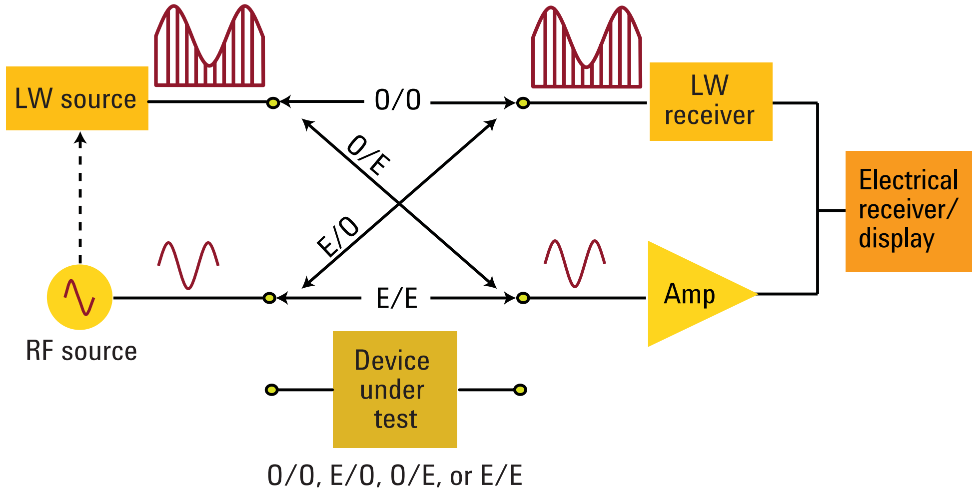
Agilent High Speed Lightwave Component Analysis Application Note

Characterizing High-Speed Opto-Electronic System Components

- Lasers, LEDs
- Integrated and external modulators
- Photo diode receivers

As lightwave transmission systems become more advanced, component designers and manufacturers must maximize the performance of their devices. For example, one parameter often used to specify digital system performance is bit error rate. However, it is difficult to specify individual components in such terms. Rather, fundamental measurements such as gain, bandwidth, frequency response and return loss can be appropriate. The lightwave component analyzer (LCA) is used to measure the linear electro-optic transmission and electrical reflection characteristics of a component as a function of modulation frequency. Calibrated and traceable measurements can be performed at modulation rates up to 67 GHz.

Figure 1.
LCA Block diagram



Agilent Technologies

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Introduction

General measurement techniques and considerations

The concept of lightwave component analysis is straightforward. Measurements are made of the small-signal linear transmission and reflection characteristics of a variety of lightwave components. A lightwave component analyzer consists of a microwave network analyzer with an optical test set attached to it. A precise electrical (signal generator) or optical (transmitter) source is used to stimulate the component under test and a very accurate and calibrated optical or electrical receiver measures the transmitted (or reflected) signal. Since characterization over a range of modulation frequencies is required, the frequency of modulation is normally swept over the bandwidth of interest.

Measurements are typically comprised of the appropriate ratio of microwave modulation current (or power) and lightwave modulation power (see Figure 2). While Figure 1 demonstrates the basic concepts of lightwave component analysis, the specific measurement processes are illustrated later. An analysis of how various signals are used in the measurement process is found in Appendix 1, "Signal Relationships in Opto-Electronic Devices."

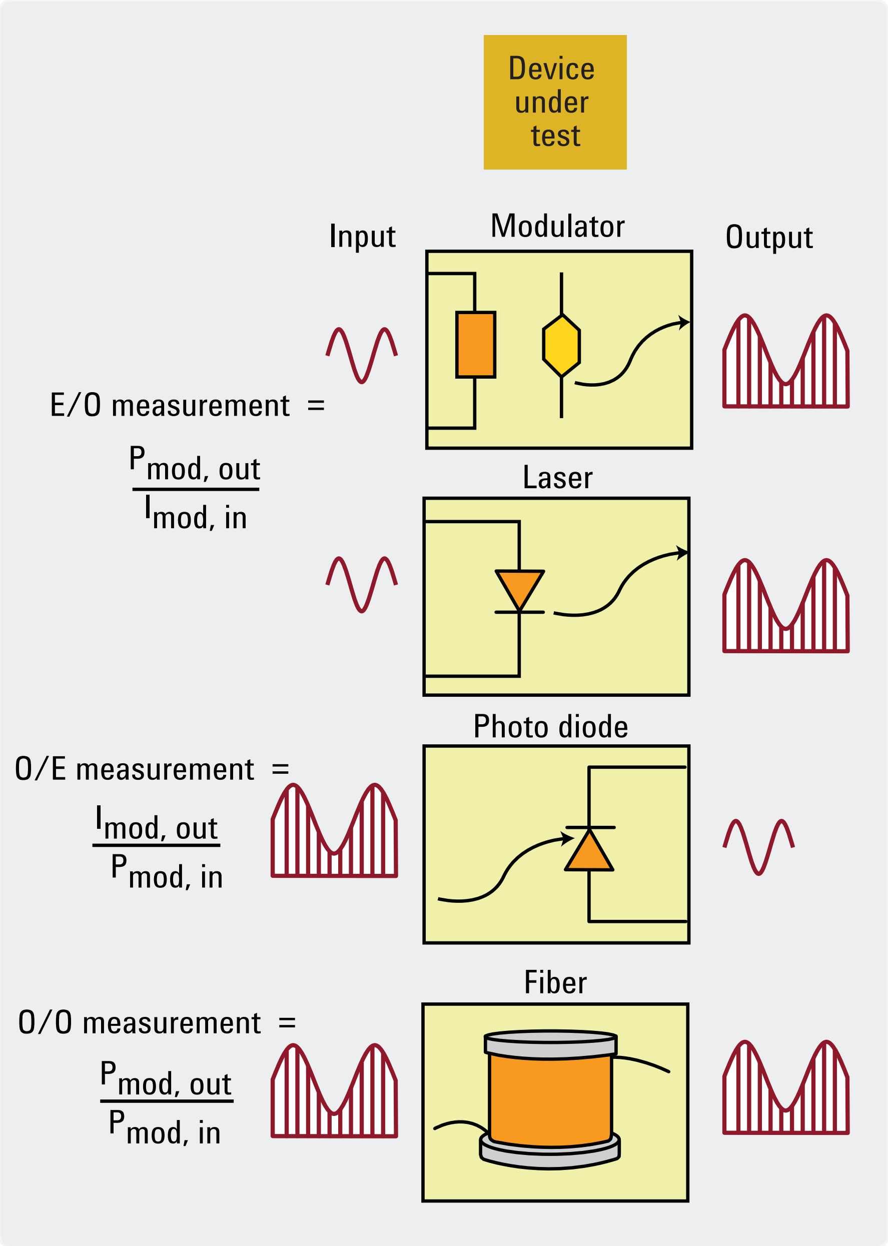


Figure 2. Measurement signals

E/O measurements (modulators, lasers, LED's)

The measurement of an E/O transducer is a combination of input modulating current or voltage and output optical modulation power. For current converting devices the slope responsivity is used to describe how a change in input current produces a change in optical power. Graphically this is shown in Figure 3. For modulators the behavior is shown in Figure 4.

An LCA measures input modulating current and output modulation power and displays the ratio of the two in Watts/Amp, either linearly or in decibels.

O/E measurements (photo diodes and receivers)

The measurement process for O/E devices is similar to E/O devices. The measurement consists of the ratio of output electrical modulation current to input optical modulation power. Slope responsivity for O/E devices describes how a change in optical power produces a change in electrical current. Graphically this is shown in Figure 5. The LCA measures the input optical modulation power and output modulation current and displays the ratio of the two in Amps/Watt.

O/O measurements

Characteristics of purely optical devices can also be measured. In this case, both the stimulus and response are modulated light. The ratio measurement is simply one of gain or loss versus modulation frequency.

The LCA Family

There are several instruments in the LCA family. Their characteristics are summarized below.

Table 1. Lightwave component analyzers

LCA	Wavelength (nm)	Fiber type	Modulation frequency range	RF ports
N4373B	1310 / 1550	SM	10 MHz to 67 GHz	2
N4374B	1310 / 1550	SM	100 kHz to 4.5 GHz	2
N4375B	1310 / 1550	SM	300 kHz / 10 MHz to 20 / 26.5 GHz	2 / 4
N4376B	850 nm	MM	300 kHz / 10 MHz to 20 / 26.5 GHz	2 / 4

Please refer to the Agilent web site (www.agilent.com/find/LCA) for a complete listing of lightwave component analyzers as well as other lightwave test equipment.

