

Introduction

Microwave devices, both passive and active, are typically packaged using some type of surface mounted device. Integrated Device Technology uses industry standard low profile QFN packages. Because measurement equipment uses connectors there must be a transition from the connector to the QFN package. This is done by mounting the package on an evaluation board. This transition can mask the true performance of the device. This application note will discuss the TRL calibration technique used to remove the effects of the evaluation board.

TRL Calibration

The most prevalent measurements for linearly characterizing RF devices are the Scattering parameters (S-parameters). S-parameters measure the transfer characteristics between any two ports. For a detailed treatment of s-parameter theory, please see the books by G. Gonzalez or J. Dunsmore listed in the [References](#) section or the application note from Hewlett-Packard (AN 95).

S-parameters are typically measured using a vector network analyzer (VNA) which allows devices to be characterized over frequency. The accuracy of these measurements are very high because VNAs use a calibration algorithm that completely characterizes the system to a reference plane. For most measurements this is typically to an RF connector, like an SMA, APC 3.5 mm, or 2.92 mm (K connector). Standards which are well defined are used to characterize or calibrate the system.

On Printed Circuit Boards (PCBs) the transition from the connector to the device can have significant insertion loss which will mask the actual performance of the device. What is needed is to create the reference plane at the actual device. One technique to create the reference plane at the device is the Transmission, Reflect, and Line (TRL) calibration technique. This includes the concept of a Line, Reflect, and Line technique (LRL).

A TRL calibration is done by first designing a new evaluation board that has a series of transmission line and a reflection standards. The line standards are frequency bounded based on the electrical length. The efficacy of the TRL calibration is that the standards do not need to be well defined. However, if a very wide frequency band is required, then multiple line lengths are needed.

Other documents that offer an in-depth discussion of the theory behind the TRL calibration technique can be found in the [References](#) section at the end of this paper.

Figure 1. F0480 Evaluation Board

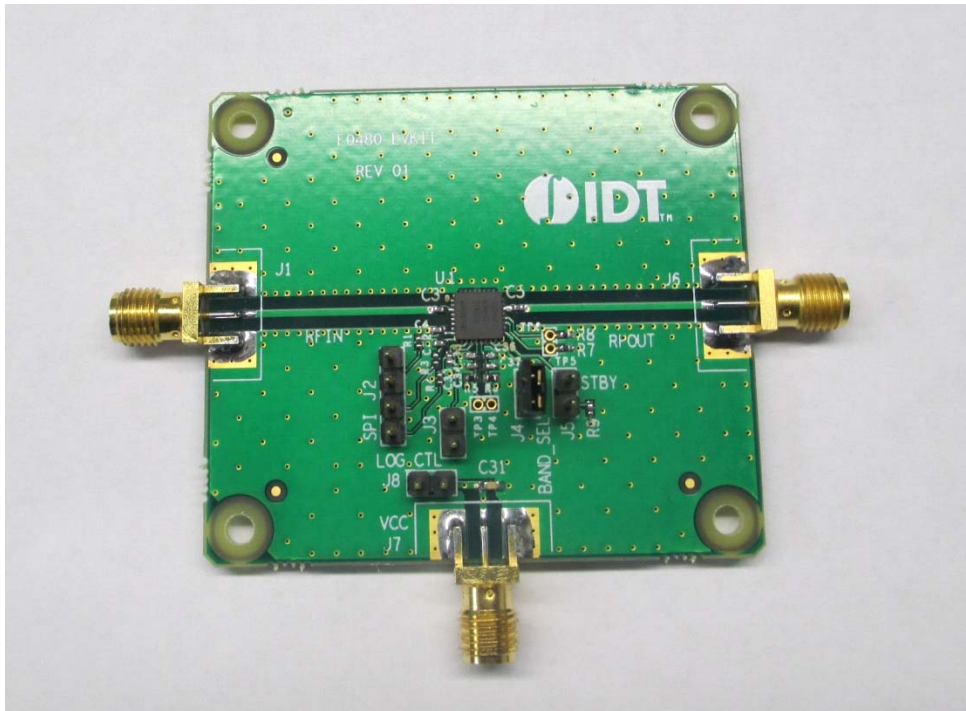
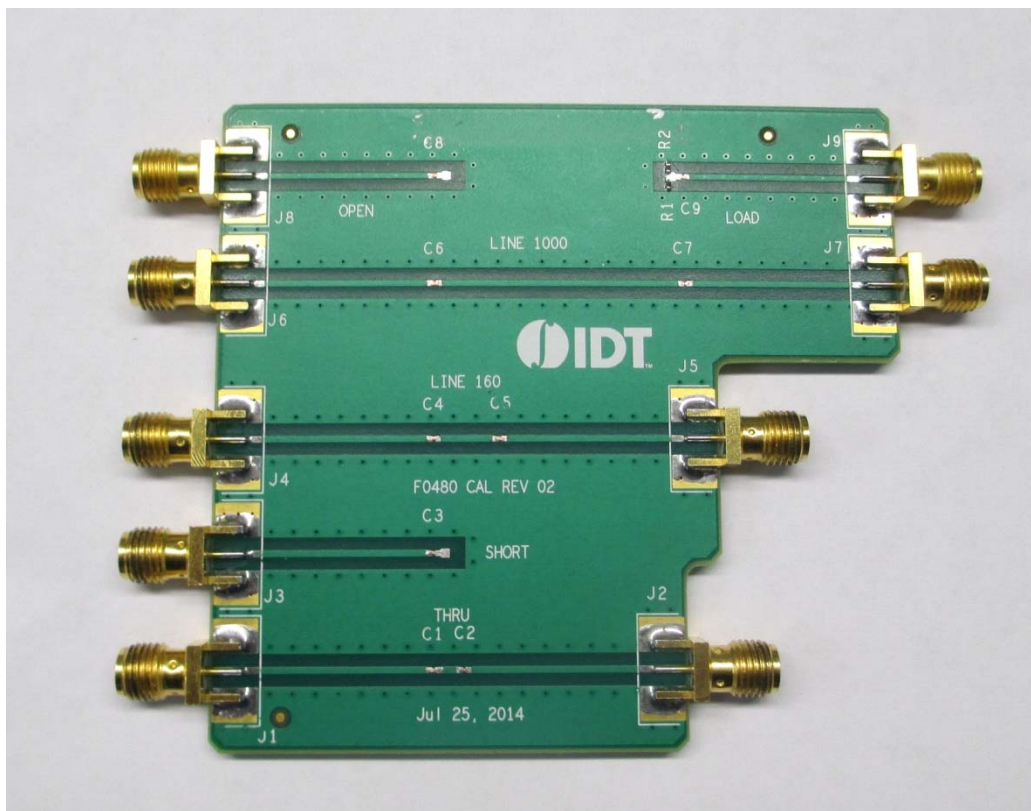


