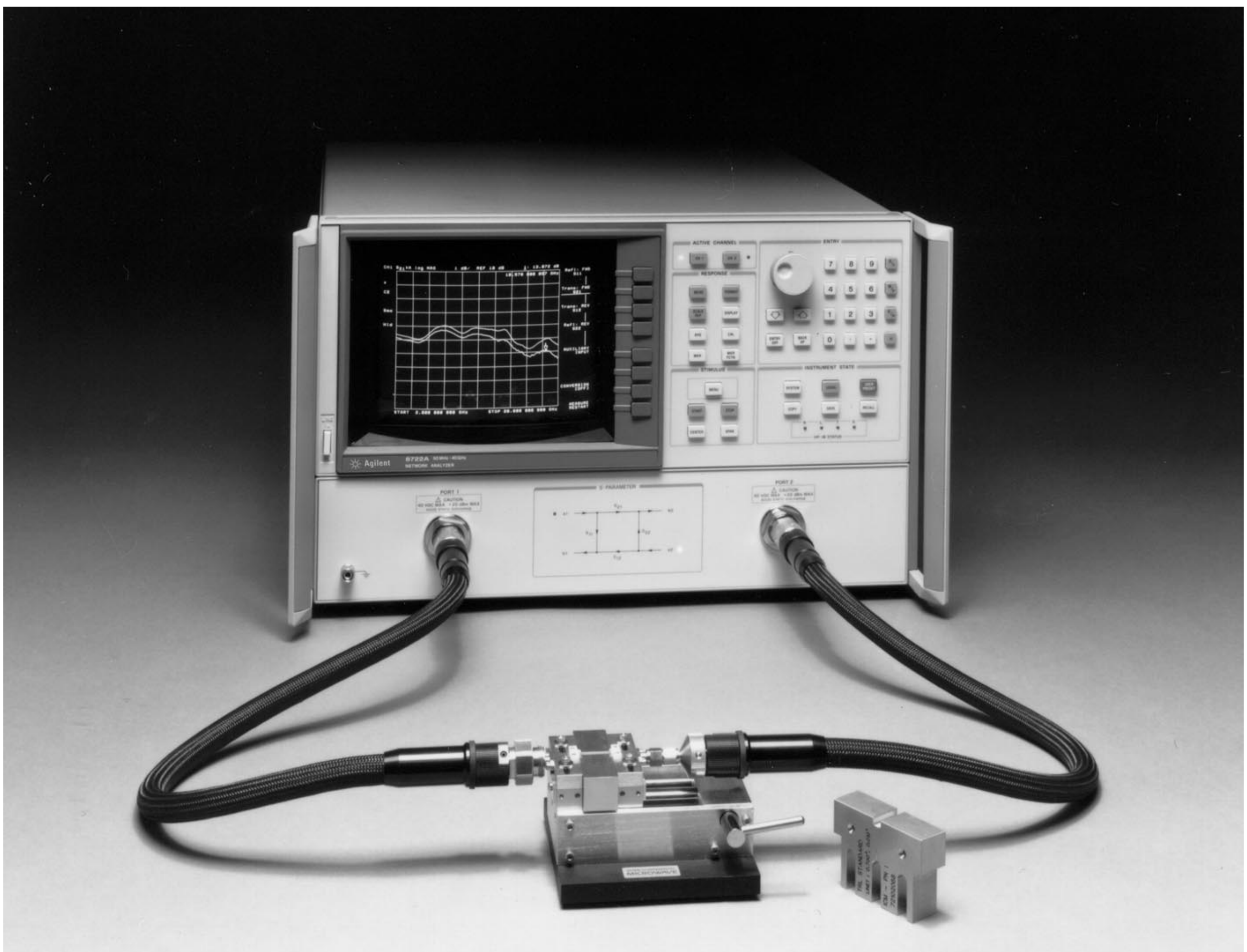
Agilent PN 8720-2

In-fixture Microstrip Device Measurements Using TRL* Calibration

Product Note



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Contents

Introduction

The Agilent Technologies 8720C, 8719C, and 8722A microwave network analyzers have the capability of making convenient in-fixture measurements of microstrip devices using the TRL* (TRL-star) calibration technique. TRL* is an implementation of TRL (as first introduced on the Agilent 8510B network analyzer) that has been adapted for the three-sampler receiver architecture used by the Agilent 8720C family of network analyzers for use in fixtured measurement environments such as microstrip. 8720B and 8719A network analyzers with firmware revision 2.0 or greater also have TRL* capability. Firmware upgrade packages are available for these network analyzers (via the Agilent 86386A/B upgrade kits).

The measurement examples shown in this note were made using an Inter-Continental Microwave (ICM) Series TF-3000 adjustable test fixture.[1]

Microstrip device measurements

Microstrip devices in the form of chips, MMIC's, packaged transistors, or beam-lead diodes cannot be connected directly to the coaxial ports of a network analyzer like the 8720C. The device under test (DUT) must be physically connected to the network analyzer by some kind of transition network or fixture. Calibration for a fixtured measurement in microstrip presents additional difficulties.

A calibration at the coaxial ports of the network analyzer removes the effects of the network analyzer and any cables or adapters before the fixture; however, the effects of the fixture itself are not accounted for. An in-fixture calibration is preferable, but high-quality Short-Open-Load-Thru (SOLT) standards are not readily available to allow a conventional Full 2-port calibration of the system at the desired measurement plane of the device. In microstrip, a short circuit is inductive, an open circuit radiates energy, and a high-quality purely resistive load is difficult to produce over a broad frequency range. The Thru-Reflect-Line* (TRL*) 2-port calibration is an alternative to the traditional SOLT Full 2-port calibration technique that utilizes simpler, more convenient standards for device measurements in the microstrip environment.

