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Test Procedure for Measuring Transmission and Reflection

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Table of Contents

List of Figures

List of Tables

1. Introduction

1.1. Executive Summary

This test procedure describes the techniques used to characterize radio frequency (RF) components and subsystems by measuring their transmission and reflection characteristics. The resulting measurements can be used to compare the performance of various devices as well as predict overall network performance when multiple devices are used together.

1.2. Scope

The purpose of this test procedure is to determine the reflection at any port, or the transmission between any two ports of a properly terminated device, as measured across a frequency range of interest. Depending on use of the data, return loss, insertion gain or loss, isolation, response variation or bandwidth can be derived.

This specification is designed for devices with a characteristic impedance of 75 ohms. However, these principles can easily be extended to devices of other characteristic impedances.

1.3. Benefits

This test procedure will yield accurate and consistent measurements of RF reflection and transmission characteristics for the device under test. Use of this test method provides the user a means to verify manufacturer published product specifications and certificates of compliance (when available).

1.4. Intended Audience

The intended audience for this test method, are manufacturers and end-users with proper laboratories and equipment to perform this test.

1.5. Areas for Further Investigation or to be Added in Future Versions

At this time, there are no considerations being given for further investigation.

2. Normative References

The following documents contain provisions which, through reference in this text, constitute provisions of this document. The editions indicated were valid at the time of subcommittee approval. All documents are subject to revision and, while parties to any agreement based on this document are encouraged to investigate the possibility of applying the most recent editions of the documents listed below, they are reminded that newer editions of those documents might not be compatible with the referenced version.

2.1. SCTE References

No normative references are applicable.

2.2. Standards from Other Organizations

No normative references are applicable.

2.3. Other Published Materials

No normative references are applicable.

3. Informative References

The following documents might provide valuable information to the reader but are not required when complying with this document.

3.1. SCTE References

[SCTE 96]	ANSI/SCTE 96 Cable Telecommunications Testing Guidelines

3.2. Standards from Other Organizations

No informative references are applicable.

3.3. Other Published Materials

No informative references are applicable.

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5. Abbreviations and Definitions

5.1. Abbreviations

CW	continuous wave
dB	decibel
dBm	decibel milliwatt
dBmV	decibel millivolt

DUT	device under test
IL	insertion loss
ISO	isolation
RF	radio frequency
R/L	return loss

5.2. Definitions

Definitions of terms used in this document are provided in this section. Defined terms that have specific meanings are capitalized. When the capitalized term is used in this document, the term has the specific meaning as defined in this section.

bandwidth	1) The amount of spectrum, measured in units of hertz, that an electromagnetic signal significantly occupies. 2) The operating passband of a device or system, typically expressed in units of hertz.
flatness	The maximum peak to valley excursion of the transmission response over the specified bandwidth. The flatness can be derived numerically from the forward transmission data. Flatness is defined with respect to an ideal response. The ideal response could have no slope, could have linear slope, or could have inverse cable equivalent slope.
frequency response	The variation of the power amplitude of the gain or signal level at each frequency of the intended frequency range. Frequency response does not include slope or tilt.
insertion gain	Insertion gain is the ratio between the power level of a signal exiting a port of a device to the power level of a signal entering a port of a device. Note that a positive insertion gain means *more* signal power out than signal power in.
insertion loss	Insertion loss is the ratio between the power level of a signal entering a port of a device to the power level of a signal exiting a port of a device. A positive insertion loss means *less* signal power out than signal power in.
isolation	The insertion loss response through a secondary path of a device typically having a higher attenuation than the primary path. For example, the path through two outputs of a splitter or the output and the coupled tap port of a symmetrical directional coupler has greater loss than the primary path from input to output. In the case of an amplifier, the insertion loss response from output to input is the secondary path. The insertion loss response through this path is called reverse isolation.
return loss	The ratio of incident signal to reflected signal, expressed in dB. Return loss is a one-port measurement.
scattering parameters (S-parameters)	Voltage transmission coefficients and voltage transmission coefficients that can be used to characterize N-port networks (components, devices, etc.). S-parameters describe the electrical behavior of linear N-port networks when those networks undergo steady-state stimuli by electrical signals.
slope	A measure of the monotonic frequency response of the network from low to high frequency. Slope is positive, or upward going, if the gain increases as the response is swept from low frequency to high frequency. Note that slope does not include the small variations in

	amplitudes of the gain or loss of a device that are included in the frequency response. Slope could be flat (the same at all frequencies), linear (increasing or decreasing linearly across the frequency range) or cable equivalent (increasing or decreasing across the frequency range in a manner that matches the loss characteristics of coaxial cable).
tilt	The variation in level across the operating range of the network. Positive tilt is defined to occur if the signals at lower frequencies are lower in amplitude than those at higher frequencies. Note that tilt does not include the small variations in amplitudes of the signals that are included in the frequency response. Tilt could be flat (the same at all frequencies), linear (increasing or increasing linearly across the frequency range) or cable equivalent (increasing or decreasing across the frequency range in a manner that matches the loss characteristics of coaxial cable).

6. Discussion

Transmission and reflection measurements can provide much useful information about a device such as components, subsystems, passive devices and amplifiers, The measurements can be used to determine gain or loss, slope and flatness (frequency response). The measured results can be used to verify manufacturer published product specifications and certificates of compliance (when available). They can also be used to predict overall performance when the measured devices are incorporated into a subsystem or network.

It is recommended that measurements be made with a vector network analyzer. Vector network analyzers are capable of measuring both the magnitude and phase of the transmission and reflection characteristics of a device under test (DUT).[1]

6.1. A Review of S-parameters

Vector network analyzers typically measure S-parameters. Scattering parameters or S-parameters are a way to characterize the steady state response of an N-port device to signals incident at any of the ports. S-parameters are always a ratio of two complex voltage quantities. S-parameter notation identifies these quantities using the numbering convention S_{xy} where x refers to the device port the signal is emerging from, and y refers to the device port where the signal is incident. For example, the s-parameter S_{21} identifies the measurement as the complex ratio of the voltage emerging at device port 2 to the incident voltage at device port 1.

Figure 1 and Table 1 show the relationship between voltages at the ports of a two port device and the s-parameters for that device. In the illustration, “a” represents the voltage entering the device and “b” represents the voltage emerging. Note that in general a and b are complex quantities. Note also that s-parameters may vary as a function of frequency.

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[1] Manufacturers of vector network analyzers include Keysight Technologies (Agilent), Anritsu (Wiltron), Advantest, and Rhode & Schwarz.

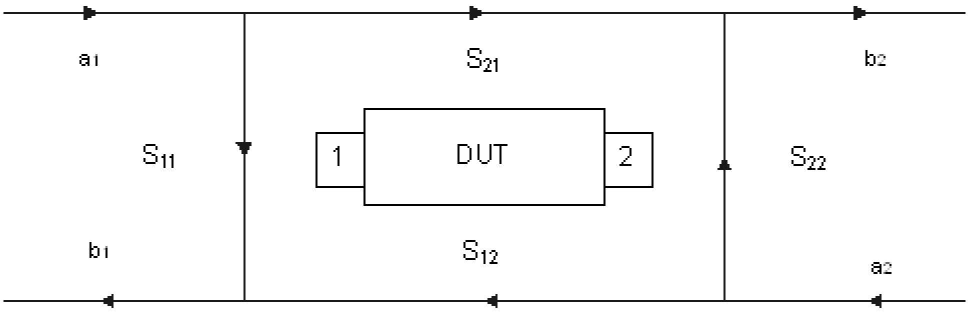

Figure 1 - S-Parameter Diagram For A 2-Port Device

Table 1 - Test Measurements To Characterize A 2-Port Device

S-Parameter	Definition		Description	Direction
S_{11}	b1/a1	a2=0	Input Reflection	FWD
S_{21}	b2/a1	a2=0	Forward Transmission	FWD
S_{12}	b1/a2	a1=0	Reverse Transmission	REV
S_{22}	b2/a2	a1=0	Output Reflection	REV

The concept of s-parameters can be extended to devices with more than two ports. This is described in Appendix A and Appendix B.

6.1.1. Transmission

S-parameters can be used to describe the forward and reverse characteristics of a device. Note that most devices are specified using the magnitude of the transmission characteristics in units of decibels. These transmission characteristics can be determined from the S-parameters using the relationships

$$Forward\ Transmission(dB) = 20\ Log_{10}(|S_{21}|)$$

$$Reverse\ Transmission(dB) = 20\ Log_{10}(|S_{12}|)$$

Note that in general S_{21} and S_{12} are complex quantities, hence the magnitude of S_{21}, $|S_{21}|$, and the magnitude of S_{12}, $|S_{12}|$.

Appendix C contains several examples of gain measurements for devices with various gain and slope tolerances. These examples illustrate trade-offs between the measured gain, slope, and frequency response. Such trade-offs may be necessary to ensure that an equitable compromise has been reached to make sure that all parameters are withing their specified tolerances. Note that in general this is not as simple as defining slope by fitting to the measured transmission values at the frequency endpoints. A best trade-off typically requires iterative adjustment of gain and slope tolerances until a best compromise is reached.

6.1.2. Reflection and Return Loss

Devices are also characterized by return loss. Note that return loss is related to the s-parameter S_{nn} where n is any port of the device under test. S_{nn} is equivalent to the voltage reflection coefficient, r, where

$$r = \frac{E_{reflected}}{E_{incident}}$$

where

$$E_{reflected} = voltage\ of\ the\ reflected\ signal$$

and

$$E_{incident} = voltage\ of\ the\ incident\ signal$$

Note that in general S_{nn} and r are complex quantities.

Return loss can be calculated from r or S_{nn} using the equation

$$return\ loss = 20\ log_{10}\left(\left|\frac{E_{incident}}{E_{reflected}}\right|\right) = 20\ log_{10}\left(\left|\frac{1}{r}\right|\right) = 20\ log_{10}\left(\left|\frac{1}{S_{nn}}\right|\right)$$

Return loss may also be calculated from the measured complex impedance at a particular port, Z1, by

$$return\ loss = 20\ log_{10}\left(\left|\frac{Z1 + Z0}{Z1 - Z0}\right|\right)$$

where Z1 is the measured impedance (may be complex) and Z0 is the reference impedance (75 ohms).

Note that when measuring reflection most network analyzers display 20 LOG_{10} ($|S_{nn}|$) not 20 LOG_{10} ($|1/S_{nn}|$). This means that the analyzer will display a negative value for reflection in dB for a properly working amplifier whereas return loss would be a positive quantity.

7. Equipment

Only equipment specific to this procedure is described in detail here. The Cable Telecommunications Testing Guidelines [SCTE 96] *should* be consulted for further information on all other equipment.

A vector network analyzer is recommended.[2] The analyzer *should* have the following characteristics:

- 75 ohm impedance
- Frequency range 5 MHz to 3000 MHz, minimum, with calibrated end points and markers available.
- Capable of doing reflection, transmission, or full two-port calibration to reduce the effect of analyzer test port mismatch and external component deficiencies.
- Capable of interfacing with a printer or creating data files for analysis of the test results.