Figure 2. TRL Calibration Board used for the F0480



TRL Calibration Board

Figure 1 and Figure 2 above show both the evaluation board and the TRL calibration board. The TRL calibration board has six standards which have the exact same transmission line from the input and output ports on the evaluation board. Also note that we have the same components in-line. At the bottom of the board is the Through line. This is a combination of the input connector to the input of the device and the output of the device to the output connector. The lines do not have to be the same, but we have designed the F0480 evaluation board so that the input and output lines are identical. Just above the Through line is the input line with a Short circuit. Then there is the first transmission line which has length of 0.160 inches (4.064 mm). Above this is the second transmission line which has a length of 1.000 inch (25.4 mm). Finally, at the top of the board there is an Open circuit on the left, along with a load on the right. Finally there are the input and output lines which are connected together to define the reference plane. The above configuration can be used because the F0480 input and output transmission lines are the same. If this is not the case, then the open, short, and load should be created on both sides of the calibration board.

The standards were designed as follows:

Standard	Position	Comment
THRU	Bottom transmission line	As a standard the frequency range is 0 to 999 GHz.
LINE 160	Middle transmission line	As a standard the frequency range is 2.2 to 17.8 GHz. The physical length of transmission line is 160 mils longer than the THRU line and was added in the middle.
LINE 1000	Second from top transmission line	As a standard the frequency range is 0.3 to 2.5 GHz. The physical length of transmission line is 1000 mils longer than the THRU line and was added in the middle.
SHORT	Between the middle and bottom transmission line	The short is created using a filled via hole. The frequency range is 0 to 999 GHz.
OPEN	Top row, on the left (input)	The open is created by leaving the coplanar waveguide transmission line open circuit. The frequency range is 0 to 999 GHz.
LOAD	Top row, on the right (output)	The load is created by allowing two 100 ohm 0402 resistor to be connected to ground. The frequency range is 0 to 999 GHz.

