NETWORK ANALYSIS OF FIXTURED DEVICES

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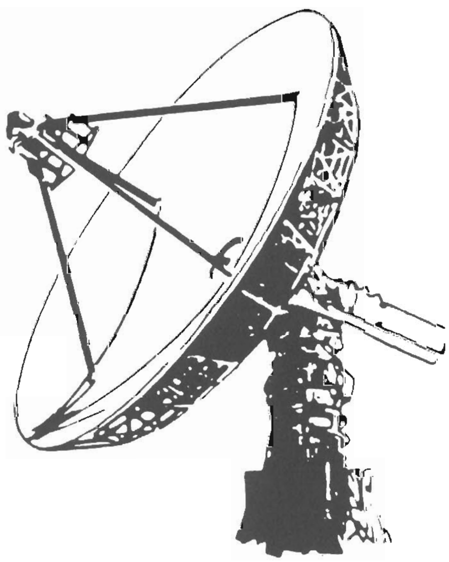

HEWLETT PACKARD

ABSTRACT

Transistors and other active devices often must be mounted in some type of fixture to be measured by an automatic network analyzer. However, suitable in-fixture calibration standards often are not available to calibrate the network analyzer system; it becomes necessary to have a method to correct the measured data for errors caused by the fixture. Some of these errors can be characterized and removed while other errors may be the result of some instability in the fixture itself.

This paper describes some techniques which may be useful for measuring fixtured devices; including a discussion of the concept known as "de-embedding". Two basic approaches for separating fixture effects from actual device data will be discussed. While not universal, these techniques can accommodate many fixturing applications, particularly if certain attributes are included in the design and fabrication of the fixture.

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NETWORK ANALYSIS OF FIXTURED DEVICES

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OUTLINE

- The Measurement Problem
- Fixture Considerations
- Error Correction Techniques
- Summary

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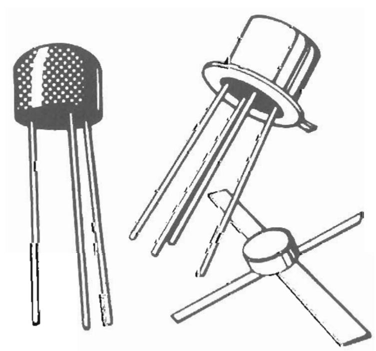
Automatic network analyzers (ANA's), such as the HP 8510 and HP 8753, can make direct measurements when calibration standards with the same connector type as the device under test exist. Many devices cannot be directly connected to the coaxial test ports of a network analyzer and require a transitional mounting fixture for measurement. The mounting fixture, however, will introduce additional errors into the measurement. Some of these errors can be characterized and removed while other errors may be the result of some instability in the fixture itself.

This paper will overview this measurement problem and describe some techniques which may be useful for measuring fixtured devices. Two basic approaches for separating fixture effects from actual device data will be discussed.



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The most common class of devices which require mounting fixtures are packaged semiconductors or chips. A variety of package and chip styles exist. Some examples are shown here. TO-can packages work well for RF frequency applications, but have significant parasitic effects in the microwave region. Microwave semiconductors are generally fabricated in stripline packages or as unpackaged chips.

Mounting fixtures for these various device types exist, including some commercially available, but for the most part each device type presents a unique measurement problem.

WHY USE NETWORK ANALYSIS?

To characterize the linear behavior of a device for some installed performance.

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Before directing attention to any specific techniques, let's take a look at why these devices are particularly difficult to measure. In the general case, network analyzers are used to characterize the linear behavior (impedance, gain) of devices. Devices are characterized by stimulating the device under test with a specific signal and then detecting the reflected or transmitted signals in a known environment.

The need for accurate and reliable data ranges from monitoring of device performance to meet existing design specifications to determining how a device will perform in a newly designed circuit.

SOURCES OF MEASUREMENT UNCERTAINTY

- **Systematic Errors**
  Tracking, Mismatch, Directivity
- **Random Errors**
  Drift, Noise, Temperature, Indeterminate Systematic Errors

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As in any measurement system, the data which is collected and displayed will differ from the actual data due to imperfections in the instrument and hardware used to hold the device. These imperfections, or sources of uncertainty, limit our confidence in the data.