Note that some analyzers are capable of doing an electronic self-calibration.

The setup *should* contain adapters and cables, as required, for connecting the device under test to the measurement system. The impedance of all cables and adapters must be 75 ohm.[3]

8. Setup

1. Follow any pre-calibration requirements recommended by the manufacturer for the network analyzer, including adequate warm-up and stabilization time. Ensure that the instrument is properly grounded and that anti-static precautions are maintained at all times. This includes an anti-static work surface and wrist strap that is grounded to the instrument.
2. Connect all necessary cables and adapters to the network analyzer.
3. Adjust the analyzer for the frequency range of interest, generally 5-3000 MHz. Data points *should* be selected wherein the output will result in data at a minimum of every 1.50 MHz interval.
4. Adjust the network analyzer power level suitable to the device under test. Note that RF power levels *should* be chosen to be not so high as not to overload the device under test but high enough to give a measurement that is not limited by noise.
    a. Passive devices can usually tolerate higher power levels than active devices
    b. If there is a maximum input power level given for a particular device, the power level *should* be set so that the power at the device under test does not exceed this value.
    c. The output power of the device under test must be considered. For example, the output level from an amplifier *should* not be so high as to overload the test equipment. Note: In cases where low analyzer output power is required, some analyzers will have greater

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[2] Leading manufacturers of vector network analyzers are Keysight Technologies (Agilent), Anritsu (Wiltron), Advantest, and Rhode & Schwarz. This identification of products or services is not an endorsement of those products or services or their suppliers.

[3] Typical connector, cable and adapter sets are:

- Keysight Technologies Model 8120-2408 Type N Cable, 75 ohm
- Keysight Technologies Model 11857B Type N Cable Set, 75 ohm
- Keysight Technologies Model 85036B 75 ohm Type N Calibration Kit
- Keysight Technologies Model 909E 75 ohm Type N Precision Termination
- Keysight Technologies Model 86211A 75 ohm Type-F Adapter Kit
- Keysight Technologies Model 85039B 75 ohm Type F Calibration Kit

or equivalent products from other manufacturers. This identification of products or services is not an endorsement of those products or services or their suppliers.

accuracy (less trace noise) if calibrated at a higher power, then the power is dropped for the measurement.

5. Perform a full calibration of the network analyzer. This calibration should include all connectors, adapters, cables, switches, and any hardware that is connected to the analyzer in order to make the measurements of the device under test. High quality reference standards (open, short and terminations) should be used for this calibration. This calibration should be stored in memory.
6. Select the s-parameter measurement relative to each channel. For example, set the measurement of channel 1 to forward reflection (S11) and set the measurement of channel 2 to forward transmission (S21).
7. Select the display format for each channel. The usual selection is LOG MAG, which displays a Cartesian graph of signal power level in dB versus frequency.
8. Select the other display characteristics to suit the measurement such as dual or single channel display, scale and reference levels of each channel, and any convenient markers.
9. With all of the functions of the analyzer optimally set for the particular test samples, proceed to calibration.
10. Once the calibration procedure is complete, save the instrument state with the error correction coefficients.

9. Procedure

9.1. Overview

Network analyzers are generally two-port instruments although recent additions to the vector network analyzer market can have three or four ports. Alternatively, a switching matrix can extend the basic two-port analyzer to 4, 8, 12, or more for automated data collection in a production environment. In general, however, the characterization of an n-port device will be a combination of one and two-port measurements. This is illustrated in the earlier definition of the s-parameter system.

Reflection is a one-port measurement. Each port of a device will have one reflection measurement associated with it. Typically, either port of the network analyzer is capable of making a reflection measurement. Some two-channel analyzers can measure the reflection of two ports simultaneously.

Transmission is a two-port measurement. The measurement is made through the device from one port to another. The measurement selection options offer either forward transmission from port 1 to port 2, or reverse transmission from port 2 to port 1. Some two-channel analyzers can measure forward and reverse transmission simultaneously. More advanced network analyzers have 4 channels that can display all four of the s-parameters of a two-port measurement simultaneously.

Some instruments can provide data for all four s-parameters in a single test. Since the post-processing of data via spreadsheet programs is an important consideration in the generation of reports or data files for design work, the data output capability of the analyzer used for these tests may have an impact on the test procedure sequencing.

In the following procedures for one-port and two-port measurements, it is assumed that the operator will ensure that the setup procedure in section 4 is satisfied. The operator *should* also ensure that anti-static precautions are taken at all times.

9.2. One-Port Reflection

1. Recall the instrument state defined in section 8 (setup).

2. Check to see that the measurement mode of channel 1 is set to reflection (S11). The appropriate test cable will be connected to port 1 on the network analyzer.
3. Connect port 1 of the analyzer to the port of the DUT where a reflection measurement is to be made.
4. Terminate all other ports of the DUT with resistive 75 ohm terminators having a return loss of greater than 25 dB throughout the test frequency range.[4]
5. Make use of the marker options to identify key features of the display such as maximums or minimums, delta relationships, or cornerstone frequencies.
6. Save the measurement for further analysis or report generation if necessary. Some of the options for saving the measurement are listed below.
    a. Save to the display memory for comparison with subsequent measurements.
    b. Save to a printer for a graphic record.
    c. Save to a data file on a disk or an external computer. Consult the network analyzer manual for the most suitable file format options.

9.3. Two-Port Transmission

1. Recall the instrument state defined in section 8 (setup).
2. Check to see that the measurement mode of channel 2 is set to forward transmission (S21).
3. Connect port 1 of the analyzer to the device port where signal is to be injected. Connect port 2 of the analyzer to the device port where the signal is to be measured.
4. Terminate all other ports of the device with resistive 75 ohm terminators having a return loss of greater than 25 dB throughout the test frequency range.
5. Make use of the marker options to identify key features of the display such as maximums or minimums, delta relationships, or cornerstone frequencies.
6. If the dual display option has been selected, the reflection and the transmission will be visible on the screen.
7. Save the measurement for further analysis or report generation if necessary. Some of the options for saving the measurement are listed below.
    a. Save to the display memory for visual comparison with subsequent measurements.
    b. Save to a printer for a graphic record.
    c. Save to a data file on a disk or an external computer. Consult the network analyzer manual for the most suitable file format options.

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[4] A network analyzer is sometimes used as the termination for an unused port. However, it should be noted that the analyzer and associated cables, connectors, adapters, switches and other associated hardware may not provide a termination that is as good as that provided by a high quality termination. If a network analyzer is used it should be calibrated at all at all ports using high quality reference standards (open, short and termination).

Appendix A Test Method for Splitters

Recall the instrument state defined in section 8 (setup). Verify that the frequency range, power level and display properties are suitable to the device.

If the display properties are changed, the new state can be saved in another memory register without recalibration.

If the frequency range or power levels are changed, recalibration is recommended to maintain error correction accuracy.

If the cables or adapters are changed, recalibration is necessary.

Define a numbering system for the ports of the splitter beginning with the input as port 1.

Follow the test procedure defined above in section 10 for two-port transmission.

Table 2 lists the order of tests and cable connections required to make a complete set of s-parameters for a two-way splitter. The bold numbers are the splitter ports. It shows how nine data sets are derived from three tests.

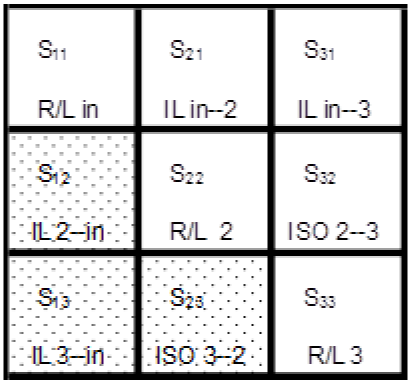
Table 2 - Test sequence to completely characterize a 2-way splitter

Test #	**NA port 1**	**NA port 2**	**Data**			
1	1	2	S_{11}	S_{21}	S_{12}	S_{22}
2	1	3		S_{31}	S_{13}	S_{33}
3	2	3		S_{32}	S_{23}	

Table 3 lists the correlation between s-parameters and RF measurements. Since the splitter response is essentially the same in both forward and reverse directions, some of the s-parameters are redundant for report purposes.

- R/L means Return Loss
- IL means Insertion Loss
- ISO means Isolation
- Each cell in the matrix represents a 201-point data set of magnitude and angle vs. frequency.

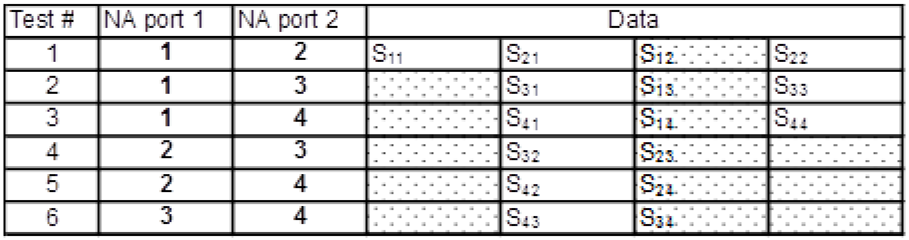
Table 3 - Matrix of all the 3-port S-parameters and corresponding splitter measurements



S_{11} R/L in	S_{21} IL in--2	S_{31} IL in--3
S_{12} IL 2--in	S_{22} R/L 2	S_{32} ISO 2--3
S_{13} IL 3--in	S_{23} ISO 3--2	S_{33} R/L 3

Table 4 lists the order of tests and cable connections required to make a complete set of s-parameters for a three-way splitter. The bold numbers are the splitter ports. It shows how 16 data sets are derived from 6 tests.

Table 4 - Test sequence to completely characterize a 3-way splitter

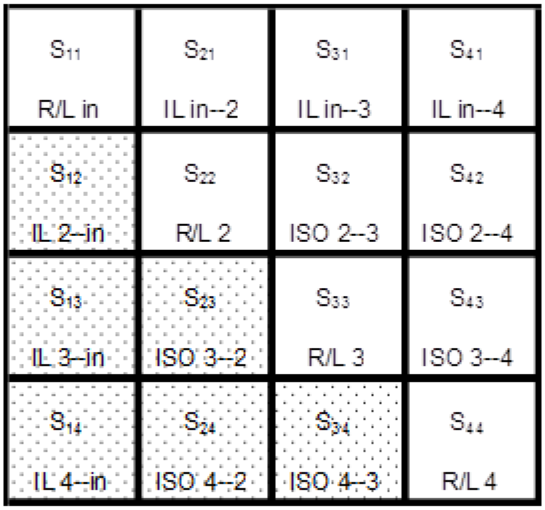


Test #	NA port 1	NA port 2	Data			
1	**1**	2	S_{11}	S_{21}	S_{12}	S_{22}
2	**1**	3		S_{31}	S_{13}	S_{33}
3	**1**	4		S_{41}	S_{14}	S_{44}
4	**2**	3		S_{32}	S_{23}	
5	**2**	4		S_{42}	S_{24}	
6	**3**	4		S_{43}	S_{34}	

Table 5 lists the correlation between s-parameter data and RF measurements. Since the splitter response is essentially the same in both forward and reverse directions, some of the s-parameters are redundant for report purposes.

