APPLICATION NOTE

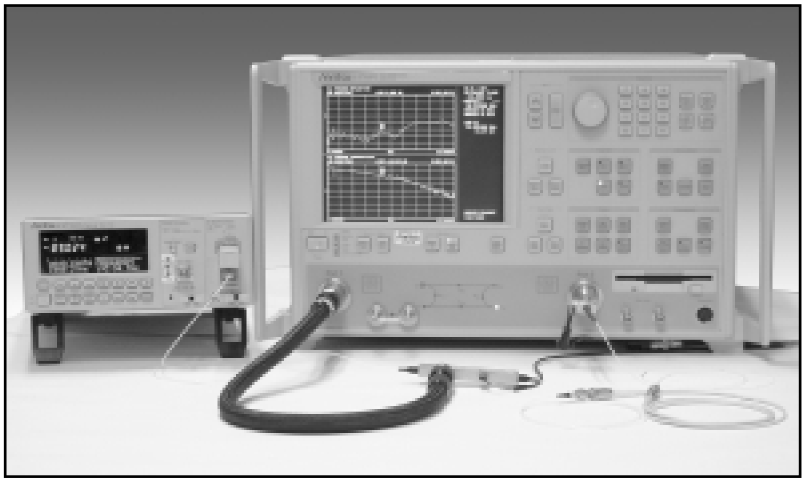
Anritsu

E/O and O/E Measurements with the 37300C Series VNA

Lightning™ VNA

Introduction

As fiber communication bandwidths increase, the need for devices capable of very high speed optical modulation and detection has grown. Commercially available optoelectronic components such as photodiodes and modulators have bandwidths beyond 50 GHz and researchers are now beginning to demonstrate performance beyond 60 GHz. As the bandwidth of these devices increases so must the capabilities of the test equipment used to verify their performance.



While many measurements are now performed in the time domain, small-signal analysis of these optoelectronic components in the frequency domain yields information about the transfer function in terms of bandwidth, flatness, and phase linearity. In turn, this data gives insight into the maximum supported data rates.

The measurements of components such as optical modulators, direct modulated lasers, integrated transmitters, photodiodes and photoreceivers are discussed in this note using the 37000C series VNAs.

E/O Measurements

E/O converters modulate an electrical signal onto light to be sent over fiber links. The transmission curve of a modulator is shown in figure 2. The performance of modulators and optical transmitters is key to determining the maximum data rate achievable in an optical communication link. These devices are generally characterized in terms of:

- Modulation bandwidth (transfer function or responsivity)
- Return loss
- Phase linearity
- Group delay

Figure 1 shows the general set-up for making E/O measurements. The optical stimulus to the modulator is provided by an external laser source. The VNA supplies a swept microwave signal over the frequency range of interest to the modulator. A photodiode transfer standard then converts the modulated optical signal back to an electrical signal which is measured by the VNA.

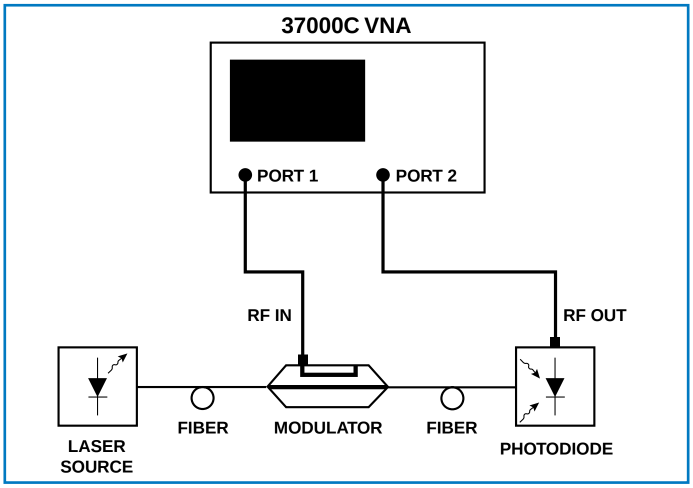


Figure 1. General E/O or O/E Measurement Setup

An electrical calibration is first performed on the VNA to remove the unwanted effects of the VNA, cables and other components in the measurement path. The next step is to remove (de-embed) the photodiode's known response to reveal the performance of the E/O converter. The de-embedding of the photodiode response is performed using the VNA's internal E/O application menu, which requires a characterization file for the photodiode in .S2P format (provided on a disk with the Anritsu 40 Gb/s photodiode calibration accessory). Once the response of the photodiode is removed, the S21 measurement displays the modulator's transfer function (ratio of modulated optical output to the electrical input signal). The 3-db bandwidth, phase linearity and group delay of the modulator can be determined from this transfer function.

