TRL CALIBRATION FOR NON-COAXIAL MEASUREMENTS

Speaker
Kevin Rochford
Hewlett-Packard Company
29 Burlington Mall Rd
Burlington, MA 01803

Author
Jim Curran
Newtwork Measurements Division
Hewlett-Packard Company
1400 Fountaingrove Parkway
Santa Rosa, CA 95403

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ABSTRACT

A major problem encountered when making network measurements in microstrip or other non-coaxial media, is the need to separate the effects of the transmission media from the device characteristics. While vector error-correction is useful for removing systematic errors in microwave network measurements, the resultant accuracy is dependent on the quality of the calibration standards. Unfortunately the impedance standards used in coaxial measurements are difficult to produce for non-coaxial transmission media.

A new calibration method, "Thru-Reflect-Line," has been added to the HP 8510B network analyzer, which relies only on the characteristic impedance of a transmission line. In addition to the simplicity of the calibration standards, this method is useful for calibration in both linear and dispersive (non-linear phase) transmission media. This paper describes the benefits of direct, fully error-corrected measurement of non-coaxial devices. Measurement examples of a microstrip transmission line, filter and microcircuit amplifier will be shown.

TRL CALIBRATION FOR NON-COAXIAL MEASUREMENTS

PAT6131

There are many devices, ranging from transistors and passive elements (resistors, inductors and capacitors) to complex microcircuits, with the common characteristic that they often do not have coaxial connectors. As a result these devices are difficult to measure with instruments that typically have coaxial test ports. This does not, however, diminish the need to accurately characterize the behavior of such devices. Out of necessity, an "adapter" or mounting fixture must be used to provide the interface between the test ports and the device.

OVERVIEW

I. Non-coaxial Measurement Problems/Techniques

II. TRL Calibration Method

III. Benefits of TRL Calibration

IV. Measurement Examples

PAT6132

This paper will address the problem of acquiring accurate S-parameter data for non-coaxial devices with a vector network analyzer. The limitations of some currently used techniques will be described. A new network analyzer calibration method will be introduced that is not constrained by these same limitations as some of the other methods. The benefits and measurement results of the new "Thru-Reflect-Line" calibration will also be shown.

I. NON-COAXIAL MEASUREMENT PROBLEMS / SOLUTIONS

1. Non-coaxial Connection Interface
   - Adapters, Fixtures, Probes
2. System Calibration
   - Network Analyzer, Cables, Adapters, Fixture

PAT6133

The first problem encountered when trying to characterize a non-coaxial device is the connection interface to the network analyzer. Due to widely ranging dimensions and package styles, a variety of "adapters" (or fixtures) are used to make this connection. Regardless of the "adapter" used, the next challenge becomes how to separate the frequency response of the device from the measured data. This measured data will include the uncorrected response of the instrumentation, any test cables, the "adapter" and the device

HP supplies precision standards which can be used to calibrate the system response up to the coaxial ports of the "adapter". Since standards for the non-coaxial ports of the "adapter" are generally not available, the same methods will not completely solve this problem.

NON-COAXIAL CONNECTION INTERFACE

Device Type(s)	Packaging	Adapter Type
Transistors, diodes	Stripline pkgs TO cans	Test fixture
Microcircuits	Substrates	Test fixture
MMICs	Wafers	Probing

PAT6134

Some typical "adapters" are listed here. Test fixtures (some commercially available) are us... connect to packaged devices like transistors a... diodes. The same approach is also often used to measure microcircuits. The development of monolithic technology for high density microwave circuits requires a different technique due to their size. Direct probing of circuits at the wafer level has provided a good solution for such devices.

NON-COAXIAL CONNECTION INTERFACE

Test Fixture Characteristics

1. Repeatable, convenient interconnection
2. Easily, accurately characterized

PAT6135

Depending on the application, there are many different requirements for the test fixture. Three of the primary characteristics will be described. First, the fixture must provide a repeatable connection to the device - to ensure consistency of results as well as assurance that the response of the fixture does not vary between calibration and measurement.