Responsivity $R_S\ (W/A) = \Delta P_{out}/\Delta I_{in}$

$R_S\ (dB) = 20 \log_{10} [R_S(W/A)/1(W/A)]$

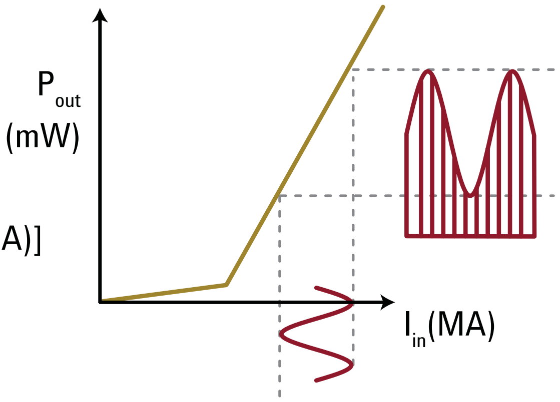


Figure 3. E/O slope responsivity of lasers and LEDs

Responsivity $R_s\ (W/A) = \Delta P_{out}/\Delta I_{in}$

$R_s\ (dB) = 20 \log_{10} [R_s(W/A)/1(W/A)]$

where $\Delta I_{in} = \Delta U_{in}/50\ \Omega$

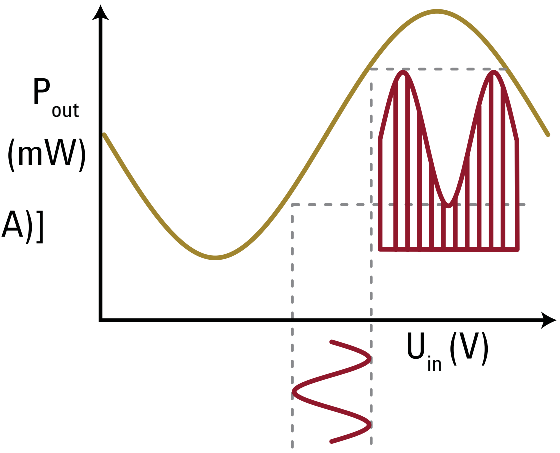


Figure 4. E/O slope responsivity of external modulators

Responsivity $R_r\ (A/W) = \Delta I_{out}/\Delta P_{in}$

$R_r\ (dB) = 20 \log_{10} [R_r(A/W)/1(A/W)]$

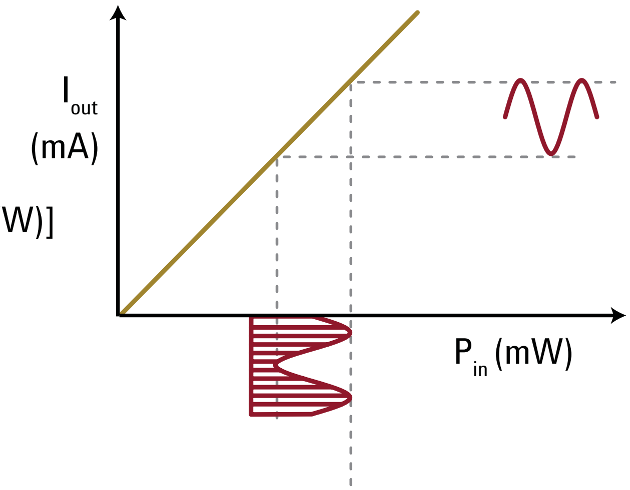


Figure 5. O/E slope responsivity

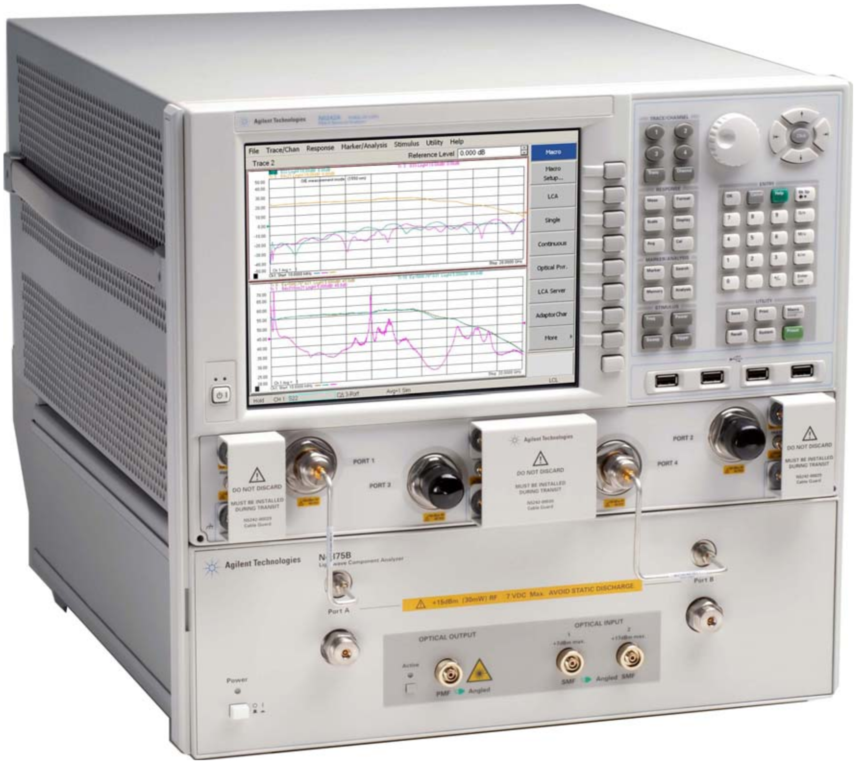


Figure 6. N4375B

LCA Measurement Process

The key to making accurate E/O, O/O, or O/E measurements is calibrated instrumentation. A calibration will allow the LCA to remove the response of the test system, including the electrical cables, optical fiber, and the instrument itself. There are a number of calibration/setup stages involved.

In the first stage prior to the actual calibration step, the LCA needs to be configured. This includes:

- Start and stop frequencies
- Sweep type (linear or logarithmic, stepped sweep)
- Number of measurement points
- IF bandwidth
- RF source power level

Electronic calibration

The next stage is the electrical calibration of the lightwave component analyzer. This calibration is performed through running an electronic calibration (ECAL) on the network analyzer. The ECAL characterizes all RF paths between the network analyzer and the device under test, and the LCA optical test-set, respectively.

A guided setup ("calibration wizard") procedure will guide you through the necessary steps. With ECAL, an automatic, full, two-port calibration can be accomplished with a single connection to the ECAL module and minimal operator interaction.

This establishes the electrical calibration reference planes for the measurements. Whenever there are additional electrical adapters or elements required for connecting the device under test these addional electrical paths can be accounted for by "RF path de-embedding" feature (see "RF Path De-Embedding").

Configuring the LCA measurement

The next stage is the LCA measurement configuration. To simplify the process of making measurements, LCAs have a built in "confguration screen" feature.

On this screen, the user can set all LCA measurement parameters. An advanced configuration screen allows the inclusion of electrical adapters (e.g., mating connectors or cables) and optical adapters (e.g., optical cables or attenuators) via parameter settings or measurement files.

Path de-embedding

The path de-embedding feature of the LCA allows to remove any additional paths between the calibration reference planes and the device under test, i.e., RF cables, adapters, or probes and optical fibres, optical attenuators. This feature is particularly helpful when path elements need to be excluded from the measurement results, like additional propagation delay introduced by fiber leads, or need to be changed after the electrical calibration, like setting different levels of optical attenuation. It is also needed when elements cannot be addressed directly by the electronic calibration at the RF cable ends, like when working with wafer probes.

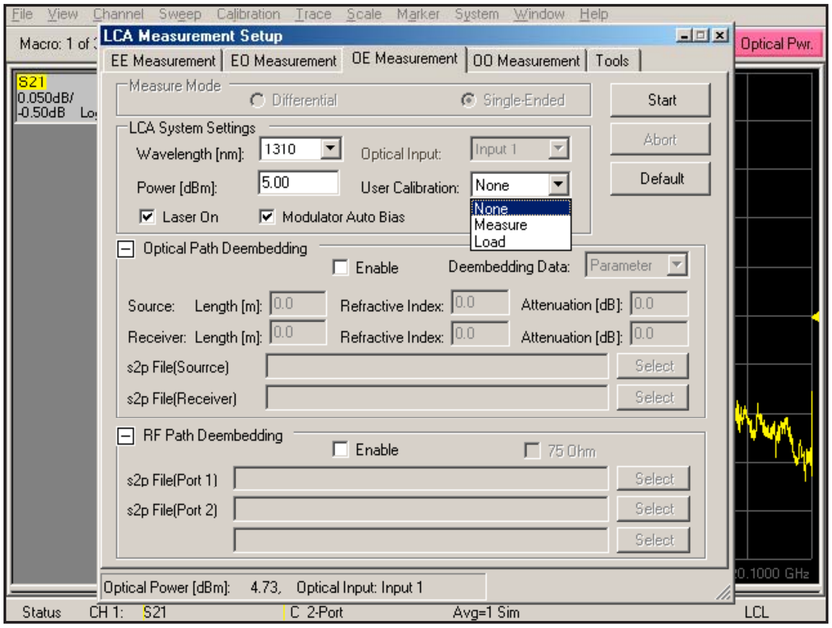
RF path de-embedding

For RF path de-embedding the RF path needs to be characterized prior to starting the LCA measurement. For characterization, we recommend to use the AdapterChar macro supplied with the network analyzer. Please refer to the online help on the network analyzer for further details.

The characterization results need to be in the form of a 2-port S-parameter data file (also known as Touchstone .s2p data files). All the S-parameters in the supplied file are used. According to the convention of the LCA (where any port can be an input or an output), these values are directional. This means port 1 of the connector is always connected to the network analyzer and port 2 is always connected to the DUT. The AdapterChar macro of the network analyzer includes this directionality in its characterization.

Optical path de-embedding

For optical path de-embedding the de-embedding information can be introduced via parameters, like fiber length, refractive index, and attenuation, or via an adapter file. The adapter file needs to be in the form of a 2-port S-parameter data file (also known as Touchstone .s2p data files). All the S-Parameters in the supplied file are used. The optical path can be characterized via an O/O measurement.



Wavelength [nm]: 1310

Power [dBm]: 5.00

Optical Input: Input 1

User Calibration: None

☑ Laser On ☑ Modulator Auto Bias

Optical Path Deembedding: ☐ Enable Deembedding Data: Parameter

Source: Length [m]: 0.0 Refractive Index: 0.0 Attenuation [dB]: 0.0

Receiver: Length [m]: 0.0 Refractive Index: 0.0 Attenuation [dB]: 0.0

s2p File(Source)

s2p File(Receiver)

RF Path Deembedding: ☐ Enable ☐ 75 Ohm

s2p File(Port 1)

s2p File(Port 2)

Optical Power [dBm]: 4.73, Optical Input: Input 1

Status CH 1: S21 C 2-Port Avg=1 Sim LCL

Figure 7. LCA configuration screen

Optical measurement calibration

The final stage is the calibration of the optical test set. This is performed automatically by the LCA macro by using the "Fixture" feature of the network analyzer. For more information on Fixtures, please refer to the documentation of the network analyzer. The instrument lightwave source and receiver are individually characterized in the factory. Thus, no special opto-electronic user calibration is needed to start an LCA measurement. However for highest precision OE and OO measurement a special user calibration can be performed. Here the user is guided through individual steps. The systematic responses of the components making up the LCA can then be re-referenced.

Measurement procedure

After the calibration steps the systematic responses of these two stages of calibration can then be deembedded, yielding the response of the device under test (DUT). (See "Signal Relationships in Opto-electric Devices" for more detail.) After the calibration is complete, one might expect to see a flat response at 0 dB indicating the test system response has been removed.

When using an Agilent N4373B, the display seen upon completion of the setup process will not necessarily be a flat line. In the case of both RF cables connected to the testset, the testset transmitter or receiver is still connected and has become the DUT. Thus, its response is displayed until it is replaced with the actual test device.

When chosing the OO configuration the measurement of a patch cord is a simple verification of system performance.

For the the Agilent N4375B/76B the reponse of testset transmitter and receiver can be checked by setting the corresponding RF paths to " internal" via the "TOOLS" screen in the LCA configuration screen.

Accuracy considerations

There are several items to consider with respect to measurement accuracy. These include:

- Keeping all electrical and optical connectors and cables clean and in good condition
- Operating the test device in linear regions (unsaturated conditions)
- Avoid overdriving the instrument receiver (especially when operating the PNA port 2 in "reverse coupler configuration")
- Minimizing cable movement
- Allowing the instrument to "warm-up"
- Keeping optical reflections at a minimum

Lightwave Transmitter Measurements (E/O)

The LCA is used to characterize the transmission and reflection parameters of electro-optic modulators, laser and LED sources with respect to modulation frequency. The transmission measurements to be discussed include:

- Modulation bandwidth and frequency response
- Conversion efficiency
- The effects of bias
- Pulse measurements
- Reflection sensitivity
- Modulation phase response
- Laser/modulator input impedance

Other laser measurements including line width, chirp, and RIN are discussed in Application Note 371. For time resolved chirp see Application Note 1550-7.