All of the cells in this matrix are necessary to assemble a complete s-parameter file that can be used for circuit simulation.

Table 5 - Matrix of all the 4-port S-parameters and the corresponding splitter measurements



S_{11} R/L in	S_{21} IL in--2	S_{31} IL in--3	S_{41} IL in--4
S_{12} IL 2--in	S_{22} R/L 2	S_{32} ISO 2--3	S_{42} ISO 2--4
S_{13} IL 3--in	S_{23} ISO 3--2	S_{33} R/L 3	S_{43} ISO 3--4
S_{14} IL 4--in	S_{24} ISO 4--2	S_{34} ISO 4--3	S_{44} R/L 4

The previous examples of data collection can be expanded as the number of ports increases. This indicates an increasing dependence on software and automation.

Appendix B Test Method for Directional Couplers

Recall the instrument state defined in section 8 (setup). Verify that the frequency range, power level and display properties are suitable to the device.

- If the display properties are changed, the new state can be saved in another memory register without recalibration.
- If the frequency range or power levels are changed, recalibration is recommended.
- If the cables or adapters are changed, recalibration is necessary.

Define a numbering system for the ports of the directional coupler beginning with the input as port 1. In this example, port 2 will be the thru port, and port 3 will be the tap port.

Follow the test procedure defined above in section 10 for two-port transmission.

Table 6 lists the order of tests and cable connections required to make a complete set of s-parameters for a 3-port directional coupler. The bold numbers are the coupler ports. It shows how nine data sets are derived from three tests.

Table 6 - Test Sequence To Completely Characterize A Directional Coupler

Test #	**NA port 1**	**NA port 2**	**Data**			
1	1	2	S_{11}	S_{21}	S_{12}	S_{22}
2	1	3		S_{31}	S_{13}	S_{33}
3	2	3		S_{32}	S_{23}	

Table 7 lists the correlation between s-parameters and RF measurements. Since the coupler response is essentially the same in both forward and reverse directions, some of the s-parameters are redundant for report purposes.

- R/L means Return Loss
- IL means Insertion Loss
- ISO means Isolation

Each cell in the matrix represents a 801-point data set of magnitude and angle vs. frequency.

Table 7 - Matrix of all the 3-port S-parameters and corresponding coupler measurements

S_{11} R/L in	S_{21} IL thru	S_{31} IL tap
S_{12} IL 2--in	S_{22} R/L thru	S_{32} ISO 2--3
S_{13} IL 3--in	S_{23} ISO 3--2	S_{33} R/L tap

Appendix C Examples of Corrections for Gain and Slope Errors

The goal of most measurements is to determine the optimum performance results. In the case of gain, it may be possible to resolve the composite gain into separate quantities such as flat gain, linear tilt, cable equivalent tilt, etc. Each of these separate quantities may be specified separately in order to obtain the best measured performance of the device under test. The following sections contain several cases that illustrate this concept.

C.1 Case 1: Nominally flat response (no tilt)

Consider the frequency response of a network subsystem, such as an analog intensity modulated optical link, that nominally introduces 0 dB of tilt across the operational band. Such a subsystem nominally has an insertion gain of G_0 dB that is constant at all frequencies within its passband. This passband is nominally defined as the frequency range between the lowest frequency, F_L, and the highest frequency, F_H, inclusive. Consequently, the ideally subsystem has a constant, gain of G_0 at all frequencies between F_L and F_H, inclusive.

Actual network subsystems do not have the ideal constant insertion gain of G_0 at all frequencies within the passband. The actual output level, G(f), will vary slightly as a function of frequency.

Consider an analog intensity modulated optical link with a passband from 200 MHz to 1000 MHz and a nominal insertion gain, G_0, of 10 dB with a tolerance of ±0.5 dB. The nominal insertion gain and actual insertion gain, G(f), of this link are shown in Figure 2.

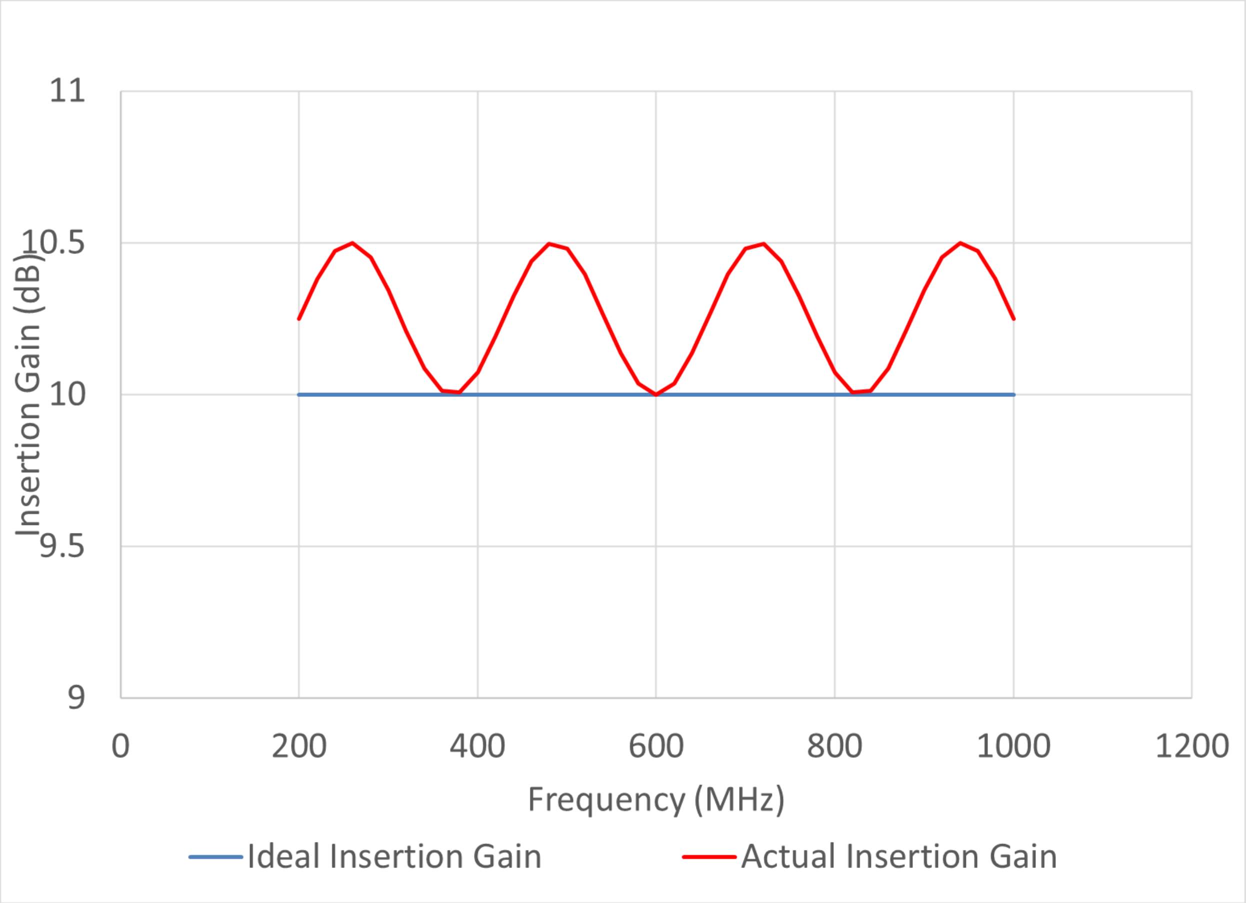


Figure 2 Ideal and Actual Insertion Gain

Note that there is some ripple in the actual insertion gain and the gain is on average slightly higher than the ideal gain. In this case the peak-to-peak value of the measured gain can easily be calculated by subtracting the lowest spot on the response curve, G_{MIN}, from the highest spot, G_{MAX}.

$$Frequency\ Response_{PP} = G_{MAX} - G_{MIN}$$

In this example the peak-to-peak frequency response can easily be seen as 0.5 dB pp or equivalently ±0.25 dB.

The ideal insertion gain of the link, G_0, is 10 dB. We can subtract the ideal gain from the actual insertion gain. The result is the normalized insertion gain, G_n (f).

$$G_n(f) = G(f) - G_0$$

This is illustrated in Figure 3.

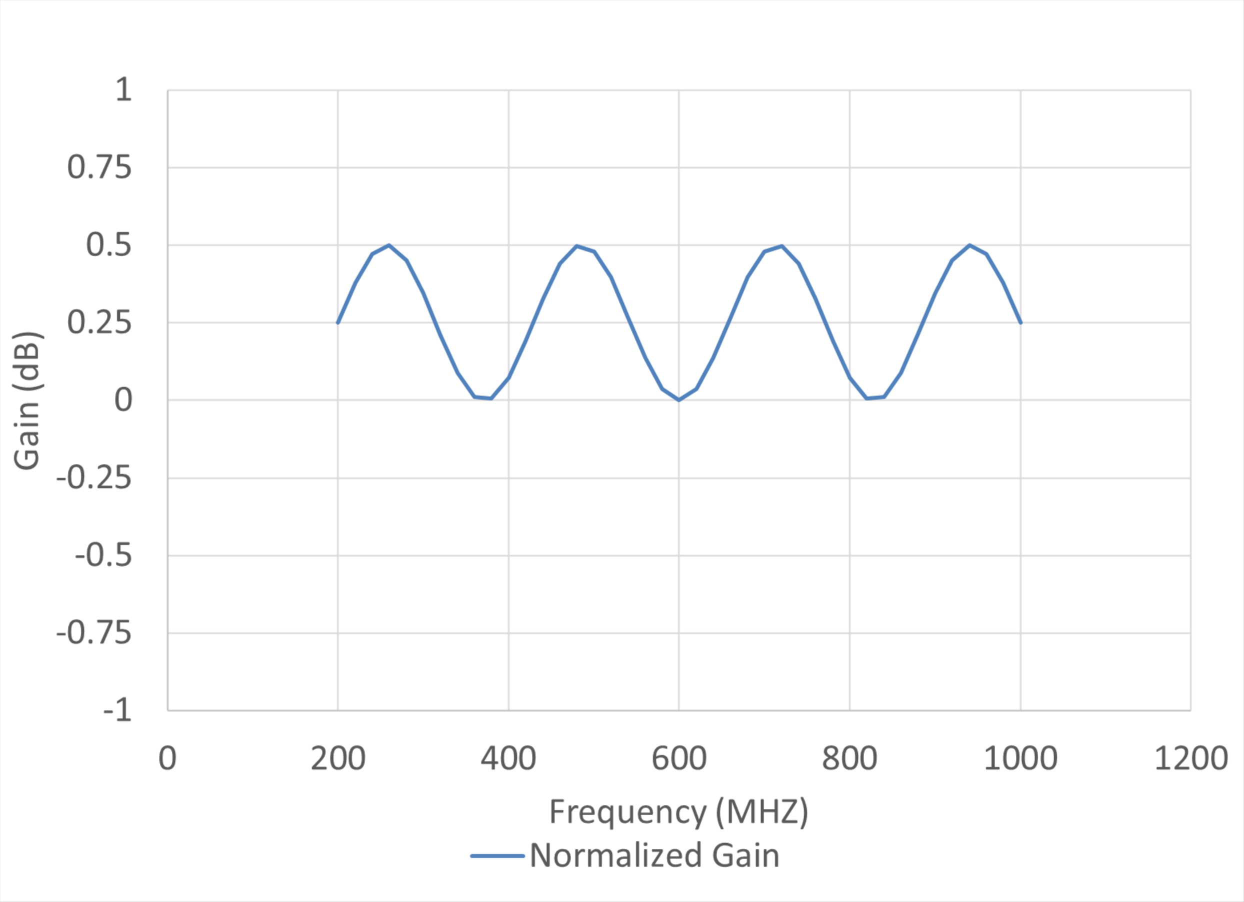


Figure 3 Normalized Gain

It is possible to determine the maximum value, $G_{n\,max}$, and the minimum value, $G_{n\,min}$, of the normalized gain. In this example $G_{n\,max} = +0.5$ dB and $G_{n\,min} = 0.0$ dB.