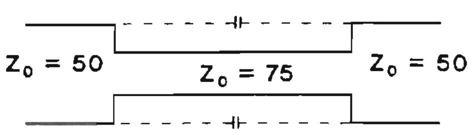
Convenient reconnection and good repeatability seem to be counter to each other. Pressure contacts are non-destructive (to device and fixture) but are generally not as repeatable methods like bonding. The thermal energy fro... bonding, however, can damage sensitive microwave devices.

Second, some way to connect or insert reference standards should be provided. For the new calibration method that will be described, this means that halves of the fixture must be separable to allow for standards and devices of different length to be inserted.

NON-COAXIAL CONNECTION INTERFACE

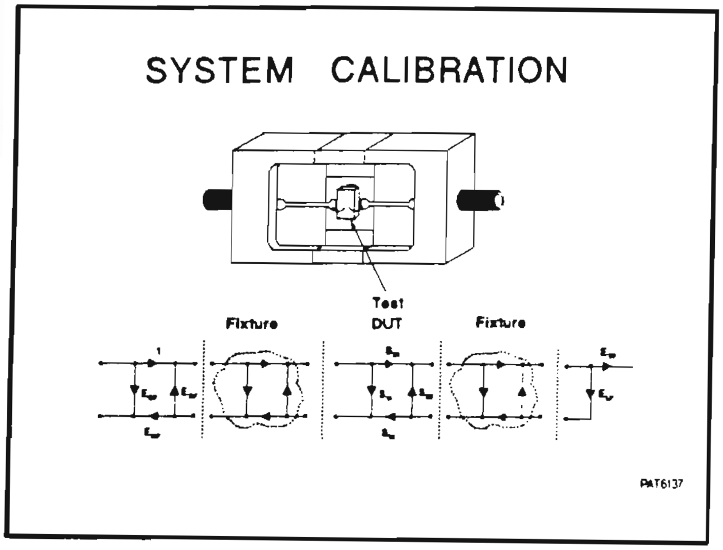
Test Fixture Characteristics

3. Provides suitable impedance



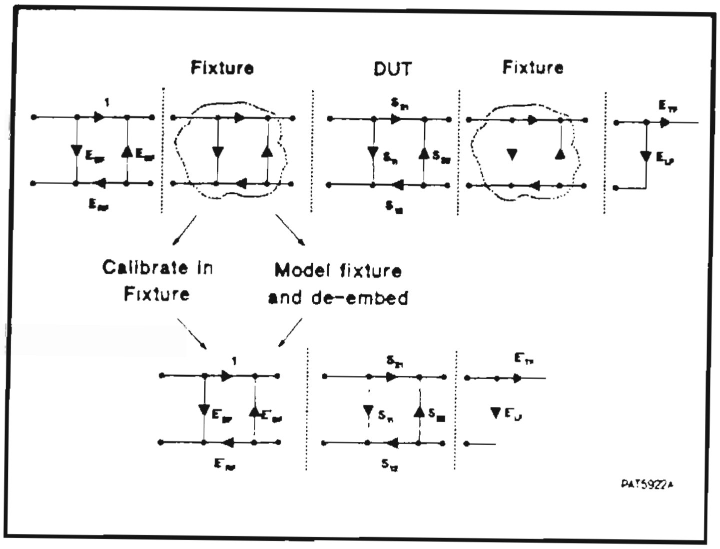
PAT6136

It is important that the fixture present an impedance which is as much like that of the final application as possible. That is, if a device is to be used in a microstrip package or cascaded with another microstrip circuit, the fixture should be of that same impedance. The impedance reference is set by measurement of a known calibration standard. However, when a discontinuity is present at the reference plane, higher order modes may be generated (and detected) that are not present during measurement or the actual application.



The signal flow graph representation of a typical fixtured measurement is shown here. By calibrating to the coaxial ports of the fixture, the response of the network analyzer and test cables is included in the coefficients of the network analyzer's error model. The problem described earlier was to now extract the S-parameters of the device from the response of the fixture.

The fixture will exhibit some insertion loss and electrical length. The coaxial launch causes an impedance discontinuity which further distorts the measured data. If the launch discontinuity is small, simple frequency response normalization may provide a good result. However, in most cases (or when precise characterization is required) the launch must be removed.