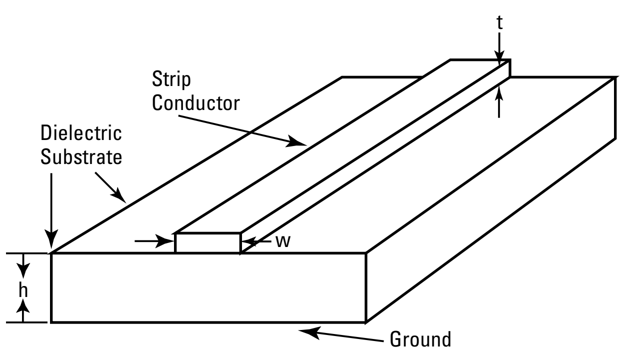

Figure 1. Microstrip transmission line geometry

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Fixtured device measurement techniques

Several techniques can be used to remove the effects of the test fixture from the measurement of a device in a microstrip environment. The technique that is best suited for a given application depends on the accuracy desired, the availability of calibration standards, and the amount of time available to implement a measurement. With each of the following techniques described here (with the exception of in-fixture calibration), it is recommended that a coaxial calibration first be performed as closely as possible to the point where the test fixture will be connected. After a coaxial calibration, the fixture's length, loss, and mismatch effects are not separated from the DUT.

Reference plane rotation
• Assumption: Fixture has negligible loss and mismatch

The 8720 family of network analyzers has two features which remove the phase effects due to the fixture length from the measured data. Electrical delay mathematically adds a delay to the reference signal path to produce a linear phase change that balances the phase due to the fixture length. A port extension, on the other hand, subtracts the delay seen at each port so the reference plane at each test port can be extended through the fixture to the device. Preferably, a port extension should be used to remove the effects of the fixture's length from the measurement. Electrical delay can then be used to measure the actual delay of the device.

For either technique, simple in-fixture calibration standards are required to establish the reference plane (open/short for reflection measurements or thru for transmission measurements). While observing the phase format of the parameter of interest, add electrical delay or port extension until the displayed trace is flat. This will mathematically extend the reference plane through the fixture to the device.

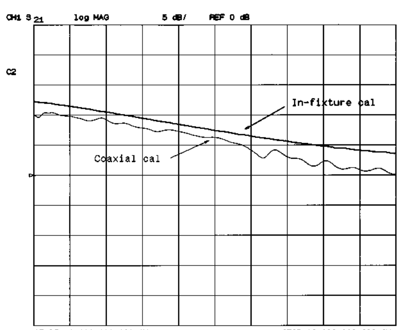

Figure 2. FET measurement comparing a coaxial calibration to an in-fixture calibration

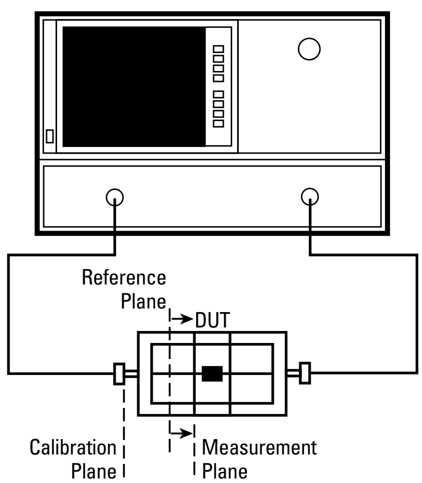

Figure 3. Reference plane definition

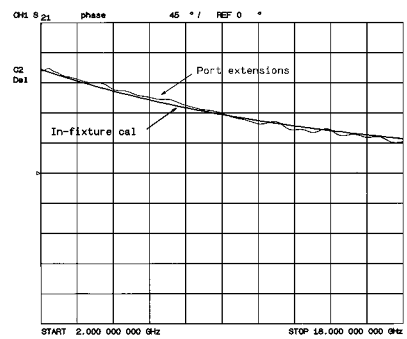

Figure 4. FET measurement comparing a port extension to an in-fixture calibration

Normalization

• Assumption: Fixture has negligible mismatch

At higher frequencies, fixtures generally do have measurable loss as well as length. Therefore, a shift in magnitude as well as phase will occur between the fixture and device. A procedure called normalization can be used to remove these effects from the displayed data. Only simple in-fixture standards are required to measure the loss and length of the fixture (open/short for reflection measurements or thru for transmission measurements). Store the data for the parameter of interest into the analyzer's internal memory and press [DATA/MEM] to subtract the fixture's effect from the measurement so that the loss and length of the device is displayed.

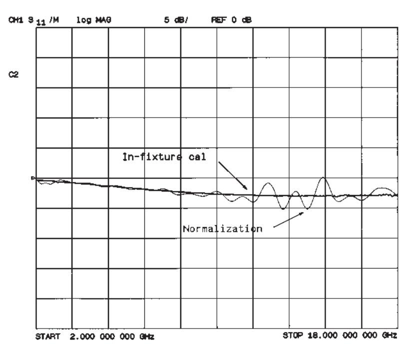

Figure 5. FET measurement comparing a normalization to an in-fixture calibration

Time domain gating

• Assumption: Fixture has negligible loss

Time domain reflectometry (TDR) can determine the exact location of reflections caused by discontinuities in the test fixture. TDR is performed by the 8720 family of network analyzers (with Option 010) by computing the inverse fast Fourier transform (FFT) of the frequency domain response, and then displaying the computed time domain response to observe the individual reflection responses contributed by the fixture. A time domain gate can then be applied to selectively remove the unwanted responses of the fixture by setting the gate start and stop markers around the device only. Activating the time domain gate effectively removes the responses outside the gate. Returning to the frequency domain with the time domain gate still applied, it is possible to view the measured device data without including the effects of the fixture's response.

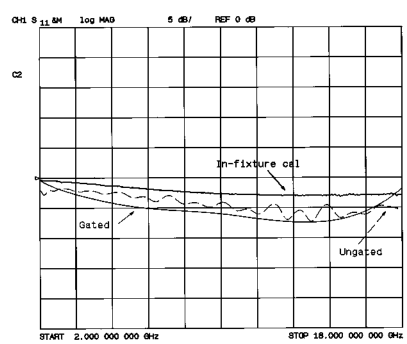

Figure 6. FET measurement comparing time domain gating (gate on and gate off) to an in-fixture calibration

De-embedding

• Assumption: Fixture characteristics are well known

De-embedding is a mathematical process that removes the effects of the fixture which are embedded in the data by subtracting out an equivalent network that represents the fixture. There are two ways to represent a fixture: with measured S-parameter data or with modeled data. Measured data requires a direct measurement of each half of the fixture at discrete frequencies. An equivalent lumped-element component model of the fixture halves requires calculating the effects of the fixture at each measurement frequency point by using a linear circuit simulator. Once the measured or modeled S-parameters of the fixture are known, they can be de-embedded (removed) from the measured response of the DUT. This technique achieves an in-fixture reference plane without performing repeated in-fixture calibrations.

