Measurements of lightwave component reflections with the Agilent 8504B precision reflectometer
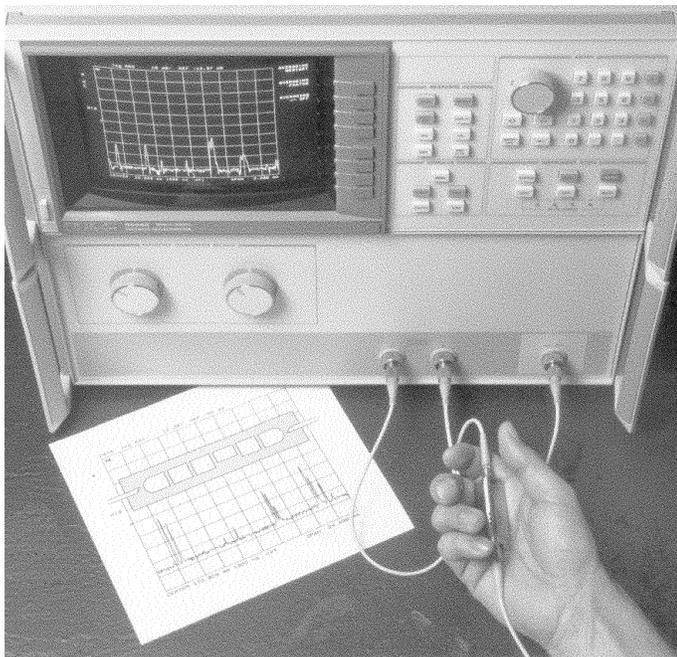
Product Note 8504-1

Agilent Technologies
Innovating the HP Way

The precision reflectometer

A new development in optical reflectometry, the Agilent 8504B precision reflectometer, significantly extends measurement capabilities. The two-event resolution is better than 25 micrometers, while the dynamic range exceeds 80 dB. A measurement tool now exists specifically for the designer and manufacturer of precision lightwave components and connectors. The sensitivity exceeds that of the best power meter solutions, while the resolution is sufficient to isolate each individual reflection within a small, complex optical assembly.

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Agilent 8504B
operation summary

The following one page operating summary is intended as a brief reference. Detailed information is discussed within the product note.

1. Warm-up the instrument: For maximum dynamic range and measurement stability, allow the instrument to warm up for two hours.

2. Clean all connections: Clean all fiber connectors and instrument test ports used in both the calibration and measurement process.

At this point you can follow the operating procedure below, or use the instrument's "Guided Setup" feature. Press **SYSTEM**, [Guided Setup].

3. Select wavelength: Press **PRESET**, **MENU**, and select the appropriate wavelength (under [SOURCE MENU]).

4. Determine reference extension length: Measure the length (L2) of fiber cable leading to the device under test (DUT). Attach extension cable L1 between the reference extension ports with length equal to or slightly less than L2. If the extension cable length L1 is greater than L2, the device may not be seen in the instrument's measurement range.

5. Perform a calibration: This removes DC offsets and polarization sensitivity, and sets a calibrated reference level. Select **CAL**, [Guided Cal]: Terminate the instrument test port with the high return loss load (>40 dB) supplied with the instrument. Adjust the polarization balance as directed.

Note: Once the polarization calibration has been performed, the reference extension cable L1 and the polarization adjustment knobs must remain stationary. Attach a fiber

cable of length L2 or slightly longer, with known return loss (typically a Fresnel reflection) to the instrument test port. Measure the standard as directed. If the system is operating correctly, there should be a single response seen, similar to the display shown below.

6. Connect the test device: Attach the device under test (DUT) to the instrument test port. Let the instrument complete a full sweep. Locate the reflections of interest and reduce the measurement span as much as possible using the **MKR FCTN** and span keys.

7. Increase sensitivity: Increased sensitivity can be achieved through averaging. Press **AVG**, [AVERAGING ON]. The number of averages is set using the [Averaging Factor] function. The number of averaged traces is displayed at the left border of the display.

Agilent 8504B Measurement Setup
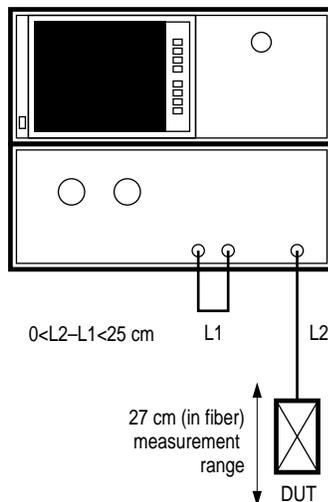
Typical Display
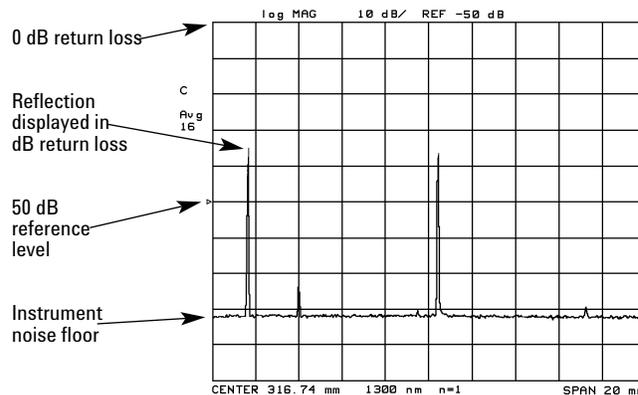
Return loss concepts and measurement techniques

Basic concepts of reflection

When light travels across the boundary between materials with different indices of refraction or densities, some portion of the light will be reflected. The figure below shows the simplest form of this concept, a plane wave traveling perpendicular to the boundary between the two materials.

Boundary

N1   **N2**

Incident   Transmitted

Reflected

The *reflection coefficient* 'ρ' of this interface is the ratio of the reflected electric field to the incident electric field and is given by the following:

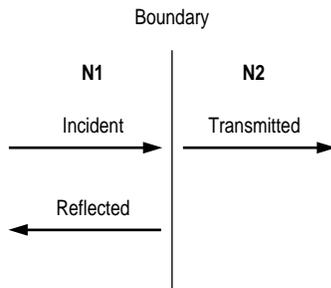$$\rho = \frac{n_1 - n_2}{n_1 + n_2}$$

where n_1 is the index of refraction for the material the light is propagating from and n_2 is the index of refraction of the material the light is traveling to.

The *reflectance* 'R' is a similar term and is defined as the ratio of the reflected beam intensity to the incident beam intensity and is given by:

$$R = \rho^2$$

$$= \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$

(In the above cases, it is assumed that the light is traveling normal to the interface plane.)

An example of this phenomenon is an air-to-glass interface. Air has an index of refraction of 1, while glass has an index of approximately 1.5.

The reflectance of this interface is then 0.04 or 4% while the reflection coefficient is –0.2. A negative reflection coefficient is an indication that the reflected field has experienced a 180-degree phase shift relative to the incident field.

The reflective properties at an interface can also be described logarithmically in decibels. This parameter is called return loss (RL) and is given by:

$$RL = -10 \log_{10}\left(\frac{\text{power reflected}}{\text{power incident}}\right)$$

$$-10 \log_{10} R$$

The air-glass interface would have a return loss of 14 dB.

Notice that the smaller the reflection, the larger the return loss. This shows the utility of using return loss to describe very small reflections.

Note: In measuring reflections, intuitively you would expect low reflections to be displayed lower than high reflections. Consequently, the Agilent 8504B uses a different convention in displaying return loss. Return loss is computed as:

$$10 \log\left(\frac{\text{power reflected}}{\text{power incident}}\right)$$

as opposed to:

$$-10 \log\left(\frac{\text{power incident}}{\text{power reflected}}\right)$$

Thus a return loss of 20 dB is displayed as –20 dB and a return loss of 50 dB is displayed as –50 dB.

The majority of this document deals with components and devices used in systems that use optical fiber. Another phenomenon that must be considered is the coupling of the reflected light back into the fiber. In general, the light from a reflective interface is not collimated and only a portion will return back through the fiber. Thus, the definition of return loss must be modified again. Return loss is then defined in terms of what actually propagates back through the fiber rather than what would be predicted solely from the differences in the refractive indices at a boundary.