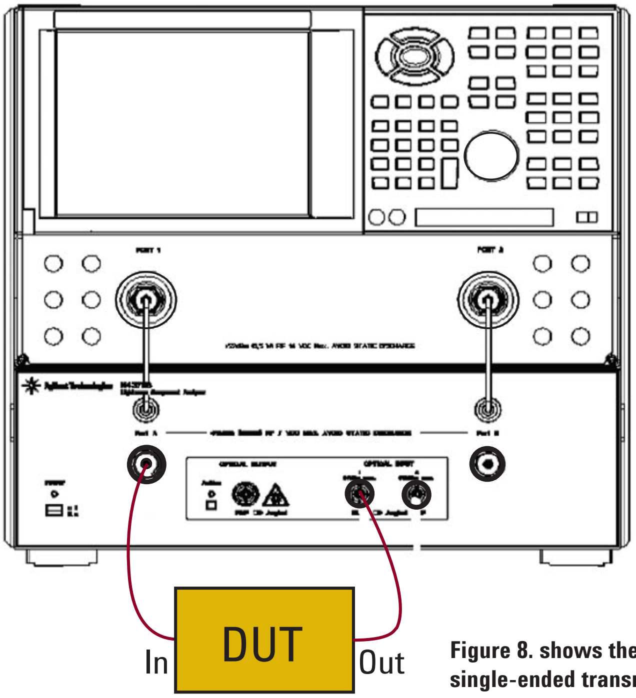


Figure 8. shows the typical set up of a single-ended transmitter measurement.

Modulation bandwidth, frequency response, and conversion efficiency

Modulation bandwidth refers to how fast an optical transmitter (laser, modulator) can be (intensity) modulated, while conversion efficiency (responsivity) refers to how efficiently an electrical signal driving a transmitter is converted to modulated light. Although responsivity is often used to describe a static or DC parameter, the conversion efficiency of a device for modulation signals is a dynamic characteristic and can be referred to as “slope responsivity.”

It is not unusual for slope responsivity to vary according to how fast the electrical signal is varied. As the frequency of modulation increases, eventually the conversion efficiency will degrade or “roll off.” The frequency where the conversion efficiency drops to one-half of the maximum is the “3 dB point” (when data is displayed logarithmically) and determines a transmitters’s modulation bandwidth.

Distortion of modulation signals will occur if the frequency response is not “flat” and there are frequency components which exceed a transmitter’s bandwidth. The measurement of modulation bandwidth consists of stimulating a laser or modulator with an electrical (microwave or RF) signal and measuring its response (modulated light) with a lightwave receiver. Normally the frequency of an electrical signal into an opto-electronic transmitter is swept to allow characterization of the transmitter over a wide range of modulation frequencies.

Laser measurements

Figure 9 shows the measurement of the conversion efficiency (S21) and electrical return loss (S11) of a laser as a function of modulation frequency. The power monitor (insert in Figure 9) displays the average optical output power of the DUT.

Optical DC Power: 5.07 dBm

Optical Input: Input 1

Figure 9. E/O modulation bandwidth measurement

The display units are Watts per Amp (the vertical axis). In this case, the display is in a logarithmic format where 0 dB represents 1 watt per amp. The horizontal axis is modulation frequency, indicating that the measurement is being made over a wide range of frequencies, in this case from 10 MHz to 20 GHz. As stated, this measurement indicates how fast the laser can be modulated. This particular laser shows the typical relaxation resonance peak at about 16.5 GHz. Beyond this frequency, the conversion efficiency is gradually degraded. There are two significant components that limit the modulation bandwidth. One is the actual construction of a laser including the physical dimensions and fabrication process. The other is how efficiently an electrical signal is delivered to the laser. The electrical return loss is an indicator for the quality of impedance matching. For the particular laser the matching is degraded at high frequencies. (For details on the impact of transmitter impedance matching see “Transmitter Input Impedance.”)

The effects of bias on laser performance

The frequency response of a laser is also dependent on biasing conditions. As the DC bias of the laser is increased, the bandwidth will generally increase. This is typically due to the “relaxation oscillation” characteristics that vary with bias. The relaxation oscillation phenomenon creates a resonance in the frequency response, noise, and distortion of the laser. Figure 10 is a composite of a bandwidth measurement made at four different bias/output power levels. Note in the two lower traces that the response tends to peak before rolling off. This is the region of relaxation oscillation. Care must be taken when modulating a laser in this region, because this is where noise and distortion properties are often at their worst. As bias is increased, both peaking and bandwidth increase. For this laser, as bias reaches a certain point, the peaking begins to saturate. (See Agilent Application Note 371, “Measuring Modulated Light.”)

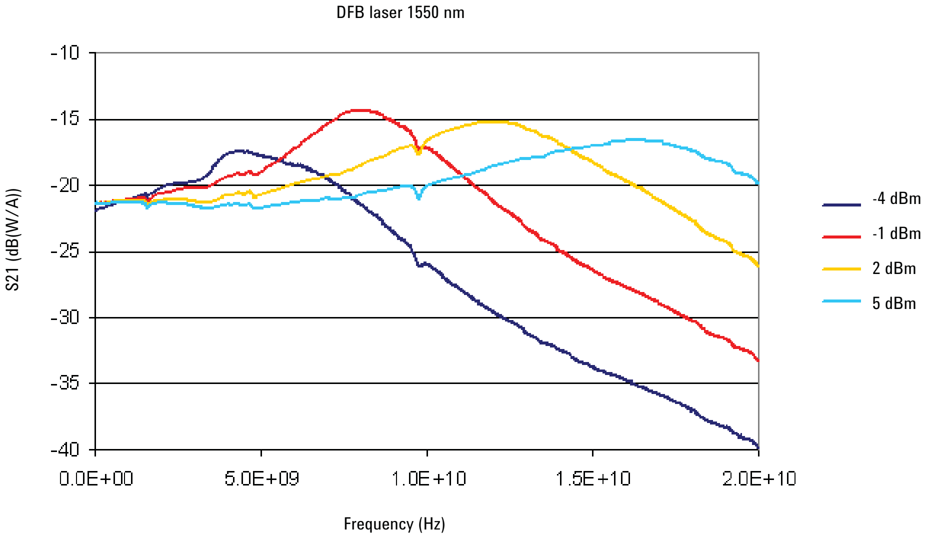
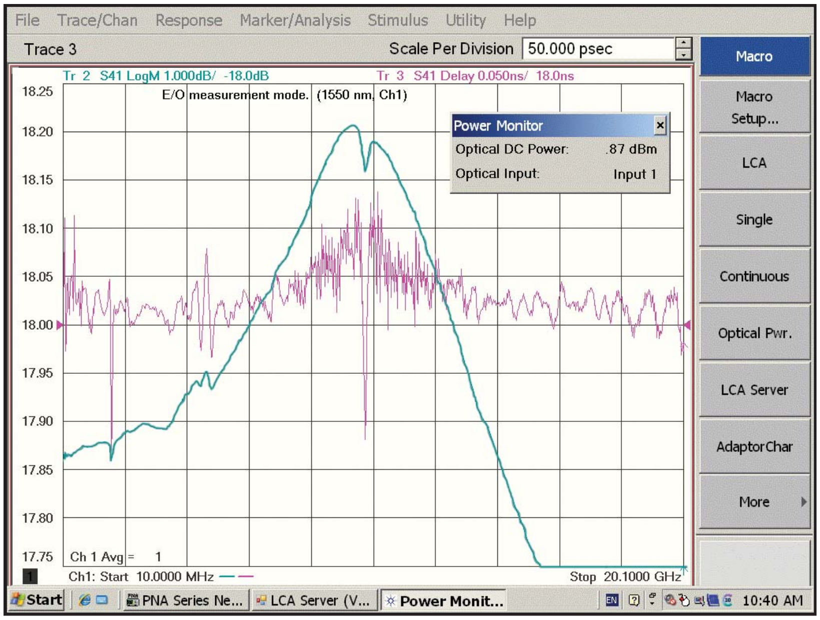


Figure 10. Bandwidth measurement of DFB laser

Modulation phase response

Ideally, a laser's modulation envelope will exhibit a linear phase response versus modulation frequency. If the relative phase relationships of the modulation frequencies do not remain constant, a form of distortion will occur. The phase response of the laser can be displayed in two ways. One way is to display the phase response directly. The second is to display the phase response in a "delay" format.



Scale Per Division 50.000 psec

Tr 2 S41 LogM 1.000dB/ -18.0dB Tr 3 S41 Delay 0.050ns/ 18.0ns

E/O measurement mode. (1550 nm, Ch1)

Optical DC Power: .87 dBm

Optical Input: Input 1

Ch 1 Avg = 1

Ch1: Start 10.0000 MHz Stop 20.1000 GHz

Figure 11. E/O delay measurement

Measurement procedure and interpretation

Phase data is displayed by simply choosing the data format to be "phase" as opposed to the default "log mag." If the DUT has any significant length in either the optical or electrical path, some compensation in length (through the electrical delay function under the "Scale Ref" key) will be required for viewing the phase response of the laser.

In this measurement, 18 ns of electrical delay is added, because the total fiber length is about 3.6 m. The phase response often "follows" the frequency response. The frequency response of this laser peaks at the same frequency range where the phase deviates from a 'linear' response. Sometimes the phase response is easier to interpret and use when viewed in the "delay" data format. The plot of delay is used to indicate the effective time it takes for a modulating signal at the input of the E/O DUT to exit the device as modulated light. Ideally, this transition time will be the same for all modulation frequencies of interest. Figure 11 shows the delay for a 10 G laser. The average propagation time over the 20 GHz bandwidth is near 18 ns.

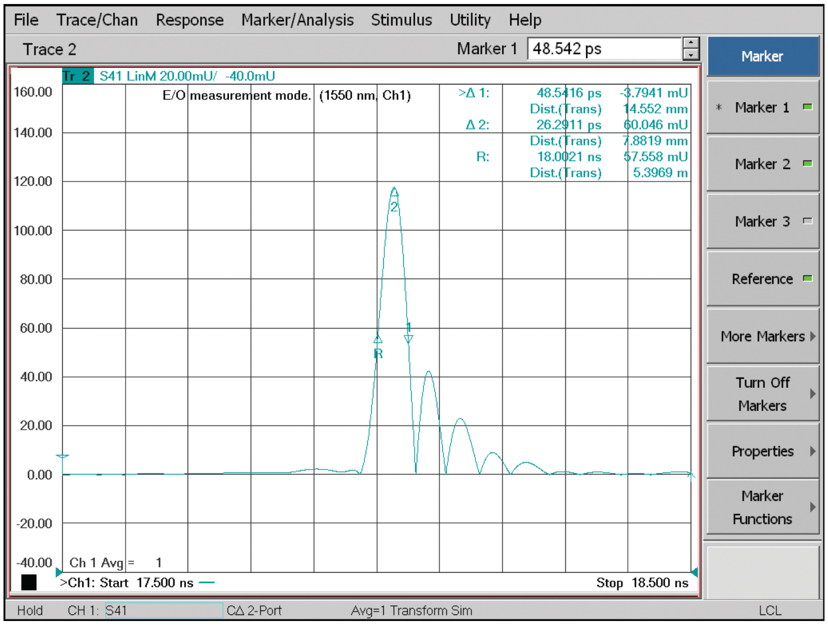
Laser pulse measurements

Frequency domain information (modulation bandwidth) is related to time domain performance using the analyzer's time domain feature. An LCA uses the measured frequency domain (bandwidth) data and mathematically manipulates it through a form of an inverse Fourier transform to predict the effective step and/or impulse response of a laser. (See Appendix 2, "Operation in the Time Domain;" Basic considerations.)