Calibration Warning

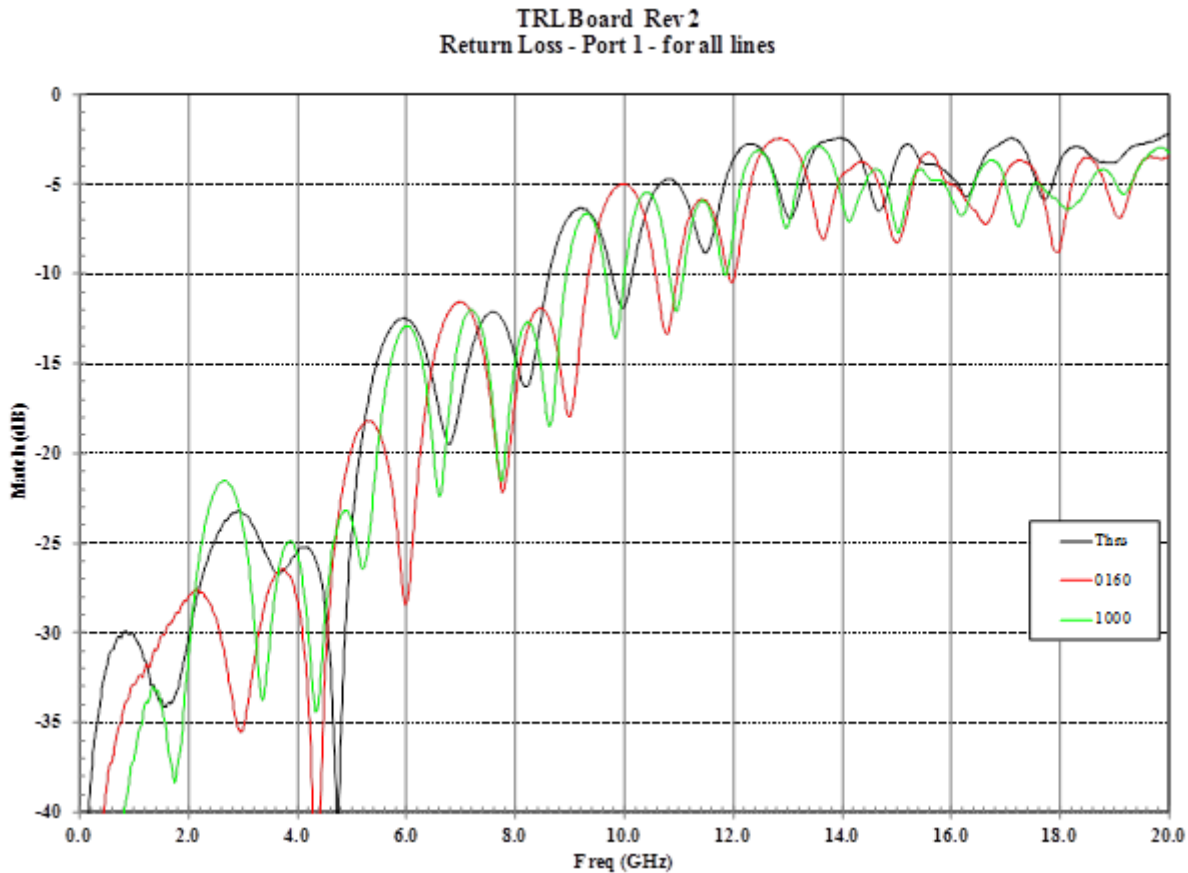
TRL calibrations do have a few unique qualifiers:

- The vector network analyzer should have two receivers for every port. This is so the source match term can be measured accurately. If this is not the case, and there is a shared reference receiver, (Agilent 8720x standard configuration), then 10 dB pads should be used on the two ports to create a better system match. Please review the Keysight product note PN 8720-2 for a discussion. Newer vector network analyzers, like the Keysight ENA and PNA series, have the required 2 receivers per port).
- If you try to use the TRL beyond the specified frequency range the vector network analyzer will prompt you that more standards are needed; restart the calibration with a new frequency range.
- It is best to place the TRL calibration standards on the same board as the device being tested. If this is not possible, then using a stable material and consistent assembly procedures is required.
- Before beginning the TRL calibration, it is best to make sure the connectors all present the same match. This is needed because the algorithm assumes the only differences are the reference planes, and is best done by comparing the gated time domain return loss of each of the connectors.

Connector Analysis

When performing time domain analysis it is worthwhile to use the highest frequency network analyzer since the time resolution is essentially the reciprocal of the frequency span. Also, for the maximum flexibility with using the time domain, use equally spaced frequency points starting at DC (0 Hz). This will allow the use of a low pass response. Below are return losses for each of the three transmission lines on the new calibration board. A 26 GHz PNA, N5242A was used, calibrated to 20 GHz, and used 2001 frequency points for the following analysis.

Figure 3. Measured S-parameters for the Input Ports of the Lines



Notice the high ripple content and the variance depending on the length of line. This is due to the mismatch of connectors resonating. Transforming to the time domain shows where the discontinuities are located.