It might be more meaningful to offset the ideal level, G_0, slightly to center the normalized response. This level offset, G_1, *should* be chosen to make the maximum and minimum value of the normalized gain of equal magnitude and centered on 0 dB. The value of G_1 *should* be chosen such that

$$G_1 = \frac{G_{n\,max} - G_{n\,min}}{2}$$

One may then calculate an adjusted output level, G_a, that includes this level offset.

$$G_a = G_0 + G_1$$

We can then calculate the adjusted normalized response, G_{an}, as

$$G_{an}(f) = G(f) - G_a$$

In this example one may determine by observation that if we offset the ideal level by +0.25 dB ($L_1 = 0.25$ dB) then the resulting normalized response will be symmetrical around 0 dB. Note that this offset is within the allowable tolerance of the ideal insertion gain of ±0.5 dB. This is shown in Figure 4.

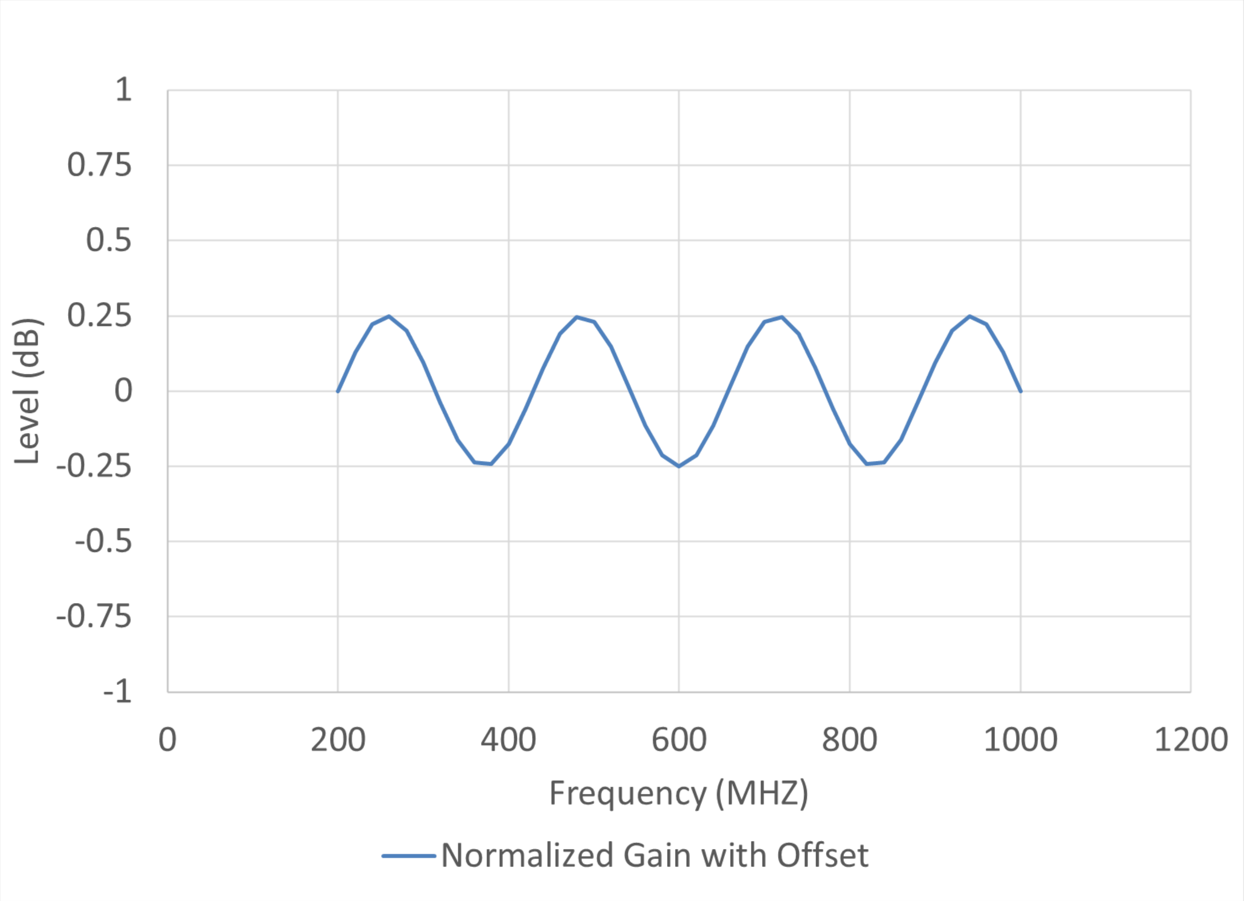


Figure 4 Normalized Gain with Offset

In this figure of the normalized gain with offset we can directly read the frequency response as ±0.25 dB or 0.5 dB peak-to peak.

C.2 Case 2: Linear Slope

Devices such as amplifiers and optical node launch amplifiers may be designed for a particular Gain, G_0, typically specified at the highest operating frequency and be designed for a particular value of linear slope, S_L across the operational passband from F_L and F_H. The ideal gain within the operational passband as a function of frequency, $G_0(f)$, will be given by

$$G_0(f) = G_0 - \left[\left(\frac{S_L}{F_H - F_L}\right)(F_H - f)\right]$$

Consider an amplifier with a passband from 200 MHz to 1000 MHz and a nominal gain, G_0, of 30 dB at 1000 MHz with a tolerance of ±1 dB and a linear slope, S_L, of 10 dB with a tolerance of ±1 dB. The ideal gain, $G_0(f)$, of this link, along with an actual measured gain, $G(f)$, is shown in Figure 5.

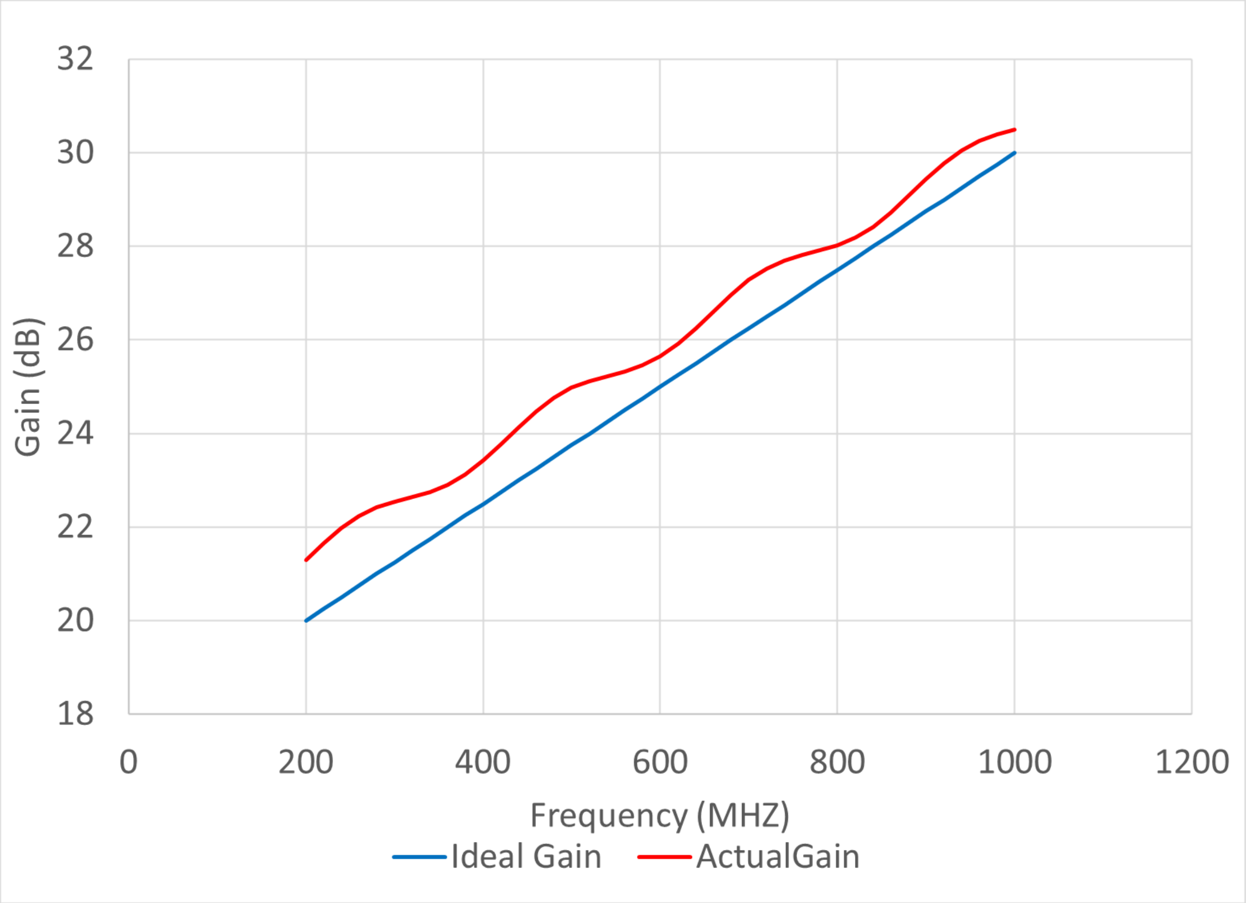


Figure 5 Ideal and Measured Gain with Linear Slope

We can create a normalized gain response, $G_n(f)$, by subtracting the ideal response from the actual response.

$$G_n(f) = G(f) - G_0(f)$$

The result is illustrated in Figure 6.