There are two fundamental approaches to characterizing test fixtures - modeling/de-embedding and direct calibration. De-embedding the modeled response of a well-behaved fixture can provide reliable results. This assumes that the frequency response of the fixture is known. The most difficult aspect of this approach is accurately estimating the parasitic effects of the non-ideal launch. These parasitic effects include lead inductance, stray capacitance as well as conductive and dielectric losses. Through careful analysis and optimization (using microwave CAD software) good fixture models can be generated. De-embedding refers to the mathematical process of combining the simulated response of a model into the network analyzer's existing error model.

Direct calibration involves inserting a complete set of device-like calibration standards at the desired reference plane.

SYSTEM CALIBRATION

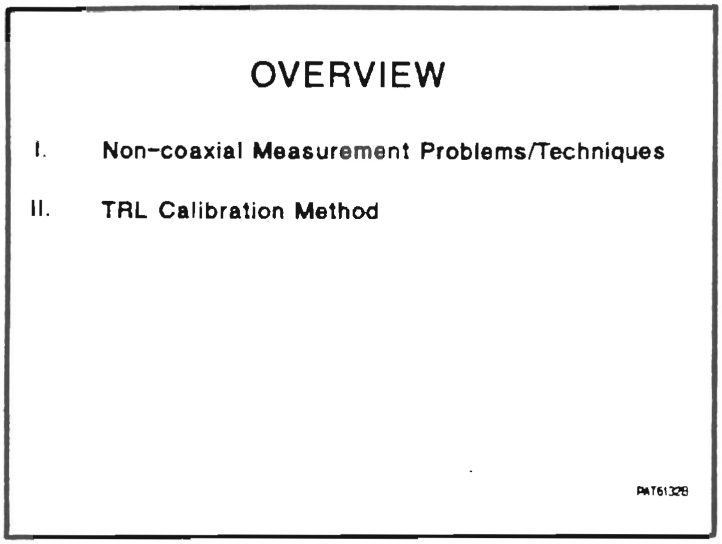
Direct Calibration Techniques

- Open/Short/Load*
- TSD (Thru-Short-Delay)
- Thru-Delay (symmetric fixture cal)
- TRL (HP 8510B)

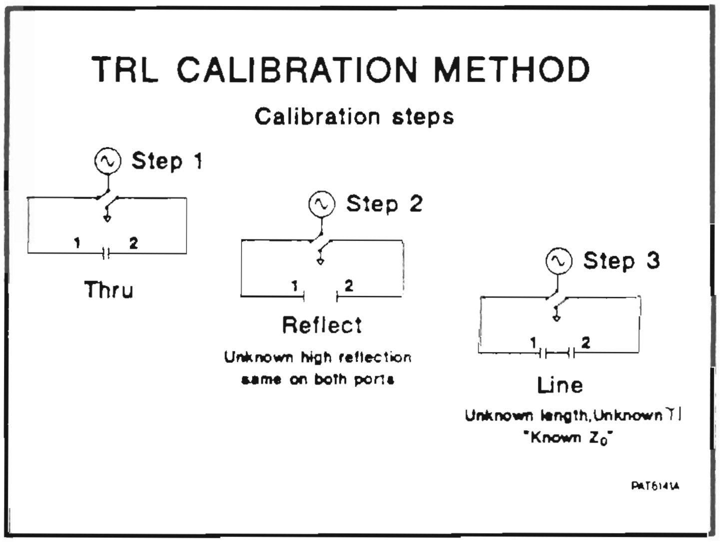
* Note: These 3 impedance standards are difficult to realize

PAT6139

Prior to the introduction of the HP 8510B network analyzer, the only direct calibration method in widespread use was the standard (open/short/load) method. For fixtured measurements, the standard (open/short/load) calibration is limited by the ability to actually realize these standards in a non-coaxial transmission media (rectangular waveguide excepted). A series of techniques such as TSD[1], Thru-Delay[2], and TRL[3] have also been developed. All of these techniques rely on the use of transmission lines as calibration standards. While each method had certain advantages, TRL was the most general implementation.