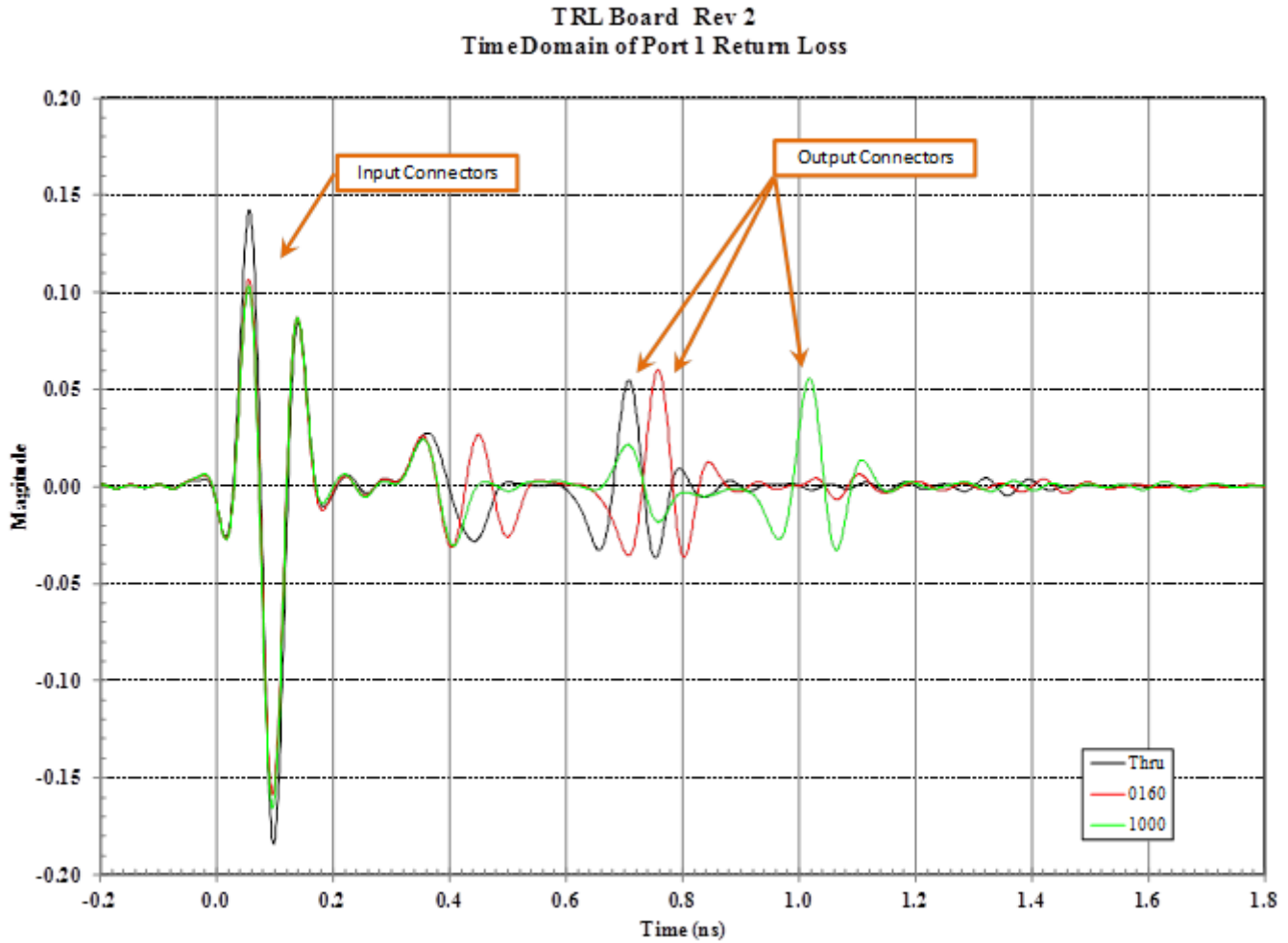
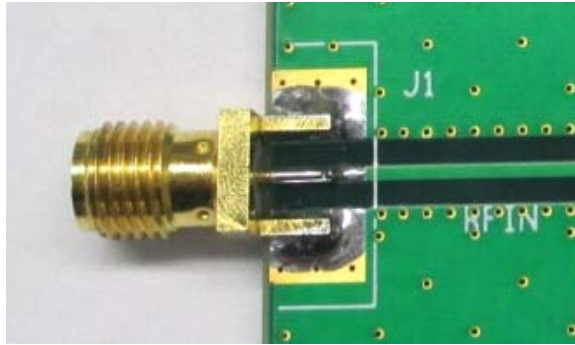
Figure 4. Time Domain Analysis of TRL Calibration Board from the Input Connector


Figure 4 shows where the discontinuities lie while using a Low pass response time domain analysis. The first discontinuity is the input connector and connection to the evaluation board. Though there are slight magnitude differences, note that the shape and position are exact. This shows that the three different connectors all very similar. The output connect can be seen between 0.7 and 1.0 ns. The magnitude is less than the input connector because of masking.