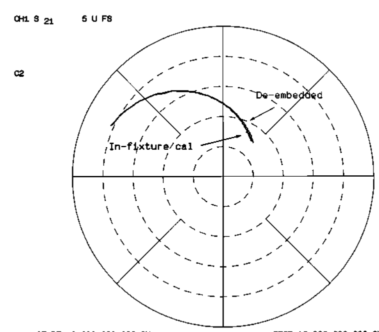

Figure 7. FET measurement comparing de-embedding to an in-fixture calibration

In-fixture calibration

• Assumption: In-fixture calibration standards are available

In order to fully remove the effects of the test fixture from the measurement, in-fixture calibration standards must be available. With the traditional SOLT (Short-Open-Load-Thru) Full 2-port calibration technique, three known impedance standards are required. A SOLT calibration can theoretically remove the effects of the fixture's loss, length, and mismatch, but high quality standards in microstrip are not generally realizeable at microwave frequencies. TRL* (Thru-Reflect-Line) is a 2-port calibration technique that can be used for measurements in microstrip at microwave frequencies. The TRL* calibration process relies on the characteristic impedance of simple transmission lines rather than on a set of discrete impedance standards. TRL* can eliminate the effects of the fixture's loss and length, but doesn't completely remove the effects due to the mismatch of the fixture.

Table 1. Fixtured Device Measurement Techniques

Technique	Simplicity	Precision	Applicable at Microwave Frequencies	Parameter Affected	Fixture Assumptions
Electrical delay	A	C	No	Single	No loss or mismatch
Port extension	A	C	No	Port 1: S_{11},S_{21},S_{12} Port 2: S_{22},S_{12},S_{21}	No loss or mismatch
Normalization	B	B	No	Single	No mismatch
Time domain gating	B	B	Yes	S_{11} or S_{22}	No loss; Responses are well separated
De-embedding	C	A	Yes	All	Modeled or measured fixture S-parameters are available
SOLT	C	B	No	All	In-fixture standards are available
TRL*	B	B	Yes	All	No mismatch; Simple in-fixture standards are available

A = more   C = less

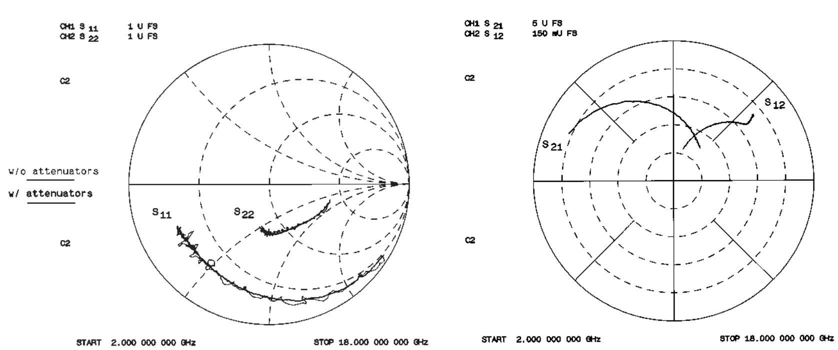

Figure 8. FET measurement using an in-fixture TRL* calibration (with fixed attenuators to improve match)

Agilent 8720C TRL* calibration

TRL* (Thru-Reflect-Line) is a 2-port calibration that results in the same 12-term error correction model as the conventional SOLT (Short-Open-Load-Thru) Full 2-port calibration. The key advantage of TRL* is that it uses transmission lines as reference standards. In addition to being one of the simplest elements to realize in a microstrip media, the impedance of transmission lines can be determined from physical dimensions and materials.

There are three basic steps in the TRL* 2-port calibration process. The first step is the same as the transmission step for a Full 2-port calibration. For the THRU step, the test ports are connected together directly or with a short length of transmission line. For the REFLECT step, identical one-port high reflection coefficient standards are connected to each test port. For the LINE step, a short length of transmission line (different in length from the THRU) is inserted between port 1 and port 2.

Because the Agilent 8720C network analyzer has a three-sampler receiver architecture, the TRL algorithm that is implemented in the 8510 (four-sampler receiver architecture) cannot be applied. The difference is that after a TRL* calibration, the effective source match and load match effects are not fully error-corrected. The residual match after a TRL* calibration is only slightly better than the raw (uncorrected) test port mismatch characteristics of the network analyzer.

For coaxial, waveguide, on-wafer, and other measurement environments where high-quality impedance standards (loads) are readily available, SOLT is still the most accurate calibration technique to use since the match terms are fully error-corrected. For a microstrip measurement environment, where SOLT standards are not practical, the TRL* calibration technique is suitable.

Improving raw source match and load match

A technique that can be used to improve the raw test port mismatch is to add high quality fixed attenuators (such as the Agilent 8493C or 8490D) as closely as possible to the measurement plane. The effective match of the system is improved because the fixed attenuators usually have a return loss that is better than that of the network analyzer. Additionally, the attenuators provide some isolation of reflected signals. The attenuators also help to minimize the difference between the source match and load match, making the ε_{11} and ε_{22} error terms more equivalent (see Appendix A – The theory behind TRL*).

With the attenuators in place, the effective port match of the system is improved so that the mismatch of the fixture transition itself dominates the measurement errors after a calibration.

LRM* (Line-Reflect-Match)

TRL* presents some limitations in certain applications. A single TRL* LINE standard is normally used over an 8:1 frequency bandwidth making it necessary to use multiple LINE standards to cover a broad frequency range. Additionally, the physical length of the LINE can become inconveniently long at low frequencies.

The LRM* (LRM-star) calibration technique is related to TRL* with the difference being that it bases the characteristic impedance of the measurement on a matched Z_o termination instead of a transmission line for the third measurement standard. Like the TRL* THRU standard, the LRM* LINE standard can either be of zero length or non-zero length. The same THRU and REFLECT standards used for TRL* apply for LRM*.