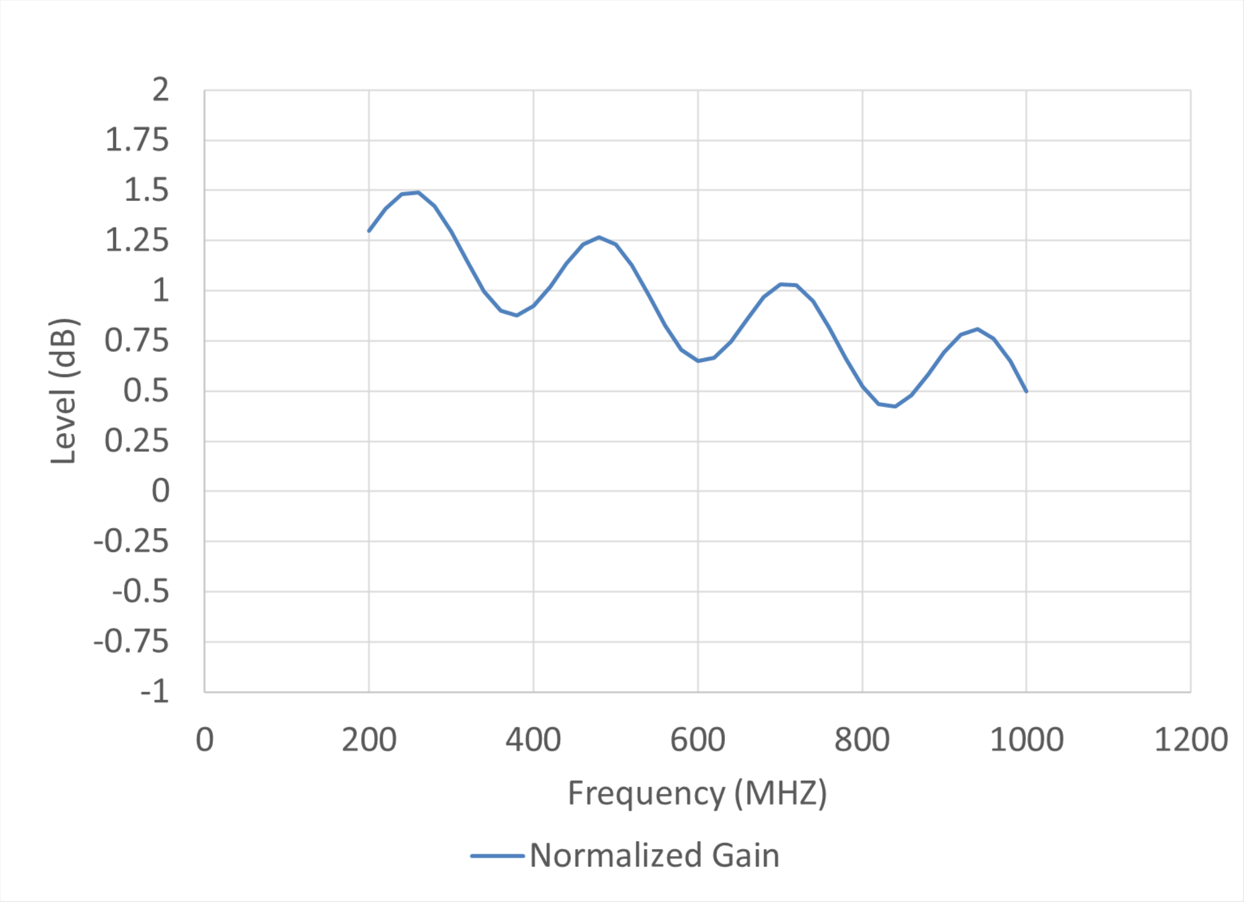


Figure 6 Normalized Gain

If we were to measure the peak-to-peak frequency response of this normalized gain (difference between the maximum value and the minimum value, the result would be approximately 1.1 dB peak-to -peak (±0.55 dB). However, this result is somewhat pessimistic.

One might consider the normalized gain shown in Figure 6 to contain the actual gain response plus a small error in flat gain (gain that is constant at all frequencies), G_1 and a slight error in linear slope, S_{L1}. Note that G_1 and S_{L1} are independent variables that must be determined for each individual device.

We can then calculate an adjusted ideal gain, $G_a(f)$, using the equation

$$G_a(f) = (G_0 + G_1) - \left[\left(\frac{S_L + S_{L1}}{F_H - F_L}\right)(F_H - f)\right]$$

We can then calculate the adjusted normalized gain response using the equation

$$G_{an}(f) = G(f) - G_a(f)$$

This can be done for our example using adjusted ideal gain, $G_a(f)$, assuming $G_1 = 0.5$ dB and $S_{L1} = 0.8$ dB. Both values are within the tolerance of flat gain of ±1 dB and the tolerance of tilt of ±1 dB.

The result is shown in Figure 7.

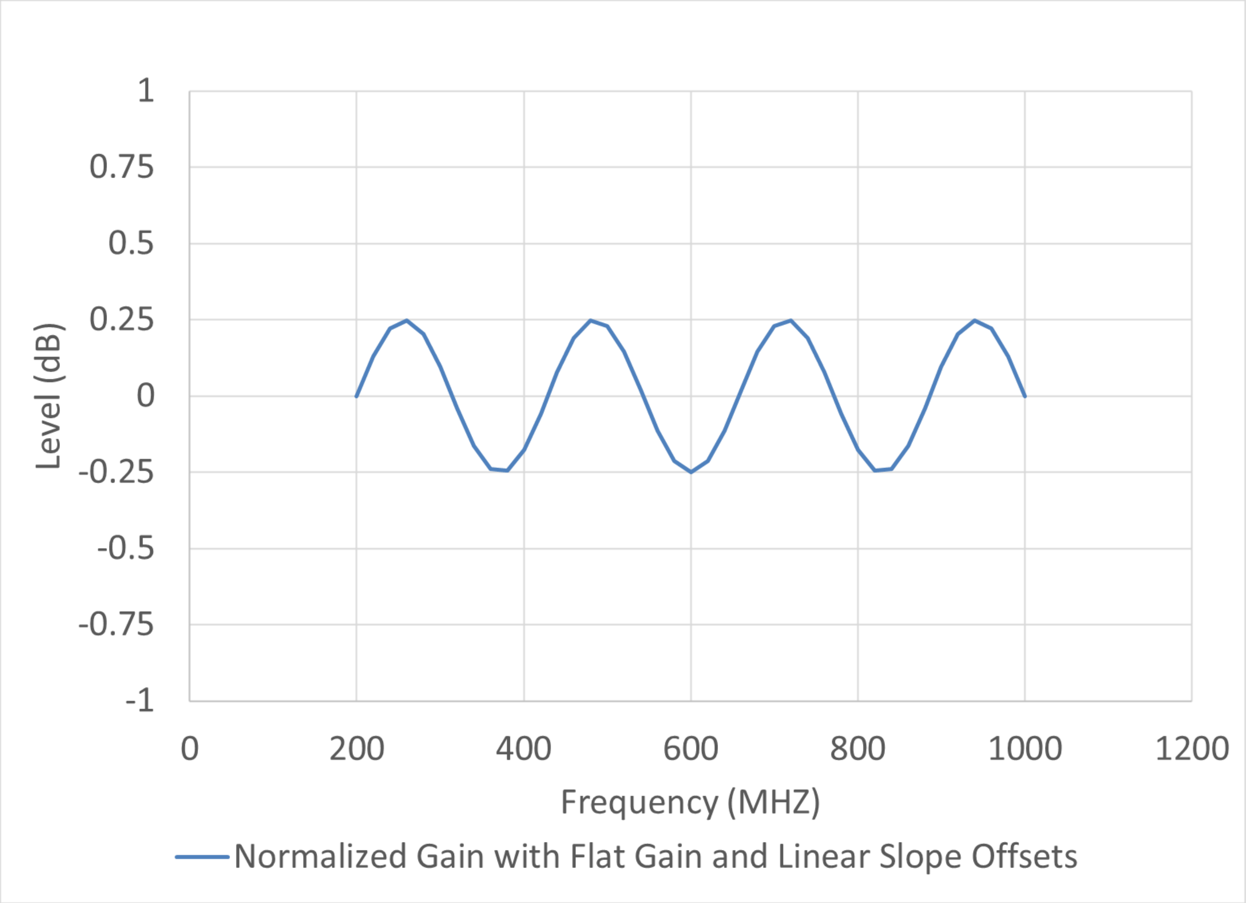


Figure 7 Normalized Gain with Flat Gain and Linear Slope Offsets

The frequency response shown in Figure 7 is +0.25 dB and -0.25 dB or 0.5 dB Peak-to-peak.

Note that this adjusted normalized gain does not contain any of the flat level error or linear slope error seen in the measured output. However, this normalized gain is much more indicative of the effect of actual gain and its effects on network performance. Unfortunately, the calculation of the normalized gain with flat gain and linear tilt offsets requires the calculation of values for G_1 and S_{L1} that give a minimum value for the normalized response peak values. Note that may or may not be the same as calculating a best fit (such as minimum rms error) between the measured gain, G(f), and the adjusted gain, $G_a(f)$. Depending on the specified tolerance for gain and slope for the device under test there may be a trade-off between gain, slope and frequency response to ensure that all meet the device specifications.

C.3 Case 3: Cable Equivalent Slope

Devices such as amplifiers and optical node launch amplifiers may also be designed for a particular Gain, G_0, typically specified at the highest operating frequency and be designed for a particular value of cable equivalent slope, S_C, across the operational passband from F_L and F_H. Cable equivalent slope is typically based on the cable loss versus frequency relationship

$$Loss_{f2} = Loss_{f1}\sqrt{\frac{f_1}{f_2}}$$

Where $Loss_{f1}$ is the loss in dB at frequency 1, f1, and $Loss_{f2}$ is the loss in dB at frequency 2, f2.

The cable equivalent tilt across the band from f1 to f2 would be given by

$$Cable\ Equivalent\ Slope = S_C = Loss_{f1} - Loss_{f2}$$

Note that cable induced loss produces a negative tilt (the level decreases as the frequency increases). In most cable applications the active devices such as amplifiers have a positive slope (inverse cable) where level increases as the frequency increases.

The ideal gain within the operational passband as a function of frequency, $G_0(f)$, will be given by

$$G_0(f) = G_0 - \left[\left(\frac{S_C}{1-\sqrt{\frac{F_L}{F_H}}}\right)\left(1-\sqrt{\frac{f}{F_H}}\right)\right]$$

Consider an amplifier with a passband from 200 MHz to 1000 MHz and a nominal Gain, G_0, of 30 dB with a tolerance of ±1 dB and a cable equivalent slope, S_C, of 10 dB with a tolerance of ±1 dB. The ideal gain as a function of frequency, $G_0(f)$, of this link, along with an actual measured Gain, G(f), is shown in Figure 8.