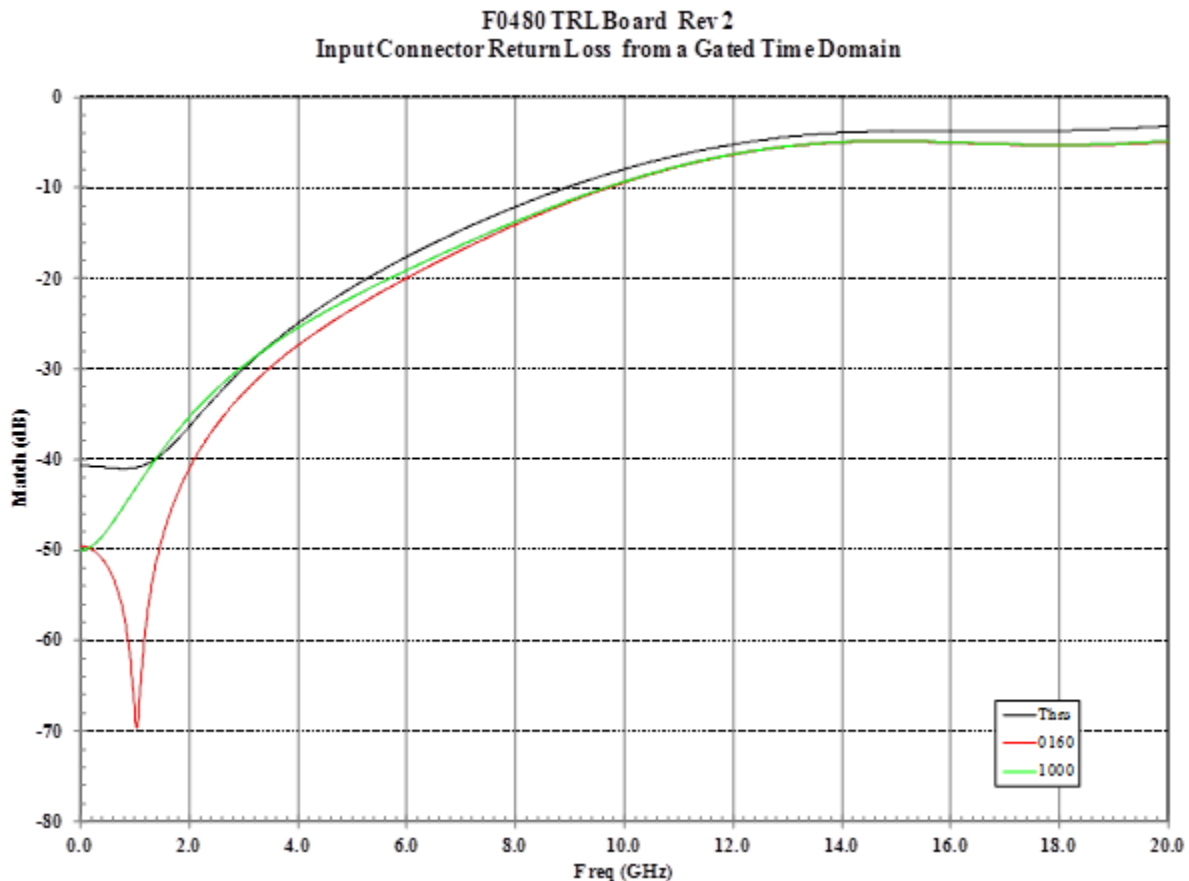
The input connector discontinuities can be described as lumped elements. The overwhelming element is the positive going peak starting at 0.03 ns which peaks at 0.05 ns, then goes negative with a negative peak at 0.10 ns. The positive (0.10) and negative (-0.15) peaks not the same value. This can be decomposed into a two elements: an offset, -0.025, and a symmetric swing of ± 0.125 . The offset correlates to resistive change while the symmetric swing shape correlates to a series inductor. This is not unexpected. Figure 5 shows a close up image of the input connector. This connector has a long center pin which is soldered down. This adds inductance which will limit the high frequency response of the evaluation board.

Figure 5. Image of Input Connector



The advantage of performing time domain analysis is that response can be gated so that the response of only the particular time window selected is examined. This is done by setting the magnitude to zero, no discontinuity. Since we want to examine what the input connector and board connection is doing, we can gate the time domain response window from -0.2 to 0.2 ns. All other time is forced to zero. Because this is the first component in the circuit, masking concerns are not needed.

Figure 6. Gated Response of the Input Connector



The input match is only for the connector and board connection. Using the gated response removed the resonance with the output connector. This shows that the inductance starts to become a factor around 2 GHz. Typically, the observance of a better than a -20 dB match would be desired if the measurements were being done at the connector.

Defining the TRL Calibration Kit

Though the standards and class assignments are standard for all network analyzers, the generation of the calibration kit is different. Please review the document for your network analyzer as the proper method.

