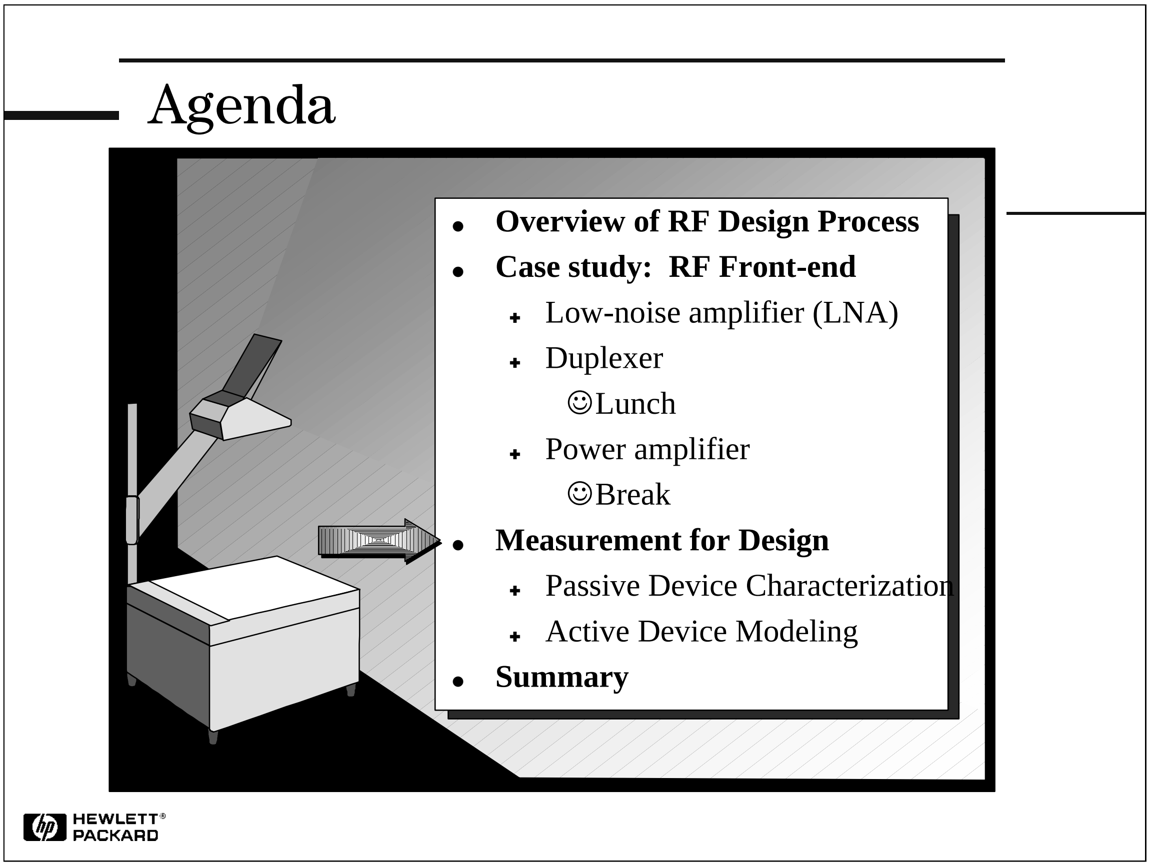
Slide #134

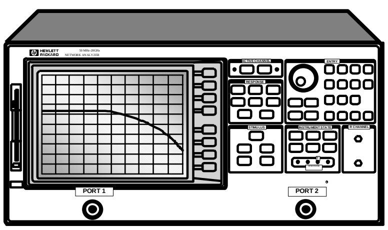


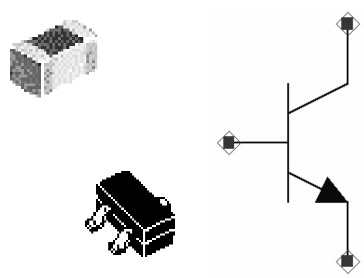
In this section, we are going to cover the fundamentals of building your own PCB fixtures for measuring surface-mount technology (SMT) devices and components. We will also cover how to make the corresponding calibration standards for accurate measurements, and how time-domain tools can be used to characterize transitions and the calibration standards.

Slide #135

Need for Measurements During Design

- ***Measure critical components to improve models***
  - when library parts don't exist
  - when library parts were measured under different conditions (e.g. shunt vs. series)
  - if unsure of measurement conditions of library parts





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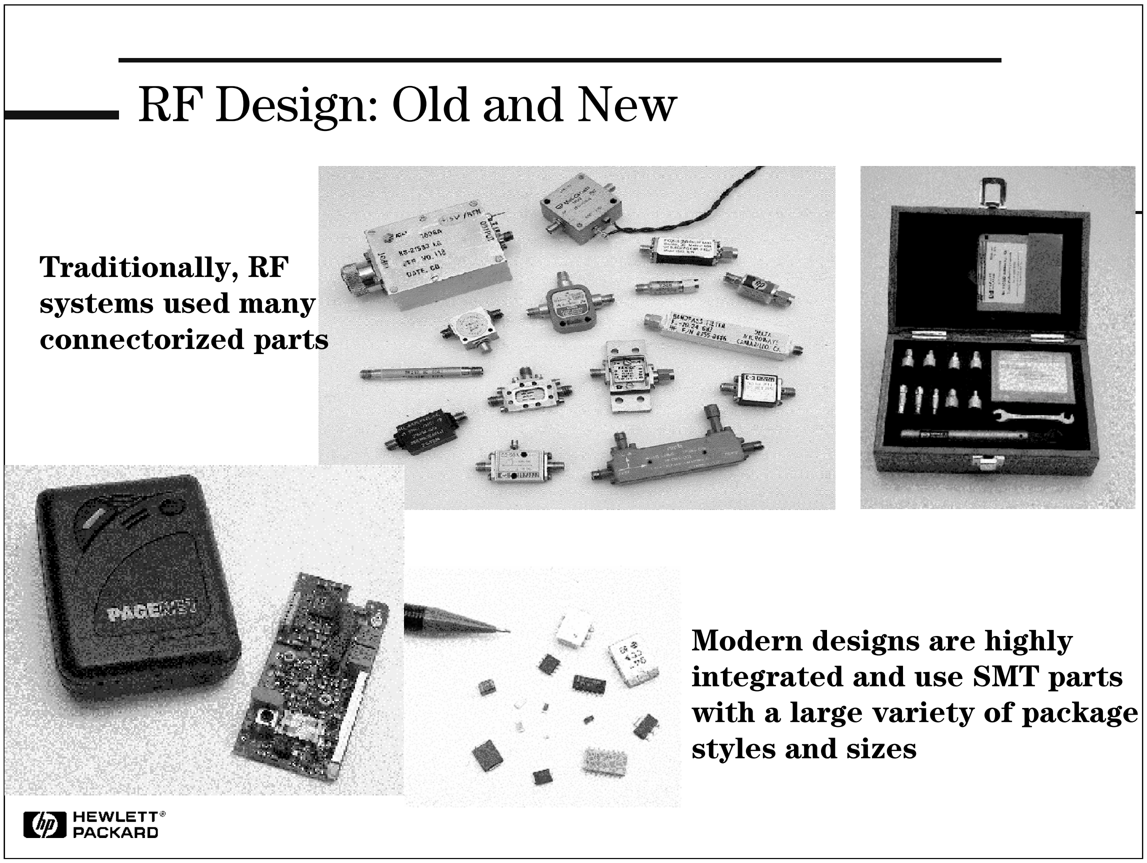
Measurements during the RF design process are very important. We need to measure critical components to improve the component models and give more accurate simulations. We measure these components when library parts don't exist, when library parts were measured under different conditions, or if we are unsure of the measurement conditions of a library part. We also need to measure our physical prototypes to improve our overall circuit and system models and to verify that we have met the circuit and system specifications.

Slide #136



Due to the rapid growth of consumer RF products such as cellular and cordless telephones, a fundamental shift has occurred in the way RF devices and components are made and used. Surface-mount technology (SMT) is pervasive in RF design, requiring sound techniques for measurement of SMT components. These components range from simple two-port devices, such as filters and amplifiers, to more complex multiport RFICs. They all share the need to be accurately characterized and verified in R&D to help develop accurate models. It wasn't that many years ago that most RF systems consisted of connectorized components, both passive and active, that were connected to form the final system. When printed-circuit boards (PCBs) were used, they consisted mostly of discrete thru-hole components such as resistors, inductors, capacitors, transistors and diodes, with RF connectors for input and output. Today, size, weight and cost constraints along with higher operating frequencies and advances in technology are driving the use of much smaller and more integrated packaged parts at the PCB level. And unlike the old days when there were just a few standard transistor packages to worry about, now there are many non-standard SMT packages to fit a multitude of RF applications. The physical dimensions of these parts vary greatly, due to differing technologies, power handling requirements, environmental conditions, and so forth. But the need for RF fixtures to accurately measure all these devices is greater than ever.