Problems that result from reflected light

The most obvious problem that occurs when light is reflected is that the transmitted signal is reduced. In the previous glass-to-air interface example, since 4% of the light was reflected, only 96% of the original signal was transmitted. This corresponds to a $(-10 \log_{10}(0.96))$ 0.2 dB loss in power.

Sometimes more important than power loss is the effect that reflected light has on the performance of lightwave components. Today's high-speed lightwave communication systems typically use narrow linewidth lasers. The relative intensity noise (RIN) and modulation characteristics of such lasers can be significantly degraded by *very* small amounts of backreflected light. Reflected light can also cause "bit errors" in digital communication systems and distortion in analog communication systems.

As light reflects off one interface, the reverse traveling waveform may be re-reflected off another interface (closer to the source). This results in two forward traveling waves. The magnitude of the composite forward traveling signal is the vector sum of these two waveforms. Depending on the phase relationship of the two signals, which is in turn dependent on wavelength and the path length that the reflected wave traveled, the two waves may add either constructively or destructively. Subtle changes in source wavelength and environmental changes (such as temperature) can cause this phase relationship to vary significantly. Thus, the total power seen at the detector will vary with time.

For these above mentioned reasons, the components used in lightwave systems such as isolators, connectors, and photodiodes typically have very high return loss (low reflections) and as few reflections as possible.

Survey of return loss measurement techniques

Contemporary methods

Virtually all return loss measurement techniques employ some type of optical reflectometry. This consists of illuminating the device under test and measuring the light that is reflected back. Optical reflectometers include power meter/coupler based systems (sometimes called optical continuous wave reflectometers or OCWR), optical time-domain reflectometers (OTDR), optical frequency-domain reflectometers (OFDR), and the Agilent 8504B precision reflectometer. Each of the above mentioned measurement techniques offer unique advantages and benefits.
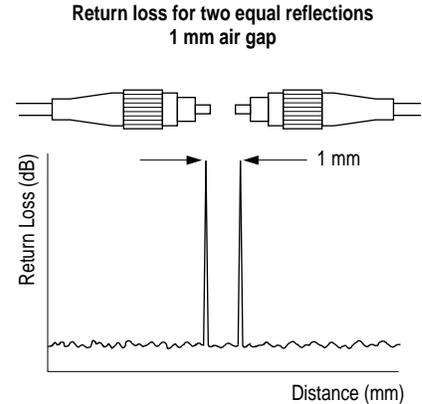
Power meter/coupler based measurements

Return loss measurements can be made using a power meter such as the Agilent 8153A lightwave multimeter and the Agilent 81534A return loss module. The return loss module contains a sensitive detector and a directional coupler. The source module of the Agilent 8153A illuminates the test device, while the directional coupler and detector sense only the power that is traveling in the reverse direction.

This system is best suited for accurate measurement of devices with a single reflection such as connectors, splices and attenuators. It is also used to measure the aggregate or "total" return loss of a device with multiple reflections.

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[1] In theory, if there were no coupling losses, the stimulus was monochromatic, and all of the signals re-reflected in the cavity were considered in addition to the primary reflections, the return loss can go to infinity, implying a resonant condition.

Return loss when there are multiple reflections

While the power meter system is both economical and easy to use, it does not provide any spatial information for resolving multiple reflections. There are two important implications to consider. First, identifying and quantifying each reflection is important in the design and manufacturing of high return loss components. Second, the total return loss of a component can vary significantly when two reflections create a Fabry-Perot resonator.
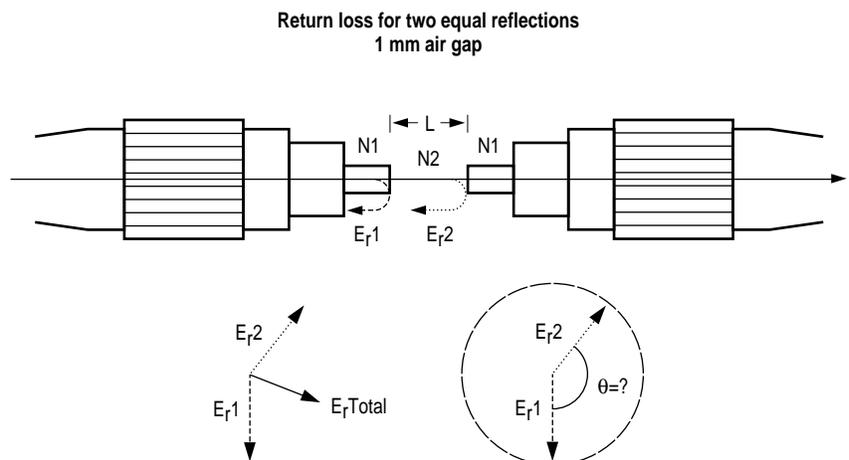
When multiple reflections exist, the spectral characteristics of the light source must be considered. If the light source has a very narrow linewidth, it will then have a very long coherence length. In brief, this implies that the phase characteristics of the light are very stable. When light reflects off two discrete interfaces there will be two reverse traveling waves. The total reverse traveling power will be related to the vector sum of the two waves. The phase relationship of these two signals is dependent upon the source wavelength and path length between the two reflecting interfaces. The relative phase between the two waves will then determine whether they will add constructively or destructively. This is related to the Fabry-Perot effect. An example of the phe-

nomenon can be demonstrated with a simple connector pair with an air gap of 1 mm.
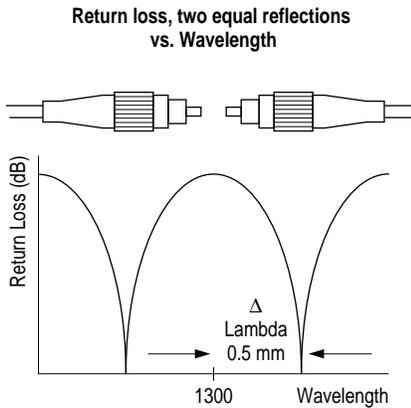
Forward-traveling light will first encounter the glass-air interface at the end of the first connector. Approximately 3.5% of the light will be reflected. The majority of the light will continue to the air-glass interface of the second connector. Again, there will be a 3.5% reflection.

At several discrete wavelengths (such as 1300 nm), the air "cavity" length is such that the two reflected waves will be precisely in phase, and the reflected power will be at a maximum. However, at other wavelengths (such as 1300.4 nm), the two waveforms will be out of phase, and the two signals will add destructively. The reflected power will be at a minimum[1].

**Return loss for two equal reflections
1 mm air gap**

**Return loss for two equal reflections
1 mm air gap**

A plot of return loss versus wavelength shows this result graphically. This effect is repetitive as a function of wavelength so that maximums and minimums will occur at several wavelengths.

Return loss, two equal reflections vs. Wavelength

It is worth mentioning again that this effect will only occur when a highly coherent source is used. This has some important implications.

The return loss of a component can vary significantly depending upon the stimulus. Return loss testing of a component may not accurately predict its behavior in a working system if the source characteristics are not similar in both situations. In addition, when components are used in a system with a high coherence laser (such as a DFB or Nd.YAG), the component return loss characteristics may change dramatically as wavelength and temperature are even slightly varied.

To more completely understand the reflection characteristics of components and subassemblies, the individual reflections must be isolated and characterized. Other measurement techniques are used to both locate and quantify individual reflections.

The OTDR

Optical time-domain reflectometry is the most familiar and commonly used reflectometry measurement for the installation and maintenance of both long- and short-haul fiber links. OTDRs locate faults by probing a fiber with an optical pulse train and measuring the reflected and backscattered light. OTDR's are typically not used for component-level measurements due to limitations in resolving small or closely spaced reflections, unless very short impulses and very high-speed, sensitive detectors are employed.

The OFDR

The two-event resolution and dead-zone problems inherent with OTDR's can be improved by using a swept modulated lightwave instead of pulses of light. The amplitude and envelope phase response is recorded over a wide frequency span. An inverse Fourier transform is performed on this data to yield the time-domain response. Depending upon the modulation bandwidth of the instrument, the two-event resolution can be better than 10 mm (20 GHz bandwidth). The receiver is synchronously tuned to the source, thus decreasing the susceptibility to noise and increasing the dynamic range to levels near 40 dB. (See product specific literature for the Agilent 8702 and Agilent 8703).