LRM* has no inherent frequency coverage limitations which makes it more convenient in some measurement situations. Additionally, because TRL* requires a different physical length for the THRU and the LINE standards, its use becomes impractical for fixtures with contacts that are at a fixed physical distance from each other.

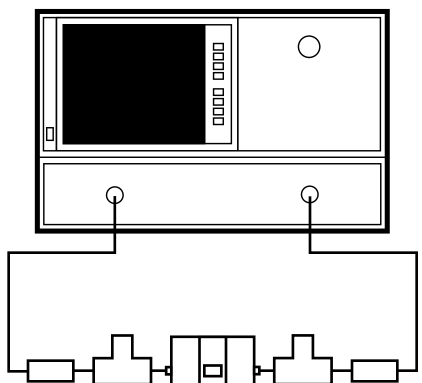

Figure 9. Typical measurement set-up

If the device measurement requires bias, it will be necessary to add external bias tees (such as the Agilent 11612A/B) between the fixed attenuators and the fixture. The internal bias tees of the 8720C will not pass the bias properly through the external fixed attenuators. Be sure to calibrate with the external bias tees in place (no bias applied during calibration) to remove their effect from the measurement.

Table 2. Comparison of Mismatch Effects

	Return loss (typical)				
	2 GHz	**8 GHz**	**13.5 GHz**	**20 GHz**	**40 GHz**
Network analyzer (uncorrected):					
8719C					
Source	18 dB	14 dB	10 dB	—	—
Load	24 dB	15 dB	12 dB	—	—
8720C					
Source	18 dB	14 dB	10 dB	10 dB	—
Load	24 dB	15 dB	12 dB	12 dB	—
8722A					
Source	20 dB	16 dB	12 dB	10 dB	10 dB
Load	24 dB	18 dB	14 dB	14 dB	12 dB
Attenuator:					
8493C	26 dB	26 dB	19 dB	19 dB	—
8490D	23 dB	23 dB	23 dB	23 dB	19 dB
Bias Tees:					
11612A	20 dB	20 dB	18 dB	14 dB	—
11612B	20 dB	20 dB	18 dB	14 dB	10 dB
Fixture:					
Microstrip	24 dB	24 dB	24 dB	20 dB	18 dB

Table 3. Improvement in Source Match vs. Degradation in Dynamic Range with Fixed Attenuator Pairs (Assumes a fixture launch with 20 dB return loss and negligible loss at 20 GHz)

	TRL* calibration with attenuators			
	None	**3 dB**	**6 dB**	**10 dB**
Effective source match				
Coaxial port	10 dB	11.5 dB	14.5 dB	17 dB
In-fixture	7.5 dB	8.5 dB	11 dB	12.5 dB
Dynamic range degradation	0 dB	6 dB	12 dB	20 dB

Because the bias tees must be placed after the attenuators, they essentially become part of the fixture. Therefore, their mismatch effects on the measurement will not be improved by the attenuators.

Although the fixed attenuators improve the raw mismatch of the network analyzer system, they also degrade the overall measurement dynamic range. Table 3 shows the effective source match and corresponding degradation in dynamic range of the measurement system for a typical microstrip fixture using the TRL* calibration method at 20 GHz (with various pairs of attenuators).

This effective mismatch of the system after calibration has the biggest effect on reflection measurements of highly reflective devices. Likewise, for well-matched devices, the effects of mismatch are negligible. This can be shown by the following approximation:

Reflection magnitude uncertainty ≈

$$E_D + E_R S_{11} + E_S (S_{11})^2 + E_L S_{21} S_{12}$$

Transmission magnitude uncertainty ≈

$$E_X + E_T S_{21} + E_S S_{11} S_{21} + E_L S_{22} S_{21}$$

where:

- E_D = effective directivity
- E_R = effective reflection tracking
- E_S = effective source match
- E_L = effective load match
- E_X = effective crosstalk
- E_T = effective transmission tracking

TRL* calibration procedure

When building a set of TRL* standards for a microstrip environment, the requirements for each of these standard types must be satisfied.

Table 4. Requirements for TRL* Standards

THRU

Zero length

* No loss and no characteristic impedance (Z_o).
* $S_{21} = S_{12} = 1 <0°$.
* $S_{11} = S_{22} = 0$.

Non-zero length

* Z_o of the THRU must be the same as the LINE (if they are not the same, the average impedance is used).
* Attenuation of the THRU need not be known.
* If the THRU is used to set the reference plane, the insertion phase or electrical length must be well-known and specified. If a non-zero length THRU is specified to have zero delay, the reference plane is established in the middle of the THRU.

REFLECT

* Reflection coefficient (Γ) magnitude is optimally 1.0, but need not be known.
* Phase of Γ must known and specified to within ± 1/4 wavelength or ± 90°. During computation of the error model, the root choice in the solution of a quadratic equation is made based on the reflection data. An error in definition would show up as a 180° error in the measured phase.
* Γ must be identical on both ports.
* If the REFLECT is used to set the reference plane, the phase response must be well-known and specified.

LINE/MATCH

LINE

* Z_o of the LINE establishes the reference impedance of the measurement (S_{11}=S_{22}=0). The system impedance is defined to be the same as Z_o of the LINE. If the Z_o is known but not the desired value (i.e., not equal to 50 Ω), the SYSTEM Z0 selection under the TRL*/LRM* options menu is used.
* Insertion phase of the LINE must not be the same as the THRU (zero length or non-zero length). The difference between the THRU and LINE must be between (20° and 160°) ± n x 180°. Measurement uncertainty will increase significantly when the insertion phase nears 0 or an integer multiple of 180°.
* Optimal LINE length is 1/4 wavelength or 90° of insertion phase relative to the THRU at the middle of the desired frequency span.[2]
* Usable bandwidth for a single THRU/LINE pair is 8:1 (frequency span:start frequency).
* Multiple THRU/LINE pairs (Z_o assumed identical) can be used to extend the bandwidth to the extent transmission lines are available.[3]
* Attenuation of the LINE need not be known.
* Insertion phase must be known and specified within ± 1/4 wavelength or ± 90°.

MATCH

* Z_o of the MATCH establishes the reference impedance of the measurement.
* Γ must be identical on both ports.