Making quality RF measurements on devices with standard coaxial connectors is relatively easy. Very accurate measurements can be made using commercial calibration kits and standard error-correction routines found in most network analyzers. Performing accurate measurements on devices with non-standard connectors is a little more difficult, requiring adapters and often custom calibration standards. Devices without connectors are the most difficult to measure, since some sort of test fixture is required to provide an electrical and mechanical connection between the device under test (DUT) and coaxial-connector-based test equipment. In addition, in-fixture calibration standards are often required to achieve the level of measurement accuracy that many of today's devices demand.

Slide #137

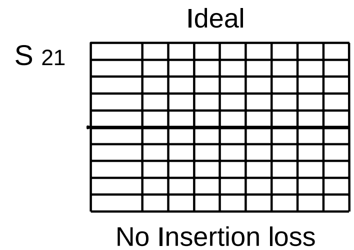
Ideal versus Real World Fixture

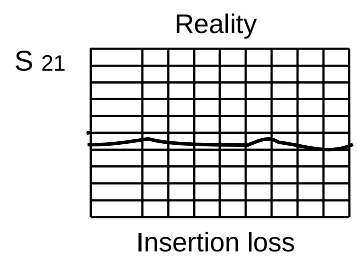
Ideal fixture:

- **provides transparent connection**
  - no loss
  - flat magnitude, linear phase
  - no mismatches
  - known electrical length
  - infinite isolation
- **uses simple calibration**
  - two-port cal at end of cables
  - port extensions for fixture

In the real world:

- fixture optimized relative to DUT
- calibration type depends on how well we approximate ideal fixture
- typically need calibration standards

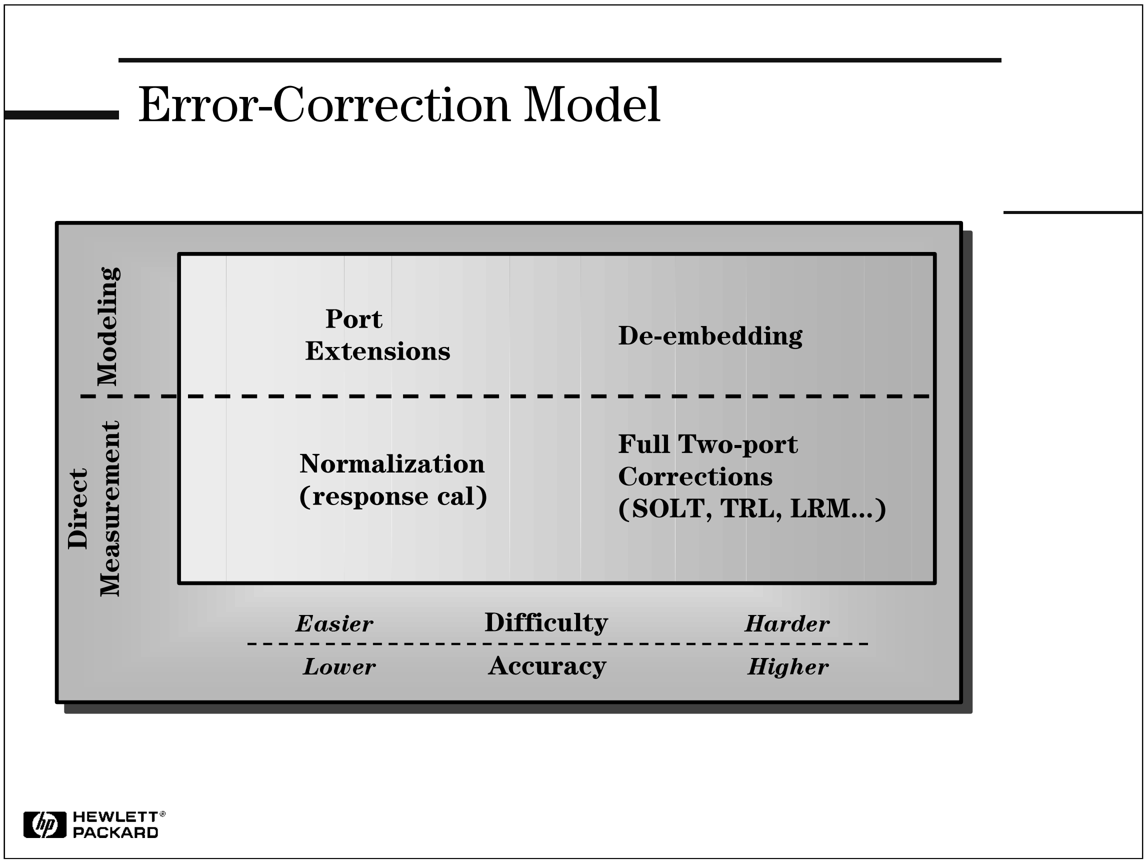




Let's examine for a moment the behavior of an ideal fixture. Simply put, it would provide a transparent connection between the test instrument and the device being tested. This would allow direct measurement of the DUT, without imposition of the fixture's characteristics. In parametric terms, this would mean the fixture would have no loss, a flat frequency response with linear phase, no mismatches, be a precisely known electrical length, and have infinite isolation between input and output (zero crosstalk). If we could achieve this, calibration would be easy. There would be no need to calibrate the fixture itself, and the overall system calibration could be done by calibrating at the end of the test port cables and applying mathematical port extensions to account for the electrical length of the fixture.

Since it is impossible to make an ideal fixture in the real world, we can only hope to approximate the ideal case as best as possible. We can do this by optimizing the performance of the test fixture relative to the performance of the DUT. We can try to make the loss of the fixture smaller than the specified gain or insertion-loss uncertainty of the DUT. The bandwidth of the fixture only needs to be large compared to the desired measurement bandwidth of the DUT. Mismatch can be minimized with good design and effective measurement tools such as time-domain reflectometry (TDR). The electrical length of the fixture can be measured, if necessary. Fixture crosstalk need only be better than the isolation of the DUT. Since we can only approximate a perfect fixture, the type of calibration required for any particular application will depend solely on how stringent the DUT specifications are.

Slide #138



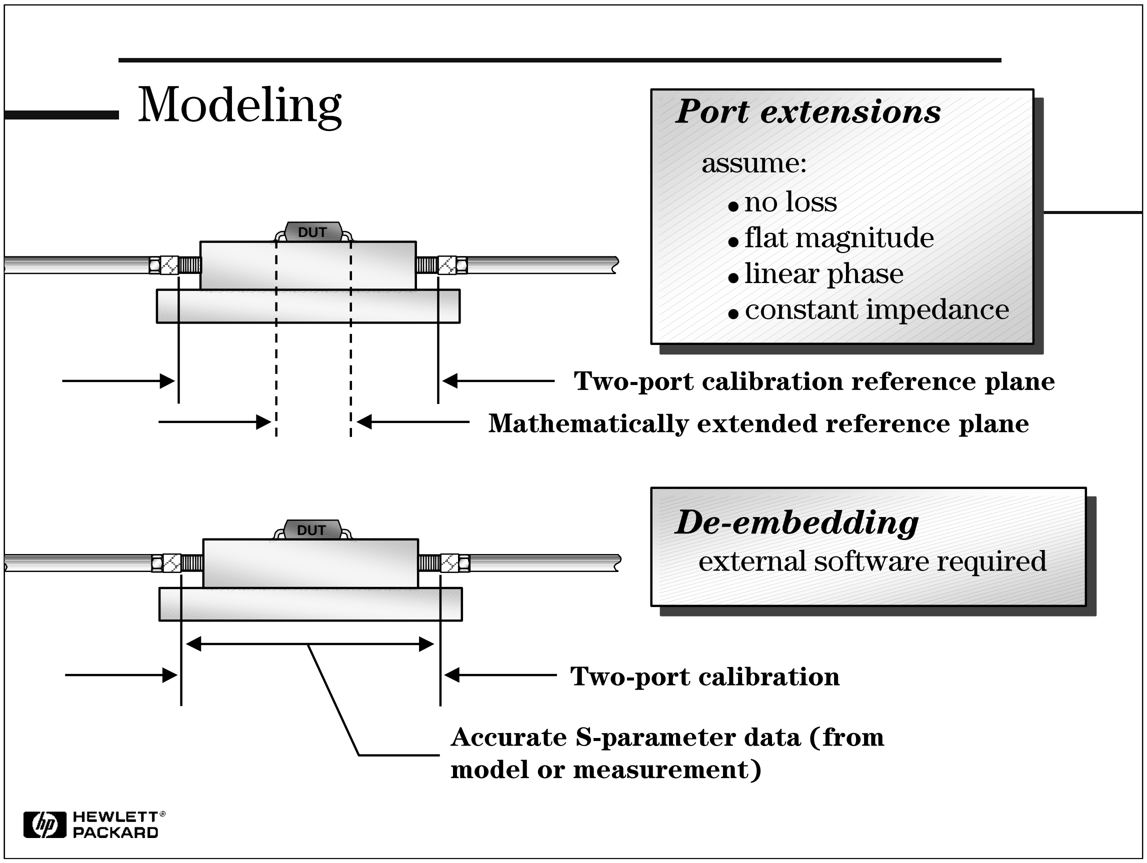
Before we get to the specifics of fixture design, we need to review the calibration choices available to decide what type of calibration standards (if any) we may need. The relative performance of our fixture compared to the specifications of the DUT that we are trying to measure will determine what level of calibration is required to meet the necessary measurement accuracy.