In network analysis, the primary errors are classified as random and systematic. Systematic effects are present in all measurements and include test port mismatch, directivity, and tracking. ANA's provide a means to characterize and remove these errors when known reference devices, called standards, are measured at the connection interface of the test devices. Random effects include drift, noise, repeatability and any systematic effects which cannot be characterized or understood.

ADDITIONAL ERRORS IN FIXTURED MEASUREMENTS

- **Connection Repeatability**
- **Transmission Media**
  Dispersion, Impedance
- **Lack of Reference Devices**

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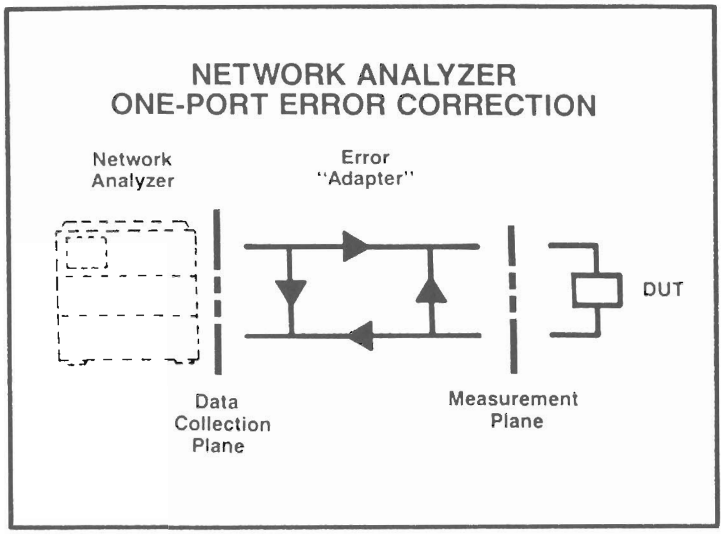
A random effect which can be a large source of uncertainty in the measurement of fixtured devices is connection repeatability. Non-repeatable effects such as this make it difficult to characterize the systematic effects.

The transmission media of fixtures and installed test devices may have dispersive (non-linear phase) effects and non-matched characteristic impedance. It is also likely that reference standards, which could be installed at the device interface, do not exist.

In order to address each of these sources of uncertainty, which current ANA techniques cannot account, the limitations of these current techniques must be understood.



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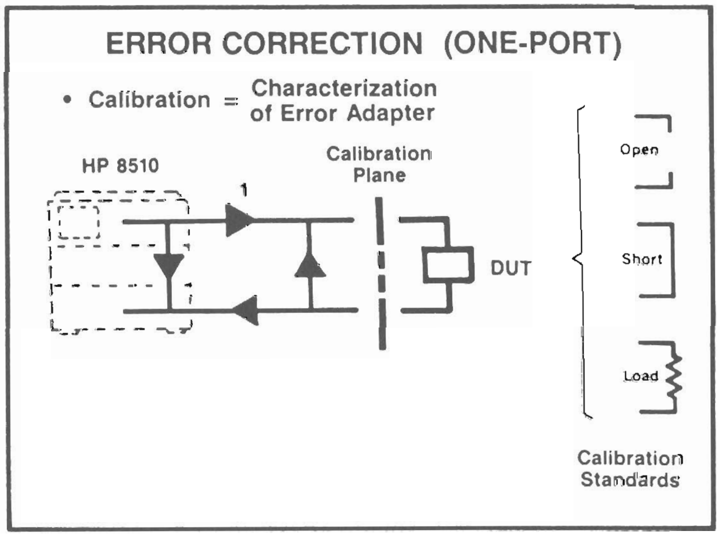
ANA's reduce uncertainty through error correction. Error correction is the process of deducing actual device data, taken at a point called the "measurement plane," from the raw data received at the "data collection plane." Collected data in a network analyzer is the detected incident, reflected and transmitted signals from a test device. The intervening hardware, which separates the ANA from the one-port DUT shown here, will corrupt the actual DUT data. The response of the intervening hardware can be represented by this network which is given the name "Error Adapter."