2. The insertion phase of the 1/4 wavelength LINE will vary with frequency. Phase (degrees) = (360 x frequency x electrical length) / c. This expression can be rearranged to solve for the electrical length of a 1/4 wavelength LINE at a center frequency. Electrical length (cm) = 15 / [start frequency (GHz) + stop frequency (GHz)]. At very high microwave frequencies (>20 GHz), a 1/4 wavelength LINE becomes very short and may be difficult to build. A solution for this problem would be to construct a THRU and LINE which differ by 1/4 wavelength. This does, however, require a non-zero length THRU.
3. If the desired frequency span must be divided to allow for multiple LINES to cover a broad frequency span, the optimal break frequency is the geometric mean frequency [√(start frequency x stop frequency)].

TRL* options

There are two selections under the TRL*/LRM* options submenu: calibration Z_o (CAL Z0) and set reference (SET REF).

The characteristic impedance used during the calibration (CAL Z0) can be referenced to either the LINE standard (LINE Z0) or to the system (SYSTEM Z0). The 8720C defaults to a reference impedance that is equal to the LINE standard (MATCH standard for LRM*).

When the LINE Z0 is selected, the impedance of the LINE standard is assumed to match the system impedance exactly (the LINE standard is reflectionless). After a calibration, all measurements are referenced to the impedance of the LINE standard. For example, when the LINE standard is remeasured, the response will appear at the center of the Smith chart. When LINE Z0 is selected, the values entered for SET SYSTEM Z0 (under CAL menu) and OFFSET Z0 (in the standard definition table) are ignored.

SYSTEM Z0 is selected when the desired measurement impedance differs from the impedance of the LINE standard. This requires a knowledge of the exact value of the Z_o of the LINE. The system reference impedance is set using SET SYSTEM Z0 under the CAL menu. The actual impedance of the LINE is set by entering the real part of the LINE impedance as the OFFSET Z0 in the calibration standard definition table. For example, if the LINE was known to have a characteristic impedance of 51 Ω (OFFSET Z0 = 51 Ω), it could still be used to calibrate for a 50 Ω measurement (SET SYSTEM Z0 = 50 Ω). After a calibration, all measurements would be referenced to 50 Ω, instead of 51 Ω. When the LINE standard is remeasured, the center of the Smith chart is at the current value of SET SYSTEM Z0 (in this case, 50 Ω). Since only one value of OFFSET Z0 can be selected for the LINE standard, the value of Z_o should be a constant value over the frequency range of interest in order to be meaningful.

The location of the reference plane (SET REF) for a TRL* measurement can be set with either the THRU or the REFLECT standard. By default the reference plane is set with the THRU standard which must have a known insertion phase or electrical length. If a non-zero length THRU is specified to have zero delay, the reference plane will be established in the middle of the THRU. The REFLECT standard may be used to set the reference plane instead of the THRU provided the phase response (offset delay, reactance values and standard type) of the REFLECT standard is known and is specified in the calibration kit definition.

Dispersion effects

Dispersion occurs when a transmission medium exhibits a variable propagation or phase velocity as a function of frequency. The result of dispersion is a non-linear phase shift versus frequency, which leads to a group delay which is not constant. Fortunately, the TRL* calibration technique accounts for dispersive effects of the test fixture up to the calibration plane, provided that:

1. The THRU (zero or non-zero length) is defined as having zero electrical length and is used to set the reference plane (SET REF: THRU).

2. The transmission lines used as calibration standards have identical dispersion characteristics (i.e., identical height, width, and relative dielectric constant).

When a non-zero length THRU is used to set the reference plane, although the THRU has physical length, it should be defined as having zero length in the TRL* standards definition. The actual electrical length of the THRU standard must then be subtracted from the actual electrical length of each LINE standard in the TRL* calibration kit definition. The device must then be mounted between two short lengths of transmission line so that each length is exactly one-half of the length of the non-zero length THRU standard. In this configuration, the measurement will be properly calibrated up to the point of the device.

Defining TRL* standards

TRL* calibration is implemented by changing the definitions of the 8720C TRL* calibration kit. A TRL* template is provided in the 8720C as a guideline, but it is not intended to cover all measurement situations.

A modified standard class assignment table and standard definition table for the 8720C are shown for a microstrip measurement. This calibration kit utilizes the TRL* technique for coverage above 0.7 GHz and LRM* for coverage below 0.7 GHz.

A zero length THRU is created by connecting the fixture halves directly together. The THRU standard (number 4) is specified to have an OFFSET DELAY of 0 ps and a frequency range of 0 to 20 GHz. A zero length THRU can be used over any frequency span that the transmission medium can support. Since the delay of a zero length THRU is accurately known, it is typically used to set the reference plane.

A flush short circuit is used as the REFLECT standard (number 1). Only nominal specification of its phase is required. It is specified to have an OFFSET DELAY of 0 ps and a frequency range of 0 to 20 GHz. If the short circuit were offset from the reference plane by more than 90° at the maximum frequency, an approximation of its delay could be entered.

The TRL* LINE/MATCH class assignment uses three standards to cover a broad frequency range. Two LINE standards (numbers 7 and 8) of known length are used to cover 0.7 to 4.3 GHz and 4.3 to 20 GHz frequency ranges. A MATCH standard (number 6) is used to cover the 0.05 to 0.7 GHz range to avoid having to use an inconveniently long LINE standard. The OFFSET LOSS of the LINE/MATCH standards does not have to be specified. The offset Z_o is specified as the known impedance of the LINE/MATCH, in this case 50 Ω. Notice that the frequency limit for each LINE/MATCH standard overlaps at the boundary frequencies of 0.7 GHz and 4.3 GHz to avoid frequency resolution errors.