Measurement results and interpretation

Figure 12 shows the predicted impulse response of a high-speed laser. The data is displayed in a linear magnitude format (as opposed to logarithmically in dB). Several items of information are available from this measurement. One is basic impulse width, which is a measure of device speed. The pulse width value is the time between markers R and 1 at the half-maximum points. However, part of the response is due to the finite bandwidth of the instrument itself.

Marker 2, at approximately 18 ns + 26.3 ps, is the delay or propagation time through the laser device from the electrical input to the optical output. The device has a long length of fiber pigtail which is the main contributor to the total delay. The delay contribution can be removed via the optical adapter deembedding feature of the LCA by specifying the length and refrective index of the fiber pigtail.



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>Δ 1:   48.5416 ps     -3.7941 mU
        Dist.(Trans)   14.552 mm
 Δ 2:   26.2911 ps     60.046 mU
        Dist.(Trans)   7.8819 mm
  R:    18.0021 ns     57.558 mU
        Dist.(Trans)   5.3969 m
```

Figure 12. E/O impulse response

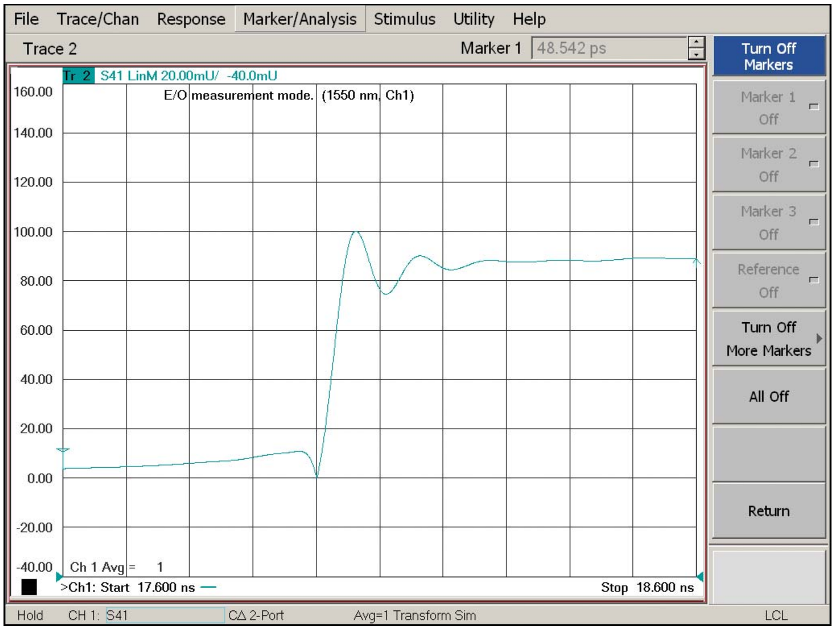


Figure 13. E/O step response of laser

Note also that there is a secondary impulse. This typically indicates the presence of relaxation oscillations. Figure 13 shows the predicted step response of the same laser. From this measurement we can determine risetime, ringing, and overshoot performance. In general, these parameters are directly related to the frequency response of the device.

Measurement procedure

Pulse measurements are generated by manipulating measured frequency response data. Consequently, the measurement procedure is almost identical to that used for the modulation bandwidth. (Potential differences exist due to requirements of the mathematical transform. See Appendix 2, "Operation in the time domain.")

Electro-optic external modulator measurements

External intensity modulators can be characterized in much the same way as laser sources. This is another class of E/O measurements where the stimulus is a swept frequency electrical signal and the response out of the modulator is intensity modulated light. In particular, modulation bandwidth, phase, and electrical impedance measurements are made with the component analyzer in the same configuration that is used for laser measurements. However, a significant difference exists due to the modulator being a three-port device. At the optical input port to the modulator a CW lightwave source is connected.

Figure 14 shows the modulator response S21 in Watt per Amps (light blue) and S11 (brown).

Similar to the process used for laser measurements, the phase response and electrical input impedance can also be characterized. The frequency domain information can also be used to predict the step and impulse responses.

Modulator responsivity scaled to Watts/Volt

Lasers are typically described by an input current versus output power relationship. However the referred description for a modulator is often an input voltage versus output power relationship.

Because LCA measurements assume a 50 Ω measurement environment, the LCA modulator measurement in Watts per Amp can be converted to Watts per volt by scaling (dividing) the measurement by 50. With the Agilent PNA Series, this can be achieved by using the “Equation” feature, dividing the trace results by 50.

Modulator responsivity scaled to reference output power level

While the frequency response of a modulator is often independent of the input optical power, the responsivity is not. The conversion efficiency of the modulator is not only a function of the electrical input, but also the level of the optical input. The LCA measurement compares the output modulation power to the input modulation current. A responsivity in Watts per Amp is then computed and displayed. If the input optical power is increased, the output modulation will typically also increase. Thus, the apparent responsivity will increase. This means that the modulator responsivity measurement is valid only for the specific optical input power (or optical output power) that existed when the measurement was performed. The frequency response is typically valid over a wide range of input powers.

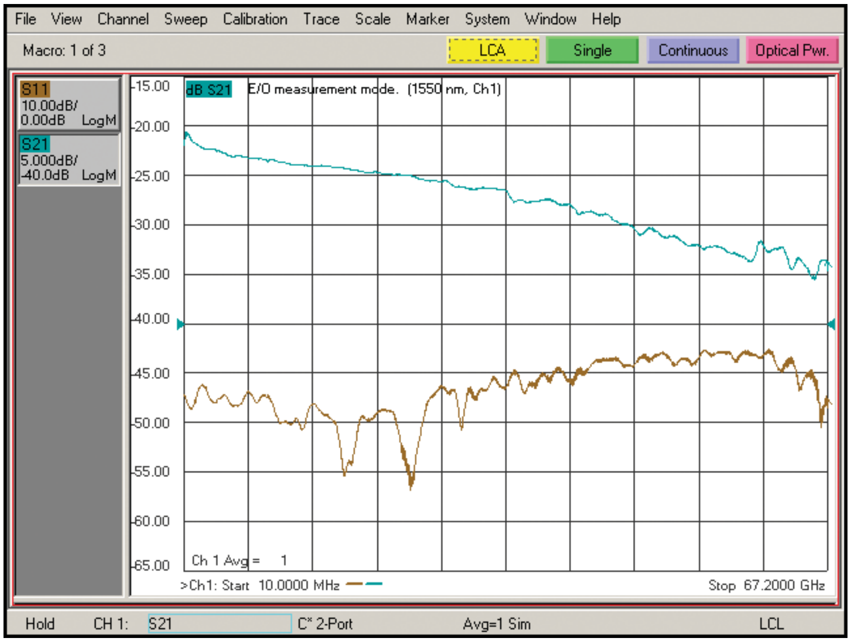


Figure 14. Modulator response S21

To display the modulator responsivity at a reference output power level use the power level measured with the internal power meter (converted to Watt) and convert the responsivity using the equation feature with equation 1 below.

Modulator analysis