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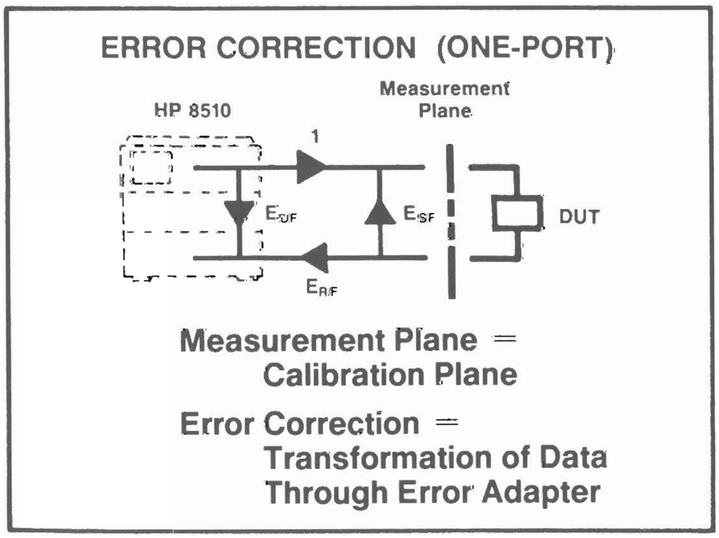
In order for the ANA to correct the raw data and provide the desired data, it is necessary to have a description of the Error Adapter. This must be a model of the manner in which it affects or corrupts the measurement which is valid at the time of DUT measurement. The description is often provided by a process called Calibration. Calibration consists of measuring a sufficient number of known devices, called calibration standards, and calculating the parameters of the Error Adapter based on that raw data. Calibration is therefore the process of characterizing the Error Adapter.

In a simple coaxial reflection calibration, the one-port standards typically used are shorts, opens and loads.



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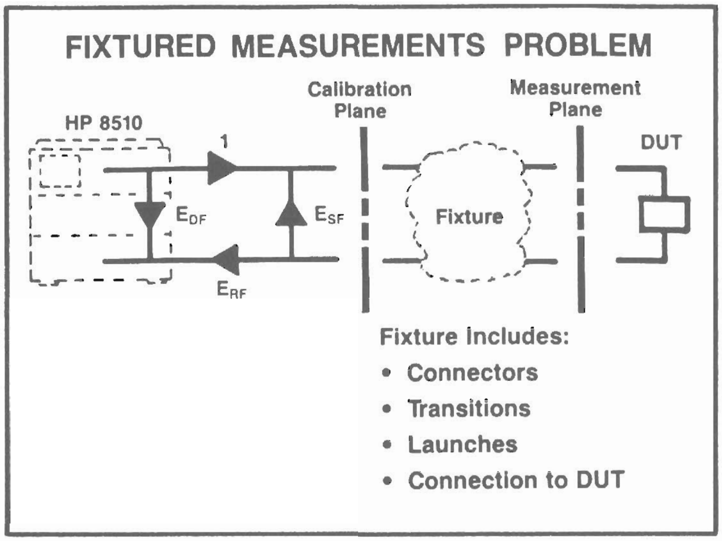
The operation of relating the characteristics of a DUT through a characterized error adapter to deduce actual data is called "Error Correction" and has been previously described.[1]

It should be noted that data which results from this process is in effect data taken as though the measurement was made at the plane established by the calibration standards. Thus, for ANA measurements, the measurement plane and calibration plane are the same.



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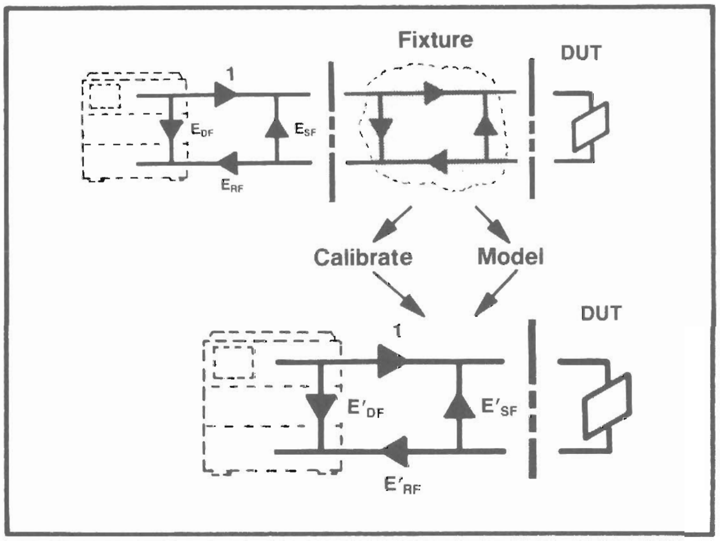
However, many devices cannot be directly connected to a calibrated network analyzer for measurement. This class of DUT measurements may be termed Fixtured Measurements, since the DUT is separated from the calibrated ANA by some kind of transitional network or fixture. An example of this is the measurement of packaged transistors. Although a structure may be devised which can serve as a transition between a coaxial connection of an ANA test set and a transistor package, suitable calibration standards may not be available to allow a conventional calibration of the system at the plane of the transistor package. As a consequence, the measurement plane which can be obtained through calibration at the coaxial connection is separated from the DUT plane of interest by a network, the fixture. In general, this fixture is not lossless and reflectionless transmission line Rather, it may be comprised of connectors, transitions between different types of transmission lines, and the connections to the DUT.[2,3]