There are two fundamental error-correction techniques: modeling and direct measurement. Each has relatively simple versions and more complicated versions that require greater work, but yield more accurate measurements.

Calibration based on modeling uses mathematical corrections derived from an accurate model of the fixture. Often, the fixture is measured as part of the process of deriving an accurate model.

Direct measurement usually involves measuring physical calibration standards and calculating error terms. This method provides accuracy that is based on how precisely we know the characteristics of our calibration standards. The number of error terms that can be corrected varies considerably depending on the type of calibration used. Normalization only removes one error term, while full two-port error correction accounts for twelve error terms. Since standard cal-kit definitions are based on coaxial standards, modifying these definitions for in-fixture calibration is very important for accurate measurements. We will cover this in more detail later in the paper.

Slide #139



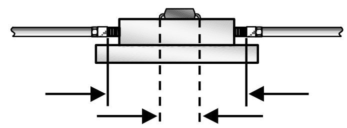
Modeling has the advantage that it does not require development of in-fixture calibration standards. The simplest form is port extensions, which mathematically extends the measurement plane to the DUT. This feature is included in the firmware of most network analyzers. Port extensions assume the fixture looks like a perfect transmission line: no loss with a flat magnitude, linear phase response, and constant impedance. Port extensions are usually done after a two-port calibration has been performed at the end of the test cables. If the fixture performance is considerably better than the specifications of the DUT, this technique may be sufficient.

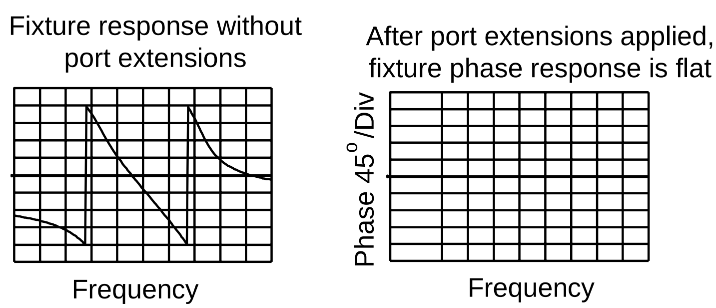
A more rigorous approach is to use de-embedding. De-embedding requires an accurate linear model of the fixture, or measured S-parameter data of the fixture. EDA tools can help analyze and optimize the model of the fixture. In-fixture calibration standards may be used to help measure the performance of the fixture. External software is needed to combine the error data from a calibration done without the fixture (using coaxial standards) with the modeled fixture error. If the error terms of the fixture are generated solely from a model, the overall measurement accuracy depends on how well the actual performance of the fixture matches the modeled performance. For fixtures that are not based on simple transmission lines, determining a precise model is usually harder than developing good in-fixture calibration standards, especially in the RF range.

Slide #140

Port Extensions

- port-extension feature of network analyzer removes linear portion of phase response
- accounts for added electrical length of fixture
- doesn't correct for loss or mismatch
- mismatch can occur from
  - launches
  - variations in transmission line impedance

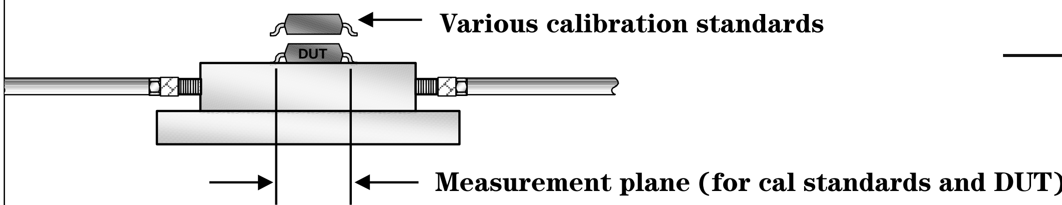




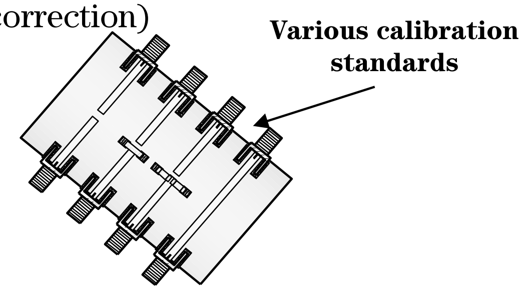
Port extensions correct for the added electrical length of the fixture, ignoring any loss and mismatch errors that may be present in the fixture (mismatch can occur from the connector launches and from variations in the impedance of the transmission lines). Port extensions use the internal electrical-delay feature of network analyzers to mathematically remove the linear portion of the fixture's phase response. After port extensions have been applied, we will only measure the phase response of our DUT.

Slide #141

Direct Measurement



- measure standards to determine systematic errors
- two major types of calibrations:
  - response (normalization) calibration
  - two-port calibration (vector-error correction)
    - short-open-load-thru (SOLT)
    - thru-reflect-line (TRL)



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Direct measurements have the advantage that the precise characteristics of fixture don't need to be known beforehand, as they are measured during the calibration process. Another benefit is that the error correction is done in the network analyzer, without an external computer as required for de-embedding. The simplest form of direct measurement is a response calibration, which is a form of normalization. A reference trace is placed in memory and subsequent traces are displayed as data divided by memory. A response calibration only requires one standard each for transmission (a thru) and reflection (a short or open).

Two-port calibration is a form of vector-error correction and provides much more accurate measurements compared to response calibration. It also requires more calibration standards. There are two basic types of two-port calibration: short-open-load-thru (SOLT) and thru-reflect-line (TRL). These are named after the types of calibration standards used in the calibration process.

Slide #142

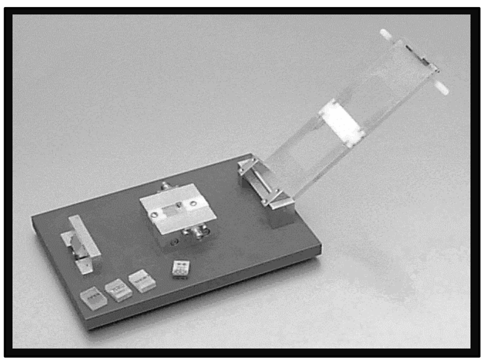
Fixturing in R&D vs. Manufacturing

Manufacturing

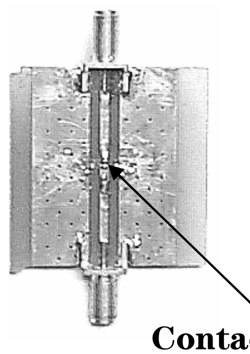
- quick insertion, alignment, clamping
- rugged for high-volume use
- compliant contacts
- usually mechanically sophisticated

R&D

- solder parts on to fixture
- ruggedness not an issue for low volumes
- soldering handles leaded / leadless parts
- often simple (e.g., PCB with connectors)



Typical fixture and calibration standards for SMT manufacturing test (example: 900 MHz filter)



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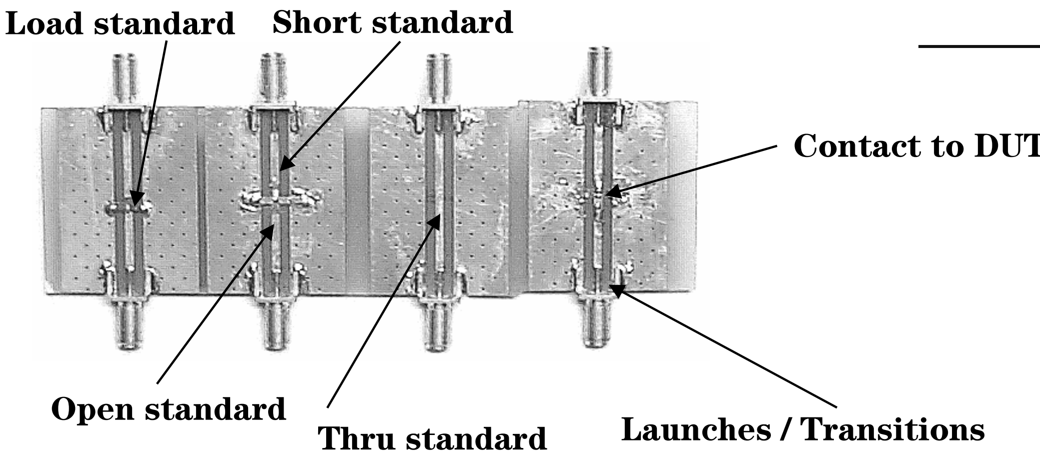
Fixtures that are intended for manufacturing applications look a lot different than those used in R&D since many of the basic design goals are different. In manufacturing, high throughput is the overriding concern. We need a fixture that allows quick insertion, alignment and clamping. It must be rugged since many thousands of parts will be inserted into the fixture over its lifetime. For many parts (leadless components, for example), we need compliant contacts to absorb the non-flatness of the contact surface of the part. For all of these reasons, fixtures designed for manufacturing use tend to be mechanically sophisticated.