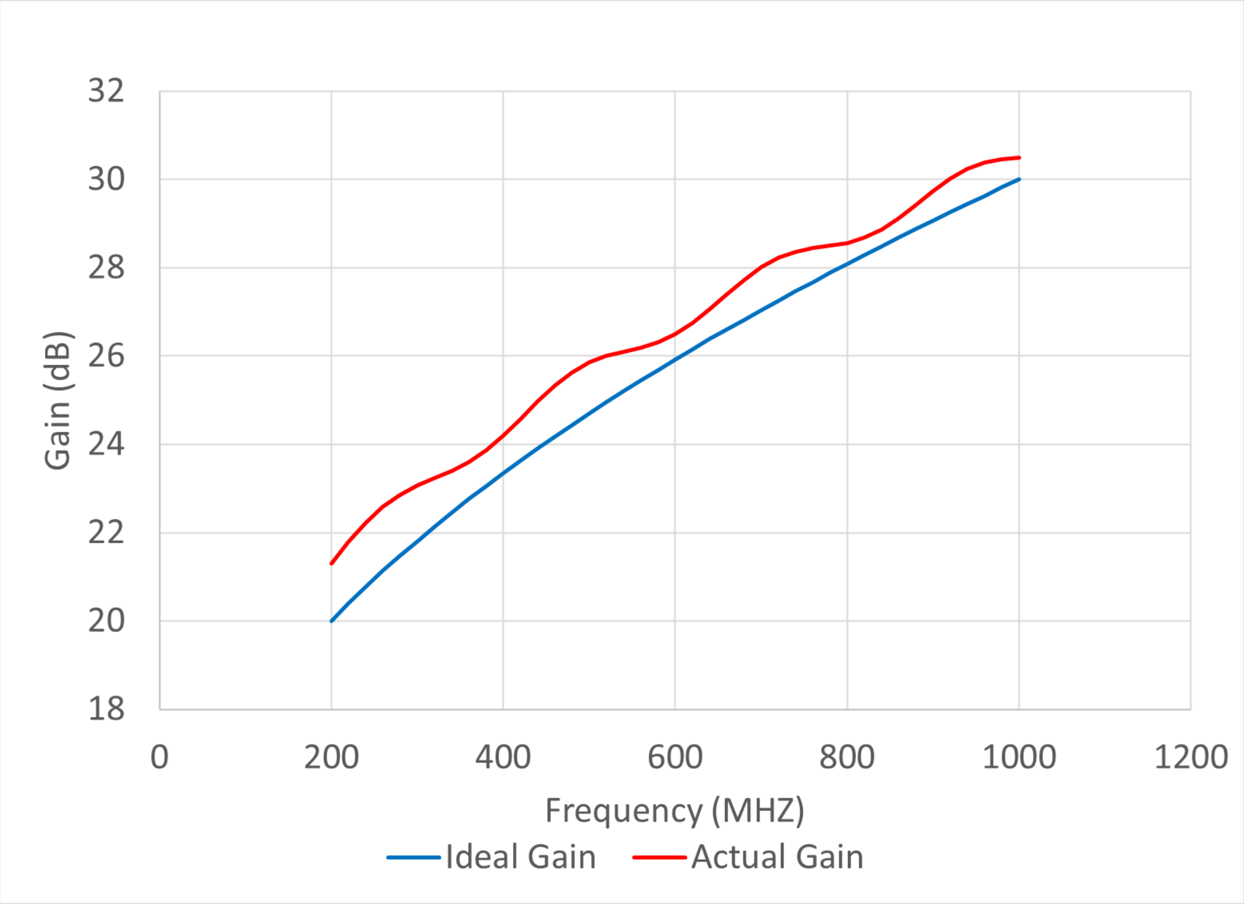


Figure 8 Ideal and Measured Gain with Cable Equivalent Slope

We can create a normalized gain response, $G_n(f)$, by subtracting the ideal response from the actual response.

$$G_n(f) = G(f) - G_0(f)$$

The result is illustrated in Figure 9.

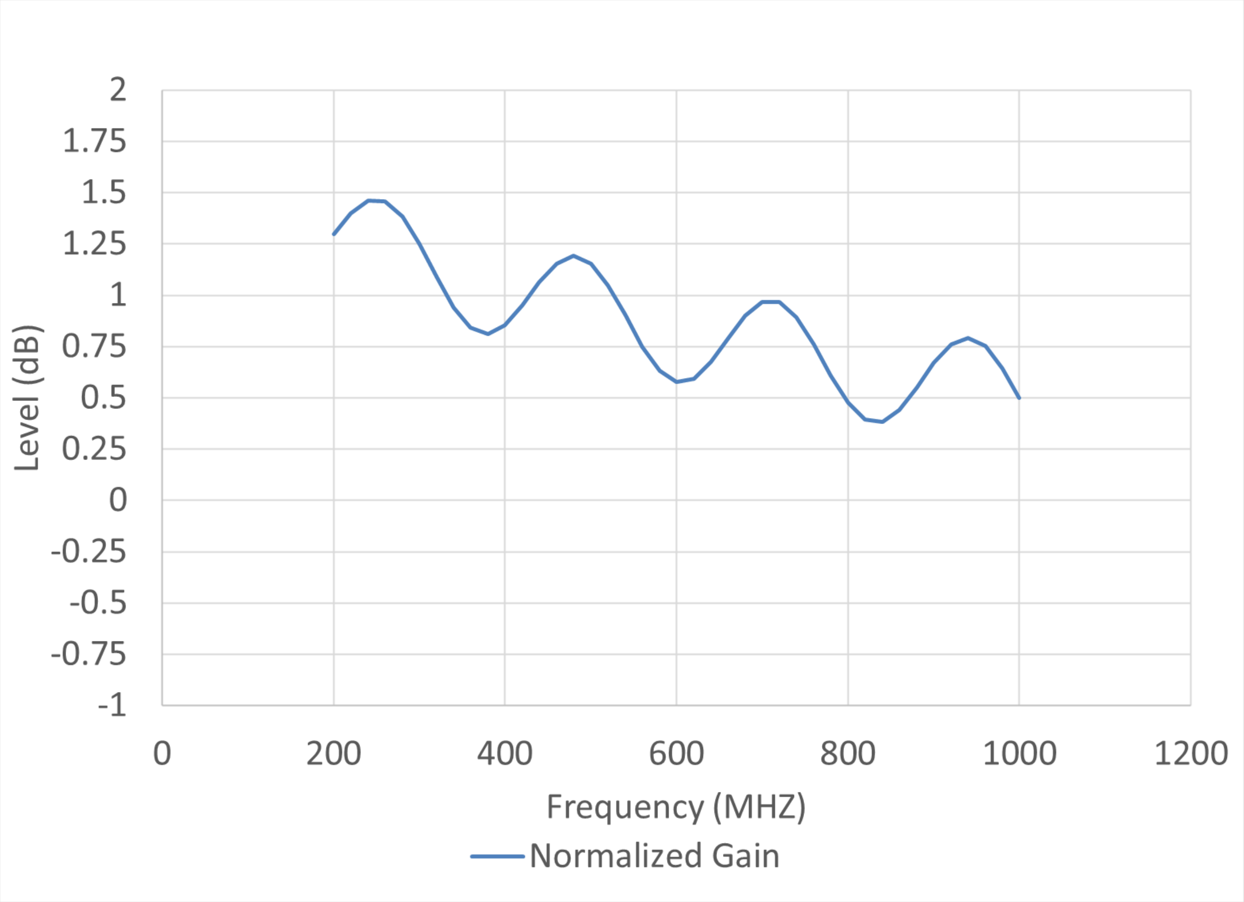


Figure 9 Normalized Gain

If we were to measure the peak-to-peak frequency response of this normalized gain (difference between the maximum value and the minimum value, the result would be approximately 1.2 dB peak-to-peak (±0.6 dB). However, this result is somewhat pessimistic.

One might consider the normalized gain shown in Figure 9 to contain the actual gain response plus a small error in flat gain (gain that is constant at all frequencies), G_1, and a slight error in cable equivalent slope, S_{C1}. As with the previous case, G_1 and S_{C1} are independent variables that must be determined for each individual device.

We can then calculate an adjusted ideal level, $L_a(f)$, using the equation

$$G_a(f) = (G_0 + G_1) - \left[\left(\frac{S_C + S_{C1}}{1 - \sqrt{\frac{F_L}{F_H}}}\right)\left(1 - \sqrt{\frac{f}{F_H}}\right)\right]$$

We can then calculate the adjusted normalized gain response using the equation

$$G_{an}(f) = G(f) - G_a(f)$$

This can be done for our example using adjusted ideal level, $G_a(f)$, assuming $G_1 = 0.5$ dB and $S_{C1} = 0.8$ dB. Both of these values are within the tolerance of flat gain of ±1 dB and the tolerance of slope of ±1 dB

The result is shown in Figure 10.

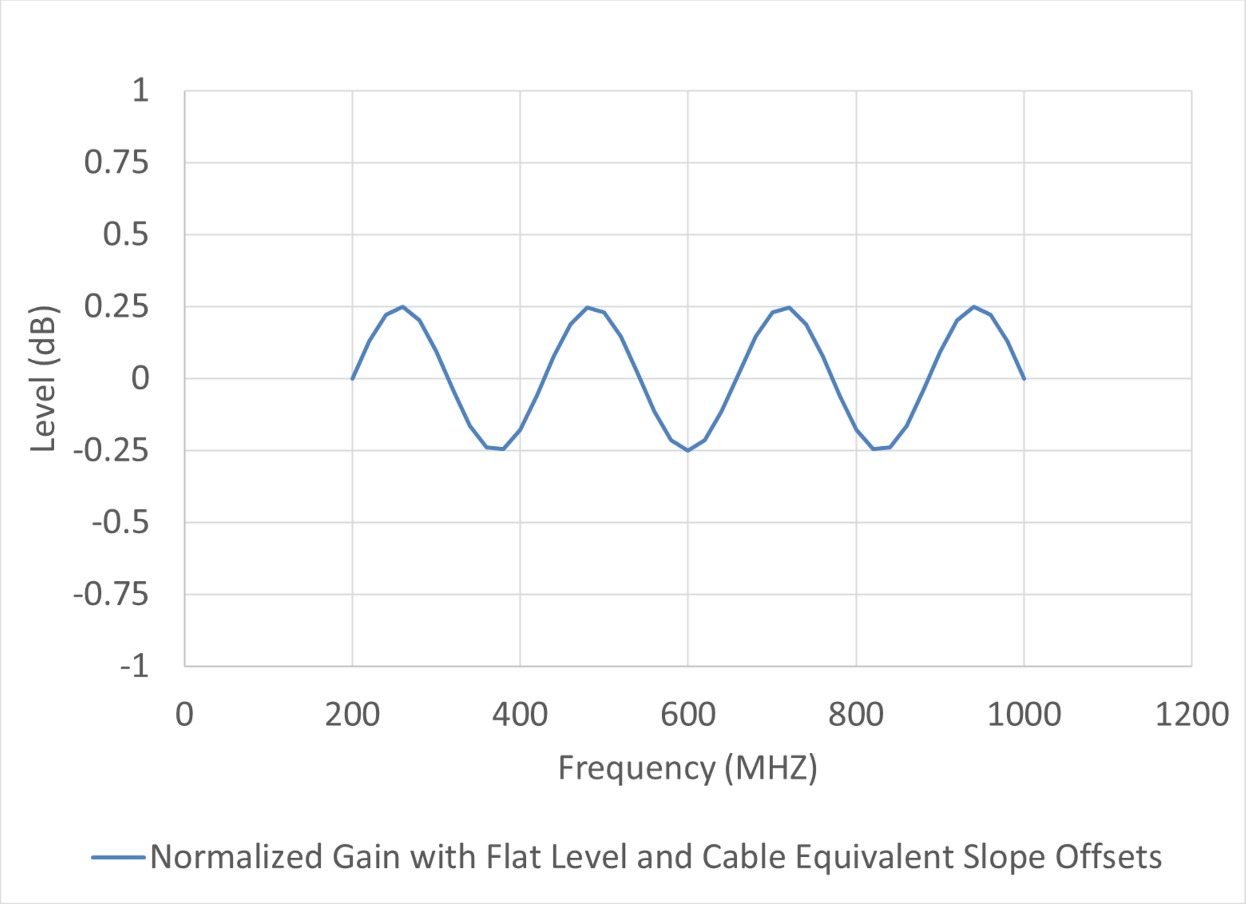


Figure 10 Normalized Gain with Flat Level and Cable Equivalent Slope Offsets

As in the previous example, the frequency response shown in Figure 10 is ±0.25 dB or 0.5 dB peak-to-peak. Note that this normalized response does not indicate any of the flat level error or cable equivalent slope error seen in the measured output. However, this normalized response is much more indicative of the effect of actual frequency response and its effects on network performance. Unfortunately, the calculation of the gain response with flat level and linear tilt offsets requires the calculation of values for G_1 and S_{C1} that give a minimum value for the normalized response peak values. Note that may or may not be the same as calculating a best fit (such as minimum rms error) between the measured response, G(f), and the adjusted level, $G_a(f)$. Depending on the specified tolerance for gain and slope for the device under test there may be a trade-off between gain, slope, and frequency response to ensure that all meet the device specifications.