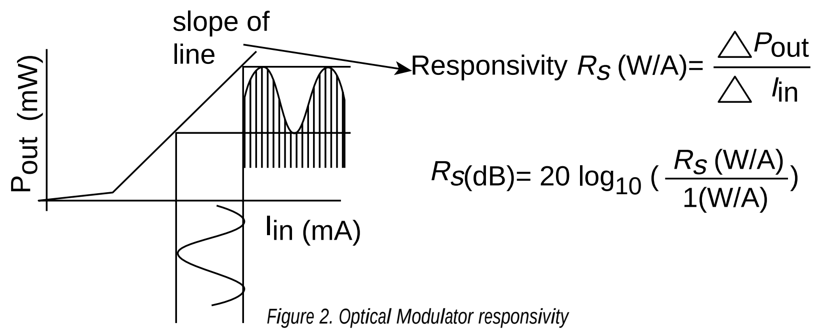


Figure 2. Optical Modulator responsivity

The following equipment is used for the measurement of a 40 Gb/s NRZ modulator:

- ***65 GHz VNA (37397C)***
- ***Optical test set (MT9810A)***
- ***Laser source 1550 nm (MU952501A-04)***
- ***40 Gb/s Characterized photodiode***
- ***Polarization controller (recommended)***

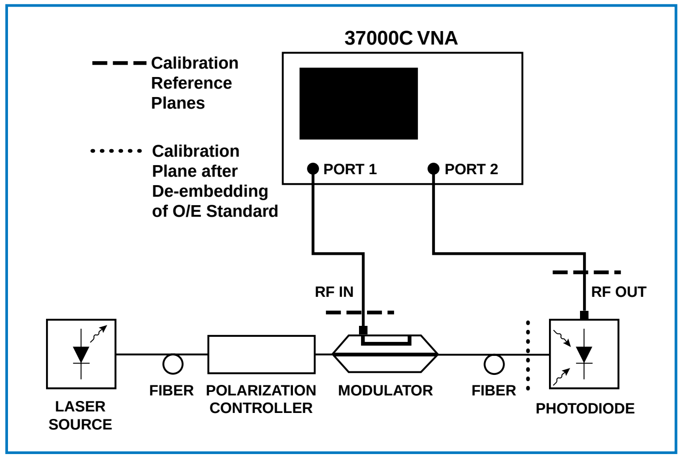


Figure 3. An E/O measurement setup with the 37000C VNA. The dashed lines represent the reference planes for the electrical calibration. After E/O de-embedding the Port 2 reference plane is shifted to the input of the photodiode, represented with the dotted line.

Measurement Steps

1. Perform a 12-term microwave calibration[2] over the bandwidth of interest at the calibration reference planes to remove the response of the VNA and the cables from the measurement (figure 3). Save the 12-term calibration to hard disk or floppy disk as it will be recalled later.

2. In the **APPLICATION** menu, select **E/O Measurement**. Under the E/O application menu (figure 4), follow the instructions to load the 12-term electrical calibration (from either the hard drive or floppy drive).

3. Load the characterization .s2p file of the photodiode standard to be de-embedded from the electrical calibration. This removes the response of the photodiode that will be used for the E/O measurement.

4. Connect the modulator DUT with the characterized photodiode in series as shown in figure 3. A polarization controller is recommended to adjust the polarization of the laser input to the modulator DUT, to achieve the maximum signal level at the input of the photodiode. This improves the Signal/Noise ratio of the measurement.