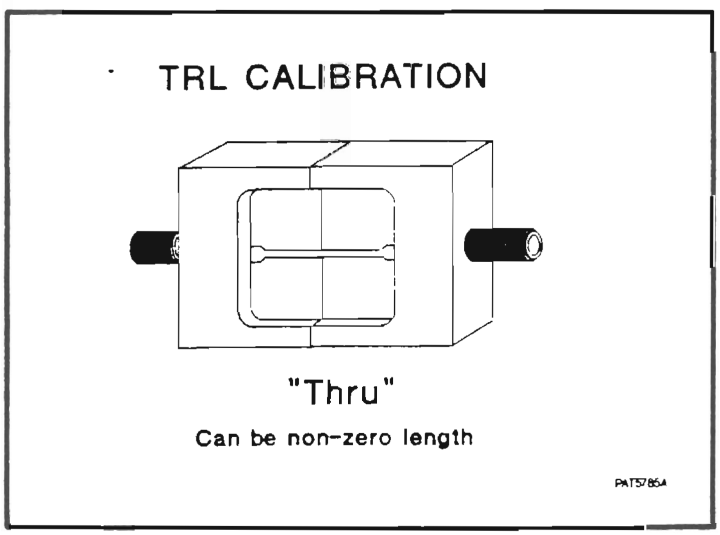


The TRL calibration technique was initially developed by the National Bureau of Standa a precision calibration method for the dual six-port. Since that time, HP has adapted this method for a conventional network analyzer. Although TRL was originally used for precision coaxial measurements, it also has direct application to non-coaxial measurements.[4] Specifically, since the only precision impedance reference is a transmission line (rather than 3 distinct known impedance standards), obtaining the required set of reference standards is a much simpler task.



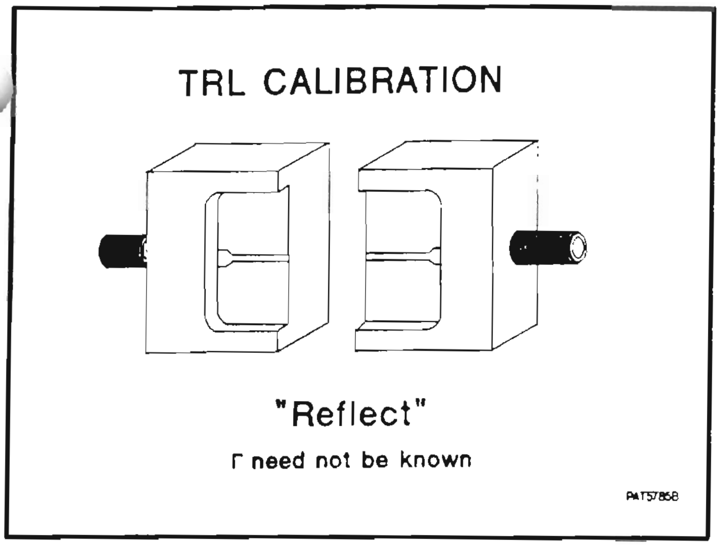
There are 3 steps to the TRL calibration process. During the first step, the test ports are connected together (directly or with a short piece of transmission line). Once connected, all four S-parameters are measured. Next, a short piece of transmission line (but different in length compared to the thru) is inserted between the test ports. Again, all four S-parameters are measured. Finally, a device with a high reflection coefficien (short or open circuit) is connected to each port The same device must be connected to port 1 and port 2.

During this process, additional measurements are taken to remove any reflections due to the RF switch inside the test set. Optionally, the crosstalk can be characterized during calibration also. Overall, 16 measurements are taken yielding 16 independent equations which can be used to solve for the coefficients of the 12-term model, the propagation constant of the Line and the reflection coefficient of the Reflect