The Agilent 8504B precision reflectometer

A new development in optical reflectometry, the Agilent 8504B precision reflectometer, significantly extends measurement capabilities. The two-event resolution is better than 25 micrometers, while the dynamic range exceeds 80 dB. A measurement tool now exists specifically for the designer and manufacturer of precision lightwave components and connectors. The sensitivity exceeds that of the best power meter solutions, while the resolution is sufficient to isolate each individual reflection within a small, complex optical assembly.

The Agilent 8504B precision reflectometer is based on the Michelson interferometer and uses the techniques of "white light" interferometry. A 1300 nm or 1550 nm low-coherence light source is sent to a power splitter. One path leads to the DUT, while the other path leads to a reference mirror. Light reflected off both the reference mirror and the DUT is recombined and detected. If the path length from the source to the reflection in the DUT is the same as from the source to the mirror, a coherent interference signal appears at the detector. By moving the position of the reference mirror, the instrument can then "scan" the test device for reflections over a 400 mm range (equivalent air distance).

**Precision lightwave reflectometer block diagram**
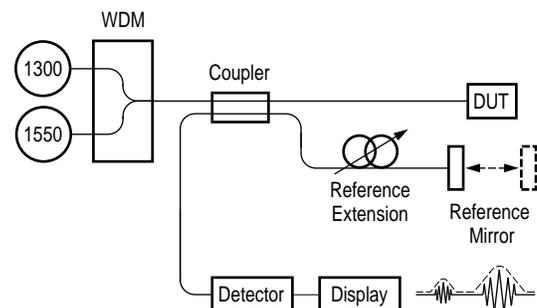
(The 400 mm measurement window can be offset by simply adding length to the reference path at the instrument front panel).

Note that in this measurement scheme there are no pulses of light transmitted as there are for the OTDR, and the light is not modulated as it is for the OFDR. It is the short coherence length of the LED source in the precision reflectometer which leads to very high resolution measurements.

To demonstrate the utility of such an instrument, consider a high-speed photodiode.
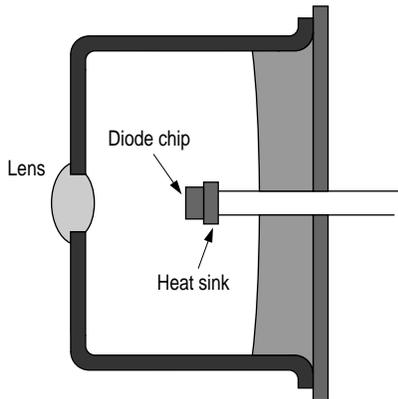
The physical dimensions of the device are much less than a centimeter, yet there are several interfaces within the device, each potentially generating a reflection and contributing to the overall return loss of the device. Very high resolution is required to locate, identify and quantify each reflection. The precision reflectometer easily performs this task, as seen in the following measurement.
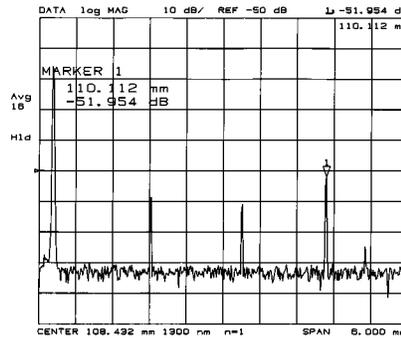
In this measurement, return loss is displayed versus the one-way path distance. The measurement span is 6 mm so the horizontal scale is 0.6 mm per division. Return loss is displayed in decibels. The top of the display is 0 dB return loss, the center of the display is –50 dB. Higher return loss levels are displayed as a lower value on the display since they correspond to lower values of reflection. (Intuitively, you would expect low reflections to be displayed at the bottom of the screen). Thus a 51.9 dB return loss value is displayed as –51.9 dB as noted by the measurement marker, which corresponds to the reflection at the front face of the diode chip.

The first reflection is the end of the fiber connector. It approaches a Fresnel reflection since the fiber does not physically contact the device. The reflections off the front and back of the lens, and the front and back of the diode chip are clearly seen. From this measurement, you see that the return loss of this device is dominated by the front face of the diode chip. However, a power meter measurement would be dominated by the reflection off the end of the fiber, making it difficult to extract any information about the photodiode itself.

It is also important to note the high dynamic range that the interferometer technique offers, several orders of magnitude beyond the capabilities of traditional methods.

The measurement range of the precision reflectometer is determined by the length that the reference mirror can travel and is 400 mm (equivalent air distance). If measurements beyond the 400 mm window are required, the window is simply offset with the appropriate reference extension patch cord.

Knowing the magnitude and spacing of the reflections yields information that is useful in determining component performance in systems with narrow linewidth lasers. Specifically, how much the return loss may vary for a given change in wavelength.

In summary, there are several techniques for measuring return loss. The easiest method is to use a power meter. When reflections need to be spatially resolved, the OTDR is used for coarse measurements of long lines. The OFDR can be configured for long-line measurements or close-in measurements, depending on the modulation bandwidth used. For the highest resolution and dynamic range, the Agilent 8504B precision reflectometer technique is optimum.

General measurement process with the Agilent 8504B

A condensed summary of the measurement procedure is found in the front of this document. In operating the instrument there are "hardkeys" and "softkeys". Hardkeys are those keys whose function is printed directly on the physical keypad. These keys are noted with bold type such as **PRESET**. Softkeys are those that are located to the right of the instrument display and whose function is displayed on the instrument display. They are noted in brackets such as [MKR ZOOM].

There are seven steps to performing a measurement.

1 Warm up the instrument
2 Clean fiber ends and instrument test ports
3 Select operating wavelength
4 Select reference extension
5 Perform a calibration
6 Connect the DUT
7 Optimize the measurement

The Agilent 8504B has a "Guided Setup" feature. Guided Setup is a powerful user interface that leads users through the steps required to make measurements. Guided Setup is implemented by pressing **SYSTEM**, [Guided Setup]. The instrument will then display each step required to setup and calibrate the instrument.

The following text describes the steps used in Guided Setup, as well as some discussion on why each step is performed.

Warm-up the instrument

The Agilent 8504B is capable of making measurements of extremely small reflections. Even very small spurious signals within the instrument can degrade dynamic range. To ensure maximum dynamic range and measurement stability, turn on the Agilent 8504B and allow it to warm up for two hours prior to mak-ing measurements. This will ensure that various DC offsets within the instrument have stabilized and can be effectively removed from subsequent measurements.

Once the instrument has been warmed up, the "Guided Setup" feature can be used.

Clean fiber ends and instrument test ports

It is a good measurement practice to clean fiber interfaces before performing calibrations and making measurements. Clean fiber ends and connector ports are essential for good measurements. All three instrument ports and any fiber ends (including the reference extension) should be kept clean. Dirty connectors can result in spurious responses and reduced dynamic range. To clean the instrument ports, the connector adapters are removed from the instrument front panel, exposing the cable ferrule.

Caution: Extreme care should be taken to avoid damaging the instrument connector ferrules. Damaged connectors reduce measurement integrity and are not user serviceable.

Please refer to the connector care document in the manual for connector cleaning and care.

Select operating wavelength

The standard configuration for the Agilent 8504B includes both 1300 nm and 1550 nm measurement capability. When not using Guided Setup, to select between 1300 or 1550 nm operation, press **MENU**, [Source Menu], and either [1300] or [1550].

Select reference extension

The first step in making a measurement is to select the appropriate length of reference extension cable. In general, the reference extension cable length should be equal to the "pigtail" or path length to the device to tested. The length of the reference extension may be slightly shorter than the pigtail, but should not be longer. If the reference extension is slightly longer than the DUT cable, some of the events to be examined may not be in the 400 mm (air) measurement span of the instrument.