Figure 15 is a measurement of the relative conversion efficiency (S_{21}) and electrical return loss (S_{11}) of two wide bandwidth (40G) external modulators as a function of modulation frequency. The unusual response of the "bad" modulator in Figure 15 in the 55GHz frequency range is due imperfections of the electrical impedance matching /RF coupling in the modulator package. The measurement examples clearly demonstrate issues in the electrical performance of the modulator above 50 GHz. The bad modulator has a sharp resonance resulting in very large S_{11} and consequently a deep notch in the S_{21} response, making the component unusable in many applications.

Transmitter input impedance

The conversion efficiency of a transmitter is dependent not only on the inherent properties of the transmitter, but also on how efficiently the electrical modulation signal is delivered to the laser or modulator chip. High speed modulation signals are generally transmitted to the chip over transmission lines with a 50 or 75 Ω characteristic impedance. Maximum power transfer will occur if the input impedance of the chip is the same as the transmission line. For instance, unfortunately the input impedance of an active laser is much lower than the transmission system used to drive it. Two problems occur when such an impedance mismatch exists. First, a significant amount of energy will be reflected at the transmission line/laser interface. This reflected energy may eventually be re-reflected and distort the desired data signal. The second problem is that the reflected energy is "wasted" since it is never effectively used to modulate the laser. Thus, the overall conversion efficiency of the laser is degraded.

S21 @ Pref [dBm] = S21 @ Optical DC Power [dBm] * 10^(0.1*(Pref [dBm]-Optical DC Power[dBm]))

Equation 1. Modulator responsivity

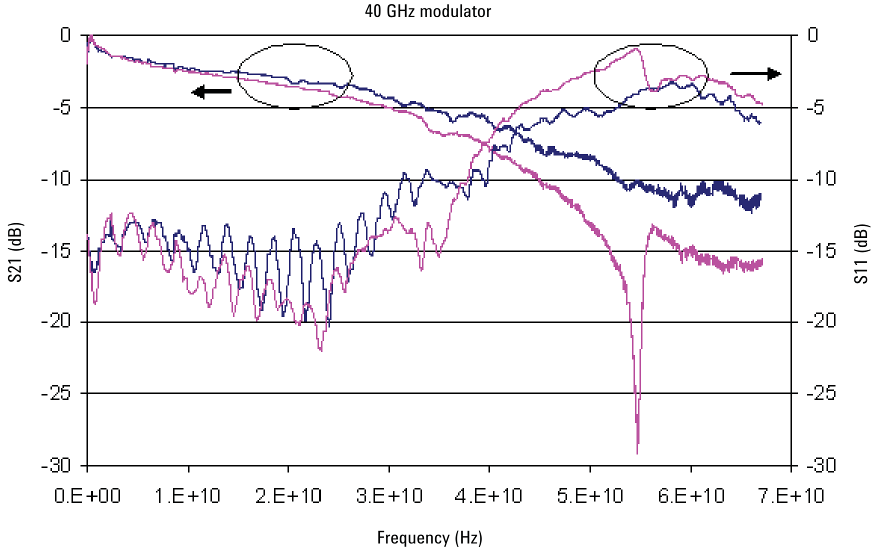


Figure 15. Modulator bandwidth S_{21} and electrical return loss S_{11} of two different 40 GHz modulators

Measurement procedure

Figure 15 shows the return loss of modulators with matching circuit as measured on the lightwave component analyzer. The measurement is made by sending a swept RF signal to the modulator under test and measuring the energy that reflects back. The setup and calibration procedure will depend on the model of LCA used. In all cases, a one port (or full two-port) calibration, preferably with an electronic calibration kit with integrated known electrical reflection standards is required for highly accurate reflection measurements.

Measurement interpretation

The return loss over the whole 67 GHz range varies from a best case of below –18 dB to a worst case of –2 dB. It is not unusual for the reflection level to get worse as the modulation frequency is increased. Return loss is the ratio of reflected to incident energy (10 Log (P refl/ P inc)). The larger the return loss magnitude, the smaller the reflected signal and the better the impedance match.

A different display for return loss plot is in the Smith chart format. A Smith chart is a form of an impedance map (e.g., see Figure 19). The display shows the input impedance as a function of frequency. For the modulator the impedance is near 50 Ω over the 30 GHz range, as the response would not deviate much from the center of the chart. The Smith chart data presentation is selected under the "Format" key menu. For more information on network analyzer display formats see Application Note AN1287-1.

Implications of impedance mismatch on measurement accuracy

When the input impedance of the E/O device under test is far from 50 Ω, a significant portion of the electrical energy sent to the device will be reflected. This reflected energy is accounted for in the full two-port measurement and thus does not degrade measurement accuracy as in previous LCA systems. However, the intrinsic device response is distorted by ripples in frequency response measurements resulting from reflection.

Lightwave Receiver Measurements (O/E)

The measurements that the LCA makes on lightwave receivers are in many ways similar to those made on lightwave sources. In this case, the stimulus will be modulated light and the response will be “demodulated” electrical signals. Measurements include:

- Photo diode responsivity and modulation bandwidth
- Photo receiver transimpedance gain
- Balanced detector/receiver differential gain, imbalance and common mode rejection ratio
- Step and impulse response
- Characterization and improvement of the electrical output impedance

As with the transmitter, bandwidth measurements are relevant to pulse rise and fall times, while impedance measurements are important to minimize signal reflections and maximize electrical power transfer.

Figure 16 shows the measurement setup for a single ended receiver measurement

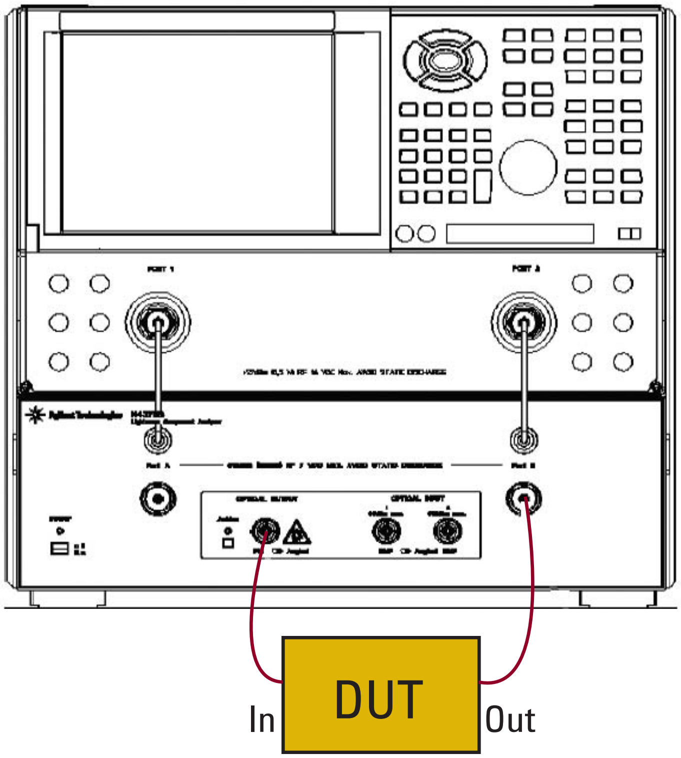


Figure 16. O/E measurement setup

Photo diode modulation bandwidth, frequency response, and conversion efficiency

As discussed earlier, photo diode conversion efficiency refers to how a change in optical power is converted to a change in output electrical current. As the frequency of modulation increases, eventually the receiver conversion efficiency will roll off. Thus, the device has a limited modulation bandwidth. The measurement of modulation bandwidth consists of stimulating the photo diode with a source of modulated light and measuring the output response (RF or microwave) current with an electrical receiver. Normally the frequency of the modulation is swept to allow examination of the photo diode or photo receiver over a wide range of modulation frequencies.