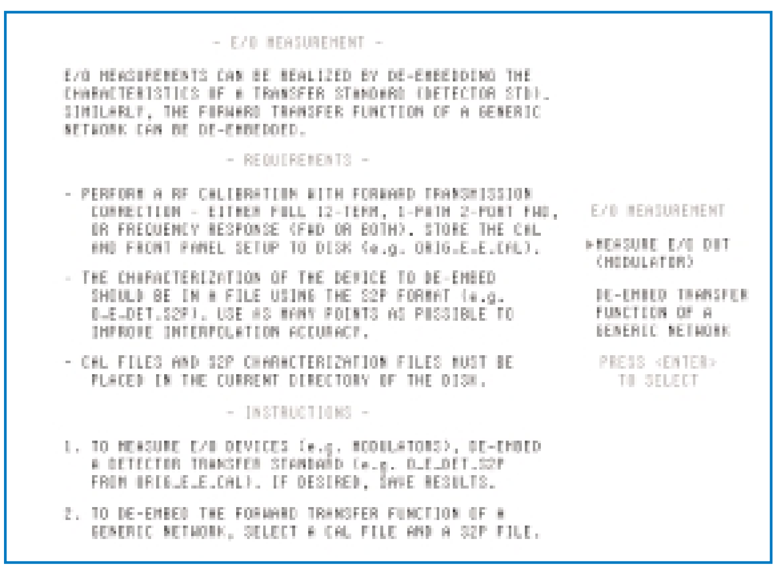


Figure 4. E/O Measurement Menu

Most E/O and O/E fiber optic components will exhibit some polarization dependence. Understanding the effects of polarization is essential to maximizing measurement efficiency. Improper alignment of the input polarization can result in severe loss of the RF signal at the input to a photodetector which reduces dynamic range. Stability is another important concern. Standard single mode fibers can alter polarization states simply by adding stress to the fiber. The following are some tips to enhance the measurement of E/O and O/E components.

- Measurement dynamic range can be maximized using a simple polarization controller before a polarization sensitive device. The VNA can be used to monitor the maximum RF output level as the polarization is adjusted.

- Polarization Maintaining Fiber (PMF) is an easy way to minimize polarization changes as a result of fiber turns and bends. Varying styles of PMF patch cords are available from manufacturers of single mode fiber.

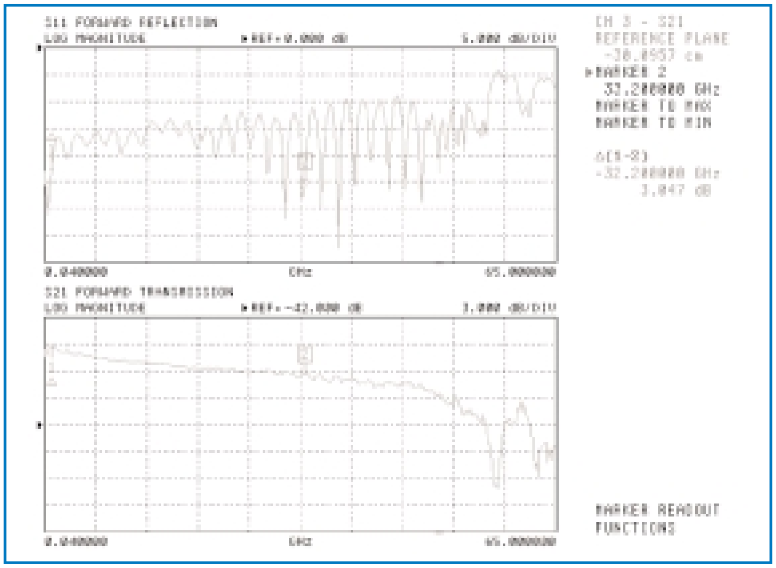


Figure 5. Measurement of a 40 Gb/s modulator: Return Loss and Transfer function. The 3 dB bandwidth of the modulator is measured to be 32 GHz.

The transfer function measurement of a 40 Gb/s modulator is shown in figure 5. The bandwidth can be measured at the 3 dB roll off point in the modulator's response - approximately 32 GHz in this case.

Similarly, phase and group delay measurements of the modulator can also be made by selecting the appropriate graph type as shown in figures 6 and 7.

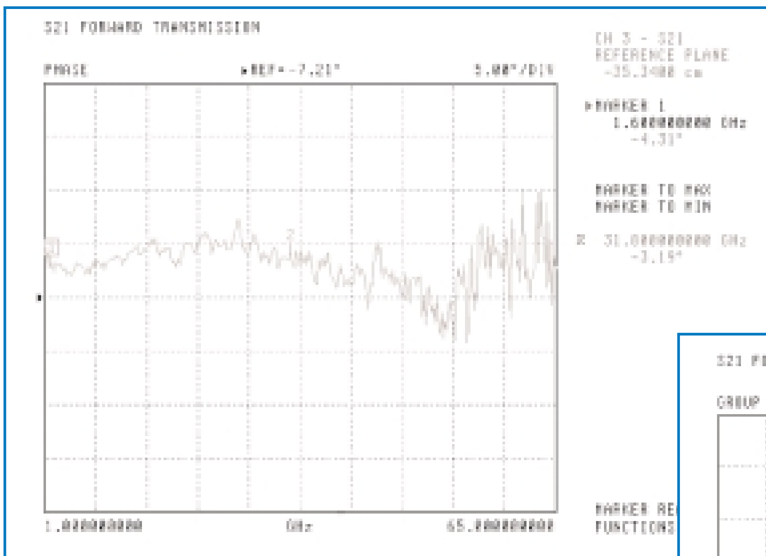


Figure 6. Phase measurement of a 40 Gb/s NRZ modulator. The reference plane was automatically adjusted using the REF PLANE menu to display phase over the 65 GHz frequency range.