The Agilent 8504B is designed so that if the reference extension length is identical to that of the DUT fiber, the first response will appear approximately one division to the right of the left edge of the display (in a 400 mm span). This means that under nominal conditions, the reference extension cable should be less than 10 millimeters equivalent air length (7 mm actual fiber length) longer than the DUT fiber. Due to the 400 mm allowable measurement span, the extension should be no more than 360 millimeters (250 mm actual fiber length) shorter than the DUT fiber. In mathematical terms, this is given by: $-7 \text{ mm} < L2 - L1 < 250 \text{ mm}$ where: L2 is the DUT fiber length and L1 is the reference extension length.

The ideal condition is to have the two cables be of equal length.

The Agilent 8504B option 001 contains reference extension cables of 40, 50, 75, 100, 125, 150, and 175 cm lengths. Optimum reference extension length depends upon the path length to the DUT.

If the DUT has no pigtail, L1 and L2 are any two cables of equal length.

Option 001 Cable connection guide

| DUT path L2 (cm)	Ref ext cables L1
40<L2<65	40
50<L2<75	50
75<L2<100	75
90<L2<115	40+50
100<L2<125	100
115<L2<140	40+75
125<L2<150	125
140<L2<165	40+100
150<L2<175	150
165<L2<190	40+125
175<L2<200	175
190<L2<215	40+150
200<L2<225	50+150
215<L2<240	40+175
225<L2<250	50+175
240<L2<265	40+50+150
250<L2<275	75+175
265<L2<290	40+50+175
275<L2<300	100+175
290<L2<315	40+75+175
300<L2<325	175+125
315<L2<340	40+175+100
325<L2<350	175+150
340<L2<365	40+175+125
350<L2<375	75+100+175
365<L2<390	40+150+175
375<L2<400	50+150+175

Measurement calibration

Once the reference extension has been selected and attached to the instrument, the instrument must go through a measurement calibration. The measurement calibration consists of balancing the polarization-diversity receiver and calibrating the instrument for accurate reflection magnitude measurements.

Balance receiver

As light travels through single mode fiber, its polarization characteristics vary. The magnitude of the detector response is potentially a function of the polarization of the reflected waveform relative to the light in the reference arm. Ideally, the detector response is only a function of the reflection magnitude. To ensure that the reflection measurement is insensitive to polarization transformation, a measurement calibration process is used. The instrument receiver consists of two photodiodes which respond to orthogonal states of polarization. During the Balance Receiver calibration, the instrument test port is terminated with a high return loss optical load (greater than 40 dB) which is supplied with the instrument. Therefore the light that hits the two detector diodes is only from the reference mirror. The polarization of this light is adjusted with the polarization adjustment knobs at the instrument front panel in such a way that the responses from each detector are equal or balanced.
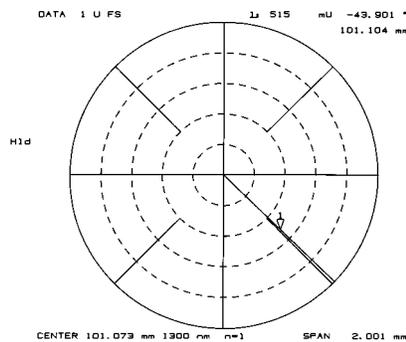
*Note: Polarization of the light in the reference path **must not be altered** once the Balance Receiver calibration has been performed. The reference extension cable and polarization adjustment knobs **must not be moved** to ensure optimum performance. If the reference extension is moved, the receiver will no longer be balanced and subsequent measurements may be in error.*

To perform the Receiver Balance step, simply follow the instructions given by the instrument.

Magnitude calibration

The magnitude calibration is a simple process consisting of measuring a known reflection. The instrument then automatically scales the measured response so the true value is displayed.

For every reference extension cable supplied in the Agilent 8504B option 001, there is a corresponding fiber of equal length which may be used as a calibration standard. The return loss of the fiber end (a super PC ferrule) is 15 dB or 3.16% reflection at 1300 nm and 14.7 dB or 3.37% at 1550 nm.

As you continue with the "Guided Setup" procedure, the instrument will display the instructions to perform the magnitude calibration. The Agilent 8504B scans through the entire measurement span and determines the value of the peak response, which should be the reflection generated at the end of the cable. If you use a reflection standard other than a Fresnel reflection, it must have a return loss greater than 14 dB to prevent saturation of the receiver.

The Agilent 8504B compares the measured value to the value entered by the user. Any differences are due to systematic errors in the measurement system. This error term is subsequently removed from all further measurements until another calibration is performed or the instrument is preset to the default settings.

As a check, the calibrated measurement of the reflection standard can be compared to the known value.

It is important to note that there is no length calibration process and consequently the Agilent 8504B does not make absolute length measurements directly. It is a common misconception that the measurement calibration process will offset the position of the reflection standard to the 0 length position. Recall that when the length of the DUT fiber is identical to that of the reference extension, the first event appears at about the 40 mm point and not 0 mm. The instrument has no knowledge of the length of the reference extension cable used, nor the length of fiber to the device under test. Therefore, all distance accuracy is in terms of relative distance to other reflections in the measurement span.

Connect and measure the test device

The calibrated instrument can now be used to measure devices. Once the device is connected, it must be located on the screen. If a device is connected while the instrument is in a measurement sweep, a response may be generated in the process of making the connection that is not related to the actual device response. Consequently, it is a good measurement practice to restart the measurement as soon as the device is attached. Press **MENU**, [Full span], **MEAS**, [Meas restart]. The instrument will then scan over its full measurement range and display all detectable reflections within a 400 mm (air) span.

Optimizing the measurement

For measurements at 1300 nm, the reference mirror in the Agilent 8504B travels at a constant velocity of 18 mm/sec (21 mm/sec at 1550 nm). A 0 to 400 mm sweep will take over 22 seconds. The sweep-to-sweep time can only be reduced by reducing the measurement span. Reducing the measurement span will also increase the spatial resolution of multiple reflections. It is recommended that once the DUT responses have been located, to reduce the measurement span to the narrowest range that includes the events of interest.

Narrowing of the span can be achieved using the **MKR FCTN** menu and [MKR ZOOM] key, or by using the **SPAN**, **CENTER**, **STOP**, and **START** keys.

Once the measurement span has been optimized to include all events of interest, the noise floor can be reduced through data averaging. Averaging reduces the effects of random noise, and can increase the measurement range by 6 or 7 dB. (Note: the narrower the measurement span, the more effective averaging becomes). Press **AVG** and [Avg on]. The default averaging factor

is 16, meaning that each new measurement is weighted by a factor of 1/16 and will contribute this value to the current measurement trace. The averaging factor can be set to any integer value between 2 and 999.

Measurement example: connector pair

In this measurement example, you will measure the return loss of a simple connector pair. In addition, you will see the connector characteristics as it makes the transition to a fully torqued connection.

Measurement procedure

Using the same general measurement process described above, select the reference extension cable. The device to be measured is a simple connector pair. One of the connectors is at the end of a 75 cm patch cord. Since the path length to the DUT is simply the length of this patch cord, the ideal length for the reference extension is 75 cm. The reference extension could be as short as 51 cm, which would place the reflection at the end of the measurement range, but should not be any longer than 75 cm.

To calibrate, follow the Guided Setup or press **CAL**, [GUIDED CAL], attach the supplied high return loss termination at the test port, adjust the polarization adjustment knobs for a balanced display as instructed by the instrument and press [DONE]. For the magnitude calibration, the calibration standard can be one of the 75 cm cables supplied with the instrument, or the DUT patchcord connector end (if the return loss is known). Connect the calibration standard to the test port. Press [FRESNEL 3.16%] when using the supplied cable or [USER STD] and enter the value for the reflection.

Press [MEASURE]. The analyzer will then measure the standard and adjust its measurement to coincide with the actual reflection value.

The patch cord to be tested can now be connected to the test port. Once it is connected, press **MENU**, [FULL SPAN]. The instrument will then bring the reference mirror to its starting position and begin a new measurement trace. The position of the mirror is indicated by a small red dot at the bottom of the instrument display. The location of the dot on the instrument display is proportional to the location of the mirror on the translation stage. For instance if the start position of the measurement is set at 0 mm and the stop position is set at 100 mm, the mirror will then be traveling back and forth over the first 25% of the available mirror movement. The mirror position indicator dot will then move back and forth from the left edge of the screen to a point 25% or 2.5 divisions away from the left screen edge. The actual data measured will be displayed across the entire screen.