Measurement results and interpretation

The instrument display of Figure 17 shows the conversion efficiency of the photo diode as a function of modulation frequency. The vertical axis display units are Amps per Watt and the horizontal axis is modulation frequency. In this case, the vertical axis is in a logarithmic format where 0 dB represents 1 Amp per Watt.

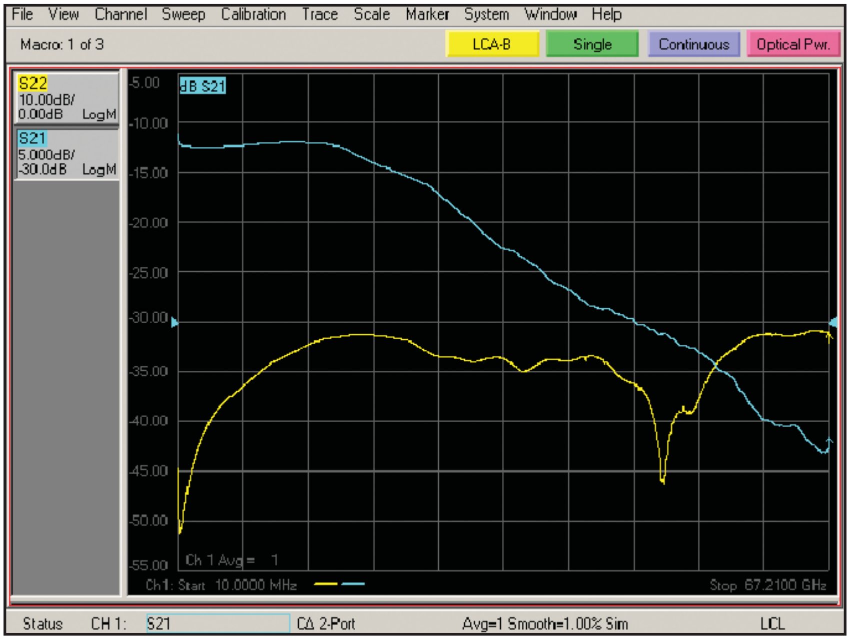


Figure 17. O/E responsivity and electrical return loss measurement

The photo diode under test has a modulation bandwidth of approximately 20 to 25 GHz. The return loss measurement exhibts the typical characteristic of a purely resistivly matched detector. It shows excellent matching at very low frequency, however with poor matching when approaching the modulation bandwidth due to practically short circuiting the matching resistor by the detector chip capacitance.

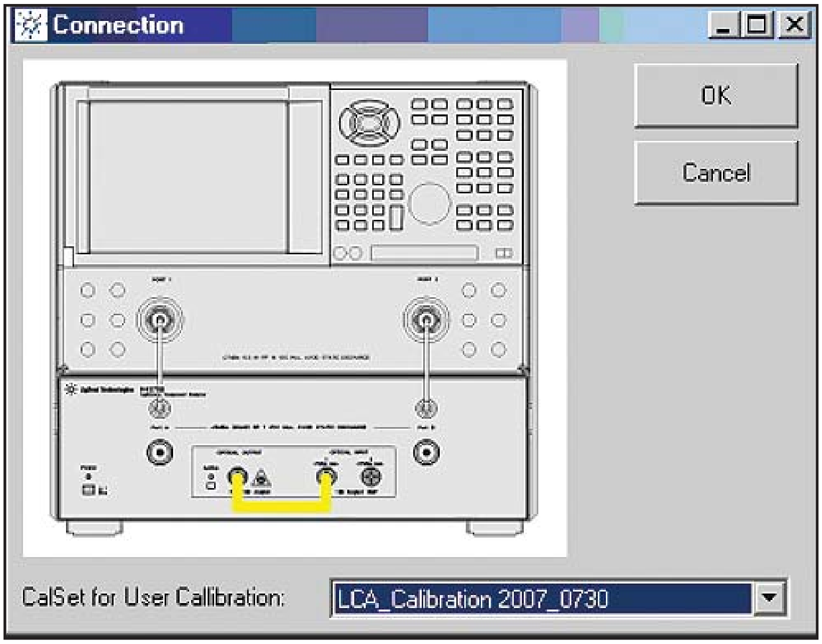
Measurement procedure

The measurement process is virtually identical to the transmitter measurement. Please follow the steps decribed in section "LCA Measurement Process". For enhanced frequency response calibration, a user calibration is offered.

A guided procedure recalibrates the LCA transmitter with the simple setup as shown in Figure 18.

After completion of the calibration, one might expect to see a flat response at 0 dB indicating the test system response has been removed. When using an Agilent N4373B, the display seen upon completion of the user calibration process will not necessarily be a flat line. The O/E receiver used in the calibration, which is still in the measurement path, has become the DUT. Thus its response is now displayed.

The receiver to be tested is placed in the measurement path and its response can be seen, as in Figure 17 "O/E responsivity and electrical return loss measurement", previously shown.



CalSet for User Calibration: LCA_Calibration 2007_0730

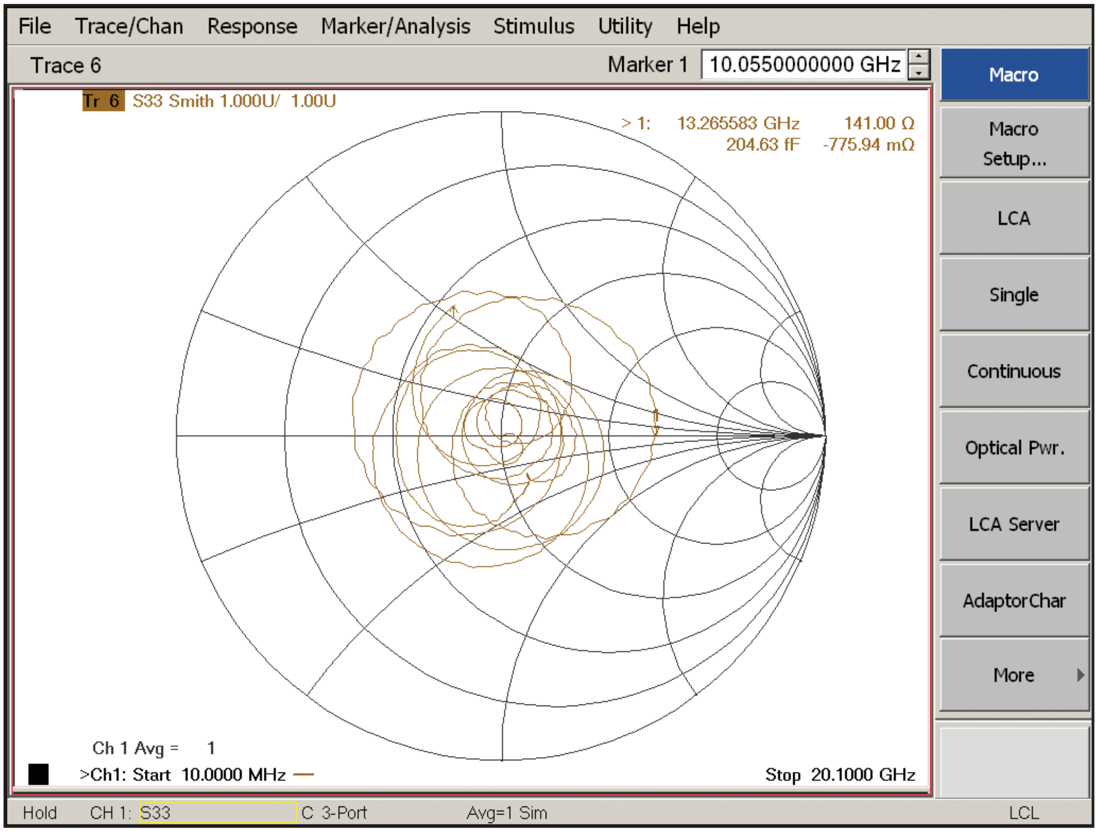
Figure 18. OE user calibration configuration

Photo diode output impedance

Once the photo diode has converted the modulated light to a proportional electrical current, the task is then to efficiently transmit the demodulated signal to any following electrical components. High-speed systems usually require this transfer over 50 or 75 Ω transmission lines. The output impedance of a photo diode is usually much higher than 50 Ω (or 75 Ω). This leads to the possibility of signal reflections and degraded conversion efficiency. If the signal transmitted from the photo diode encounters another impedance mismatch along the transmission path, energy will be reflected back towards the photo diode. The energy will then be re-reflected in the forward direction and potentially interfere with primary signals. Thus, reflections can lead to communication degradation.

Measurement procedure and interpretation

The setup and measurement of photo diode return loss are identical to the procedure used in characterizing laser return loss. See “Laser input impedance”. Figure 19 shows the return loss of an optical receiver measured with the component analyzer, displayed on a Smith chart. A Smith chart is a form of an impedance map. The display shows the output impedance as a function of frequency.



Trace 6

Marker 1 10.0550000000 GHz

Tr 6 S33 Smith 1.000U/ 1.00U

> 1: 13.265583 GHz 141.00 Ω
204.63 fF -775.94 mΩ

Ch 1 Avg = 1

>Ch1: Start 10.0000 MHz

Stop 20.1000 GHz

Hold CH 1: S33 C 3-Port Avg=1 Sim LCL

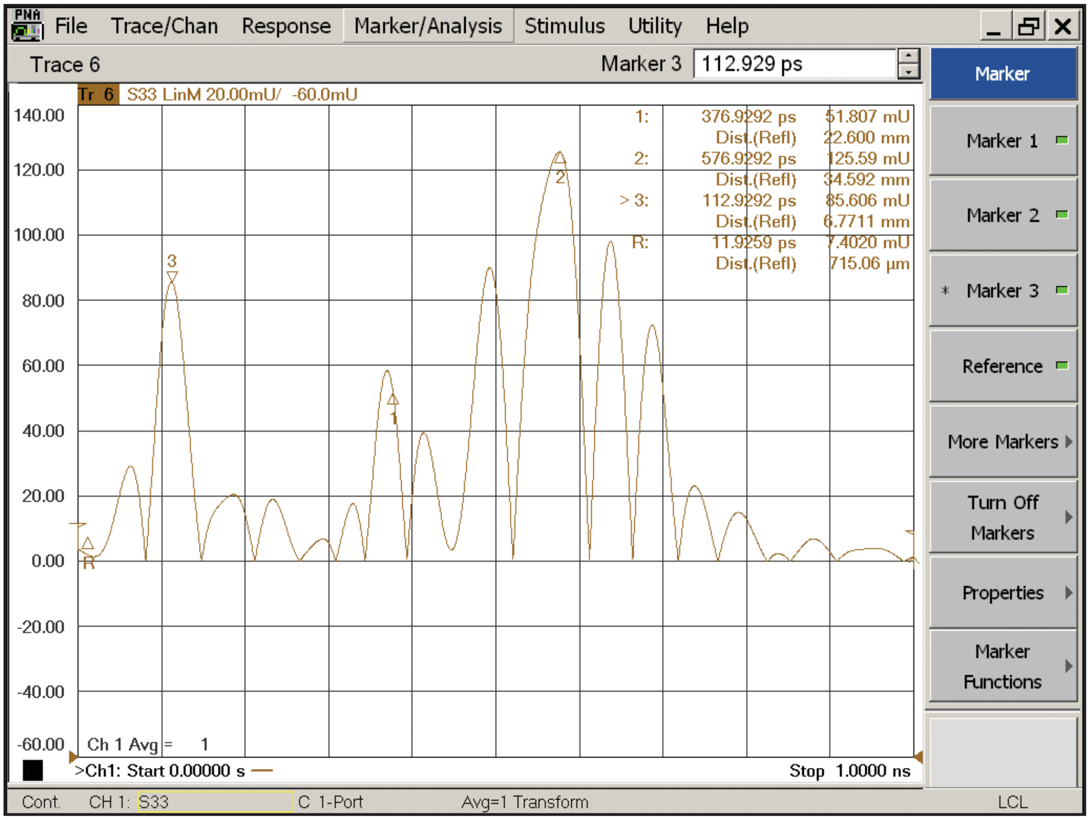
Figure 19. Return loss of optical receiver in Smith chart format

For this receiver, an electrical amplifier follows the photo diode, so the measured impedance is essentially that of the amplifier. Over the 20 GHz measurement range, the impedance strongly deviates from 50 Ωs (the center of the Smith chart). The ideal case would be for the impedance to be a constant 50 Ω (or 75 Ω). The Smith chart data presentation is selected under the “Format” key menu.

The data can also be displayed simply as return loss, the ratio of reflected to incident power (10 Log (P refl/ P inc) as displayed in the yellow trace of Figure 17.

Using the time domain feature of the LCA can help to determine the locations of any discontinuities in the electrical path of the photo diode assembly.

Figure 20 is a time/distance representation looking back into a ROSA (receiver optical subassembly) device mounted in a test fixture. The reflection at marker 3 stems from a surface mount blocking capacitor. At marker 1 one sees reflections at the connection of ROSA connection pins to test fixture and at marker 2 one sees the key reflection from ROSA output chip.



Trace 6

Marker 3 112.929 ps

Tr 6 S33 LinM 20.00mU/ -60.0mU