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There are two fundamental approaches used in accounting for fixture effects - calibration and modeling. Calibration is used to characterize both network analyzer and fixture effects through measurement of device-like standards. When obtaining device-like standards is not possible, estimation of fixture effects with an equivalent circuit model may provide a useful solution. These characterization approaches and other elements of the fixtured measurement problem will be described.

However, before considering how to characterize and remove systematic fixture effects, we should first evaluate the quality of the mounting fixture itself.

FIXTURE CONSIDERATIONS

- Fixture/DUT Compatibility
- Fixture/DUT Dependence
- Repeatability

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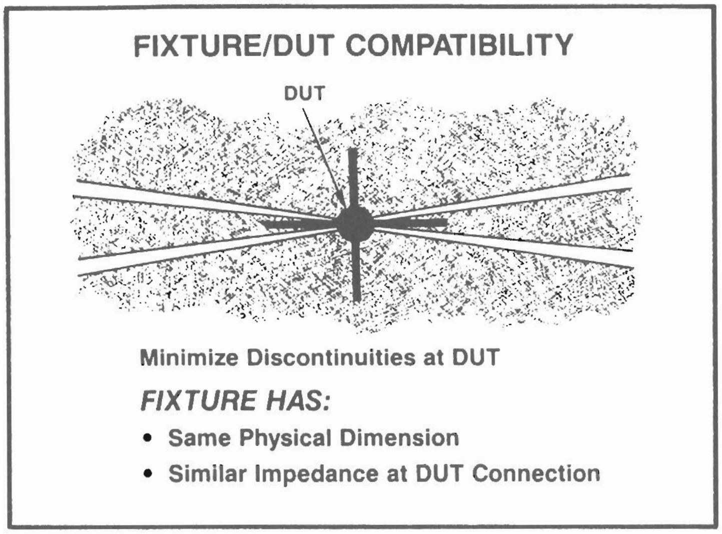
It is at this point where the fixtured measurement problem becomes very general. Each device type requires its own fixture of some specific construction. While it would be desirable, it would be very difficult to design a "universal" fixture. Instead, let's look at a short list of some elements of good fixture design. A thorough treatment of the design problem is beyond the scope of this presentation, but some general comments may be made.



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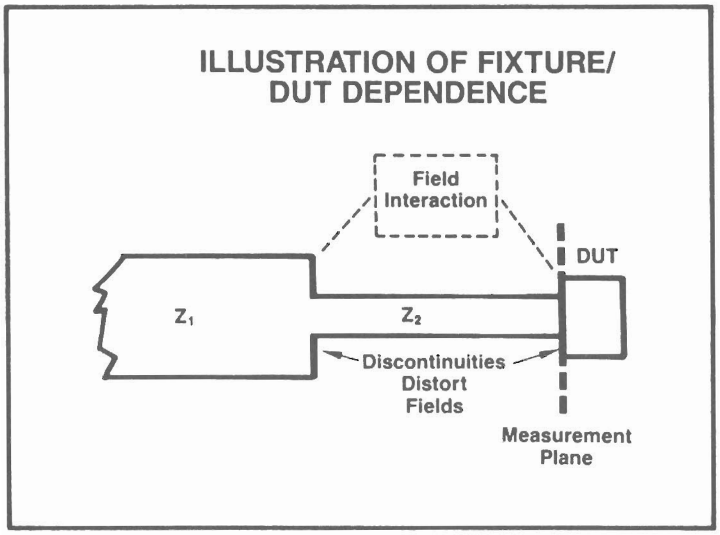
One goal of a fixture is to provide a measurement environment for a DUT which is as much like the application environment as possible. This is especially desirable for devices which have performance which is strongly environment dependent. As an example, common lead impedance in transistors with low input or output impedances can dramatically affect device performance in both a measurement fixture and an application. Also, it is desirable to have a fixture which is optimized for the range of impedances being measured. In the case of very low impedance devices, this may require a fixture which transforms the calibration impedance to the range of interest.[2,3]