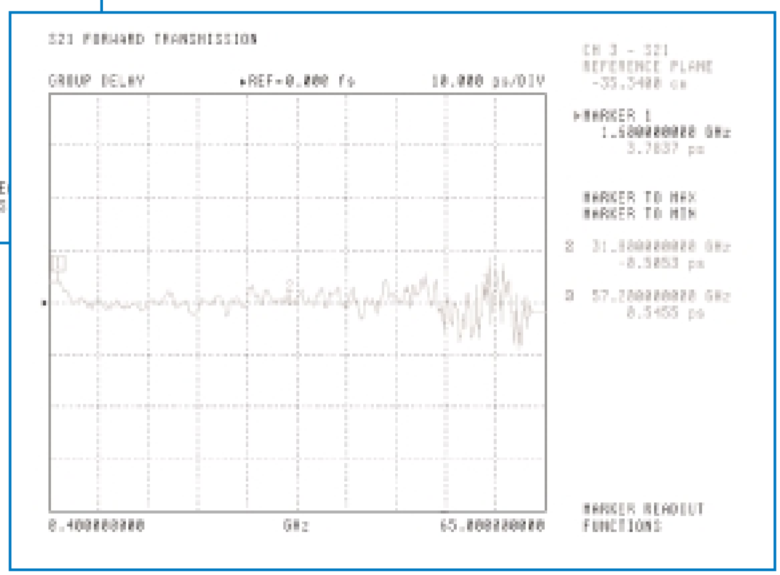


Figure 7. Group delay of a 40 Gb/s modulator. The frequency aperture (Δf) was set to 5% for this measurement.

Phase measurements are generally comprised of multiple phase transitions due to the electrical length of the DUT. A representation of phase linearity through the device can be obtained by removing the fixed electrical length. The **REF PLANE** menu can be used to compensate for the phase change over frequency to display the variation from linear phase.

By measuring S11, the electrical input impedance (i.e. the return loss of the modulator) can also be characterized.

Analysis of the S11 data over distance, using the VNA's time domain function[1], can help in locating discontinuities and imperfections in the modulator.

O/E Measurements

The setup shown in figure 1 can also be applied to O/E measurements of a photodiode or photoreceiver DUT. Photodiodes demodulate the electrical signal from the optically modulated light in a fiber optic transmission network. An external laser source, used with a characterized modulator, provides the input to the O/E DUT. The response of the characterized modulator is de-embedded from the setup using the O/E application menu. The characterization file for the modulator used can be generated using a characterized photodiode standard. See Appendix A for instructions on generating an s2p file.

Once the response of the modulator is removed, the S21 parameter displays the ratio of the output electrical signal to the input optical modulated signal. This is the DUT's transfer function (figure 9). The 3 dB bandwidth can be determined from the measurement – approximately 53 GHz in this example.

Phase linearity, group delay, and return loss of the O/E DUT can also be extracted from this measurement setup.