As the mirror travels across its full 400 mm range, the reflection from the end of the 75 cm patch cord should be seen at approximately the 40 mm point. Because the connector is not terminated, a return loss of about −15 dB should be seen.
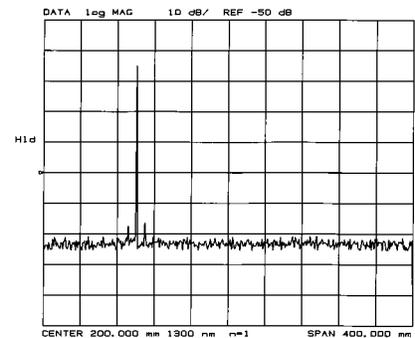
Increasing the measurement rate

To increase the measurement rate, the measurement span must be reduced. Press **MKR FCTN**, [MAX SEARCH], [MKR ZOOM]. The marker zoom function places the event indicated by the marker (in this case the maximum response) to the center of the screen and sequentially decreases the measurement span each time the function is activated. Repeat the process until the span is 20 mm.
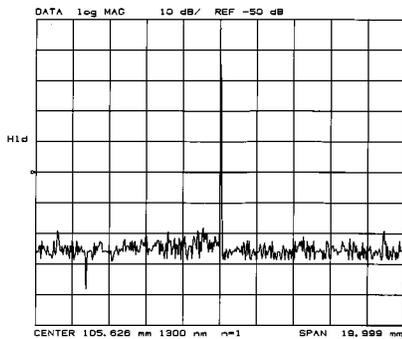

Next, examine the return loss as the second half of the connector pair is mated with the first. As the second ferrule approaches the first, you see two reflections, spaced 2.5 mm apart. The reflection off the second ferrule is low because not all of the reflected light is coupled into the fiber.
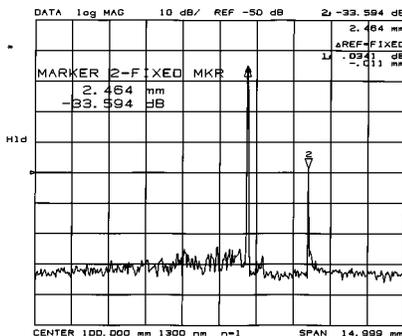
As the two ferrules are brought closer together, the second reflection appears larger as the coupling efficiency increases. Notice also that re-reflections are also seen to the right of the second reflection. The air gap between the two ferrules is now only 32 microns.
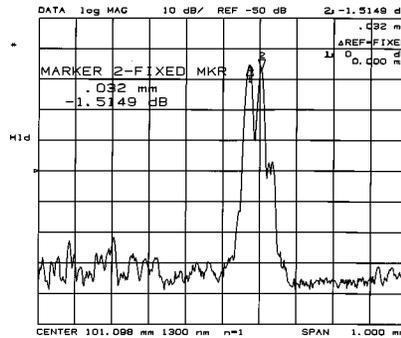
As the connector pair is fully torqued, the two ferrules make physical contact and the two reflections become one. The return loss increases to approximately 40 dB, which is a function of the type of connector tested and its cleanliness.
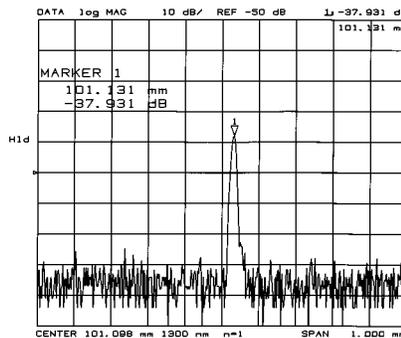
Although this example is of a very simple device, it shows the two basic measurement parameters of the precision reflectometer, specifically high spatial resolution and high dynamic range. The following example shows the usefulness of these measurement capabilities.

Measurement Example: Characterizing a photodiode assembly

In this example you will measure a component that is physically very small, yet has several optical interfaces, each generating a reflection.

Measurement Procedure

The procedure for measuring this device is virtually identical to that used for the connector pair. Because the photodiode does not have a pigtail, we simply connect it to the end of the test port patchcord. The response will be more interesting due to its more intricate construction.

Follow the connector pair measurement example to the point where the end of the connector is first measured. At this point connect the photodiode. The display should then show several closely spaced responses.
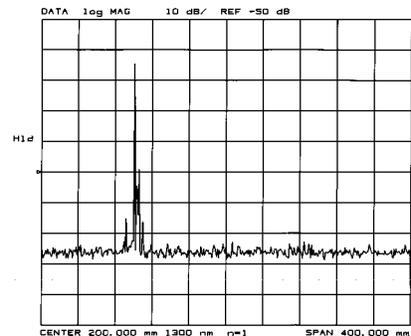

Optimizing the instrument setup

To speed up the measurement rate and increase the measurement resolution, the measurement span should be decreased to the smallest span that still displays all the responses of interest. Narrowing of the span can be achieved using the **SPAN**, **CENTER**, **STOP**, and **START** keys, or by using the keys under the **MKR FCTN** menu.

Press **MKR FCTN**, and use the knob to move the marker slightly to the left of the first event on the screen. Press [Mkr–> Start]. Then use the knob to move the marker to the right of the last event on the display. Press [Mkr–> Stop].
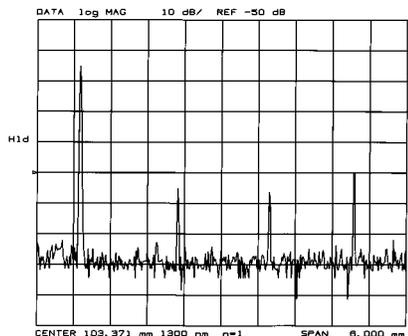

In this measurement, there are several reflections, some which are very small. Through averaging, the measurement sensitivity can be increased. Press **AVG**, [Averaging On], and let the instrument take several sweeps. This allows us to see reflections that may not have been visible before. In this measurement, a fifth reflection is now clearly visible.
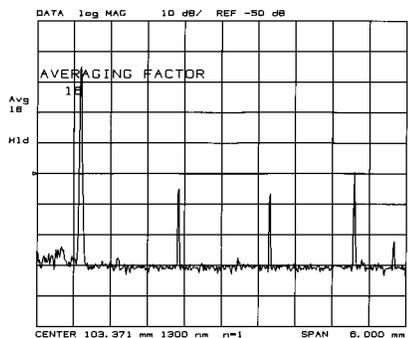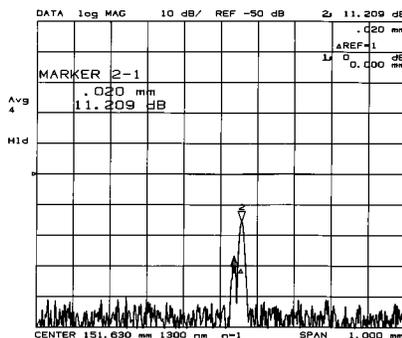

Measurement example: High return loss air-gap connector

An example of this is a very high return loss beveled-edge connector. The connector response is easily seen.
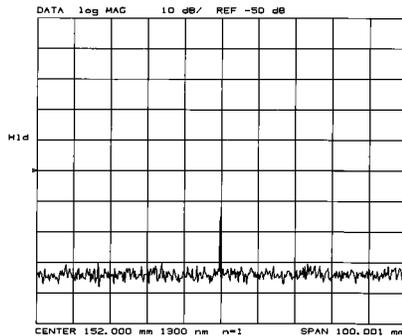
For this particular connector, you not only measure the return loss, by decreasing the measurement span to 1 mm, you measure the gap between the connector ferrules.

Applications

The following sections demonstrate how the Agilent 8504B precision reflectometer can be used to measure a variety of lightwave components. Although the measurement examples are just a small sample of potential measurements, they do provide a diverse survey of the instruments capabilities and the types of measurements that can be made.

In virtually all cases, the processes for performing the measurements are the same as those described in the previous sections for measuring the photodiode assembly and the connector pair. When measurement techniques not previously introduced are encountered, these will be described in appropriate detail.