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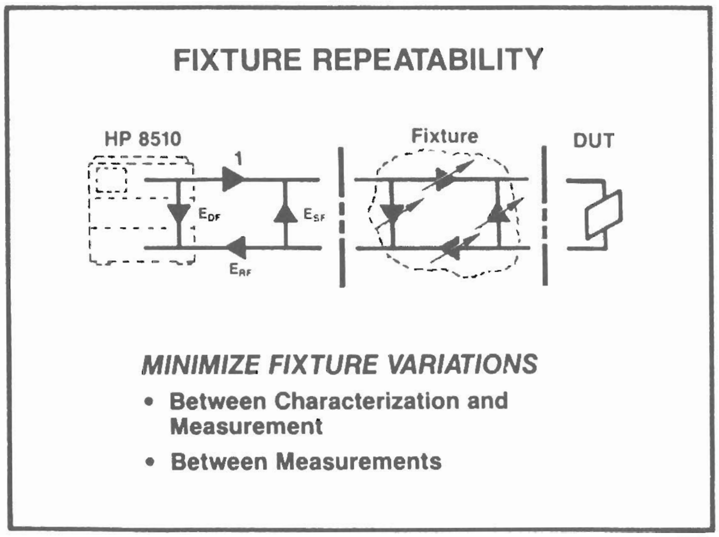
The built-in ANA error correction algorithm requires that the characteristics of the fixture must be independent of the device which is being measured.

This figure illustrates the dependence or coupling which can exist across the measurement plane between the discontinuity due to the DUT and an additional discontinuity within the fixture. Such fixture discontinuities need to be made small enough and be separated far enough from the measurement plane to allow a linear model to adequately describe the fixture.[2,3]



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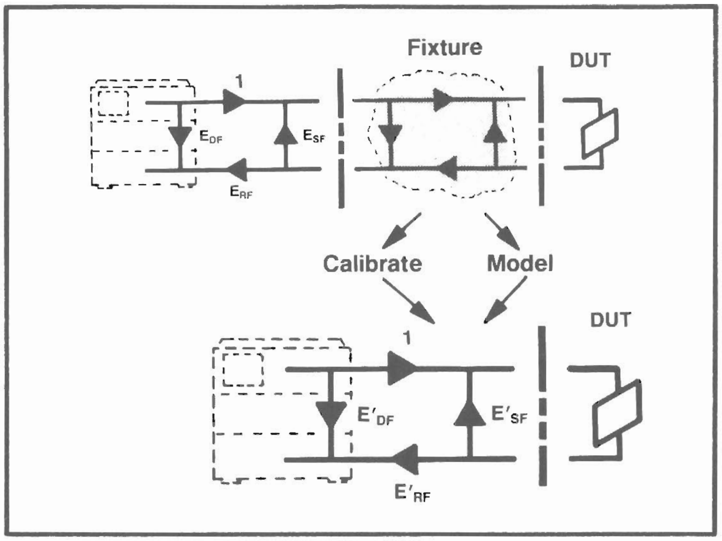
For an error corrected measurement to be accurate, the fixture's characteristics must not change between the time the fixture is characterized and the time the measurement is made. Fixture repeatability establishes fundamental bounds for accuracy since nonrepeatable errors cannot be corrected.[2,3]

Characterizing the repeatable or systematic effects of the fixture requires that the fixture is measured with some known device-like standard installed. A provision for installing such devices should be considered at the design stage.

This list of considerations is not intended to be exhaustive, but rather a starting point for fixture evaluation or design.