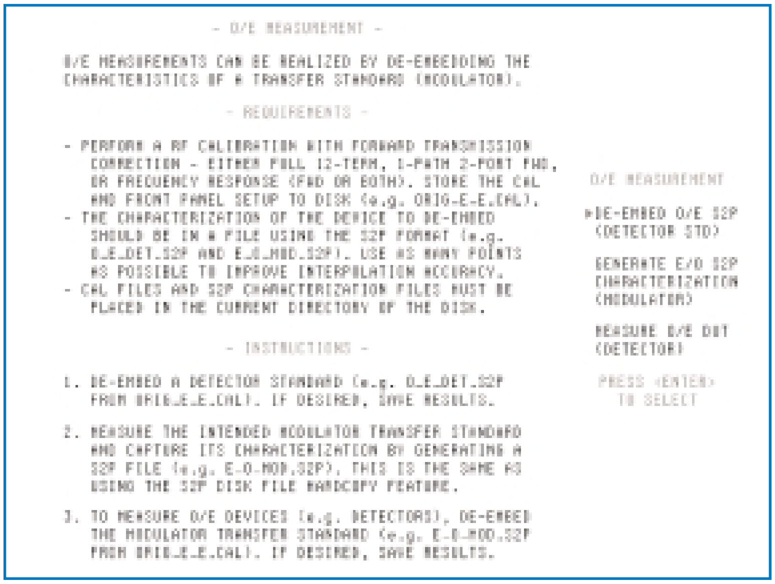


Figure 8. O/E Measurement Menu

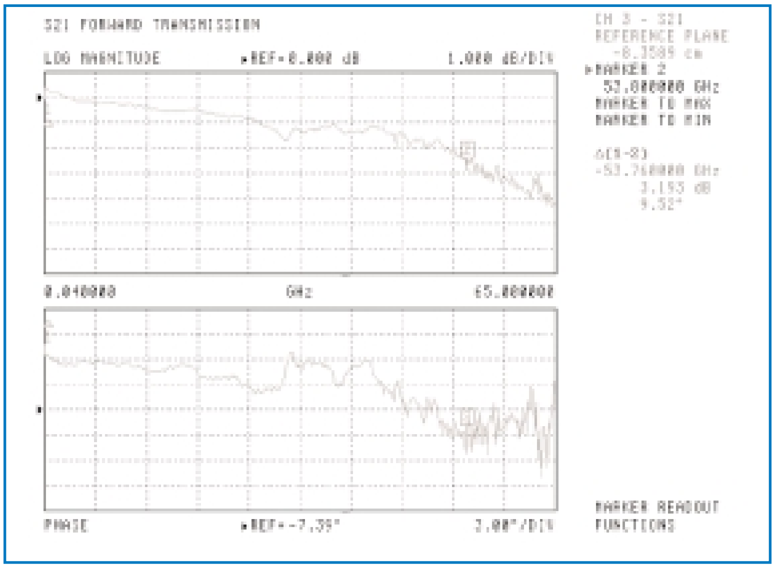


Figure 9. Transfer function measurement (Magnitude and Phase) of a 40 Gb/s Photodiode. The 3 dB bandwidth of the diode is measured to be 53 GHz.

Additional Equipment required for an O/E Measurement:

- ***Characterized optical modulator***

Measurement Steps

1. Perform a 12-term calibration on the VNA over the frequency range of interest. Save the calibration as it will be recalled later.
2. Press the **APPL** menu button on the VNA's front panel. Select **O/E MEASUREMENT** and then press **MEASURE O/E DUT**. Follow the instructions in the menu (Figure 8) to load the 12-term electrical calibration that was saved in step 1.
3. After entering the S2P file for the characterized modulator, the VNA is now calibrated and ready to make O/E measurements. Connect the characterized modulator and detector under test as shown in Figure 1*.

**** See Appendix A for instructions on characterizing modulator for O/E Measurement***

Appendix A: Creating a Modulator Characterization File for O/E Measurements

A characterized photodiode accessory can be used to generate a characterization file for the modulator to be used in O/E measurements. The following is a guide for characterizing a modulator.

1. Perform a 12-term calibration over the frequency range of interest. Save this calibration to disk.
2. Press the **APPL** button on the Front Panel and choose **O/E MEASUREMENT** and **DE-EMBED O/E S2P**. When asked to load the original cal file, select the calibration that was saved in step 1.
3. After loading the VNA calibration, load the s2p file for the 40Gb/s Characterized photodiode. It should be on the hard disk or saved to floppy.
4. Connect the optical components together as shown in Figure 3. Apply bias to the photodiode and the modulator before turning on the laser. Remember to observe all ESD precautions, especially when handling the photodiode.
5. Turn the laser ON and adjust polarization to achieve maximum signal level. To enhance the response, use a lower I.F. Bandwidth and add appropriate Averaging.
6. Turn the laser power up to 10 dBm and allow system to settle for 20 seconds.

At this point the laser is on maximum power, the S21 should show an E/O response over the entire frequency range of the cal. The next steps will generate the modulator s2p file.

7. Press the **APPL**, **O/E MEASUREMENT**, **GENERATE E/O S2P**, and **AUTOSCALE**.
8. The screen should now display S21 (magnitude and phase) for the E/O modulator. The data can then be stored as an S2P file. Press **STORE E/O S2P** and name the file appropriately.

Appendix B: Optoelectronic Measurement Considerations

Linearity

The linearity of the 40 Gb/s characterized photodiode directly affects the accuracy of the S21 measurement. The linear optical input power at which RF photocurrent will remain linear is important. An easy way to guarantee that the measurement path is still linear is to normalize the S21 plot against itself and increase the optical power. For example, set the optical power on the laser to 4 or 5 dBm. Wait for one full sweep and store the S21 to memory. This is performed by pressing the **TRACE MEMORY** button on the front panel. After storing the data, press **VIEW DATA/MEMORY** and set the scale of the graph to REF=0.0dB and SCALE=2dB/DIV.

