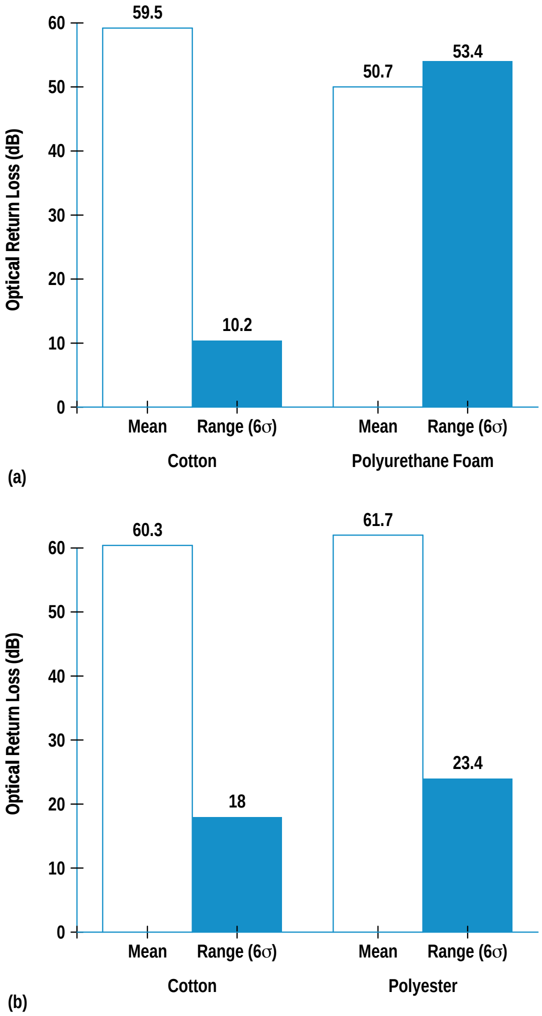

Fig. 3. Optical return loss measurement results presented as average reflectivity and range (6σ) values for cleaning procedures comparing (a) cotton swabs with polyurethane foam swabs and (b) cotton swabs with polyester swabs.

polyester swabs. The standard deviation for cleaning with cotton swabs was 3.0 dB but spread slightly to 3.9 dB with polyester swabs.

This test shows that there can be quite a variation in cleanliness just because of changes in the swab material. Using the HP 8504B, the measurement problems were linked to the use of polyurethane foam swabs. A switch to cotton swabs eliminated these problems.

This measurement technique can also measure connector optical return loss repeatability. As manufacturers improve the design of angled connectors, increasing the optical return loss, the HP 8504B can be used to measure their return loss up to 80 dB.

Optical Isolator Characterization

High-performance optical isolators are used to protect sources from reflected light by transmitting light in one direction and translating light away from the return optical path in the reverse direction.[4] Large levels of reflected light can cause linewidth and power output variations in distributed feedback lasers[5] and in Fabry-Perot lasers. In addition to attenuating light from any downstream reflections the isolator itself must not cause reflections, or in other words, it must have high optical return loss. A precision reflectometer with high sensitivity is ideal for identifying which optical interface limits the optical return loss within the isolator.

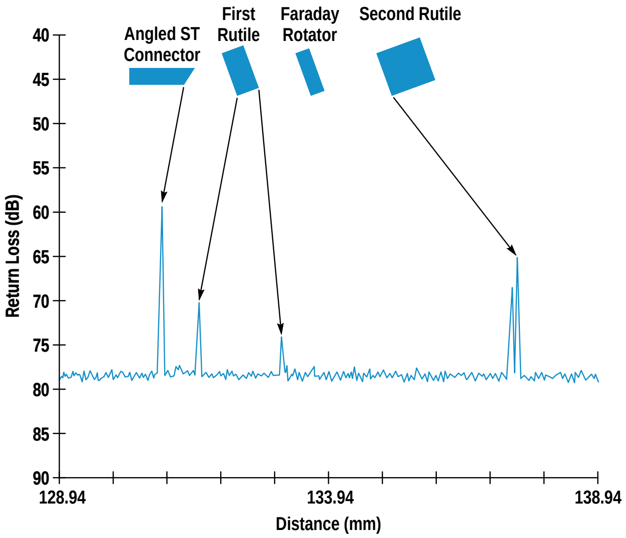

Fig. 4. A reflectometer measurement of an isolator component. Both large and small reflections can be measured with no spurious responses. Knowing the placement of the components within the isolator, the largest reflection is determined to be from the angled ST connector. A double reflection from the front face of the second rutile is observed because the first rutile is birefringent.

Fig. 4 shows a measurement of an optical isolator. For this unit the highest level of reflected light occurs at the angled fiber tip with the next largest reflection occurring at the front face of the second rutile (TiO_2). With this information the designers can correctly focus their energy on the fiber as the subcomponent with the greatest potential for improving the optical return loss of the isolator. The large sensitivity and high spatial resolution of the HP 8504B enable the designer or production line to measure and identify these low reflections of the internal isolator components.

Polarization-Mode Dispersion Measurement

Polarization-mode dispersion (PMD) is a result of birefringence in both optical fibers and components. For an in-depth article on PMD see page 27.

Polarization-mode dispersion of lightwave components can be measured with a Michelson interferometer instrument such as the HP 8504B. Fig. 5 shows a block diagram of the measurement system. Placing the DUT in the reflectometer

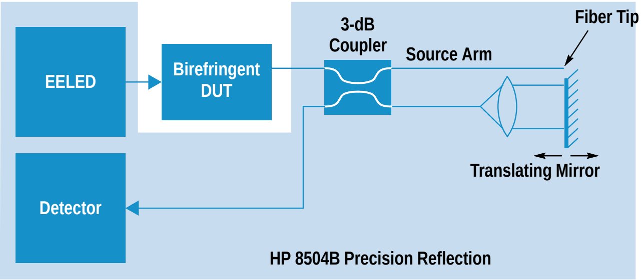

Fig. 5. Test setup used for measuring polarization-mode dispersion. The device under test is placed in the source arm of the HP 8504B.