Measuring the reflections from an optical isolator

Isolators are used to minimize the impact of reflected light on other components, in particular narrow linewidth high-speed lasers. Not only must the isolator perform the function of attenuating backreflected light, it must do so without generating reflections of its own.

In general, isolators consist of a variety of components including lenses, crystals and Faraday elements. Each individual component may generate a reflection.

The procedure to measure the isolator is similar to that used for the photodiode in the previous section under "Measurement example: Characterizing a photodiode assembly." Once the instrument has been configured and calibrated, the isolator is connected and the display optimized.
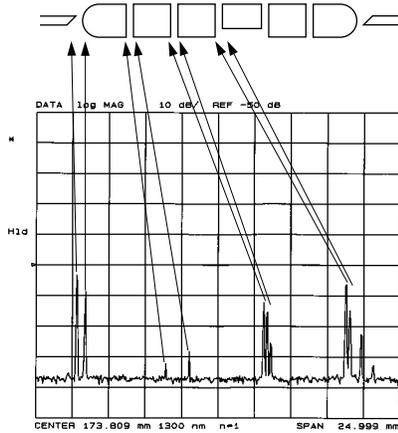

This device has several interfaces, so there are several reflections. The measurement span is 30 mm. The largest reflection, generated from the angled fiber end, is approximately 60 dB. Beyond the Faraday element, there are no reflections, indicating that the isolator is performing its intended function.

Characterizing reflections within a laser assembly

As mentioned earlier, lightwave source performance can be degraded by backreflected light. Measuring the reflections by probing back into the laser can give us insight into how light reflects internally as well as how back-reflected light may be re-reflected from the laser.

The device shown below will first be measured according to the previous procedures for measuring components.
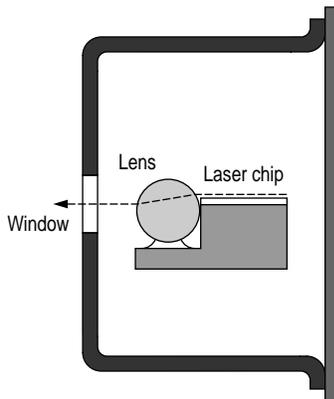

This particular laser module consists of a protective window, a ball lens, and the laser chip. During normal operation of the laser, light propagates from the chip and is focused and aligned through the ball lens before leaving through the window into an attached fiber. Light traveling back into the laser will follow a similar path.

The resulting measurement shows the reflections generated at each interface. The largest reflection is the fiber end. Marker 1 shows the reflection from the front of the window, 2, the back of the window, 3, the front of the ball lens, and 4, the back of the laser chip.
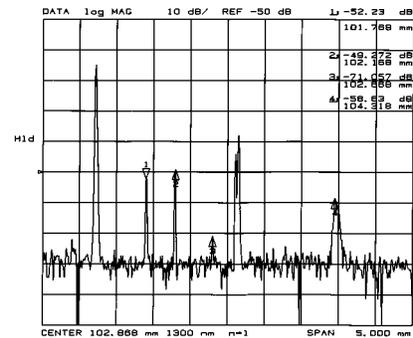

The response between marker 3 and 4 indicates where the back of the ball lens and front of the laser chip meet. Zooming in, we will examine this region.
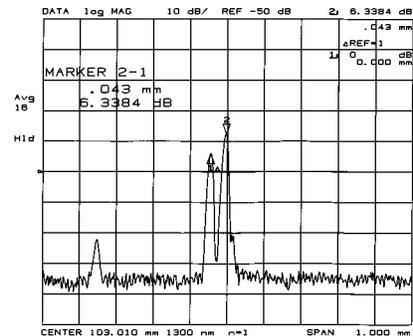
Here we see that there are actually two reflections since there is a small gap between the lens and the laser chip. The size of the gap is 43 microns.

Part of the transmission path of this device is the semiconductor material of the laser. This material is more transparent at 1550 nm than at 1300 nm. By making the measurement at 1550 nm (this requires a new measurement calibration), the reflected energy from the end of the laser chip experiences less attenuation and is then effectively larger.
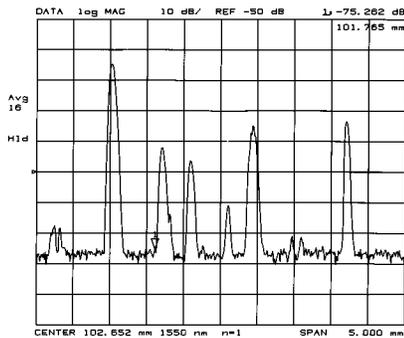

Typically, the transparency of the semiconductor material will vary with the bias current through the laser. However, if the laser is biased above threshold, the transmitted energy may be sufficient enough to saturate the receiver of the Agilent 8504B. Therefore, care must be taken in setting the laser current to optimize the tradeoffs between material transparency and instrument saturation level.

Characterizing devices pigtailed with multimode fiber

The Agilent 8504B precision reflectometer measurement system detects reflections when the path length to the reflection is identical to the path length to the reference mirror. Because the light traveling through multimode fiber will propagate over many different paths, the measurement of reflected energy through multimode fiber will be different than if the device were pigtailed with single mode fiber.

In essence, the reflection responses tend to be broadened. An example of this would be to measure the Fresnel reflection at the end of a 1.25m length of 62.5/125 multimode fiber compared to a similar measurement with 9/125 single mode fiber.
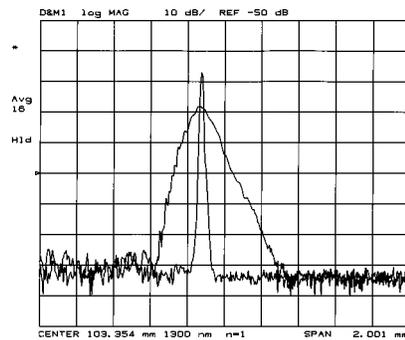
Two things are apparent in the above plot. First, the response is significantly broadened. The 3 dB width is about 75 microns, compared to less than 15 microns for the single mode case. Second, the amplitude of the reflection is reduced. This is due to two factors. The total energy of the reflection is distributed over a wider range, which decreases the peak amplitude. In addition, a significant amount of the reflected energy is lost at the multimode to single mode core mismatch at the instrument test port.

The above measurement is for a specific length of multimode fiber. As the length of fiber increases, so does the effective pulse spreading. In addition, for multimode fiber lengths much beyond one meter, the multimode effect will generate multiple responses for a single event.

It is interesting to examine the impact that this spreading has on measurements. Consider the photodiode measurement introduced on page 11.
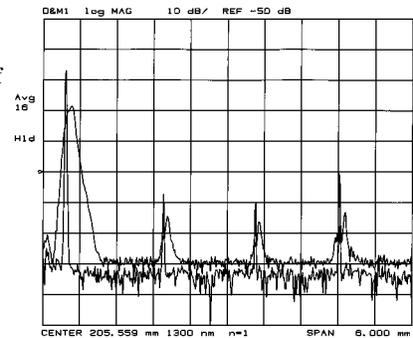
The above plot is a composite measurement of the same device. One measurement is with single mode fiber, while the other is with a 1.25m length of multimode fiber. Each reflection is still visible, and the relative magnitude information is still valid.

Although the measurement capability of the Agilent 8504B degrades when using multimode fiber, the dynamic range and two-event resolution provide very useful information in locating and identifying reflections.

Precision measurements of differential length: 1xN coupler

The Agilent 8504B is capable of making relative length measurements with very high resolution. This capability can be used to measure relative differences in path length. An example of this would be to measure a simple 1x2 coupler.
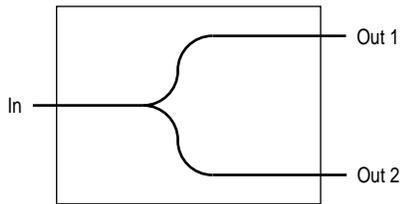

The function of the coupler is to divide the input power into two paths. In some applications, it is desirable to have the two path lengths as closely matched as possible. By monitoring the positions of the reflections at the coupler outputs, we can determine the differential path length.