Now increase the laser power by approximately 1 dB. Continue increasing the optical power level until some compression is seen in the normalized plot. At that point, decrease the optical power level until it is out of compression. Make sure that the maximum DC current for the photodiode is not exceeded. Refer to manufacturers data sheet for a list of the specifications.

Laser Power and Photodetector Bias Sequencing

Always make sure the photodiode is biased properly before turning the laser on. Improper bias or no bias can degrade photodiode performance and can also result in damage.

Instructions on handling and biasing of the photodiode are shipped with the characterized photodiode accessory. Always observe ESD precautions as these devices are very sensitive to static discharge.

Optical Fiber Lengths

The measurement setup will typically require optical fibers to interconnect optical components with different connectors. For example, a modulator with an FC/PC connector at the output will require an optical patch cord to adapt to the FC/APC connector on the input of the characterized photodiode accessory.

Optical fibers have negligible frequency dependent loss over the modulation bandwidths discussed here (figure 10). Thus, adding short lengths of optical patch cords to the setup does not affect the accuracy of transfer function measurements. The recommended lengths for optical patch cords for this application is <10 m.

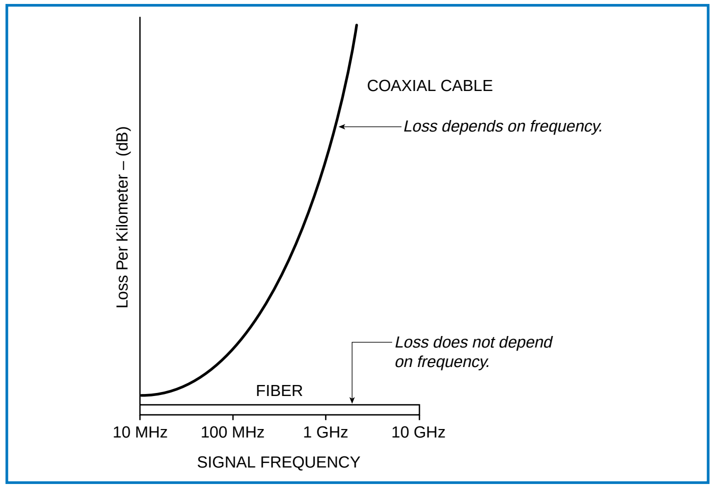


Figure 10: Loss as a function of frequency for coaxial and fiber optic cables

Modulator Bias Control

Lithium Niobate modulators are generally biased using a modulator bias controller (MBC) to control the operating point of the modulator. When biased in quadrature, the input RF signal linearly modulates the optical carrier. Note that when an MBC is applied, it must be designed for small signal operation. The default power from the Port 1 test port is –7dBm for the 65 GHz VNA (37397C). This results in a modulation depth of <10% (for most commercially available modulators). In order for the VNA to function properly the modulator must always be linearly modulated.

A DC power supply can be used in place of an MBC. However, the stability of the S21 measurement may be degraded due to drift in the modulator's bias point.

Appendix C: Measurement Uncertainty

Uncertainty in E/O and O/E Measurements

In the measurements just described, the uncertainty can be broken into two categories

1) Uncertainty associated with the characterization of the available photodiode accessory

2) Uncertainty in the measurement with the DUT

Typically the user will purchase a characterized photodiode and receive a data file describing that device's transfer function. There is some uncertainty associated with that data based on the characterization technique.

There are different levels of characterization possible. A direct characterization using such optical techniques as electro-optic sampling[3] or the heterodyne method[4] would be termed 1st tier. It is outside the scope of this note to go into detail on these characterization techniques. These characterization processes are time consuming and expensive so a typical user will not employ such a standard. A 2nd tier standard is characterized by a laboratory based on a 1st tier standard. It would be generated using a process similar to the O/E technique discussed previously but under carefully controlled conditions (bias, temperature, wavelength, etc.) using a 1st tier standard as the characterization device. The uncertainties for a 2nd tier standard will be used in later calculations. The uncertainty penalty in going to 2nd tier is typically small (on the order of 0.1 dB additional).