For R&D applications, the fixture can be much more simple and less rugged. These type of fixtures are often PCB based. Since we are usually only testing a few devices, we can get by with soldering parts in and out of the fixture.

Slide #143

R&D Fixture with Cal Standards



- short, thru are **easiest**
- open requires **characterization**
- load is most difficult (quality determines corrected directivity)

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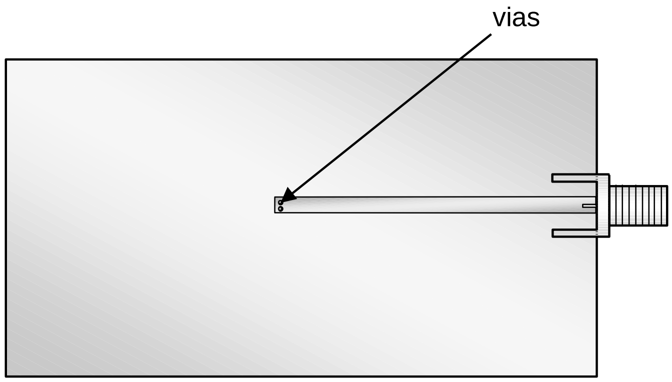
When designing a fixture, we need to to consider how to calibrate the network analyzer. It is best to fabricate the standards in the same board material that the devices are measured. We incorporated short, open, load, and thru (SOLT) standards on our DUT test board.

For RF applications, using SOLT-based error correction for calibrating the fixture is very attractive because the standards and fixtures can be simple and inexpensive. It is relatively easy to make broadband calibration standards at RF. The short and thru are the easiest to make since characterization is not required. The open requires minimal characterization, and the load presents the biggest challenge. The quality of the load will determine our corrected system directivity which in turn determines how much uncertainty we will have for reflection measurements.

In the following slides we will discuss the design of a homemade fixture and the procedure for storing the calibration data into a user cal kit. The following description is complex, but you will only need to perform it once.

Slide #144

Short Standard



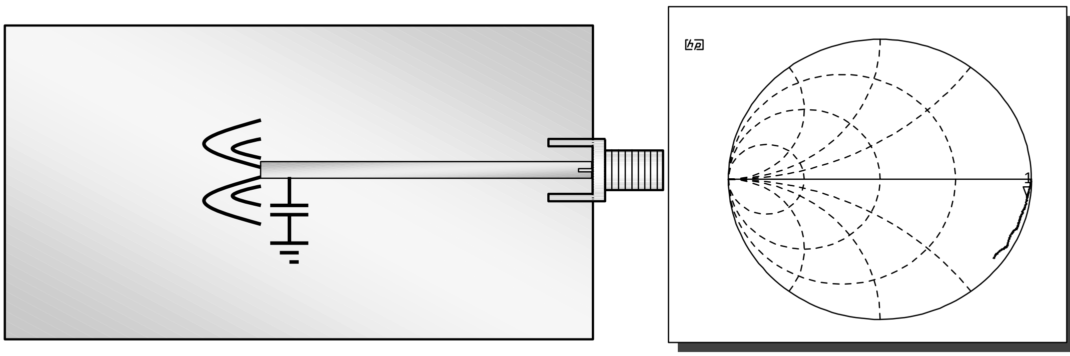
- ideal: **unity** reflection with 180° phase shift
- simply **short** signal conductor to ground (e.g. vias or metal bar)
- if using coplanar lines, short to **both** ground planes
- avoid **excess** inductance by keeping length short

The electrical definition of an ideal short is unity reflection with 180 degrees of phase shift. This means all of the incident energy is reflected back to the source, perfectly out of phase with the reference. A simple short-circuit from signal conductor to ground makes a good short standard. For example, the short can be a few vias to ground at the end of a microstrip transmission line. If coplanar transmission lines are used, the short should go to both ground planes.

To reduce the inductance of the short, avoid excess length. A good RF ground should be nearby the signal trace to accomplish this. If the short is not exactly at the contact plane of the DUT, an offset length can be entered (in terms of electrical delay) as part of the user cal kit definition.

Slide #145

Open Standard



- can be **unterminated** transmission line
- ideal: unity reflection with **no** phase shift
- actual model accounts for **fringing** capacitance
  (a concern around 300 MHz and above)

The open standard is typically realized as an unterminated transmission line. The electrical definition of an ideal open is unity reflection with no phase shift. The actual model for the open, however, does have some phase shift due to fringing capacitance.

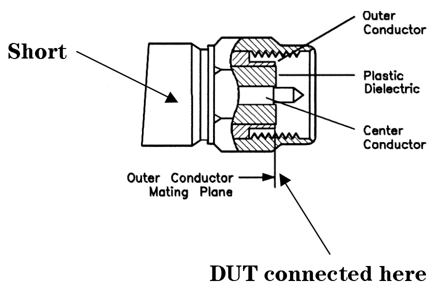
Slide #146

Calibration Kit Definition File

Calibration standards are defined in calibration kit definition file

- Network analyzer contains standard (coaxial) cal-kit definitions
- Custom standards (e.g. those used with fixtures), require user to characterize and enter definitions for standards
- Cal-kit definition must match actual standards for accurate measurements

	Open	Short	Load	Thru/ Line
Capacitance	✓			
Inductance		✓		
Offset delay	✓	✓	✓	✓
Offset Zo	✓	✓	✓	✓
Offset loss	✓	✓	✓	✓
Min/max frequency	✓	✓	✓	✓
Coax/waveguide	✓	✓	✓	✓
Fixed/sliding/offset			✓	



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Network analyzers contain standard cal kit definition files that describe the characteristics of the various calibration standards. These cal kit definitions usually cover the major types of coaxial connectors used for component and circuit measurements. Most high-performance network analyzers allow the user to modify these standard definitions for the calibration standards. This is very important for fixture-based measurements, since the in-fixture calibration standards will rarely have all of the same attributes as any of the standard coaxial-based calibration kits. Custom calibration standards, such as those used with fixtures, require the user to characterize and enter definitions for the standards. The cal kit definition must match the actual standards for accurate measurements. Definitions of the in-fixture calibration standards can be stored in the analyzer as a custom user cal kit.

While there are many characteristics that are used to describe calibration standards, only a few need to be modified for most fixture applications. The checks shown in red above (open capacitance, open offset delay, short inductance, short offset delay, thru/line offset delay, thru/line offset loss) indicate the parameters that should be considered when using fixture based calibration standards. For a properly designed PCB fixture, only the fringing capacitance of the open standard needs to be characterized.

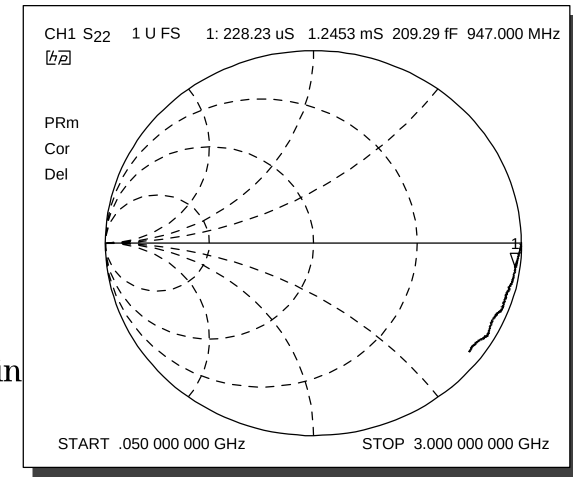
For additional reference material on calibration standards, contact your local field engineer and request the following product note:

Specifying calibration standards for the HP 8510 network analyzer, Product Note 8510-5A (HP 5956-4352)

Slide #147

Determining Open Capacitance

- **perform one-port calibration** at end of test cable
- **measure load**, store data in memory, display data-mem
- **measure short**, add port extension until flat 180° phase
- **measure open**, read capacitance from admittance Smith chart
- **enter capacitance** coefficient(s) in cal kit definition of open