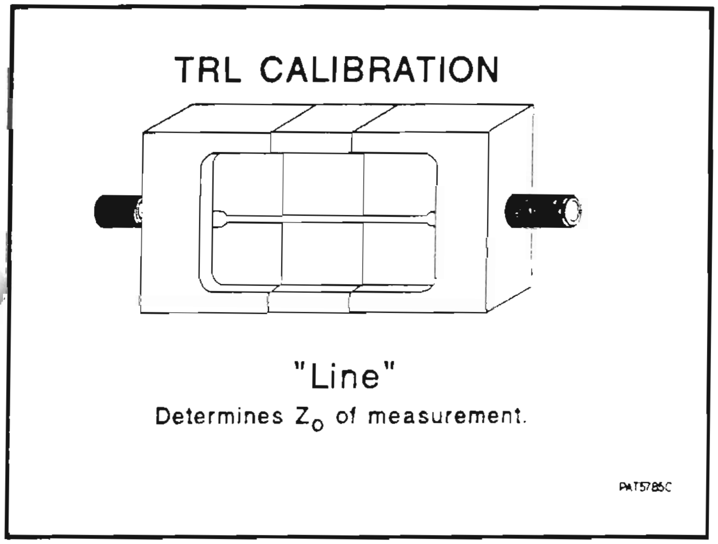


Let's illustrate this process for a typical fixture For this example, each half of the fixture is a simple coax-to-microstrip launch onto a 1 cm long 50 ohm microstrip substrate. For the Thru step, the input and output fixture halves are connected together. Since the desired reference plane will be at the open ends of the microstrip substrate when a direct connection is made, there is no electrical length between the reference planes. This Thru is defined to have a transmission coefficient of 1 with zero degrees of phase.

Once connected, all four S-parameters are measured as well as two measurements for switch correction.

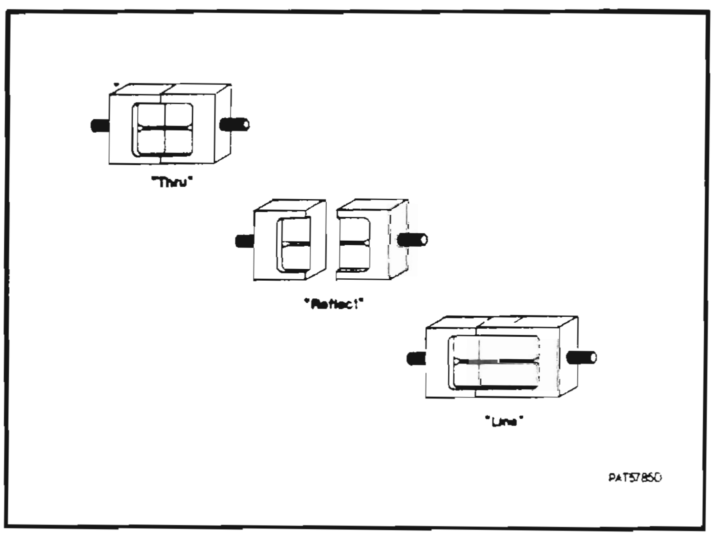


For the next step, a high reflection coefficient device must be connected to port 1 and then to port 2. Both S11 and S22 are measured. These terminations must be the same on both ports.



For the last step, a short piece of transmission line is inserted between the fixture halves. Again, all four S-parameters are measured as well as the switch. The characteristic impedance (Z_0) of this Line becomes the absolute impedance reference. That is, S_{11} and S_{22} of the Line are defined equal to zero. Therefore, any measured reflection must be due to directivity or test port mismatch. If an impedance reference is desired that is different than the Z_0 of the Line, this can also be accomplished.

The basic TRL calibration process is now complete although forward and reverse crosstalk correction can be included.



In reviewing this process, we note the impedance reference comes from the Z_0 of the Line and the reference plane was set by specifying the Thru as zero-length (Offset Delay = 0 picoseconds). Due to the general implementation of this calibration, the reference plane may also be set by specifying the electrical length of the Reflect standard. The reference impedance can also be set to an impedance other than that of the Line. (For example, if the line was known to have a Z_0 = 51 ohms, it could still be used to calibrate for a 50 ohm system impedance). This is simply done by specifying both the desired reference impedance (SET Z_0) and the actual Z_0 of the Line (Offset Z_0).