Table 1 show the six standards that need to be defined. Depending on the network analyzer, you may need either the medium (COAX or Waveguide) or the connector. For this calibration kit, a connector was defined as TRL and made as a sexless connector. The coefficient terms (Cx/Lx) do not need to be defined since they are only used for a Short-Open-Load-Thru (SOLT) calibration.

Table 1: TRL Calibration Standard

ID	Standard Type	C0/L0 Term Z	C1/L1	C2/L2	C3/L3	Load Type	Offset Delay	Offset Z0	Offset Loss	Min Freq (GHz)	Max Freq (GHz)	Medium	Connector	Standard Label
1	Open						0	50	0	0	999	COAX	TRL	OPEN
2	Short						0	50	0	0	999	COAX	TRL	SHORT
3	Load					Fixed	0	50	0	0	999	COAX	TRL	LOAD
4	Delay/Thru						0	50	0	0	999	COAX	TRL	THRU
5	Delay/Thru						0	50	0	0.3	2.5	COAX	TRL	LINE1000
6	Delay/Thru						0	50	0	2.2	17.8	COAX	TRL	LINE0160

For a calibration, the standards must be assigned to a particular class for either a SOLT or TRL calibration. Table 2 shows how the Class Assignments are defined for the TRL calibration. Do not enter any standard for the SOLT calibration.

Table 2: TRL Calibration Class Assignment

	A	B	C	D	E	F	G	Standard Class Label
TRL Thru or Line	4							Thru
TRL Select	1	2	3					Reflect
TRL Line or Match	5	6						Line

Below are the procedural steps for entering the TRL calibration kit into Keysight Technologies E5072B or E5072C.

1. Press the [CAL] Button. The soft keys on the right of the screen will change.
2. Select t[Cal Kit].
3. Select a [User] kit. You might have scroll down.
4. Select [Modify Cal Kit].
5. Select [Define STDs].
6. Select [1. No Name].
7. Select [Label] and type in Open.
8. Select [STD Type] and then select [Open].
9. No other information needs to be entered. Scroll down and select [Return].
10. Repeat steps 6 through 9 for standards 2, 3, and 4.
11. Select [5. No Name].

12. Select [Label] and type in LINE1000.
13. Select [STD Type] and then select [Delay/Thru].
14. Scroll down and select [Min. Frequency] and enter 0.3 GHz.
15. Select [Max. Frequency] and enter 2.5 GHz.
16. Scroll down and select [Return].
17. Repeat steps for 11 to 16 for standard 6.
18. Scroll down and select [Return]. You should be back at the “Modify Cal Kit” Menu.
19. Select [Specify CLS].
20. By default you have Sub Class 1.
21. Select [TRL Thru].
22. Select [Set All].
23. Select Standard [4. Thru].
24. Select [Return].
25. Select [TRL Reflect].
26. Select [Set All].
27. Select Standard [2. Short].
28. Select TRL Line/Match].
29. Select [Set All].
30. Select Standard [5. LINE1000].
31. Select [Return].
32. Select [Sub Class] and then select [Sub Class 2].
33. Select TRL Line/Match].
34. Select [Set All].
35. Select Standard [6. LINE0160].
36. Select [Return].
37. Select [TRL Options].
38. Set [Impedance] to Line.
39. Set [Reference Plane] to Thru.
40. Select [Return].
41. Select [Label Kit] and enter F0480 R2.
42. For further use, Export Cal Kit to the hard drive.
43. Select [Return] to get back to the Calibration menu.

Next, perform a calibration. Set up the network analyzer for frequency range with the calibration kit. The minimum frequency is 0.3 GHz and the maximum frequency is 8.5 GHz. Set the network analyzer IF bandwidth and the number of points to values you would like to use.

1. At the Calibration Menu [Cal] Select [Calibrate].
2. Select [2-Port TRL].

3. If this is a 4 port network analyzer, select the two ports you want to be calibrated. For this discussion, [1-2] has been selected.
4. Select [Thru/Line].
5. Connect the two ports to the Thru line on the calibration board and select the standard [Thru].
6. Select [Return].
7. Select [Reflect].
8. Connect the Port 1 to the Short standard on the calibration board and select [Port1 Reflect].
9. Connect the Port 2 to the Short standard on the calibration board and select [Port2 Reflect].
10. Select [Return].
11. Select [Line/Match].
12. Select [1-2 Line/Match].
13. Connect the Ports to the Line 0160 on the calibration board and select [LINE0160].
14. Connect the Ports to the Line 1000 on the calibration board and select [LINE1000].
15. Select [Return].
16. Select [Return].
17. Select [Done].

Comparison of Calibrations

Two calibrations have now been completed. The first was done using an Electronic Calibration module at the SMA connectors. The second was done using the above TRL calibration board and calibration kit. Notice that with the TRL calibration, the actual amplifier has 1dB higher gain at 3GHz.