- watch out for "negative" capacitance (due to long or inductive short)
  - adjust with negative offset delay in open <*or*>
  - positive offset delay in short

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Determining the fringing capacitance for our cal kit definition is only worth doing above 300 MHz or so. The fringing capacitance can be measured directly as follows: first perform a one-port calibration at the end of the test cable using the closest connector type before the fixture. For example, use APC 3.5 standards for a fixture using SMA connectors. Next, connect the fixture and measure the load standard. This data should be stored in memory, and the display changed to data minus memory. This step subtracts out the reflection of the edge connector (assuming good consistency between connectors), so that we will only be characterizing the open (an alternative to this is to use time domain gating to remove the effect of the connector). Next, we measure the short standard. Set the port extension to get a flat 180° phase response. To fine-tune the value of port extension, set the phase offset value for the trace to 180° and expand the degrees-per-division scale. Mismatch and directivity reflections may cause a slight ripple so use your best judgment for determining the flattest trace, or use marker statistics (set the mean value to zero). Now measure the open standard, change the marker display format to an *admittance* Smith chart. This displays G+jB instead of the more common R+jX of an *impedance* Smith chart. Admittance must be used because the fringing capacitance is modeled as a shunt element, not a series element. The fringing capacitance (typically .03 to 0.25 pF) can be directly read at the frequency of interest using a trace marker. At RF, a single capacitance value (C_o) is generally adequate for the cal kit definition of the open.

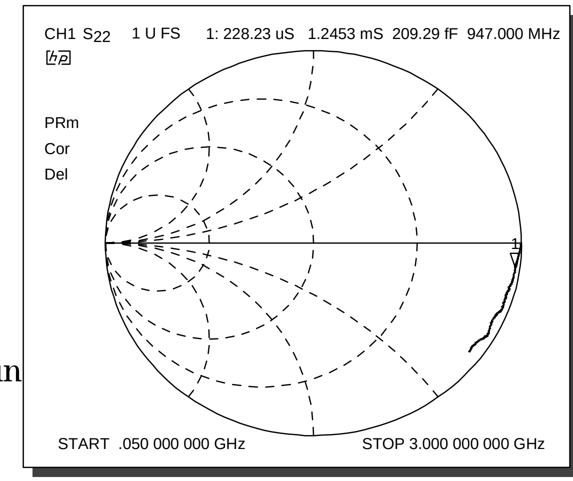
In some cases, a single capacitance number may not be adequate, as capacitance can vary with frequency. This is particularly true for measurements that extend well into the microwave frequency range. Most cal kit definitions allow a third-order polynomial to be used to describe the fringing capacitance versus frequency. The polynomial is of the form $C_0 + C_1 f + C_2 f^2 + C_3 f^3$. The user must fit the measured data to this polynomial to determine the correct capacitive coefficients.

RF Design and Measurement Seminar

Slide #148

Determining Open Capacitance

- **perform one-port calibration** at end of test cable
- **measure load**, store data in memory, display data-mem
- **measure short**, add port extension until flat 180° phase
- **measure open**, read capacitance from admittance Smith chart
- **enter capacitance** coefficient(s) in cal-kit definition of open



- watch out for "negative" capacitance (due to long or inductive short)
  - adjust with negative offset-delay in open <*or*>
  - positive offset-delay in short

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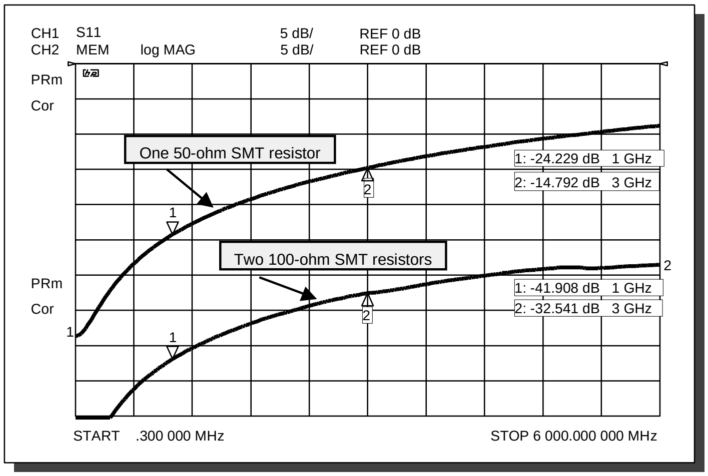
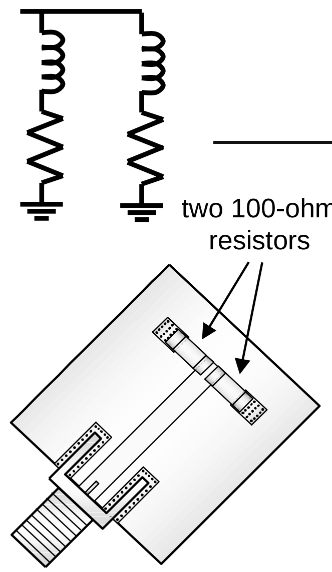
When measuring the fringing capacitance, a problem can arise if the short standard is electrically longer than the open standard. The impedance of the open circuit will appear to be the result of a negative capacitor. This is indicated by a trace that rotates backwards (counter-clockwise) on the Smith chart. The problem is a result of using the longer short-standard as a 180^0 phase reference. The electrically-shorter open will then appear to have positive phase. A remedy for this is to decrease the port extension until the phase is monotonically negative. Then the model for the open can have a normal (positive) capacitance value. The value of negative offset delay that needs to be included in the open standard definition is simply the amount the port extension was reduced (i.e., the difference in the port extension values between the short and the open). In effect, we have now set the reference plane at the short. Alternatively, the offset delay of the open can be set to zero, and a small positive offset delay can be added to the model of the short standard. This will set the effective reference plane at the open.

Slide #149

Load Standard





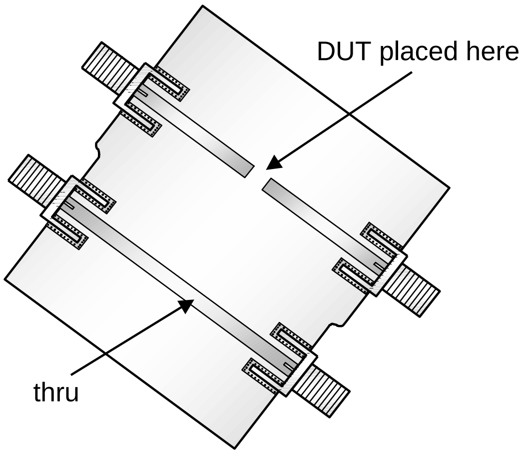
- ideal: zero reflection at **all** frequencies
- can only **approximate** at best (usually somewhat inductive)
- **two** 100-ohm resistors in parallel better than a single 50-ohm resistor

An ideal load reflects none of the incident signal, thereby providing a perfect termination over a broad frequency range. We can only approximate an ideal load with a real termination because some reflection always occurs at some frequency, especially with noncoaxial standards.

At RF, we can build a good load using standard surface mount resistors. Usually, it is better to use two 100-ohm resistors in parallel instead of a single 50-ohm resistor, as the parasitic inductance is cut in half. For example, "0805" size SMT resistors have about 1.2 nH series inductance and 0.2 pF parallel capacitance. Two parallel 100-ohm 0805 resistors have nearly a 20 dB better match than a single 50-ohm resistor.

Slide #150

Thru Standard



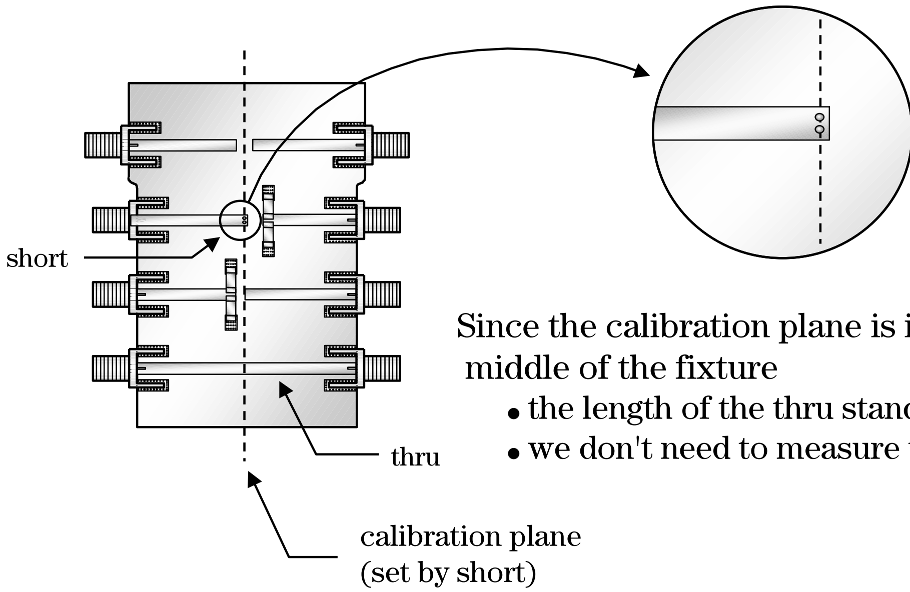
- thru is a simple **transmission line**
- desire **constant impedance** and **minimal mismatch** at ends

The thru standard is usually a simple transmission line between two coaxial connectors on the fixture. A good thru should have minimal mismatch at the connector launches, and maintain a constant impedance over its length (which is generally the case for PCB thru's). The impedance of the thru should match the impedance of the transmission lines used with the other standards (all of which should be 50 ohms).