TRL CALIBRATION METHOD

Choice of line length

$$\ell \stackrel{\Delta}{=} \ell_d - \ell_T = \frac{15}{f_1 + f_2}\ \text{cm}$$

ℓ_d = length of delay line
ℓ_T = length of thru line (conveniently short)
f_1 & f_2 in GHz

$$\varnothing_{F1} = 180 - \varnothing_{F2} = \frac{180}{1 + f_2/f_1}\ \text{deg}$$

$$\varnothing_F = 12\ell f\ \text{deg}$$

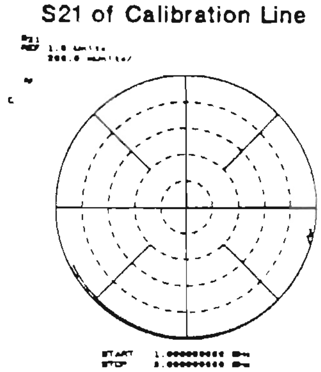
Keep phase at $f_1 > 20°$
Keep phase at $f_2 < 16°$

One requirement that may require some additional explanation is the "required" electrical length of the Thru and Line. To ensure that the equations that arise from the Thru and Line steps are independent, S21 and S12 of the Thru and Line must always be distinct. If the phase of the line reaches 180 degrees (or any other integer multiple of pi), then there would not be enough independent equations to compute the error model. A 20 degree phase margin is recommended.

There are some cases (most notably on-wafer) where it is impossible to achieve a zero-length Thru. In such cases, these requirements apply to the difference in length between the Thru and Line.

TRL CALIBRATION

S21 of Calibration Line



PAT6147

The measured response of the Line, shown here, has insertion phase equal to 16 degrees at 1.0 GHz and 157 degrees at 9 GHz. A single Line can be used for up to an 8:1 bandwidth (that is, BW/Start Freq.). When the desired measurement bandwidth is larger than 8:1, an additional line is required.

OVERVIEW

I. Non-coaxial Measurement Problems/Techniques

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III. Benefits of TRL Calibration

PAT6132C

BENEFITS OF TRL CALIBRATION

- o Simple, Realizable Standards
- o Correcting Fixture Dispersion
- o Normalized or Absolute Impedance Measurements

PAT6149

We have focused on the TRL calibration process and some of the requirements. Let's now consider some of the benefits.

SIMPLE, REALIZABLE STANDARDS

- o REFLECT Impedance is Unspecified
  - stray C,L difficult to determine
- o Propagation Characteristics of LINE Not Precisely Specified
  - αl, βl may be non-linear
- o Impedance Determined by Actual Z_0 of the Transmission Line Used - Known or Otherwise
  - Z_0 may not be constant

PAT6150

The TRL calibration method provides a means to direct calibration in non-coaxial transmission media. Primary among the benefits of this method is that it is much more simple to realize a complete set of standards. The Reflect standard must be highly reflective, but does not have to be a known impedance. It is not necessary to characterize the parasitics like stray capacitance and lead inductance. The benefit is that the accuracy of the TRL method is not dependent on how well this standard is known (provided that it is highly reflective). This is one of the key differences between TRL and the TSD calibration

The insertion loss and phase of the Line do not have to be precisely specified. Since these characteristics are difficult to predict in planar transmission media like microstrip, this benefit is obvious. (Note when a non-zero length Thru is used, precise definition of the electrical length of the short Thru transmission line is required.)

CORRECTING FIXTURE DISPERSION

- o γl of Planar Transmission Line is Nonlinear
  - TRL calibration accurately characterizes the fixture's actual response using standards that may be dispersive

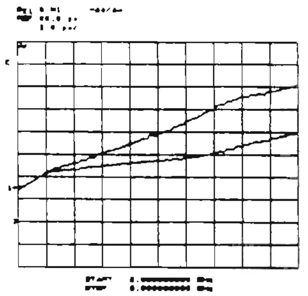
PAT6151

In-fixture TRL calibration allows for complete characterization of the system's frequency response. Since the connection interface is located inside the fixture, a part of the measurement system will itself be dispersive. The transmission line standards are also dispersive. This, however, is of no consequence to the TRL calibration

(Again, the problem is somewhat more complex when a non-zero length Thru is used since the electrical length of the Thru must be specified.)

CORRECTING FIXTURE DISPERSION

1 cm Transmission Line
Linear Port Extension and In-fixture TRL



PAT6152

To illustrate, this is the measurement of a microstrip transmission line in a microstrip fixture. System calibration was performed (1 the coaxial fixture ports and then electrical d of 321 picoseconds applied to move the reference plane to the center (2) in-fixture using TRL. The lower trace is the measured group delay of the line using TRL. The delay is about 85 ps with a variation of 5 ps over frequency. The other measurement shows a group delay variation of 9 ps. This measured variation is greater because only the linear phase component is removed. The fixture adds another 4 ps of phase distortion which can only be removed using a direct calibration method.