The measurement is straightforward. After setup and calibration, the coupler is connected to the system. The output ports of the coupler are left unterminated, which generates two large reflections.
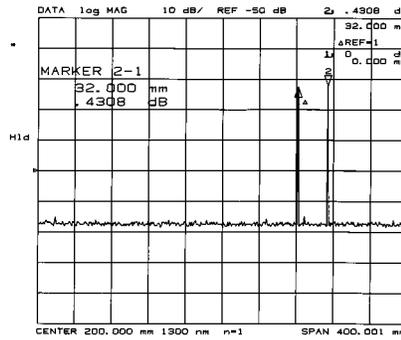
Determining the differential path length is a simple matter of placing a marker on each reflection. Press **MKR FCTN**, [Max Search], [Mkr–>Fixed Mkr], [MKR 2], **MKR FCTN**, [Peak search], [Next highest peak]. The analyzer will then display the one-way distance between marker 1 and marker 2. The measured distance value is the equivalent distance traveled in air, which in this case is the differential path length to the two output ports. To determine the physical path length difference, the index of refraction value must be entered into the instrument. In the case of glass fiber, the index of refraction is 1.46. Press **MEAS**, [N VALUE], and enter **1.46 x1**. The displayed distance is now the true one-way physical length difference.
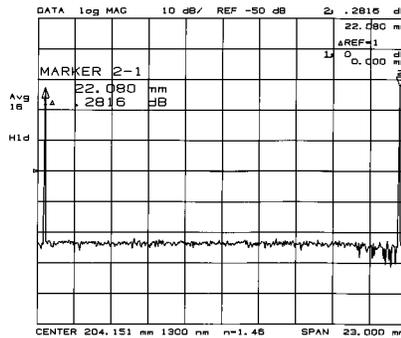
In order to identify each path, we simply terminate one of the ports. As expected, one of the measured reflections will decrease in magnitude thus indicating which response coincides with the terminated port.

This procedure can be used for virtually any 1xN coupler. The measurement limitations are sensitivity and two-event resolution. As the power is divided into more and more paths, the magnitude of the reflected energy from each output port will decrease. However, the sensitivity of the Agilent 8504B is such that the power could be divided into over 1000 ports and the reflections still be detectable.

Thus the Agilent 8504B is sensitive enough to measure virtually any 1xN coupler. Obviously, the practical measurement limitation then becomes the two-event resolution. As the differential length of two paths get smaller and smaller, the reflected signals displayed by the instrument will eventually overlap. The two-event resolution is 25 microns at 1300 nm and can be 65 microns at 1550 nm. Therefore, differential path lengths as small as 25 microns (air distance) can be measured.

The differential distance measurements can also be interpreted in a "time" mode format. This is used to indicate the differential time of flight or propagation time between events. Time format can be activated by pressing **FORMAT**, [TIME].
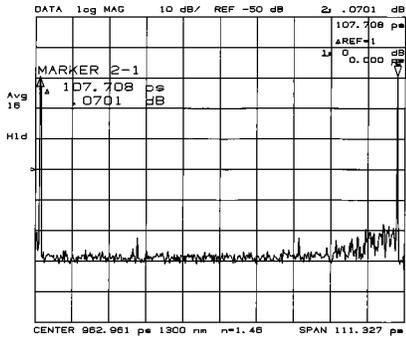

Using the time format, we can now determine the effective delay that one signal path experiences relative to others. With 25 micron two-event resolution, propagation delays as small as 80 femtoseconds can be characterized.

Characterizing high return loss terminations: index matching gel

Index matching gel is commonly used to terminate an optical fiber in an attempt to minimize reflected light generated at the fiber end. Once the gel has been applied to the fiber end, the common assumption is that virtually all of the light is scattered or "absorbed" and essentially no light is reflected back.

The high sensitivity of the Agilent 8504B allows us to see the real performance of matching gel. The results can be surprising.

The measurement is quite simple. The Fresnel reflection at the end of a cable is located and the instrument span is reduced to 1 mm. Then the end of the fiber is dipped in the matching gel. Typically, the result is that the single reflection is reduced to a return loss value better than 50 dB.
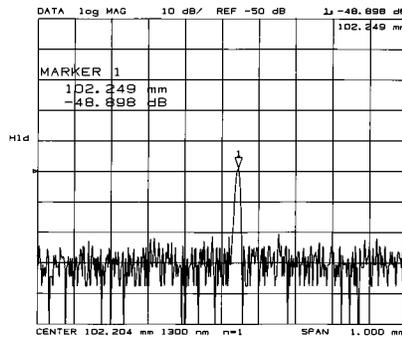
However, there are cases when two reflections exist, one at the glass/gel interface and a second reflection at the gel/air interface.
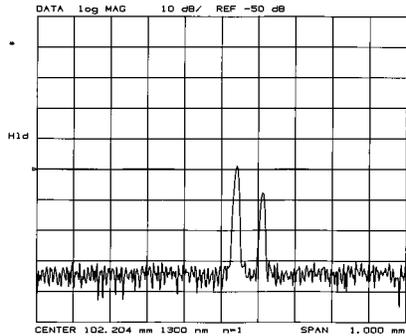
In most applications, the gel termination provides an adequate fiber termination. However, it is not safe to assume that it completely eliminates backreflections.

Common questions and answers

The following section deals with a variety of commonly asked questions about the Agilent 8504B precision reflectometer and the techniques used to make measurements.

Q. *Can the Agilent 8504B detect fiber backscatter?*

The coherence length of the Agilent 8504B source is approximately 10 to 15 um. The energy reflected from the DUT must have been generated within this length in order to be detected. Although there will be backscatter generated over this length, the amount of reflected energy is too small to be detected by the Agilent 8504B.

Q. *Can the Agilent 8504B measure fusion splices?*

The measurement sensitivity of Agilent 8504B allows reflections with return loss values up to 80 dB to be measured. In general, this is not sufficient to detect good fusion splices.

Q. *The Agilent 8504B displays 401 measurement points in any measurement span. Is it possible for an event to be between these points and therefore not be detected?*

The Agilent 8504B is designed to make a measurement every 2.5 microns along the measurement path, independent of the measurement span. The coherence length of the internal source is 10 to 15 microns. Thus several points will be measured within this coherence length. Consequently a reflection will always be detected, even if it falls between the actual points of detection.

For wide measurement spans, there are still only 401 data points displayed, yet measurements are made every 2.5 microns. For a 10 cm measurement span, there will be

40,000 measurements made. A point will be displayed every 250 microns (401 points over a 10 cm span). Thus each displayed point will represent the largest response detected over 100 actual measurements. This also indicates why the highest two-event resolution is achieved in the narrowest measurement spans.

Q. *Can the Agilent 8504B be used to measure devices pigtailed with multimode fiber?*

The Agilent 8504B can be used to make measurements in multimode fiber. However, amplitude accuracy and spatial resolution will be degraded. See "Characterizing devices pigtailed with multimode fiber" on page 14.

Q. *What happens when devices with polarization maintaining fiber (PMF) are measured?*

Depending upon how light is launched into PMF, it will travel at different velocities. Light traveling on one principal axis will travel at a different rate than light traveling on the other principal axis. The light emitted from the Agilent 8504B source is only partially polarized, thus light will typically be traveling on both axes. Thus for a single reflection, two extra responses may appear.

Q. *Will the moving mechanical components wear out?*

The gears and motors in the Agilent 8504B are all designed to work with much heavier loads and stresses than what is actually required. However, to avoid unnecessary wear, the Agilent 8504B will automatically go into trigger hold mode and stop sweeping whenever the instrument makes 500 sweeps (or the specified number of averages, whichever is greater) without the operator pressing a front panel key. Simply press **MEAS**, [Continuous], to resume sweeping.

Q. *Why are the interferometer fringe patterns not seen?*

An envelope detector is used to smooth out the fringe patterns, so only one response within the source coherence length is displayed.

Q. *What is the difference between measurements made with a power meter versus the Agilent 8504B and can I determine total return loss using the Agilent 8504B?*

Total return loss and spatially resolved return loss were discussed in "Survey of return loss measurement techniques" on page 5. Total return loss is a function of the source characteristics as well as the reflection magnitudes and their spacing. The 8504B can yield insight into the components of total return loss, but not give an actual value.