Notice in the above drawing that the PCB is wider for the transmission line where the DUT will be soldered. Since we want the two halves of this line to be equal in electrical length to the thru line, the PCB must be widened by the length of the gap between the two lines.

Slide #151

Characterizing Thru Standard



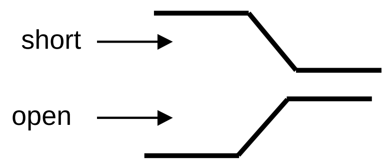
Since the calibration plane is in the middle of the fixture
- the length of the thru standard is zero
- we don't need to measure thru loss

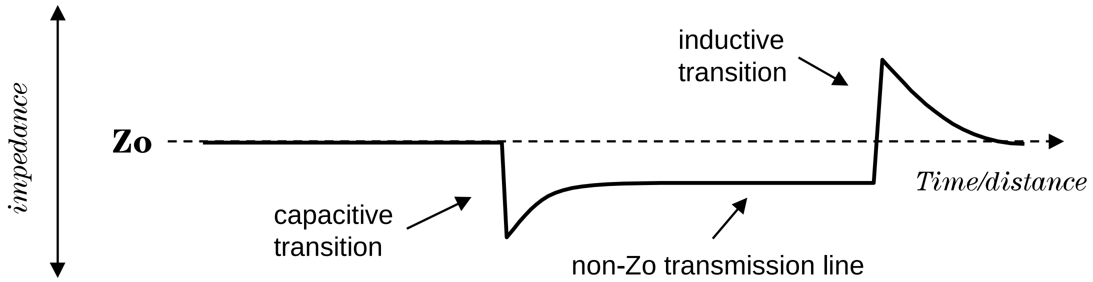
With a properly designed PCB fixture, the short (or open) defines the calibration plane to be in the center of the fixture. This means that the thru will have a length of zero (which is usually not the case for fixtures used in manufacturing applications, where a set of calibration standards are inserted into a single fixture). Since the length is zero, we don't have to worry about characterizing the loss of the thru.

Slide #152

Using TDR to Evaluate Fixture and Standards

- what is TDR?
  - time-domain reflectometry
  - analyze impedance versus time
  - distinguish between inductive and capacitive transitions
- with gating:
  - analyze transitions
  - analyzer standards





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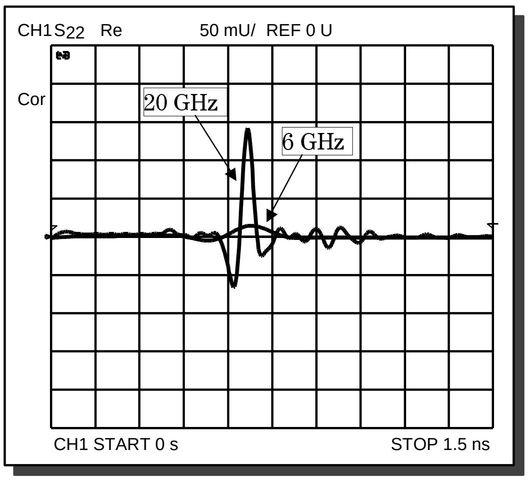
Time-domain reflectometry (TDR) is a wonderful tool that lets us look at impedance versus distance. We can distinguish between capacitive and inductive transitions, and see non-Zo transmission lines. TDR can help us determine the magnitude and distance of reflections of the fixture and calibration standards. Once the fixture has been designed and fabricated, we can use TDR to effectively evaluate how well we have minimized reflections.

As long as we have enough spatial resolution, we can see the reflections of the connector launches independently from the reflections of the calibration standards. With time domain gating, we can isolate various sections of the fixture and see the effects in the frequency domain. For example, we can choose to look at just the connector launches (without interference from the reflections of the calibration standards), or just the calibration standards by themselves.

Slide #153

TDR Basics Using a Network Analyzer

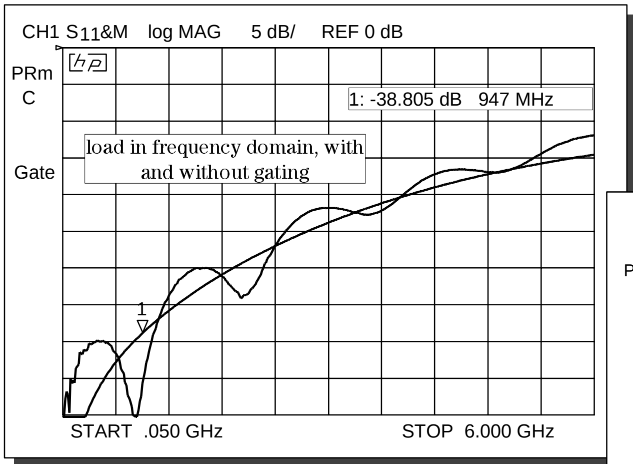
- start with broadband frequency sweep (often requires microwave VNA)
- inverse FFT to compute time domain
- resolution inversely proportionate to frequency span



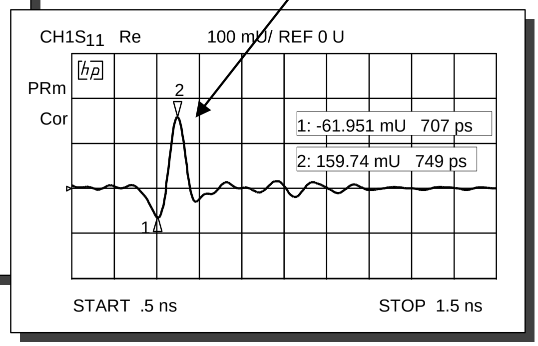
TDR measurements using a vector network analyzer start with a broadband sweep in the frequency domain. The inverse-Fourier transform is used to transform the frequency domain data to the time domain, yielding TDR measurements. When using a network analyzer, the spatial resolution is inversely proportional to the frequency span of the measurement - i.e., the higher the stop frequency, the smaller the distance that can be resolved. For this reason, it is generally necessary to make microwave measurements on the fixture to get sufficient resolution to analyze the various transitions. Providing sufficient spacing between transitions may eliminate the need for microwave characterization, but can result in very large fixtures. The plot above of a fixtured load standard shows the extra resolution obtained with a 20 GHz sweep versus only a 6 GHz sweep.

Slide #154

Time Domain Gating



load mismatch due to inductance



- use time domain gating to see load reflections independent from fixture
- use time domain to compensate for imperfect load (e.g. try to cancel out inductance)

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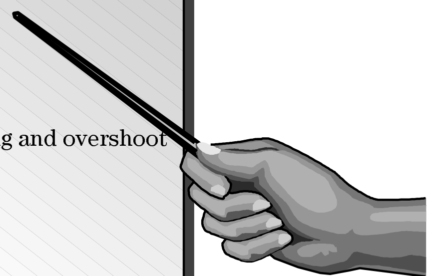
Time domain gating can be a very useful tool to evaluate how well our load is performing. We can gate out the response of the fixture and just look at reflections due to the load standard, provided we can get enough spatial resolution (this may require the use of a microwave vector network analyzer). The smoother trace on the plot on the left shows the gated response of a load standard, giving a fairly typical match of about 38 dB at 1 GHz, and around 30 dB at 2 GHz. The right-hand plot shows that the load standard looks somewhat inductive, which is fairly typical.

It is possible to adjust ("tweak") our load standard to compensate for the unavoidable parasitics that degrade the reflection response. Time domain gating is an excellent tool that helps determine the proper compensation. For example, we could see the effect in both the time and frequency domains of adding a small amount of capacitance to cancel out some of the inductance of the load standard.