C.4 A Discussion of Best Fit versus Minimum Peak-to-Peak Response

Consider a frequency response such as that shown in Figure 11. As with the other examples, this is the output of a device designed to operate from 200 MHz to 1000 MHz (F_L = 200 MHZ and F_H = 1000 MHz. Most of the slope has been removed for the sake of simplicity.

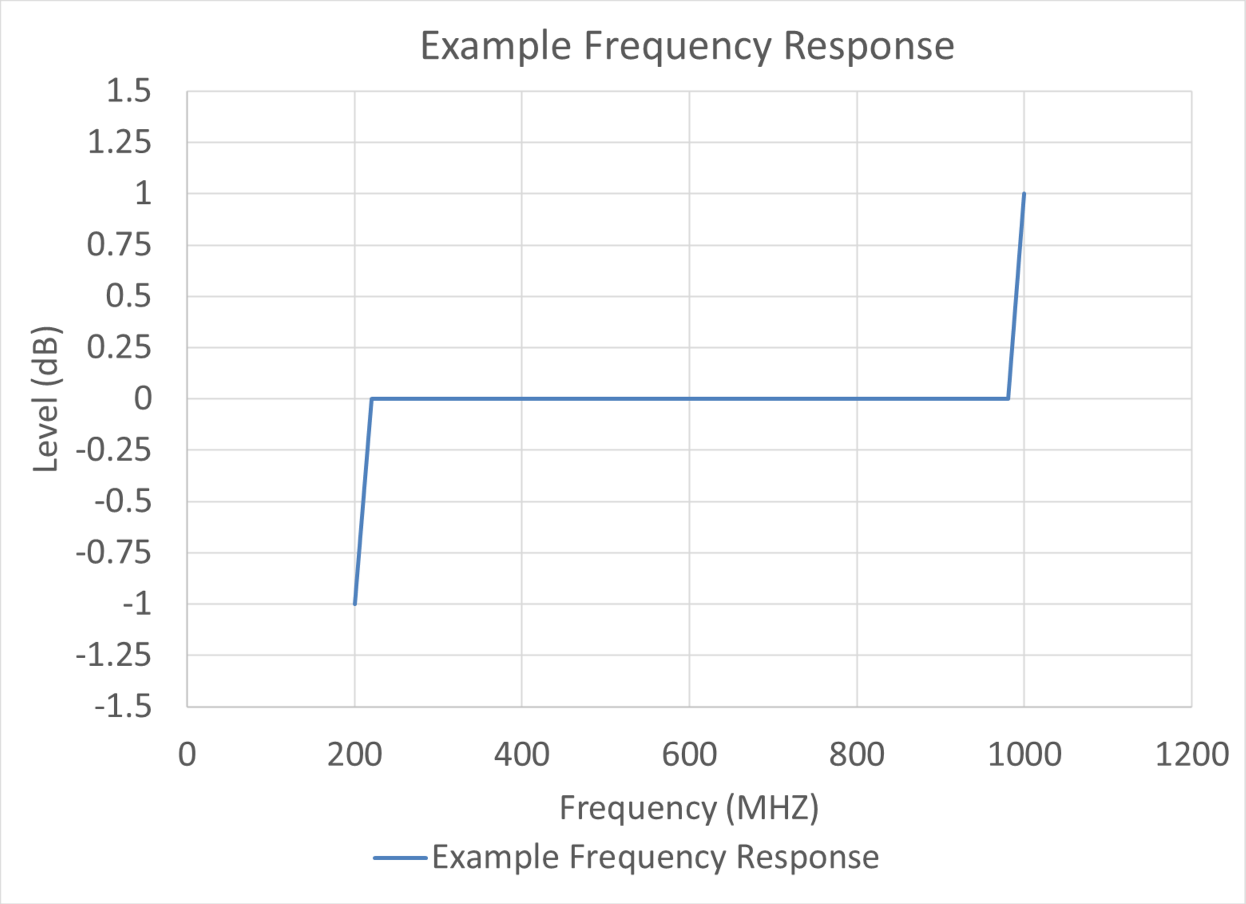


Figure 11 Example Frequency Response

This might be an amplifier that has low end roll-off and a peak circuit to boost the gain at the high end. The response is simplified for illustration purposes. It is assumed that this is a device that has linear slope, most of which has been removed in Figure 11.

One way to come up with a normalized frequency response would be to determine best least square fit of linear slope to match this response. An iterative approach was attempted in which a linear slope was increased by 0.1 dB increments until a best fit was obtained. Such a best fit occurs with 0.3 dB of linear slope. Note that it was necessary to also adjust the flat gain of the response by 0.15 dB in order to get a best fit. This best least square match is shown in Figure 12.

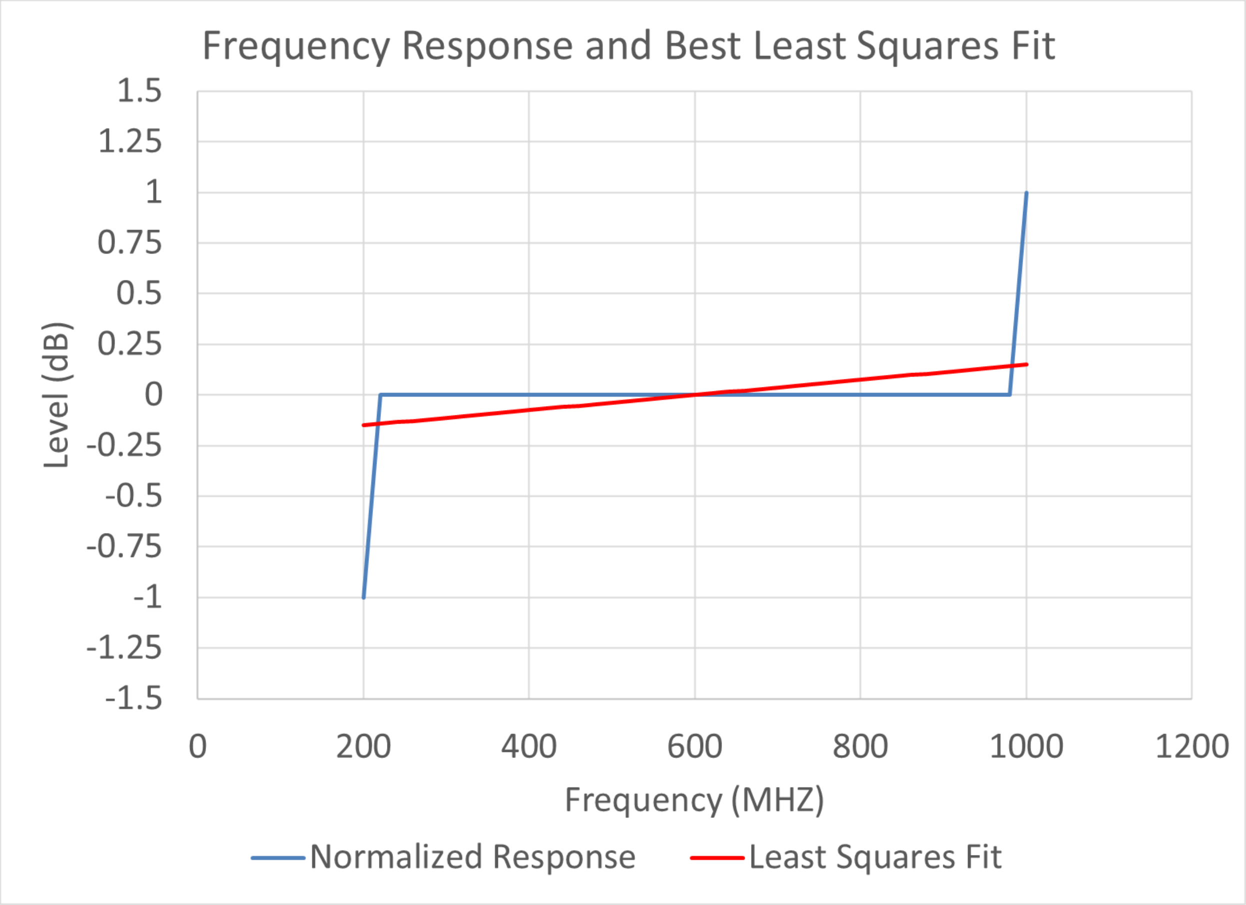


Figure 12 Best Least Squares Fit

Note that this best least square fit was based on frequency response data that was taken every 20 MHz. A slightly different best fit might result when more data points or fewer data points are used.

The data was normalized with respect to this best fit and the result is shown in Figure 13.