NORMALIZED OR ABSOLUTE IMPEDANCE

- The LINE is Assumed Reflectionless
  Z_0 = SET Z_0
- LINE Z_0 may be Difficult to Precisely Define
  - If LINE Z_0 is the same as final application, normalizes to "matched" conditions
  - Specified Offset Z_0, provides reference to absolute impedance (i.e., true 50 ohms)

PAT6153

In design, it may only be necessary to measure relative to the impedance of a transmission line. That is, to know when the device is matched. This is similar to error-correction in waveguide, where "normalized" impedance is generally measured. In cases where absolute impedance information is required, the Z_0 of the Line must be specified.

OVERVIEW

I. Non-coaxial Measurement Problems/Techniques

II. TRL Calibration Method

III. Benefits of TRL Calibration

IV. Measurement Examples

PAT6132D

Now, let's look at some typical measurement results.

MEASUREMENT EXAMPLES

- Microstrip Transmission Line
- Low Pass Filter
- Microcircuit Amplifier

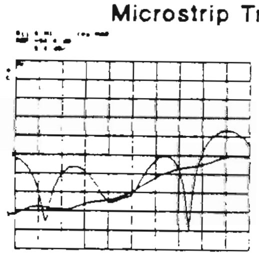
PAT6155

These measurement examples range from simple microwave elements to more complex microcircuits.

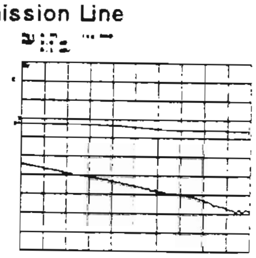
MEASUREMENT EXAMPLES

Comparison of Linear Fixture Model (1) vs. In-fixture TRL (2)

Microstrip Transmission Line



Return Loss



Insertion Loss

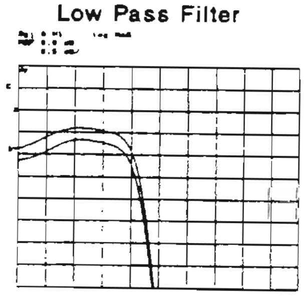
PAT6156

This is the measured response of a 1 cm 50 ohm microstrip line - return and insertion loss. Note: To evaluate reflection measurements, a transmission line different than the one used to calibrate must be used. Re-measuring the reflection coefficient of the calibration line is merely an indication of repeatability.

For comparison, the fixture was calibrated at the fixture's coaxial ports as well as inside the fixture using TRL. The measured return loss is smooth, compared to the out-of-fixture calibration. The peaks and nulls in the first measurement are created by the reflections of the launches. When TRL is applied, these launches are removed. The transmission response shows that the insertion loss of the test fixture has also been removed.

MEASUREMENT EXAMPLES

Low Pass Filter



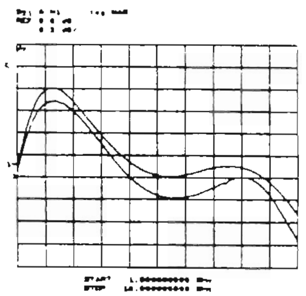
Passband Loss

PAT6157

The measured passband loss of a 4 GHz low pass filter is shown here. When calibrated using TRL the fixture's loss is completely removed, allowing for more precise characterization of the passband loss and variation.

MEASUREMENT EXAMPLES

Microcircuit Amplifier



S21 Gain

PAT6158

The measured gain of this microcircuit amplifier is about 0.5 dB higher when the fixture's respo[illegible]e is removed. All of the measurements shown [illegible] the TRL calibration applied appear to be smo[illegible] and resonance-free.

OVERVIEW

I. Non-coaxial Measurement Problems/Techniques

II. TRL Calibration Method

III. Benefits of TRL Calibration

IV. Measurement Examples

PAT6132A

This paper has described some of the problems associated with making accurate measurements of non-coaxial devices. To illustrate, the TRL calibration process was described and applied to an example microstrip fixture.

The benefits of TRL calibration were discussed and measurement results were shown.

T