Slide #155

Ten Steps for Performing TDR

1. Set up desired frequency range
   (need wide span for good spatial resolution)
2. Under SYSTEM, transform menu, press "set freq low pass"
3. Perform one- or two-port calibration
4. Select S11 measurement *
5. Turn on transform (low pass step) *
6. Set format to real *
7. Adjust transform window to trade off rise time with ringing and overshoot *
8. Adjust start and stop times if desired
9. For gating:
   - set start and stop frequencies for gate
   - turn gating on *
   - adjust gate shape to trade off resolution with ripple *
10. To display gated response in frequency domain
    - turn transform off (leave gating on) *
    - change format to log-magnitude *



* *If using two channels (even if coupled), these parameters must be set independently for second channel*

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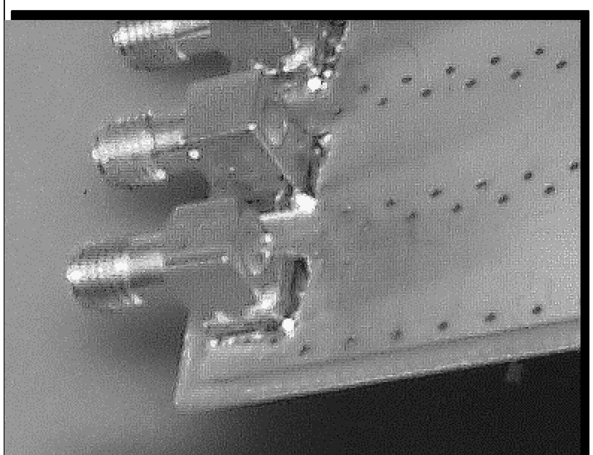
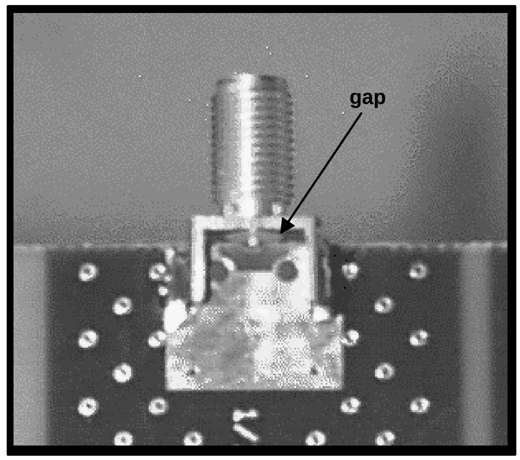
Here is a summary of how to perform TDR measurements. Without such a checklist, it is easy to overlook some of the more subtle steps, resulting in confusing or misleading measurements. A one-port calibration is all that is needed when characterizing connectors and the open, short and load standards. A two-port calibration is needed to characterize the reflection or line impedance of the thru standard.

Slide #156

Connectors on Fixtures

- transition at the connector launch causes reflection due to mismatch
- when cal standards are inserted in fixture, connector match is removed
- when each cal standard has connectors, consistency is very important



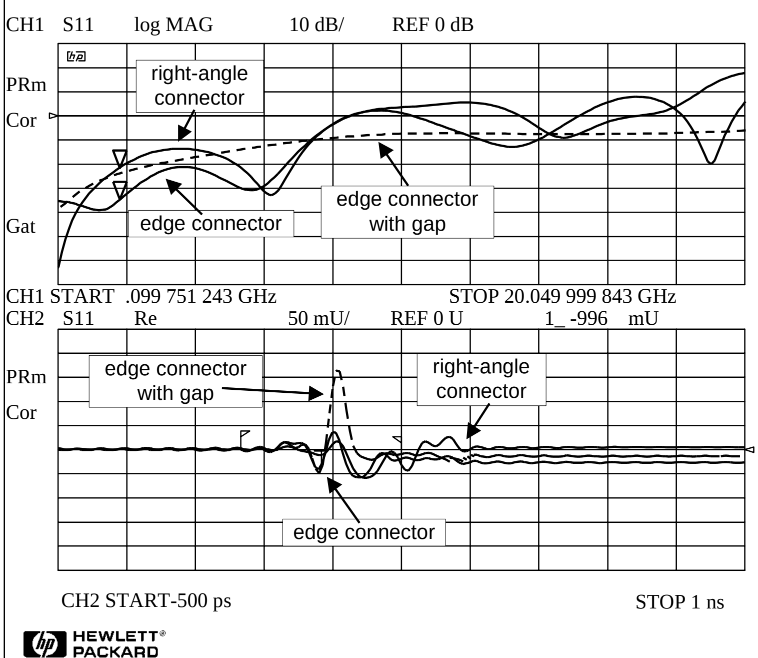


When using PCB-based fixtures the performance at the connector transition is important, and the consistency between connectors is very important. To completely remove the effect of connector mismatch when using multiple connectors (a pair for each calibration standard), we must have excellent consistency between the connectors. In this case, the connector mismatched will be removed as part of the calibration process.

As we developed the fixture used in our case study, we encountered two examples of poor connector performance and repeatability. The first was when we used right-angle SMA connectors. Because of their internal construction, their match was both poor and not very consistent (repeatable) between connectors. The second example was when we did not properly solder the edge-mounted SMA connectors to our PC board. By not providing notches in the PC board to accommodate the shoulders of the connector, we did not achieve a flush mount. The resulting air gap (which can be seen above in the right-hand picture) provided considerable mismatch. A properly mounted edge connector provided satisfactory performance.

Slide #157

Connector Performance



1.900 GHz
1_: -23.753 dB
1_: -32.297 dB

frequency domain

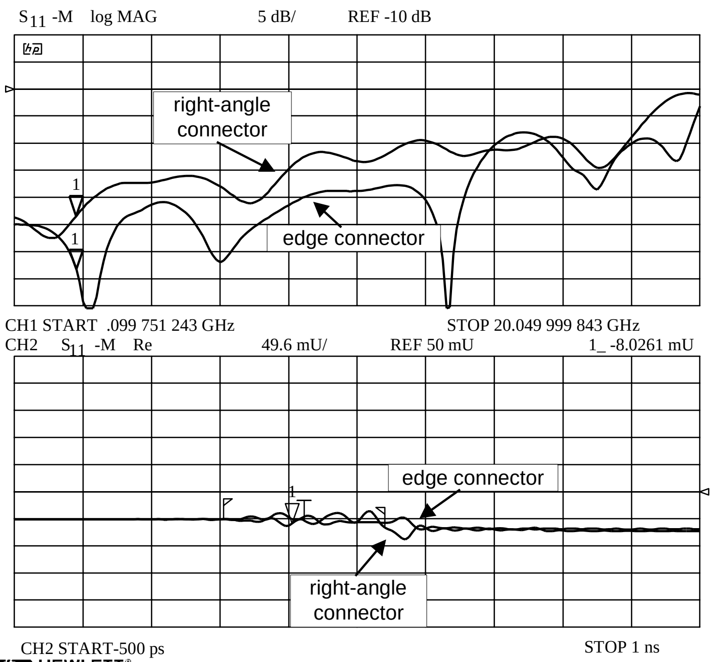
Comparing match of right-angle and edge-mount connectors (with and without gap)

time domain

Here is data comparing the right-angle and edge-mount SMA connectors. In the frequency domain, it is clear that the edge-mount connector gives the lowest reflection (about a 32 dB match at 1.9 GHz). Gating was used to remove the reflections of the calibration standards. The time domain plot on the bottom shows that the edge connector with the air gap is clearly inductive.