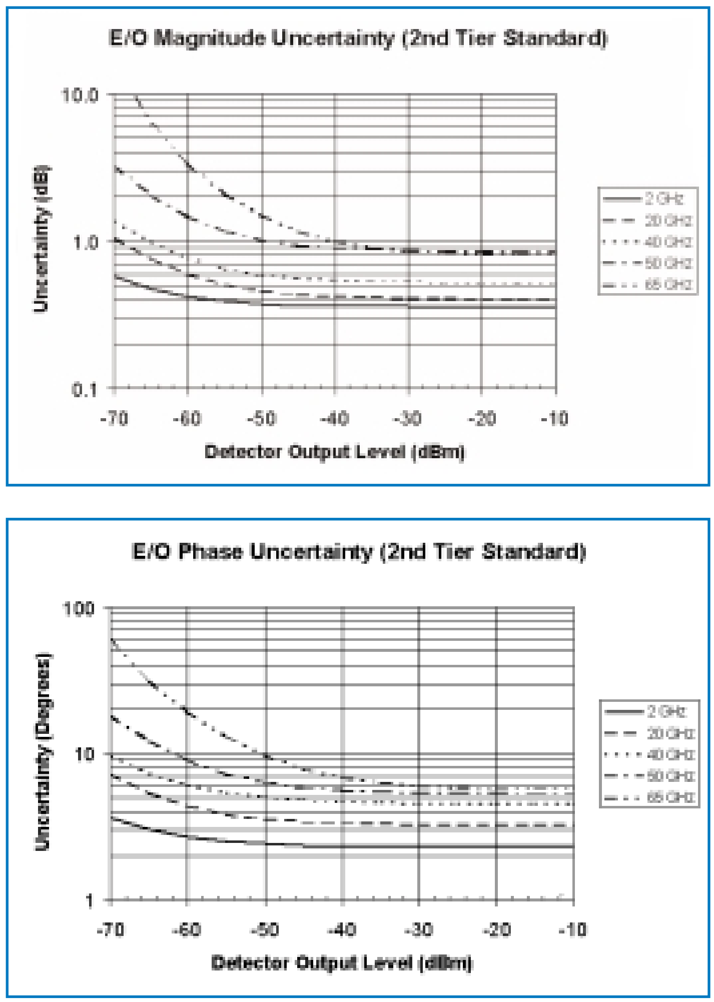


Figure 11a. Magnitude and phase uncertainties for E/O measurements are shown here versus signal level and frequency. A 2nd tier characterized photodiode was used as the basis for the uncertainty analysis.

When measuring the DUT, there is an uncertainty associated just with the VNA measurement which is discussed in other documents [5]. Since the characterized photodiode response is then de-embedded, the characterization uncertainty must be combined with the VNA measurement uncertainty to obtain an overall value. In the case of an O/E measurement, there are actually two user measurements involved (one with a modulator and the characterized photodiode and one with that modulator and the DUT) so an additional uncertainty must also be included. Typically these uncertainties are all added on a root-sum-square basis since the measurements are assumed to be uncorrelated.

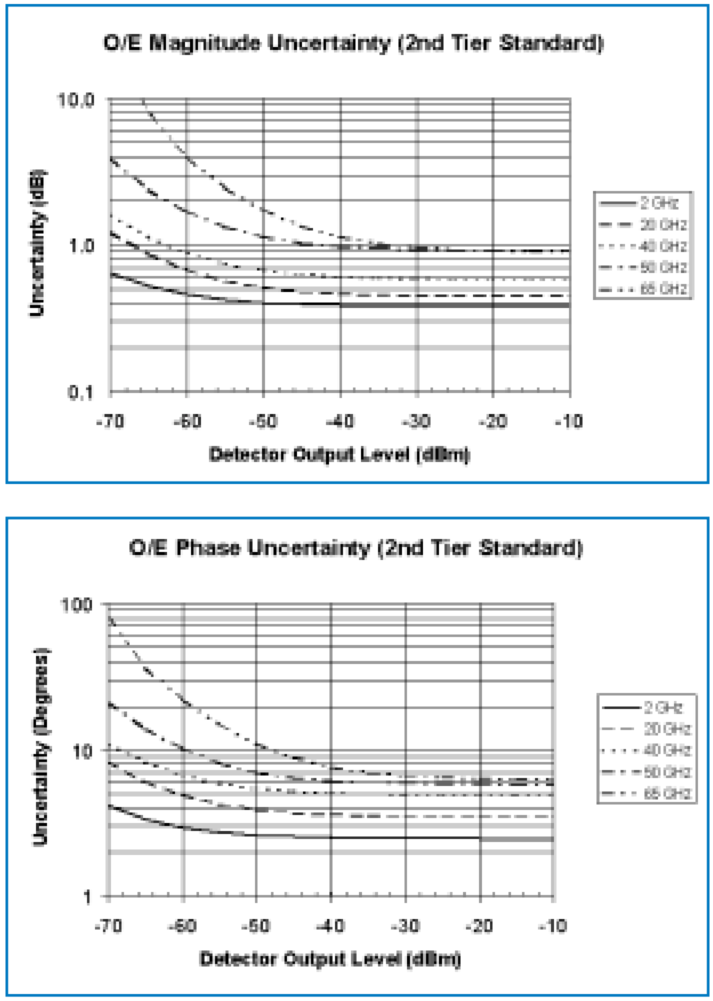


Figure 11b. Magnitude and phase uncertainties for O/E measurements are shown here versus signal level and frequency. A 2nd tier characterized photodiode was used as the basis for the uncertainty analysis.