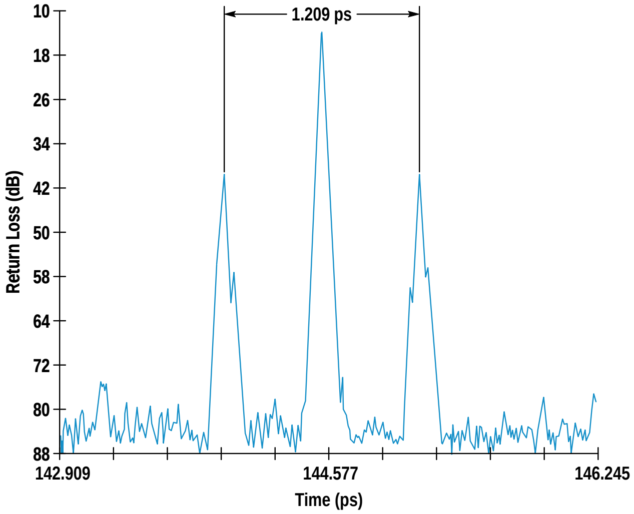

Fig. 6. Measured plot of a birefringent isolator. Three characteristic reflections are observed giving a polarization-mode dispersion measurement of 1.209 ps.

source arm allows partially polarized light from the HP 8504B EELED source to travel on both the slow and fast polarization axes of a birefringent device. The light on the slow polarization axis is delayed by an amount $\Delta\tau$ relative to the light on the fast axis. The HP 8504B produces a pair of responses when the moving mirror is positioned such that the optical path length of its arm is first longer and then shorter than the fixed-length interferometer arm by an amount corresponding to $\Delta\tau$. A response also occurs when the position of the moving mirror is such that the interferometer arms are of equal optical length, regardless of the PMD of the device.

Device PMD can be determined by configuring the HP 8504B horizontal axis in a time format and using the markers to measure the time difference between a symmetrical pair of DUT responses. Measuring between the pair of DUT responses corrects for the fact that as a reflection measurement instrument, the HP 8504B presents distance or time-of-flight measurement results in a "one-way" format. The minimum detectable dispersion is directly proportional to the HP 8504B's spatial two-event resolution and is 160 femtoseconds at 1300 nm and as low as 320 femtoseconds at 1550 nm.

This measurement technique lends itself very well to bulk optic devices such as isolators. Fig. 6 shows the measurement response at 1300 nm of an isolator placed in the source arm of the HP 8504B. The PMD value of the isolator is 1.209 ps.

The EELED source of the HP 8504B has a spectral width approaching 60 nm which means that the measured PMD is a composite over the bandwidth of the EELED. If there is significant mode coupling in the DUT, as can occur in single-mode fiber, the differential group delay (typically used to describe PMD at a single wavelength) can vary significantly as a function of wavelength. The HP 8504B measurement technique for such a DUT will not yield discrete interferometer responses. Jones matrix eigenanalysis and wavelength scanning methods, both available in the HP 8509A/B polarization analyzers, are preferred for characterizing single-mode fiber. For more on measuring PMD in single-mode fiber see the article on page 27.

Conclusion

An optical low-coherence reflectometer with large sensitivity, high spatial resolution, and an insignificant level of spurious responses is an effective tool for many measurement applications. The HP 8504B offers this measurement capability in a calibrated, easy-to-use instrument.

Acknowledgments

The development of the upgraded HP 8504B precision reflectometer benefited from the contributions of a large number of people. We acknowledge Howard Booster, Harry Chou, Mike Hart, Steve Mifsud, and Fred Rawson as members of the instrument design team and Susan Sloan, Tim Bagwell, Patricia Beck, Marilyn Planting, Joan Henderson, and Nance Andring for the edge-emitting light-emitting diode development. We thank Don Cropper, Steve Scheppelmann, and Tamas Varadi for assistance with the measurements of fiber endfaces. Finally, to Bob Bray and Jack Dupre go special thanks for their guidance and encouragement throughout this instrument development.

References

1. D.H. Booster, H. Chou, M.G. Hart, S.J. Mifsud, and R.F. Rawson, "Design of a Precision Optical Low-Coherence Reflectometer," *Hewlett-Packard Journal,* Vol. 44, no. 1, February 1993, pp. 39-48.
2. H. Chou and W.V. Sorin, "High-Resolution and High-Sensitivity Optical Reflection Measurements Using White-Light Interferometry," *Hewlett-Packard Journal,* Vol. 44, no. 1, February 1993, pp. 52-59.
3. W.V. Sorin, D.M. Baney, and S.A. Newton, "Characterization of Optical Components using High-Resolution Optical Reflectometry Techniques," *Proceedings of the Symposium on Optical Fiber Measurements,* Boulder, Colorado, September 1994.
4. K.W. Chang, S. Schmidt, W.V. Sorin, J.L. Yarnell, H. Chou, and S.A. Newton, "A High-Performance Optical Isolator for Lightwave Systems," *Hewlett-Packard Journal,* Vol. 42, no. 1, February 1991, pp. 45-50.
5. R.W. Tkach and A.R. Chraplyvy, "Linewidth Broadening and Mode Splitting Due to Weak Feedback in Single-Frequency 1.5-µm Lasers," *Electronics Letters,* 1985, pp. 1081-1083.