Slide #158

Connector Consistency



1.900 GHz
1_:-33.392 dB
1_ -43.278 dB

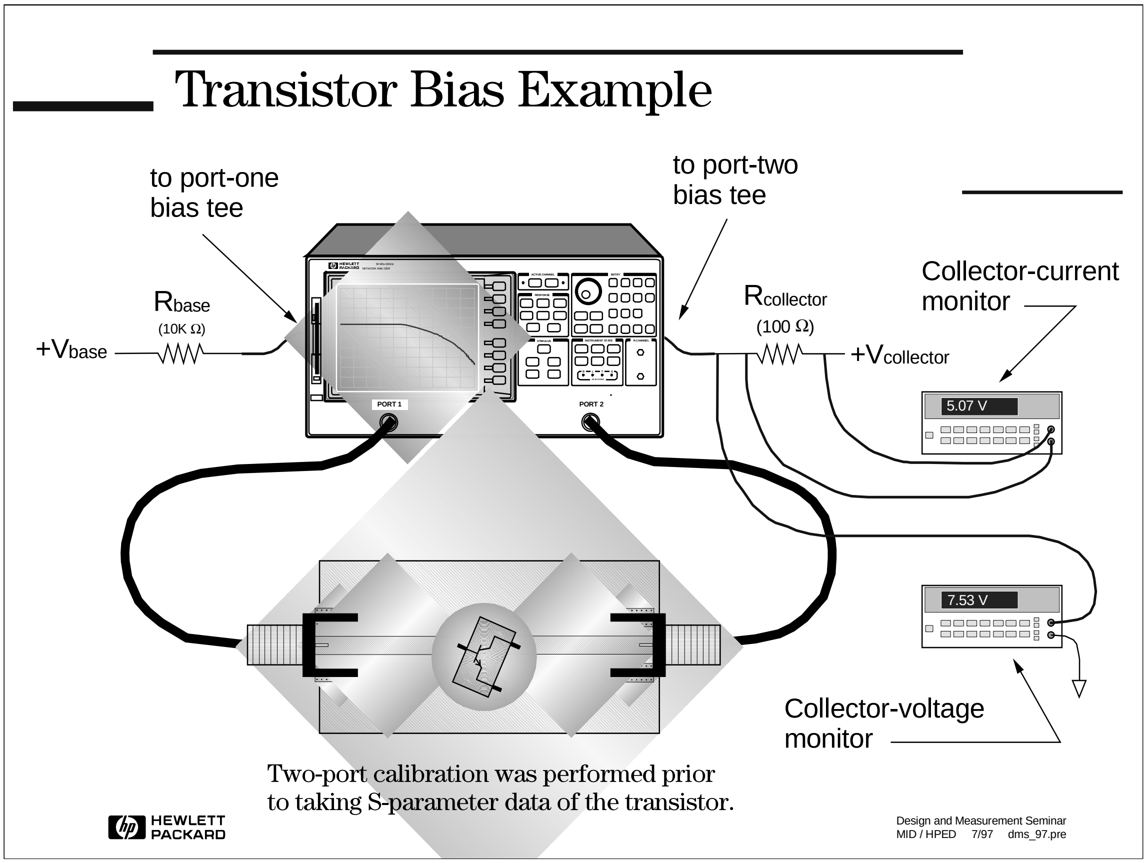
frequency domain

Use [data - memory] to check consistency of connectors

time domain

Here is the data showing the consistency between the connectors. We used the data-minus-memory feature of the network analyzer to show the measured difference between connectors. The edge-mount connectors have a 10 dB advantage over the right-angle connectors up to around 12 GHz. This is a significant advantage as the reflections from the connectors can only be removed by error correction to the level of the consistency between the connectors. A value of -43 dB (at 1.9 GHz) is fairly decent.

Slide #159



Now that we have completed the design of our PCB fixture, and stored the calibration standards into user files, we are ready to measure devices. We used the fixture to measure passive and active devices.

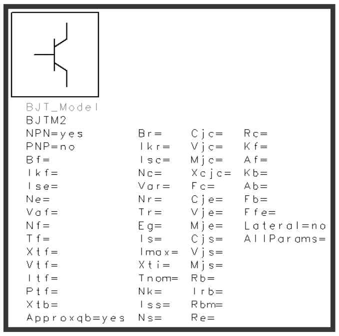
Here is an example depicting how bias was supplied to one of the silicon transistors used in our case study. The power supplies are not shown, but they would be connected to the +Vbase and +Vcollector nodes. The +Vbase voltage controls the collector current, and the +Vcollector voltage controls the collector-to-emitter voltage on the transistor. For the base resistor, it is important that a fairly large value be used (such as 10K ohms), so that the voltage adjustment is not too sensitive. It is convenient to use two digital voltmeters to monitor the collector current and collector-to-emitter voltage simultaneously. A two-port calibration was performed prior to taking the S-parameter data of the transistor.

Slide #160

Linear versus Non- Linear Models

```
!Freq.[Hz] MagS11[dB] PhaseS11[DEG] MagS21[dB] PhaseS21[DEG] MagS12[dB] PhaseS12[DEG]
300000 -5.986E-07 -1.151E-02 -7.394E+01 8.997E+01 -7.394E+01 8.997E+01 -5.986E-07 -1.151E-02
315229 -6.384E-07 -1.210E-02 -7.351E+01 8.997E+01 -7.351E+01 8.997E+01 -6.384E-07 -1.210E-02
331231 -6.812E-07 -1.271E-02 -7.308E+01 8.997E+01 -7.308E+01 8.997E+01 -6.812E-07 -1.271E-02
348046 -7.273E-07 -1.336E-02 -7.265E+01 8.997E+01 -7.265E+01 8.997E+01 -7.273E-07 -1.336E-02
365714 -7.769E-07 -1.403E-02 -7.222E+01 8.997E+01 -7.222E+01 8.997E+01 -7.769E-07 -1.403E-02
384279 -8.303E-07 -1.475E-02 -7.179E+01 8.997E+01 -7.179E+01 8.997E+01 -8.303E-07 -1.475E-02
403787 -8.879E-07 -1.550E-02 -7.136E+01 8.997E+01 -7.136E+01 8.997E+01 -8.879E-07 -1.550E-02
424285 -9.501E-07 -1.628E-02 -7.093E+01 8.997E+01 -7.093E+01 8.997E+01 -9.501E-07 -1.628E-02
445823 -1.017E-06 -1.711E-02 -7.050E+01 8.997E+01 -7.050E+01 8.997E+01 -1.017E-06 -1.711E-02
468455 -1.090E-06 -1.798E-02 -7.007E+01 8.997E+01 -7.007E+01 8.997E+01 -1.090E-06 -1.798E-02
492235 -1.168E-06 -1.889E-02 -6.964E+01 8.997E+01 -6.964E+01 8.997E+01 -1.168E-06 -1.889E-02
517223 -1.252E-06 -1.985E-02 -6.921E+01 8.997E+01 -6.921E+01 8.997E+01 -1.252E-06 -1.985E-02
543479 -1.344E-06 -2.086E-02 -6.878E+01 8.997E+01 -6.878E+01 8.997E+01 -1.344E-06 -2.086E-02
```

- valid for one bias condition
- valid for small signal



- device completely characterized
- valid for all bias conditions
- valid for non-linear operation

$Ibe=(IBbif(exp(Vbe/NbfVT)-1.0))+Ise(exp(Vbe/(NexVt))-1.0)$

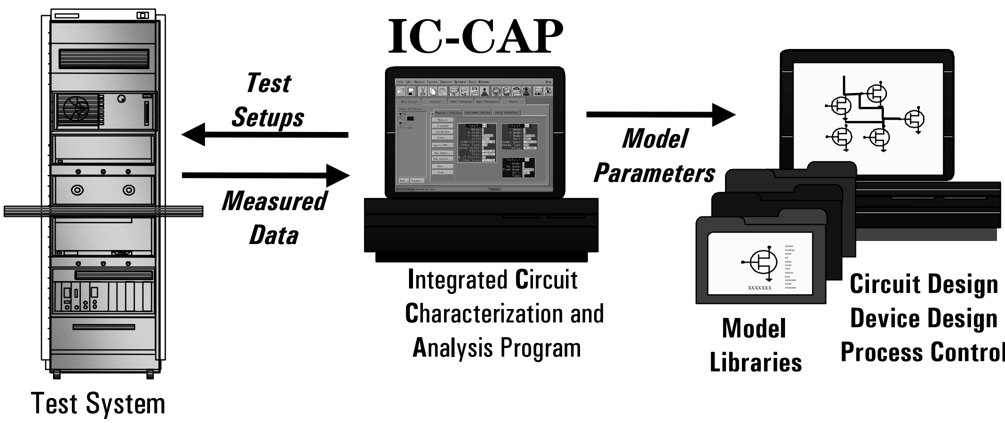
Using our PCB fixture, we measured the S-parameters around our bias point. This data is valid for small signal performance of the device. What if we wanted to change our bias or if the operation of the device was non-linear? What we need is a non-linear device model. If one doesn't exist in the library or it was taken under different conditions, the final option is to extract a model yourself or have a device modeling team do this.

There are two aspects to accurate models; the model equations that predict device behavior, and the model parameters that come from the characterization of a specific device. The model equations (e.g. BSIM3) available today can predict high-frequency behavior, but in order to take advantage of these models, we need to completely characterize the device and extract accurate model parameters from the device data.

The overall characterization and modeling process is very similar to the one for measuring S-parameter data shown earlier. It begins with quantifying and then minimizing measurement errors, followed by device characterization. The difference is that instead of the model consisting of measured S-parameter data, the parameters for the generic model equations are extracted. The end result is a set of specific model equations for your particular device.

Slide #161

IC-CAP: Integrated Circuit Characterization and Analysis Program



Extracting accurate model parameters is complicated, so Hewlett-Packard has developed an application which facilitates this characterization process, IC-CAP (Integrated Circuit Characterization and Analysis Program). IC-CAP is a software environment that controls test setups and test systems, extracts the model parameters, and builds model libraries for circuit design.

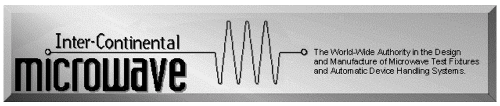
The system consists of a network analyzer for RF measurements and a parametric analyzer for DC characterization.

RF Design and Measurement Seminar

Slide #162

References and More Information

- ***Fixtures - www.icmicrowave.com***



- ***TDR - www.hp.com***

- ***IC-CAP - www.hp.com***

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