Table 5. TRL* Standard Class Assignments and Standard Definitions

	A	B	C	D	E	F	G	Standard Class Label
TRL Thru	*4*							*TRL THRU*
TRL Reflect	*1*							*TRL SHORT*
TRL Line/Match	*6*	*7*	*8*					*TRL LINE/MATCH*

Standard		CO $x10^{-15}F$	C1 $x10^{-27}F/Hz$	C2 $x10^{-36}F/Hz^2$	C3 $x10^{-45}F/Hz^3$	Fixed or Sliding	Terminal Impedance Ω	Offset			Frequency (GHz)		Coax or Waveguide	Standard Label
No.	Type							Delay ps	Z_0 Ω	Loss G Ω /s	Min.	Max.		
1	*SHORT*							*0*	*50*		*0*	*20*	*COAX*	*SHORT*
2														
3														
4	*DELAY/ THRU*							*0*	*50*		*0*	*20*	*COAX*	*THRU*
5														
6	*LOAD*							*0*	*50*		*.05*	*.71*	*COAX*	*MATCH*
7	*DELAY/ THRU*							*85.6*	*50*		*.69*	*4.31*	*COAX*	*LINE 1*
8	*DELAY/ THRU*							*17.3*	*50*		*4.29*	*20*	*COAX*	*LINE 2*

Storing a modified USER KIT

After modifying the TRL* calibration kit, be sure to label the kit appropriately and save it by pressing [SAVE USER KIT]. This USER KIT is saved in nonvolatile memory. It is always a good idea to store the modified kit to disk via an external disk drive for future retrieval. Press [CAL] [CAL KIT] [USER KIT] [SAVE] [STORE TO DISK] [STORE (title file)]. The USER KIT must be the active kit at the time of the storage.

For more information on how to define calibration kits for the Agilent 8720 family of network analyzers, see the Operating and Programming manual.

Calibration sequence

The following procedure describes a typical calibration procedure for a fixtured microstrip device measurement made on the 8720C network analyzer:

1. Configure the 8720C for a 2-port S-parameter measurement. Connect a 10 dB fixed attenuator to each port, then connect the fixture between the attenuators. If the device requires bias, connect external bias tees between the attenuators and the fixture.

2. Set the desired stimulus conditions for the measurement (such as start and stop frequencies, number of points, power level, IF bandwidth, etc.).

3. Press [CAL] [CAL KIT] [USER KIT] [RETURN] [CALIBRATE MENU] [TRL*/LRM* 2-PORT]. The TRL*/LRM* calibration submenu will be displayed. The THRU, S11 REFL, S22 REFL, ISOLATION, LINE/MATCH steps of the calibration can be performed in any convenient order.

4. Connect the fixture halves together with a THRU and press [THRU THRU]. All four S-parameters are measured and THRU is underlined when these measurements are complete.

5. Disconnect the fixture halves and insert a high REFLECT standard (short circuit) between the fixture halves. Press [S11 REFL SHORT] and the reflection coefficient is measured and SHORT is underlined. Press [S22 REFL SHORT] and the reflection coefficient is measured and SHORT is underlined.

6. To measure the systematic crosstalk in the test set of the network analyzer, the isolation is measured (S_{21} and S_{12}) with each port terminated. When the systematic crosstalk is sufficiently below the levels that are to be measured, as in this instance, it does not have to be characterized. Press [ISOLATION] [OMIT ISOLATION].

7. Remove the short circuit and insert the LINE standard between the fixture halves. Press [LINE/MATCH] [DO BOTH FWD + REV] [LINE] and measure all four S-parameters. If the frequency span is beyond the range of a single line, another LINE or a MATCH standard could be measured at this point.

8. Press [DONE TRL*/LRM* CAL] and save the calibration into a register by pressing [SAVE REG1].

9. Connect the device between the fixture halves and press [MEAS] so that all four S-parameters are updated.

Measurement results

For many microstrip device measurements, TRL* is a viable calibration technique that utilizes simple and available in-fixture calibration standards. But, because the source and load match terms are not fully corrected, the measurement may benefit from the addition of a pair of fixed attenuators at the coaxial ports of the fixture. Figure 10 shows the results of a measurement made with and without 10 dB fixed attenuators to improve the mismatch error of the fixture. If the greatest accuracy for an in-fixture measurement is desired, the SOLT calibration technique will yield the best overall results, provided the calibration standards are available and precisely known.

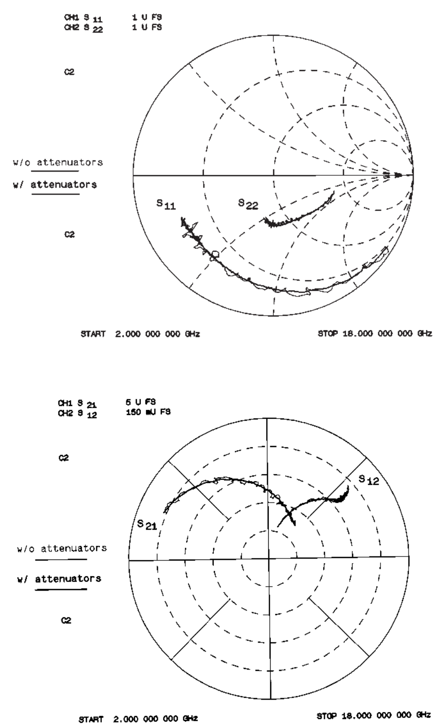

Figure 10. FET measurement using TRL* calibration with and without 10 dB fixed attenuators

Appendix A— The theory behind TRL*

Measurement errors

Errors which result from imperfections of the measurement system (including the network analyzer, test set, cables, adapters, fixtures, etc.) can be classified as either random or systematic. Systematic errors are the repeatable errors such as mismatch, directivity, and tracking errors. These can be measured then mathematically removed from the measurement with the built-in error-correction techniques of the Agilent 8720 network analyzer. Random errors such as noise, drift, and connection repeatability cannot be improved using vector error-correction techniques, but they can be minimized using other tools available in the network analyzer (averaging, IF bandwidth, etc.).

During a measurement calibration, a series of known devices (standards) are connected. The systematic errors are determined from the difference between the measured and known responses of the standards. Once characterized, these errors can be mathematically related by solving a signal flow graph. The 12-term error model shown in Figure 11 includes all the significant systematic effects for the measurement of a 2-port device.

In a conventional SOLT Full 2-port calibration, three known impedance standards and a single transmission standard are required. The accuracy to which these standards are known establishes how well the systematic errors can be characterized. A well-established figure of merit for a calibrated system is the magnitude of the residual systematic effects (effective directivity, effective source match, etc.). These residual effects are the portion of the uncorrected systematic error that remain because of imperfections in the calibration standards.