Before proceeding to some uncertainty values, it may be useful to examine dependencies. On the VNA side, S21 uncertainty is typically quite low for medium power levels but will deviate at high signal levels (receiver compression, not an issue in these measurements) and at low signal levels (effects of the receiver noise floor). Thus the overall uncertainty will be a function of detector output signal level (getting worse as the signal level gets closer to the noise floor). Results can be improved by using higher RF drive levels (keeping all devices linear of course) and high optical power levels (same caveat). The RF match of the modulator and photodiode will also influence uncertainties to some degree (at all signal levels) but the dependence is relatively weak as long as return loss is better than a few dB. For the plots in figures 11a and 11b, a modulator match of –24 dB at low frequencies to –15 dB at 65 GHz and a detector match of –20 dB at low frequencies to –9 dB at 65 GHz were assumed as is typical for some commercial devices. Making both matches worse by 5 dB causes an uncertainty degradation of about 0.15 dB.

On the optical side, there is little high level signal dependence as long as the devices are linear. The characterized photodiodes are usually chosen to be very linear over wide power ranges to keep this from being an issue. The characterized detectors typically also have very weak wavelength dependencies; usually less than a few hundredths of a dB over 40 nm. When using a modulator as a transfer standard (as in an O/E measurement), however, it is important that the same wavelength be used in the different measurements with that modulator since much greater wavelength sensitivity exists in that component.

Specifications for the Anritsu 37397C 65 GHz VNA and 3654B V Calibration Kit were used to calculate VNA uncertainties at various frequencies. The use of different VNAs and/or calibration kits may result in slightly different values. Characterization uncertainties of the Anritsu 40 Gb/s photodiode were used for the standard part of the model. Optical system drift is included in the error model but it is assumed that all components are mechanically and thermally stable. Connector repeatability is also included in the model but all connectors are assumed to be in very good condition. The results are shown with an independent variable of photodiode output power and plotted for both magnitude and phase for the two different types of measurements. Frequency is used as a parameter.

As can be seen in figures 11a and 11b, the uncertainty reaches an asymptote for detector output levels above about –40 to –50 dBm. Above this level, the dominant source of uncertainty passes from measurement signal-to-noise ratio to characterization uncertainty.

There is some frequency dependence for several reasons:

(1) Noise floor is higher at higher frequencies.

(2) The characterization uncertainty goes up with frequency.

(3) The basic VNA uncertainty (due to residual mismatch, etc.) goes up with frequency.

Appendix D: Connector Care

It is important to establish proper cleaning procedures when connecting fiber optic devices together. Fiber optic cores are made of glass and can easily be scratched or chipped if care is not taken.

The connectors found on the 40Gb/s Characterized Photodiode are the FC/APC connector. APC (Angled Physical Contact) is chosen to help minimize back-reflection. The 8° angle at the endface of the APC connector has an optical return loss of better than –50 dB. DFB lasers require large amounts of isolation to function properly. The optical return loss from a common PC connector can be as large as –30 dB or higher, depending upon the polish and cleanliness of the connector.

The following are some tips to help ensure quality connections.

- Always clean connectors after every connection.
- Use a fiber optic scope often to ensure there are no defects on the connector end face that can cause damage to other connectors.
- Use insertable patch cords for expensive devices that require many connections.
- Always use a cloth that is free of fiberglass to clean the connectors. If necessary, use alcohol to remove stubborn dirt and oil. Thoroughly remove any alcohol residue before reconnecting.
- Avoid using any oils for connecting two cables together. Oils are messy and very difficult to clean up.
- Optical connectors do not need torque. Some connections are better when the two fibers are barely touching. Tightening the connector too much will result in higher insertion loss, more reflection, and in some cases damage to the connector.
- Always observe proper mating to APC connectors. Connecting APC to PC connectors will damage the connectors.

References:

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2. 37000C VNA Operation Manual, 11410-00226
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4. P. D. Hale and C. M. Wang, "Calibration Service for Evaluating and Expressing Optoelectronic Frequency Response at 1319 nm for Combined Photodiode/RF Power Sensor Transfer Standards," NIST Special Publ 250-51, 1999.
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7. "Understanding Fiber Optics", Jeff Hecht, pp. 28-31, 1999, Prentice Hall Inc.

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