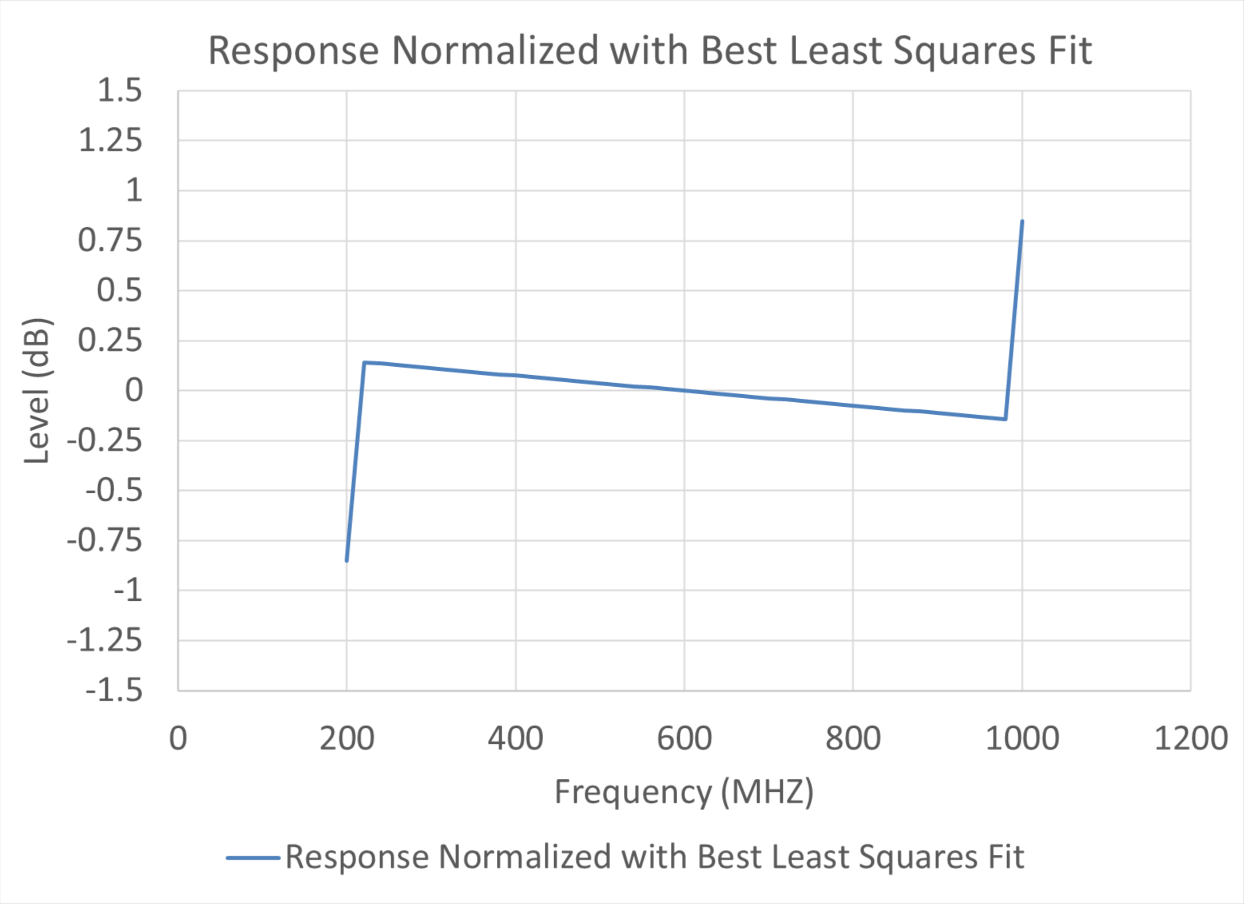


Figure 13 Normalized Response Based on Least Squares Fit

Based on the normalized response shown in Figure 13 the response of this device is 0.85 dB peak or 1.7 dB pp (+/- 0.85 dB).

If we repeat the iterative process with the slope and flat gain, but instead of looking for a minimum in the squares of the normalized response data points we simply look for smallest values for the maximum and minimum values of the response we get a different result. This is shown in Figure 14.

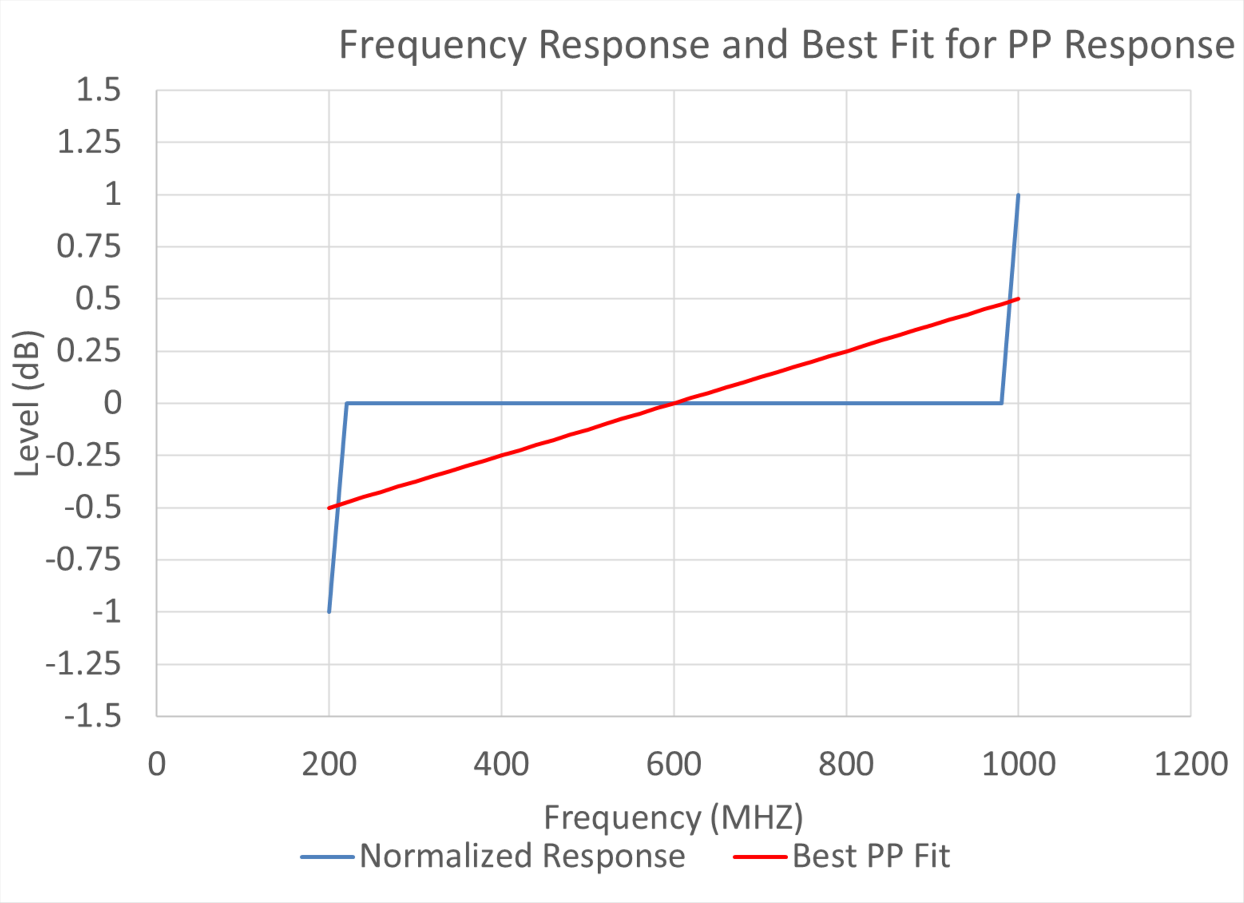


Figure 14 Frequency Response that Gives Best Normalized PP Value

In this case the best fit has 1 dB of linear Tilt and 1 dB of flat gain. (As before the flat gain must be adjusted to give a best fit.)

If we normalize the response with this new best fit, we get the response shown in Figure 15.

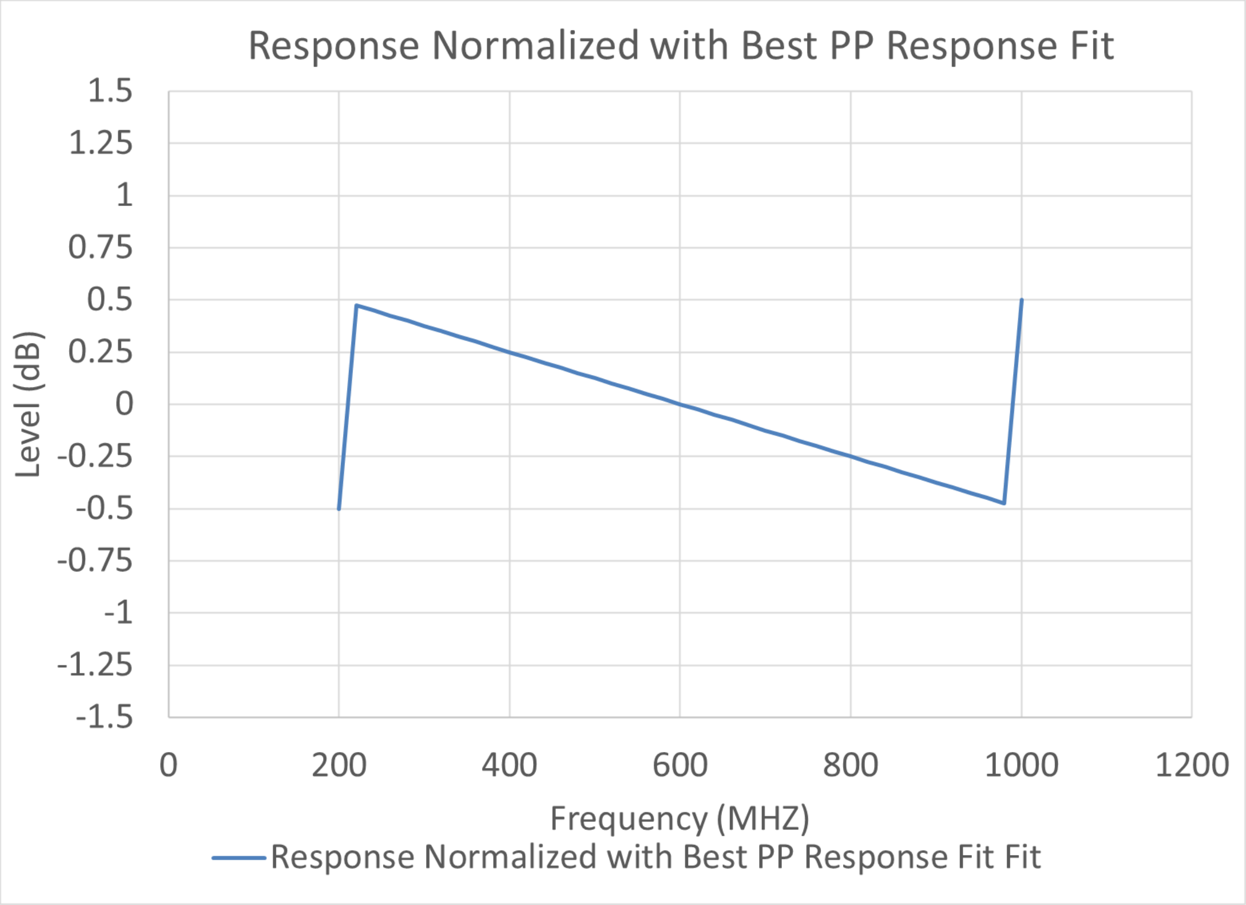


Figure 15 Frequency Response Normalized for Best PP Response

Based on the results in Figure 15 the response of this device is 0.5 dB peak or 1.0 dB pp. (+/- 0.5 dB). Note that this is a much better result than the result of 0.85 dB peak or 1.7 dB pp (+/- 0.85 dB) obtained in Figure 13 when we did a best least square curve fit of the data.

One may conclude that doing a best curve fit of the measured data might not give the best results when trying to obtain the best trade-off between flat gain, slope and frequency response for a device under test.