TRL* error model

For an 8720C TRL* 2-port calibration, a total of 10 measurements are made to quantify eight unknowns (not including the two isolation error terms). Assume the two transmission leakage terms, E_{XF} and E_{XR}, are measured using the conventional technique. The eight TRL* error terms are represented by the error adapters shown in Figure 13. Although this error model is slightly different from the traditional Full 2-port 12-term model, the conventional error terms may be derived from it. For example, the forward reflection tracking (E_{RF}) is represented by the product of ε_{10} and ε_{01}. Also notice that the forward source match (E_{SF}) and reverse load match (E_{LR}) are both represented by ε_{11}, while the reverse source match (E_{SR}) and forward load match (E_{LF}) are both represented by ε_{22}. In order to solve for these eight unknown TRL* error terms, eight linearly independent equations are required.

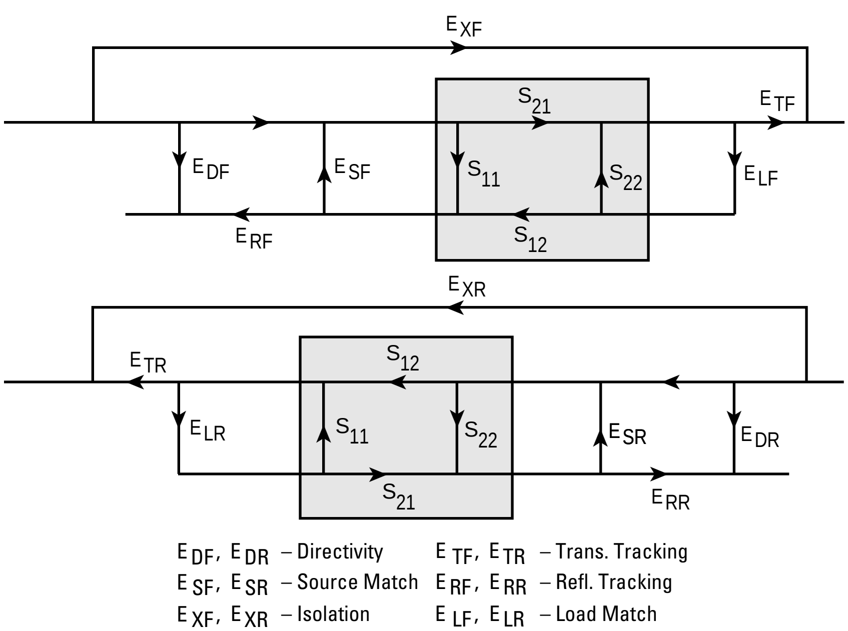

Figure 11. Two-port 12-term error model

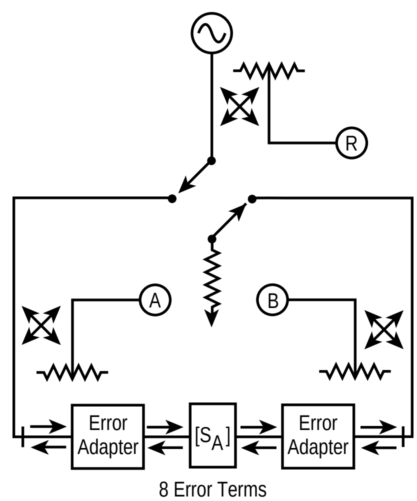

Figure 12. Agilent 8720C functional block diagram for a 2-port error-corrected measurement system

The first step in the TRL* 2-port calibration process is the same as the transmission step for a Full 2-port calibration. For the THRU step, the test ports are connected together directly (zero length THRU) or with a short length of transmission line (non-zero length THRU) and the transmission frequency response and port match are measured in both directions by measuring all four S-parameters.

For the REFLECT step, identical high reflection coefficient standards (typically open or short circuits) are connected to each test port and measured (S_{11} and S_{22}).

For the LINE step, a short length of transmission line (different in length from the THRU) is inserted between port 1 and port 2 and again the frequency response and port match are measured in both directions by measuring all four S-parameters.

In total, ten measurements are made, resulting in ten independent equations. However, the TRL* error model has only eight error terms to solve for. Because there are more measurements than unknowns, two constants defining the calibration devices can also be determined. In the TRL* solution, the complex reflection coefficient of the REFLECT standard andthe propagation constant of the LINE standard are determined. Because these terms are solved for, they do not have to be specified initially. The characteristic impedance of the LINE standard becomes the measurement reference and, therefore, has to be assumed ideal (or known and defined precisely).

At this point, the forward and reverse directivity (E_{DF} and E_{DR}), transmission tracking (E_{TF} and E_{TR}), and reflection tracking (E_{RF} and E_{RR}) terms may be derived from the TRL* error terms. This leaves the isolation (E_{XF} and E_{XR}), source match (E_{SF} and E_{SR}) and load match (E_{LF} and E_{LR}) terms to discuss.

Isolation

Two additional measurements are required to solve for the isolation terms (E_{XF} and E_{XR}). Isolation is characterized in the same manner as the Full 2-port calibration. Forward and reverse isolation are measured as the leakage (or crosstalk) from port 1 to port 2 with each port terminated. The isolation part of the calibration is generally only necessary when measuring high loss devices (greater than 70 dB). If an isolation calibration is performed, the fixture leakage must be the same during the isolation calibration and the measurement.

Source match and load match

A TRL* calibration assumes a perfectly balanced test set architecture as shown by the ε_{11} term which represents both the forward source match (E_{SF}) and reverse load match (E_{LR}) and by the ε_{22} term which represents both the reverse source match (E_{SR}) and forward load match (E_{LF}). However, in any switching test set, the source and load match terms are not equal because the transfer switch presents a different terminating impedance as it is changed between port 1 and port 2.

Because the 8720C family of network analyzers is based on a three-sampler receiver architecture, it is not possible to differentiate the source match from the load match terms. The terminating impedance of the switch is assumed to be the same in either direction. Therefore, the test port mismatch cannot be fully corrected. An assumption is made that:

forward source match (E_{SF}) =
  reverse load match (E_{LR}) = ε_{11}
reverse source match (E_{SR}) =
  forward load match (E_{LF}) = ε_{22}

After a TRL* calibration, the residual source match and load match are only slightly better than the raw (uncorrected) test port mismatch characteristics of the network analyzer. This is how TRL* on the 8720C network analyzer differs from TRL on the 8510 network analyzer.