```
   1:   376.9292 ps    51.807 mU
        Dist.(Refl)    22.600 mm
   2:   576.9292 ps    125.59 mU
        Dist.(Refl)    34.592 mm
 > 3:   112.9292 ps    85.606 mU
        Dist.(Refl)    6.7711 mm
   R:   11.9259 ps     7.4020 mU
        Dist.(Refl)    715.06 µm
```

Ch 1 Avg = 1

>Ch1: Start 0.00000 s — Stop 1.0000 ns

Cont. CH 1: S33 C 1-Port Avg=1 Transform LCL

Figure 20. Time domain display of electrical reflections

Balanced Device Measurements

Optical transceivers for 10 GE applications or new (complex) modulation formats require balanced devices, often having one optical port and two electrical ports. Examples are ROSA (receive optical sub-assembly) which is a photodetector integrated with a transimpendance amplifier with dual electrical outputs and dual drive LiNbO3 modulators for 43 Gb/s low drive voltage modulation.

Usually these balanced devices are 3-port devices. These electrical ports operate in push-pull operation, namely with 180° phase offset. The multiport network analyzer of the LCA is capable of measuring both individual single-ended transmission characteristics from every electrical input port to the optical output port and vice versa as well as the balanced characteristic from the differential electrical ports to the single-ended optical port.

Port configuration

For balanced measurement, it is required to assign network analyzer (physical) ports to logical ports (see Figures 22 and 23). The logical port configuration is as follows: (logical) port 1 is assigned to the single ended, unbalanced port and (logical) port 2 is assigned to the balanced, differential port.

For OE measurements the single ended (SE) port 1 is assigned to network analyzer port 1 and the balanced (BAL) port 2 is assigned to nework analyzer ports 2 and 3 (see Figure 22). For EO measurement the single ended (SE) port 1 is assigned to network analyzer port 4 and the balanced (BAL) port 2 is assigned to network analyzer ports 2 and 3 (see Figure 23).

The network analyzer now allows to display traces of interest for balanced devices like differential responsivity S, common mode rejection or port imbalance. Since opto-electronic components are uni-directional, non-reciprocal devices only the measurement types encircled in

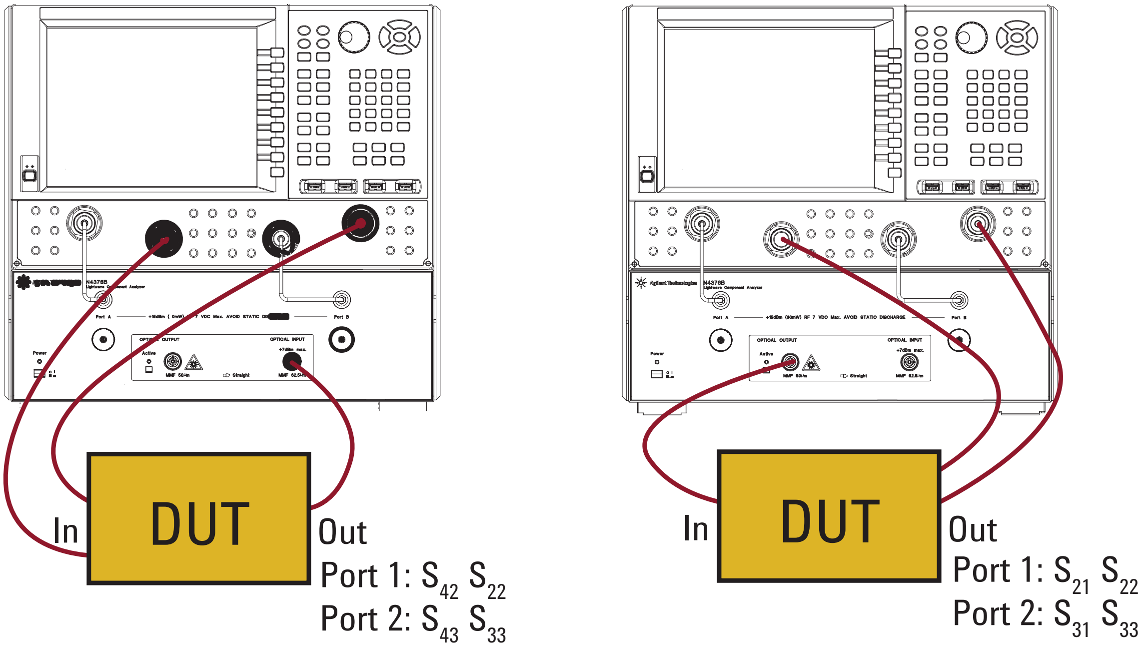
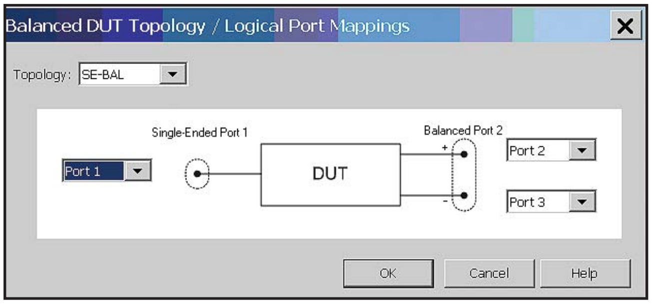


Figure 21. Balanced EO and OE device measurement setup

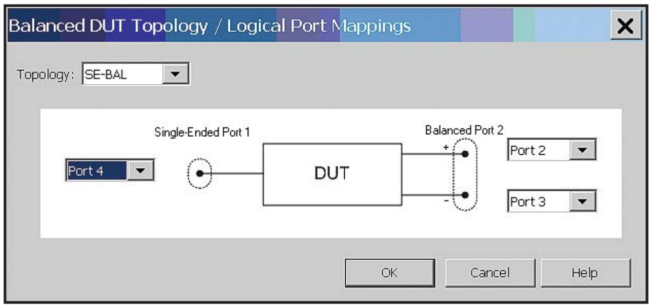


Topology: SE-BAL

Single-Ended Port 1: Port 1

Balanced Port 2: Port 2, Port 3

Figure 22. Logical port mapping for OE measurement

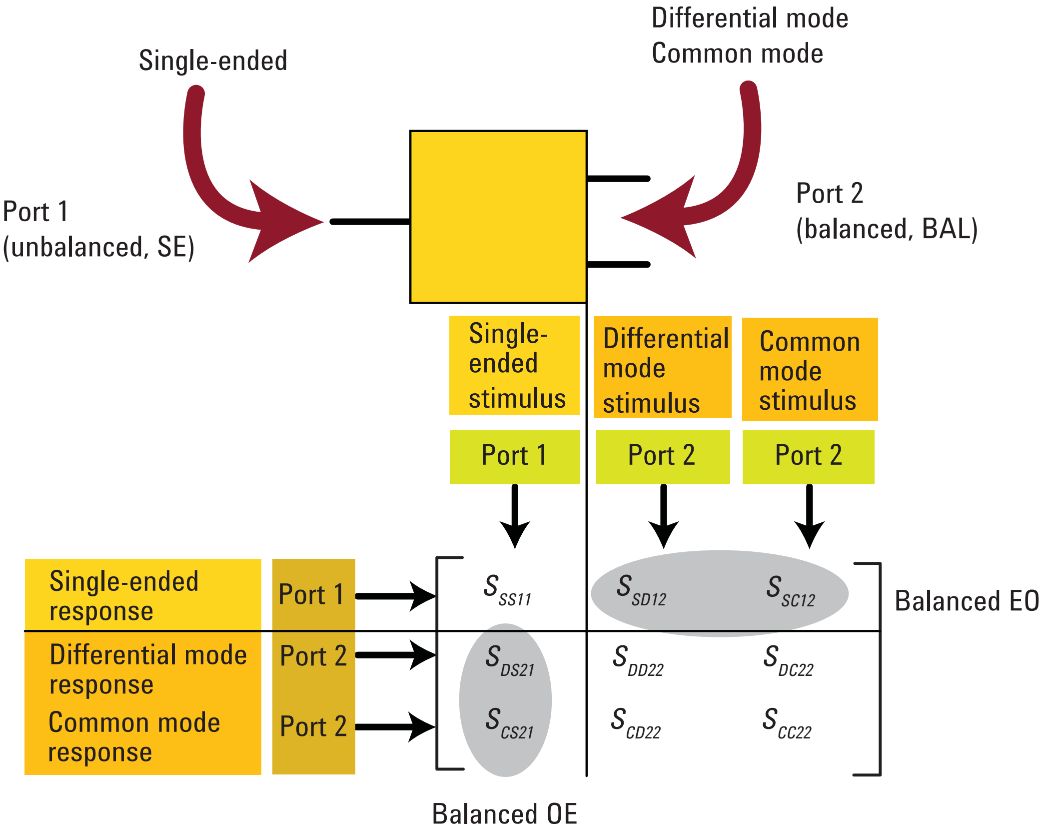


Topology: SE-BAL

Single-Ended Port 1: Port 4

Balanced Port 2: Port 2, Port 3

Figure 23. Logical port mapping for EO measurement



	Single-ended stimulus Port 1	Differential mode stimulus Port 2	Common mode stimulus Port 2
Single-ended response — Port 1	S_{SS11}	S_{SD12}	S_{SC12}
Differential mode response — Port 2	S_{DS21}	S_{DD22}	S_{DC22}
Common mode response — Port 2	S_{CS21}	S_{CD22}	S_{CC22}

Figure 24. Balanced measurement types for opto-electronic components

Optical receiver measurement

The following example is a ROSA (receiver optical subassembly) device measurement. The ROSA consists of a InGaAsP PIN photo-detector packaged with a broadband transimpedance amplifier with two electrical outputs (A,B), which operate with 180° phase difference. The ROSA is designed for high sensitivity at -20 dBm optical input power. The measurement setup in Figure 25 uses an optical attenuator to set optical power to the system relevant input power levels to ROSA.

A current meter is used to measure the photocurrent for determination of photo detector quantum efficiency. For correct measurement of the overall receiver conversion efficiency the attenuator needs to be deembedded. The attenuation level is set in the attenuation field in the “Optical Path De-embedding” section of the OE configuration setup screen (see Figure 26).

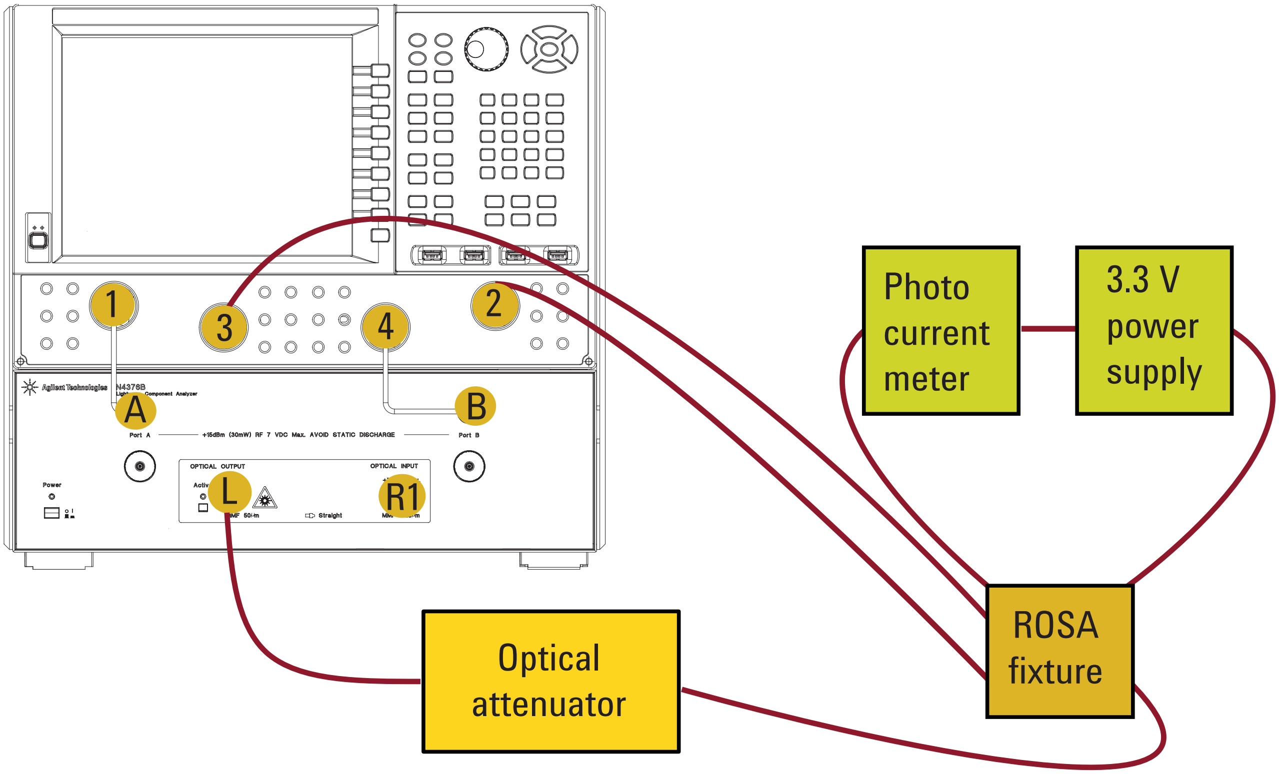


Figure 25. ROSA measurement setup

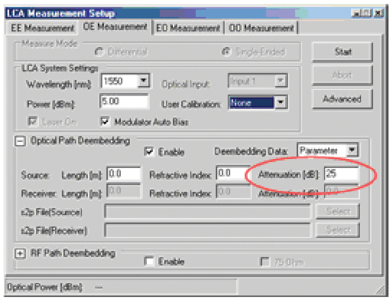
Measurement procedure and interpretation

Figure 26 shows a typical measurement screen for the differential efficiency, electrical port return loss, trans-impedance of each individual port and normalized common mode rejection.

$$T = \frac{50\ \Omega}{\eta_{DC}} \bullet S_{OE}$$

Equation 2. Trans-impedance definition

The trans-impedance is defined in Equation 2. The photo detector quantum efficiency is measured with the current meter. The equation editor of the PNA allows to directly calculate and display the transimpedance of each individual OE path. The encircled section on the lower screen of Figure 25 demonstrates an imbalance between the transimpedance gains of port A and B, resulting in strong reduction of common mode rejection.



Wavelength [nm]: 1550
Optical Input: Input 1
Power [dBm]: 5.00
User Calibration: None
☑ Laser On
☑ Modulator Auto Bias
☑ Enable
Deembedding Data: Parameter
Source: Length [m]: 0.0 Refractive Index: 0.0 Attenuation [dB]: 25
Receiver: Length [m]: 0.0 Refractive Index: 0.0 Attenuation [dB]: 0.0
s2p File(Source)
s2p File(Receiver)
☐ Enable
☐ 75 Ohm
Optical Power [dBm] —

Figure 26. Attenuation level setting

Differential efficiency [dB(A/W)]

S22 S33

Transimpedance [dB(Ω)] output A, B

Common mode rejection [dB] normalized to differential efficiency

Figure 27. Balanced measurement screen for ROSA

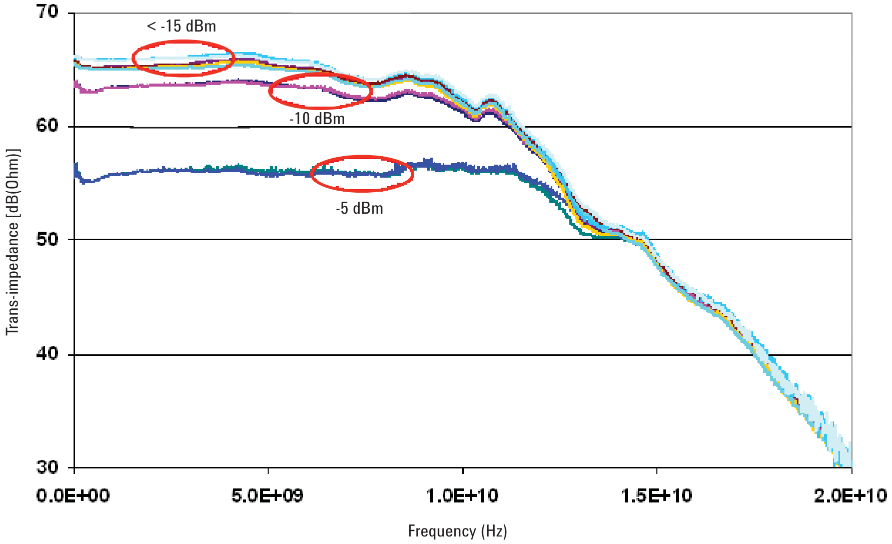


Figure 28. ROSA trans-impedance for various optical input power levels

Figure 28 shows the ROSA behavior for optical input power levels between -25 dBm to -5 dBm. The trans-impedance saturates for power levels above -10 dBm, resulting in clipping effects.

Electrical Component Measurements (E/E)

Lightwave component analyzers have the capability to operate as RF and microwave network analyzers. They can then be used to characterize the electrical components used in lightwave systems including amplifiers, filters, couplers etc.

Signal Relationships in Opto-Electronic Devices

Signal relationships used in component measurements

The LCA measurement technique is built upon concepts used in characterizing RF and microwave devices. "S-parameter" or scattering matrix techniques have proven to be convenient ways to characterize device performance. The following section will discuss how similar techniques are used in characterizing devices in the lightwave domain. This is intended to show the basis on which E/O and O/E responsivity measurements are defined.

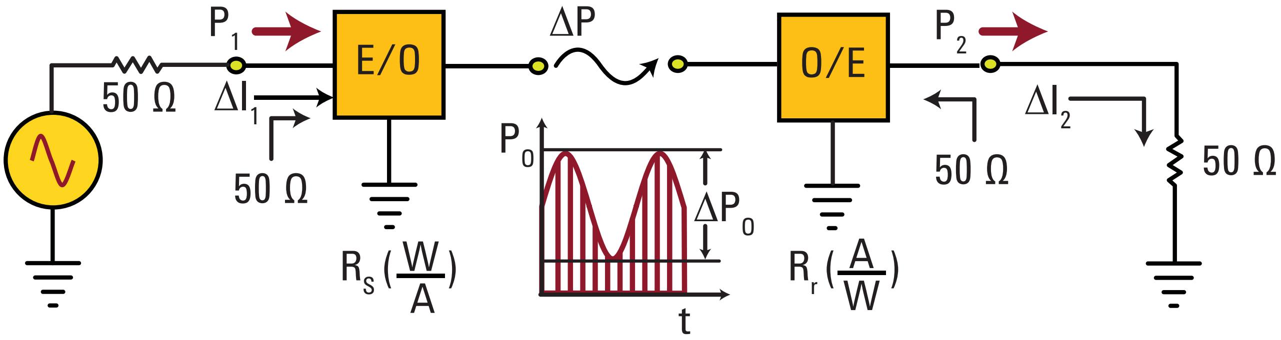


Figure 29. Signal definitions

Figure 29 is a general representation of a lightwave system, showing input and output signals in terms of terminal voltages, input and output currents, and optical modulation power. S-parameters are used to describe the transmitted and reflected signal flow within a device or network.

For the model, the following S-parameters are defined:

$$S_{11} = \frac{b_1}{a_1} \ (a_2 = 0)$$

$$S_{22} = \frac{b_2}{a_2} \ (a_1 = 0)$$

Where:

$a_1 = \frac{\Delta V_1}{\sqrt{Z_0}}$ ► Incident on E/O device

$= \Delta I_1 \bullet \sqrt{Z_0}$

$b_1 = \frac{\Delta V_1}{\sqrt{Z_0}}$ ► Reflected from E/O device

$a_2 = \frac{\Delta V_2}{\sqrt{Z_0}}$ ► Incident on O/E device

$b_2 = \frac{\Delta V_2}{\sqrt{Z_0}}$ ► Transmitted from O/E device

$= \Delta I_2 \bullet \sqrt{Z_0}$

It is interesting to note that "delta" voltages and currents are used as opposed to RMS values. This is done because we deal with modulation signals in describing lightwave transducers, where a change in optical power is proportional to a change in electrical current or voltage. The overall system forward gain is defined as:

$$S_{21} = \frac{b_2}{a_1} \ (a_2 = 0)$$

$S_{12} = 0$ ► No reverse transmission is assumed