Figure 7. Comparison of the Gain for the F0480 with 0dB Attenuation

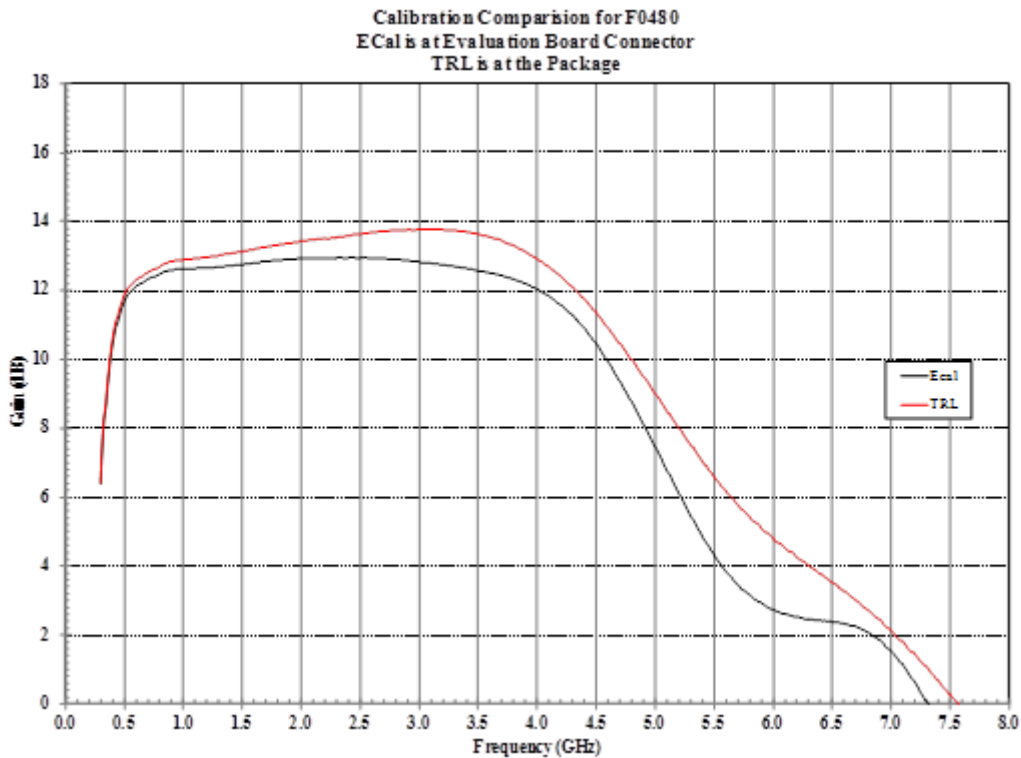


Figure 8. Comparison of the Input Match for the F0480 with 0dB Attenuation

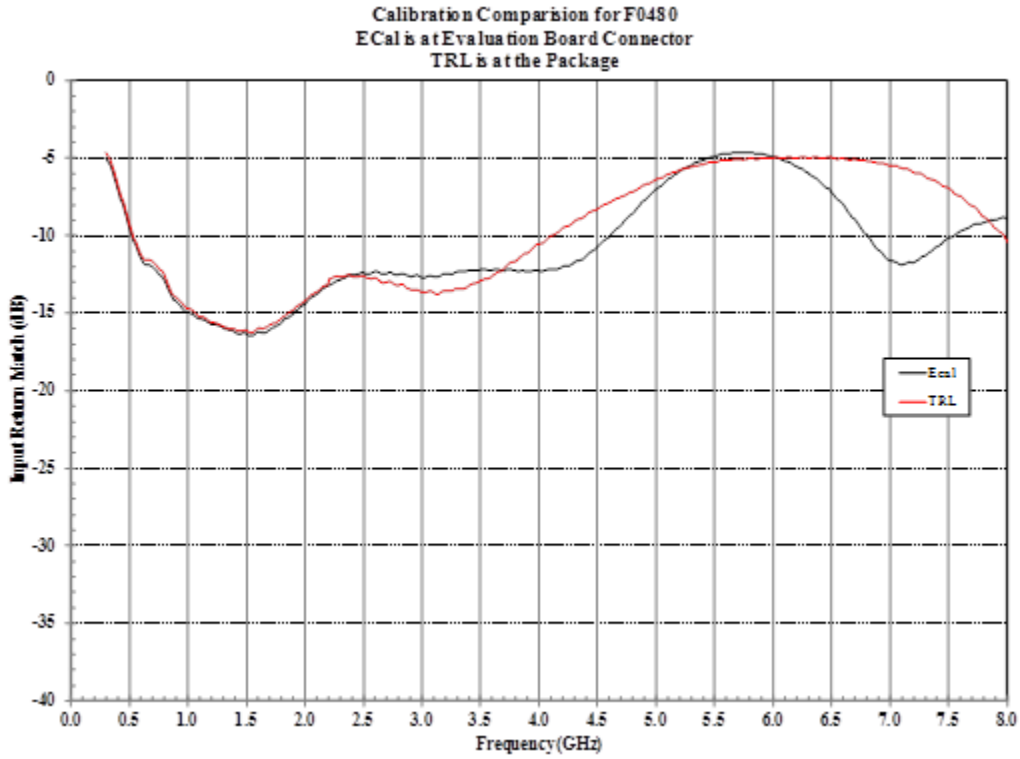
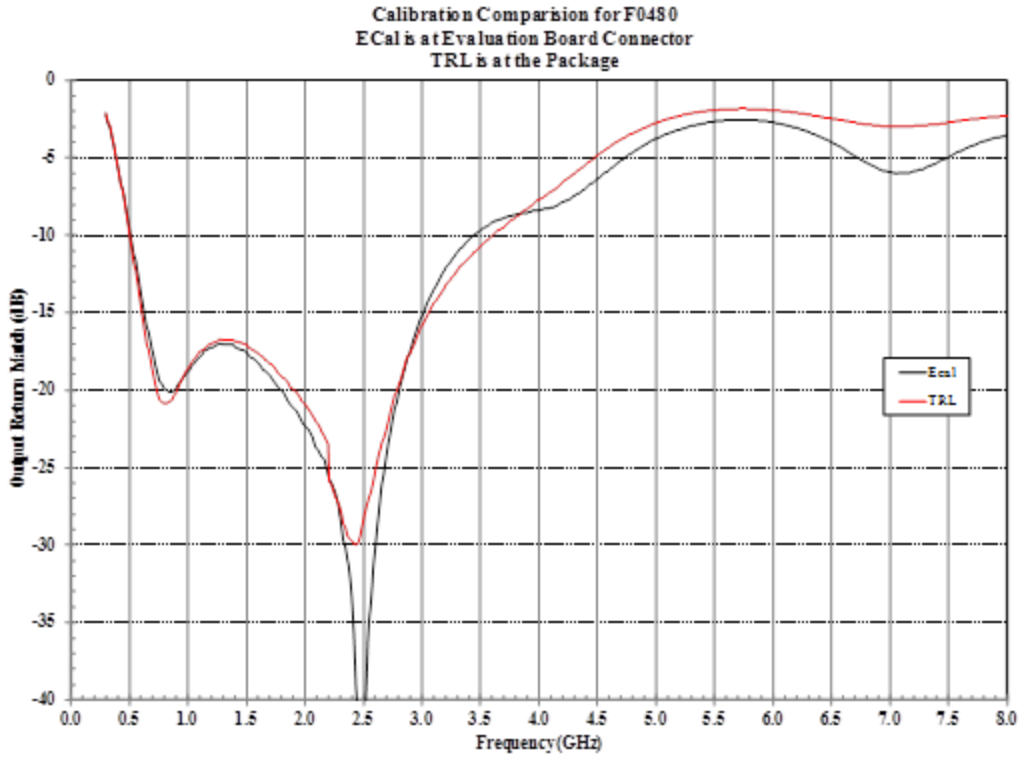


Figure 9. Comparison of the Output Match for the F0480 with 0dB Attenuation



References

Books:

Dunsmore, Joel P., (2012). Handbook of Microwave Component Measurements: With Advanced, VNA Techniques, Chichester West Sussex, England, John Wiley & Sons, Ltd. ISBN-9781119979555

G. Gonzalez (1984), 'Microwave Transistor Amplifiers: Analysis and Design', Prentice Hall, ISBN 0135816467.

Anritsu (2009). The Essentials of Vector Network Analysis: From α to Z_0 .

Application Notes from Keysight Technologies (formerly Agilent Technologies)

[S-Parameters... Circuit Analysis and Design \(AN 95\)](#)

[Network Analysis Basics - Applying Error Correction To Network Analyzer Measurements \(AN 1287-3\)](#)

[Impedance Characteristic Evaluation of SMD by Using the ENA with Inter-Continental Microwave \(ICM\)](#)

[8720 Calibration - In-fixture Measurements Using TRL* Calibration \(PN 8720-2\)](#)

[Specifying Calibration Standards and Kits for Keysight Vector Network Analyzers \(AN 1287-11\)](#)

[Time Domain Analysis With a Network Analyzer Application Note \(AN 1287-12\)](#)

[S-parameter Series: Using the Time-Domain Reflectometer Application Note](#)

[8720 Calibration - In-fixture Measurements Using TRL* Calibration \(PN 8720-2\)](#)



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