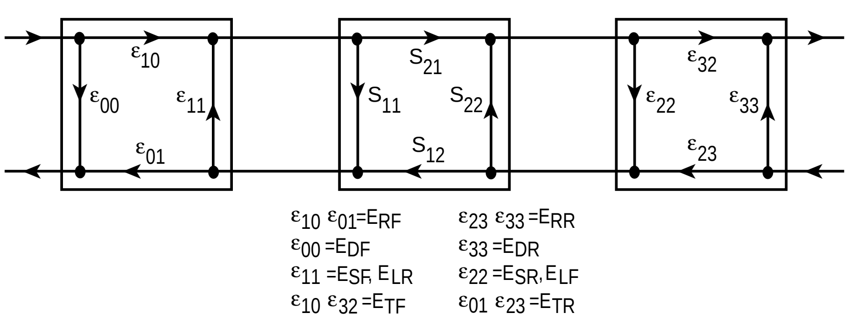

Figure 13. 8-term TRL* error model and generalized coefficients

Comparisons to the Agilent 8510

The 8510 implementation of TRL calibration requires a total of fourteen measurements to quantify ten unknowns (not including the two isolation error terms). Because of the four-sampler receiver architecture of the 8510, additional correction of the source match and load match terms is achieved by measuring the ratio of the incident signals (a1 and a2) during the THRU and LINE steps. Once the impedance of the switch is measured, it is used to modify the ε_{11} and ε_{22} error terms. The ε_{11} term is modified to produce forward source match (E_{SF}) and reverse load match (E_{LR}). Likewise, ε_{22} is modified to produce reverse source match (E_{SR}) and forward load match (E_{LF}). In the case of the 8510 network analyzer, all twelve terms of the 2-port error model can be determined.

The Agilent 8510 network analyzer's implementation of TRL is well established as the ideal calibration technique for high accuracy as well as convenient in-fixture measurements. Device measurements made using the 8510 four-sampler implementation of TRL compared to the 8720C three-sampler implementation of TRL* can give a practical demonstration of situations where TRL* with the 8720C is appropriate. Figure 15 compares 8510 measurements that were made with no external attenuators, with 8720C measurements that were made using a pair of external 10 dB fixed attenuators and bias tees before the fixture.

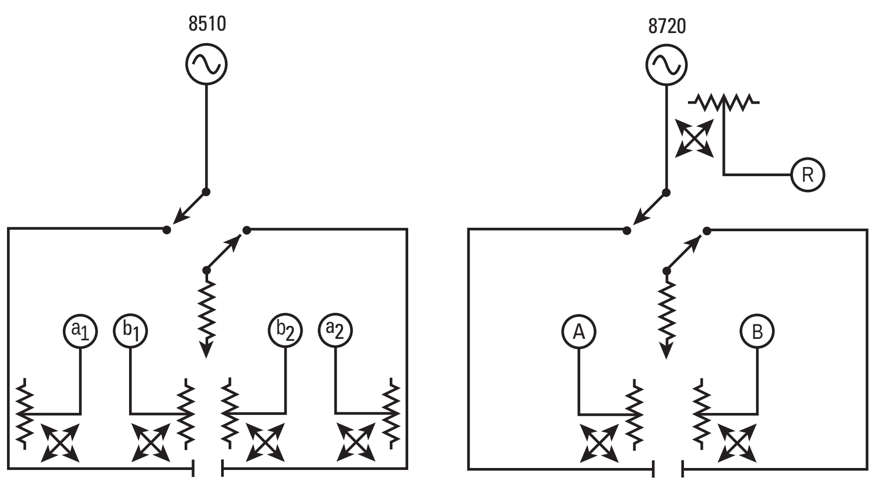

Figure 14. Comparison of Agilent 8720 (a) and 8510 (b) functional block diagrams for a 2-port error corrected measurement system

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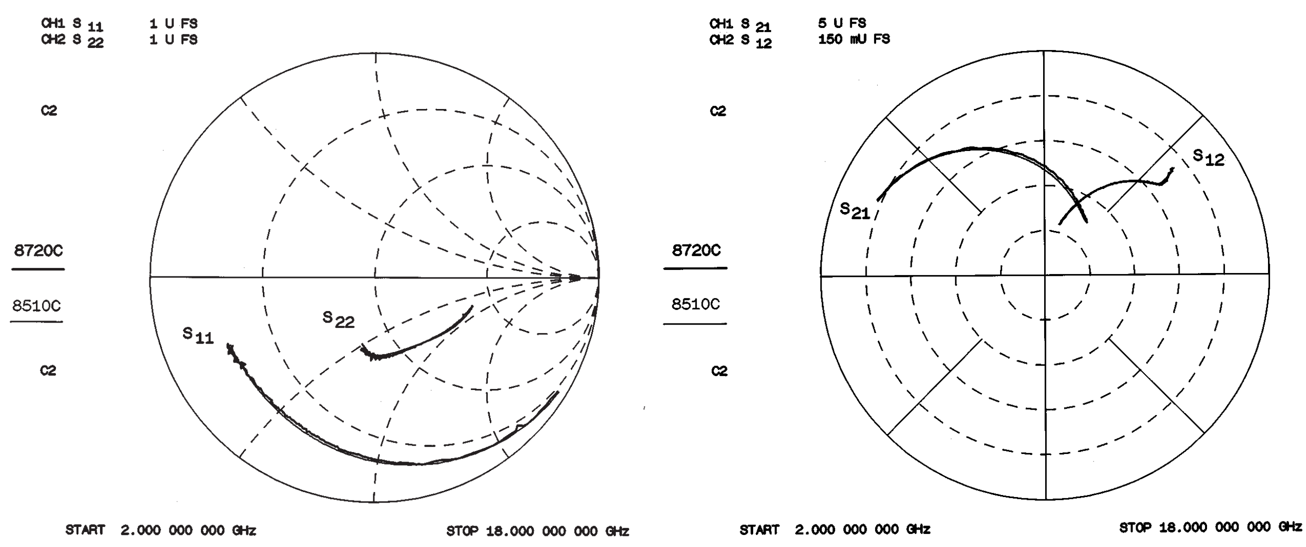

Figure 15. FET measurement made on an Agilent 8510 and 8720

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