Q. *What effects do connectors or other losses have when placed in front of the DUT?*

Losses will reduce the measurement sensitivity of the Agilent 8504. If these losses are not included in the magnitude calibration, they will also decrease the measured value of reflections.

Q. *What happens when I measure a narrowband device such as a WDM filter?*

The high spatial resolution of the Agilent 8504B is based upon the wide spectral width and subsequent short coherence length of its LED source. If a test device's response varies versus wavelength over the spectrum of the source, amplitude accuracy and spatial resolution may be degraded.

Understanding Measurement Accuracy

There are several elements which affect the accuracy of any measurement made with the Agilent 8504B Precision Reflectometer. In general, various contributions to measurement error include systematic errors that are inherent in the Precision Reflectometer measurement technique and items that degrade measurement accuracy, yet can be minimized by the user through good measurement techniques.

Measurement errors can also be classified into those that affect amplitude measurement accuracy and those that affect positional or spatial accuracy.

Amplitude accuracy issues

The uncertainty in the Agilent 8504B measurement of return loss magnitude comes from several different factors including:

• Dynamic accuracy
• Connector repeatability
• Transmission path losses
• Measurement flatness vs. position
• Sweep-to-sweep repeatability
• Polarization sensitivity
• Calibration accuracy
• Chromatic dispersion effects
• Source spectral width

Dynamic accuracy

Dynamic accuracy refers to the ability of the Agilent 8504B to accurately measure over a wide range of return loss values. The Agilent 8504B is typically calibrated at the level of a Fresnel reflection. Ideally the response of the receiver block in the Agilent 8504B will be linear versus return loss. However, as the reflected signals from the DUT become very small, the response from the detector can deviate from this ideal linear relationship. Optimization of the receiver has minimized this effect. The resulting contribution to amplitude measurement accuracy is dependent upon the reflection magnitude. It is typically less than ±1.5

dB, but degrades as the reflection magnitude approaches 80 dB. Refer to the curves in the specification tables of the Agilent 8504B operating manual for detailed information.

For measurements of small reflections, dynamic accuracy can be a significant uncertainty term.

Connector repeatability

There will always be some insertion loss in any fiber optic connection. When the Agilent 8504B magnitude calibration is executed, the loss at the test port connection is effectively removed from the measurement of the calibration standard. However, when the DUT is connected to the test port, the insertion loss of this connection may be different than the connection made during calibration. If the insertion loss is higher by 0.5 dB, subsequent return loss measurements will be twice this or 1 dB larger than the actual value. This is because both the stimulus signal and the reflected signal will experience a 0.5 dB attenuation. Similarly, when the DUT connection to the test port is better than the connection at calibration, return loss values will be worse than actual by two times the insertion loss improvement.

It is therefore important that proper connector care and usage be observed to minimize the effects of connector repeatability.

Transmission path losses

Transmission path losses in the DUT affect measurements in a way similar to connector insertion loss repeatability.

Large reflections can degrade the measurement of other reflections further into the DUT. An example would be if a simple Fresnel air gap existed in front of other reflections. 3.5% of the energy is reflected at the glass-to-air interface, 96.5%

travels to the air-to-glass interface where again 3.5% of the energy is reflected. The net result is that only 93% of the stimulus signal (an 0.3 dB loss) reaches reflections beyond the air gap. Similarly, only 93% of the reflected energy will reach the instrument detector. The result is similar to having an 0.3 dB lossy splice, which would lead to 0.6 dB measurement errors.

Measurement accuracy vs. position

A portion of the internal light path to the reference mirror in the Agilent 8504B is an open beam environment. As the reference mirror is moved and the length of the open beam path is increased, there will be some beam divergence. This beam divergence can result in power variation in the reference beam at the detector. This phenomenon is very repeatable. Consequently, most of this effect is removed from the measurement as part of the factory calibration process.

The Agilent 8504B detection scheme requires that the reference mirror ideally moves at a constant velocity. However, there will be some velocity jitter.

The error due to the combination of the above two error sources is approximately ±1 dB.
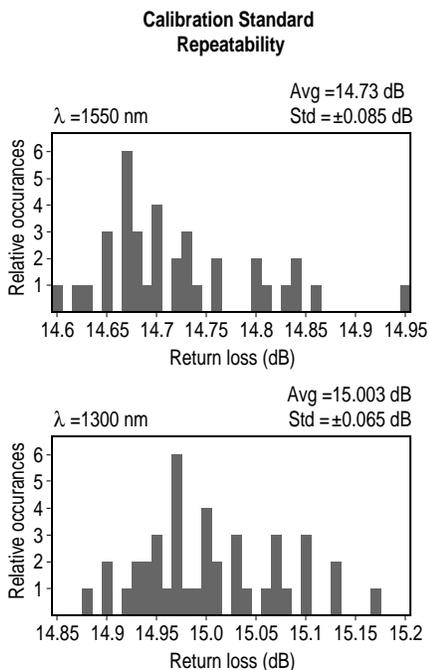
Sweep-to-sweep repeatability

Sweep-to-sweep repeatability is the sweep-to-sweep amplitude variation seen when measuring a known stable reflection. This error source is also related to the mechanical movement of the interferometer mirror. It does not include the effects of noise when measuring reflections near the instrument noise noise floor. It is specified to be less than ±0.5 dB.

Polarization sensitivity

The stimulus signal from the Agilent 8504B is randomly or only partially polarized. As the light travels to and from the DUT, its state of polarization will vary. Although the Agilent 8504B receiver is designed to be insensitive to the polarization characteristics of the reflected light, there will be some uncertainty in amplitude measurement accuracy due to polarization, even if the source stimulus is randomly polarized. This uncertainty is typically less than ±0.75 dB.

Calibration uncertainty

When a magnitude calibration is performed with the Agilent 8504B, the instrument uses the known return loss value of a calibration standard to remove many systematic errors in subsequent measurements. The cables supplied with the Agilent 8504B can be used as a reflection standard. The return loss value at the open end is consistent within ±0.1 dB. This uncertainty in the actual return loss of the calibration standard will result in uncertainty in DUT measurements of approximately ±0.1 dB.

**Calibration Standard
Repeatability**

Avg = 14.73 dB
Std = ±0.085 dB
λ = 1550 nm

Avg = 15.003 dB
Std = ±0.065 dB
λ = 1300 nm

To maintain this low uncertainty, the calibration standards (typically the end of a fiber patch cord) must be clean and undamaged.

Chromatic dispersion effects

Part of the propagation path of the reference signal is in an open beam. In most cases, light traveling in the DUT path is all in fiber. When making measurements at 1550 nm, the amount of chromatic dispersion experienced by the light traveling in the reference path will be less than that in the DUT path. This mismatch in dispersion results in a broadening and subsequent drop in the peak value of the displayed reflection "impulse".

The peak value will decrease monotonically as a function of the length of dispersion mismatch. This effect is consistent and has been corrected out by the Agilent 8504B. The instrument assumes a dispersion coefficient of 17 ps/(nm*km). The result of this correction leaves a residual error on the order of ±0.3 dB.

The problem becomes difficult when the path to the DUT is both in fiber and an open beam. The effects are then very difficult to remove from the measurement, and subsequent uncertainties due to chromatic dispersion can approach 5 dB. The user has the option of disabling the internal dispersion correction to facilitate his own correction methods.

Effects of source spectral width

The spectral width of the Agilent 8504B source is approximately 55 nm. Another uncertainty component will exist if the DUT reflection characteristics vary over this spectral range. The level of uncertainty is dependent on the DUT characteristics.

Positional Accuracy Issues

The accuracy of the Agilent 8504B in determining the relative location of reflections is based on its ability to control and monitor the position and velocity of the reference mirror. This uncertainty is less than 2% of the measurement span. To have the highest accuracy, the narrowest span that includes the two events of interest should be used.

Summary

In general, the individual error components are uncorrelated. The total measurement uncertainty is determined with an "RSS" (Root Sum Square) analysis, and not a linear summation.

Bibliography

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H. Booster, H. Chou, *"Higher Resolution for Backscatter Measurements"*, Lasers and Optronics, October 1991, pp. 27-30

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