Though the overall system gain is defined as an S-parameter, the individual transfer functions of the E/O and O/E devices are typically defined in terms of responsivities, because signals in both the optical and electrical domain are used and optical signals do not lend themselves conveniently to S-parameter definitions. Initially, the input impedance of the E/O converter and the output impedance of the O/E converter will be assumed to be Z_0 (thus S_{11} and S_{22} are zero).

$$R_S = \frac{\Delta P_0}{\Delta I_i} = \text{E/O source responsivity}$$

and

$$R_r = \frac{\Delta I_2}{\Delta P_0} = \text{O/E receiver responsivity}$$

Using the above relationships, we can rewrite S_{21} in terms of the transducer responsivities R_S and R_R:

$$S_{21} = \frac{b_2}{a_1}$$

$$= \frac{\Delta I_2}{\Delta I_1}$$

$$= \frac{(R_r \bullet \Delta P)}{(\Delta P / R_S)}$$

$$= (R_S \bullet R_r)$$

It is convenient to express the transducer functions logarithmically in decibels. The system power gain from a Z_0 source to a Z_0 load can be defined using the above relationships:

$|a_1|^2$ = Power incident on the E/O

$|b_2|^2$ = Power delivered to a Z_0 load

$$|S_{21}|^2 = \frac{|b_2|^2}{|a_1|^2}$$

$$= |R_S \bullet R_r|^2$$

= System power gain

$20 \log_{10} |S_{21}|$ = System gain in dB

$$= 20 \log_{10} |R_s \bullet R_r|$$

The responsivities R_s and R_r need to be related to some value in order to have meaning as individual quantities expressed logarithmically, just as 0 dB represents an S_{21} of unity or gain of 1. Consequently source responsivity will be expressed in Watts per Amp, which in decibels will be related to a conversion efficiency of 1 W/A. Similarly, receiver conversion efficiency will be relative to 1 A/W.

$$20 \log_{10} |R_s \cdot R_r| = 20 \log_{10} \frac{R_s\,(\mathrm{W/A})}{1\,(\mathrm{W/A})} \bullet \frac{R_r\,(\mathrm{A/W})}{1\,(\mathrm{A/W})}$$

The individual responsivities can now be expressed individually in decibels:

$$R_s\,(\mathrm{dB}) = 20 \log_{10} \frac{R_s\,(\mathrm{W/A})}{1\,(\mathrm{W/A})}$$

This now allows us to express the original equations for responsivity in logarithmic terms:

$$R_s\,(\mathrm{dB}) = 20 \log_{10} \frac{R_s\,(\mathrm{W/A})}{1\,(\mathrm{W/A})}$$

Responsivity measurements are now based on the LCA's ability to accurately measure optical modulation power (ΔP_0) and modulation current ($\Delta I_{1,2}$). The measurement of modulation current is derived from the system characteristic impedance and a measurement of electrical power. The measurement of optical modulation power is based on a "standard" lightwave receiver whose characteristics are predetermined and known by the LCA.

Appendix 2

Operation in the Time Domain

Basic considerations

The LCA makes its measurements by sweeping the frequency of modulation. Thus data is measured in the frequency domain. However, the LCA also has the capability to mathematically interpret the frequency domain information and present it in a time domain format. We can then estimate how a device will respond to specific waveforms such as a “step” or “impulse”. The time domain transformation can be used in both transmission and reflection measurements, with each supplying different insights into component characteristics. Note: Because the time domain response is derived from the small-signal linear frequency response, it too provides a smallsignal, linear prediction of the step and impulse device responses. To use an LCA for impulse response testing, we make measurements at specific sinusoidal frequencies. The process of adding these discrete sine wave components is expressed mathematically by the inverse discrete Fourier transform (DFT^{-1}). The time domain conversion process uses a sophisticated, high-speed algorithm that converts frequency domain data to the time domain. The algorithm will calculate the equivalent of either an impulse (“low pass impulse” mode), a step (“low pass step” mode), or an RF burst (“bandpass” mode). The result calculated by the time domain algorithm is the same result that would be measured by the corresponding direct measuring system (oscilloscope, pulse generator etc.) with the same bandwidth and pulse shape.

There are advantages and disadvantages in each of the three transform modes. The step response is calculated by taking the integral of the impulse response. The step mode not only provides risetime and transient information, it can also be used to characterize the nature of electrical discontinuities (capacitive, inductive etc.) when making electrical reflection measurements. The low pass impulse mode provides the highest resolution in impulse measurements. Both the step and impulse modes require that the frequency points be harmonically related, and the sweep has to start at the fundamental so the DC term can be extrapolated. (The PNAs used for the LCA’s have a function called “SET FREQ LOW PASS” which ensures harmonically-related frequency points.)

Range and resolution

Measurement range

Measurement range is used to describe the largest time span (and consequently the longest distance) that can be displayed within the bounds of the transform. The mathematical transform used generates an “impulse train” in the time domain, not a single pulse. Consequently, after a certain length of time, the pulse is repeated. This leads to “alias” responses. We cannot distinguish which of the pulses are true responses when we are outside of the alias-free range. The alias free range, in seconds, is given by:
AFR = (N–1) / Freq. span, where ‘N’ is the number of measurement points. Ambiguous measurements will also be generated when the phase rotation through a device is greater than 180 degrees over the frequency step size.

Measurement resolution

Measurement resolution is a measure of the LCA’s ability to locate a single response, in seconds, and is defined as:

$$MR = \frac{(\text{Time span})}{(\text{N-1})}$$

where measurement span is the span of time displayed on the LCA (with the transform active) and N is the number of data points. As the time span is reduced, the single-event measurement resolution will eventually be limited by the phase accuracy of the instrument. The measurement resolution, in seconds, due to phase accuracy uncertainty is then:

$$MR = \left(\frac{(0.003 \cdot \text{Phase uncertainty (deg)}}{\text{Aperature (Hz)}}\right)$$

where the aperture is the measurement frequency range. Phase uncertainty will vary depending upon the type of measurement made, but typically is better than 2 degrees, which leads to sub-pico-second time uncertainties and sub-millimeter distance uncertainties.

Response resolution

Response resolution is the smallest time (proportional to distance) between two responses, where each response can be isolated and identified.

Table 2: Approximate relationship between frequency span, window selection

Window	Low-pass step (10% to 90%	Low-pass impulse (50%)	Bandpass impulse
Minimum	0.45/frequency span	0.60/frequency span	1.20/frequency span
Normal	0.99/frequency span	0.98/frequency span	1.95/frequency span
Maximum	1.48/frequency span	1.39/frequency span	2.77/frequency span

Improving measurement accuracy through gating

Reflected signals can interfere with primary signals, leading to measurement uncertainty. Operating in the time domain, reflected signals can be isolated and mathematically removed, thus improving measurement accuracy. For transmission measurements of E/O, O/E, O/O, and E/E devices, a reflection-free time-domain impulse response will be shown as a single event. If there are significant reflections in the DUT, there will be additional impulse responses. The time-domain gating function acts as a time "bandpass" filter that passes the primary response and removes the responses due to reflections. Once the reflections have been "gated out", the measurement can be returned to the frequency domain. The frequency response displayed is as if the reflected signals were no longer present.

For additional information on time domain see Application Note AN1287-12.

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