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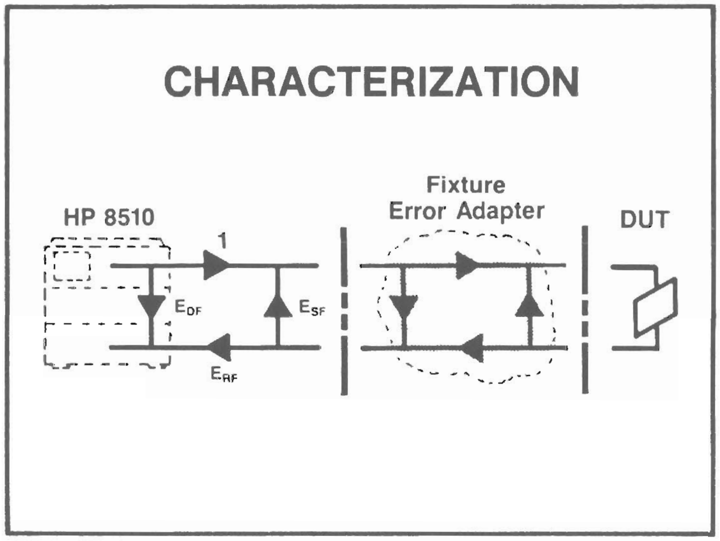
Once the random effects of the fixture have been addressed and any necessary improvements made, the systematic effects can be characterized and mathematically removed. This is a two step process. The first step involves characterization of the fixture effects. The fixture characterization process used will largely depend on the errors present in the fixture and the feasibility of making or obtaining standards.

The second step is the mathematical transformation of measured data to corrected data. The error correction algorithm is dependent on the characterization method.



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Both characterization approaches - calibration and modeling - rely (to varying degrees) on the availability of device-like reference standards. We will consider three general cases: 1) Simple modeling techniques that utilize built-in ANA capability; 2) Direct calibrations (including characterization and correction); 3) Fixture modeling and correction through de-embedding.

These three cases are not meant to be all inclusive, but rather to identify that a variety of techniques exist.

CASE 1
SIMPLE TECHNIQUES

Fixture exhibits response of a coaxial transmission line.

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When the fixture's response is similar to that of a coaxial transmission line, (even though it may have some other physical structure) built-in ANA features can be used to remove a specified length of lossy coaxial line from the measured data. The characteristics of the fixture must be measured with some device-like standard installed, or its response theoretically postulated.

Even though it has already been stated that fixtures generally exhibit complex responses, under certain conditions approximate data may be sufficient. For example, reliable low frequency or narrow band measurements can sometimes be made with these techniques. It is the increasing effects of fixture parasitics at higher frequencies and non-TEM wave propagation that limits its usefulness.

PORT EXTENSION

- Removes Linear Phase Response

MODIFIED DESCRIPTION OF COAXIAL STANDARD

- Removes Skin Effect Loss, Linear Phase, and Z_o Mismatch

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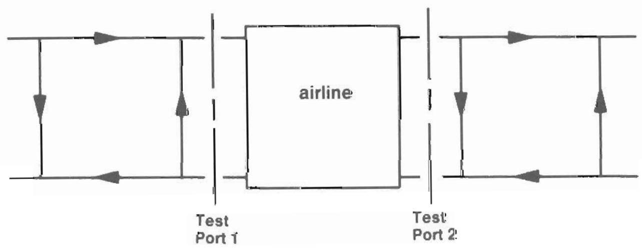
Both of these methods involve modification to the existing built-in ANA calibration procedure. The first is an ANA feature called Port Extensions, which removes or adds phase shift characteristic of a lossless coaxial airline to the measured data. The phase shift in degrees is computed as 360 x frequency x length/(speed of light). This feature allows the effective measurement plane to be moved relative to the calibration plane through a lossless environment.

A second method involves modification of the length, loss and/or characteristic impedance definitions of existing coaxial standards. ANA's such as the HP 8510 and HP 8753 accept calibration standard models which exhibit skin effect loss, linear phase and real Z_o.[4] By including a modeled response for the fixture into the definition of the simple coaxial standards, the modeled response will be effectively removed through the built-in ANA error correction routine.

EXAMPLE
LOSSY COAXIAL LINE



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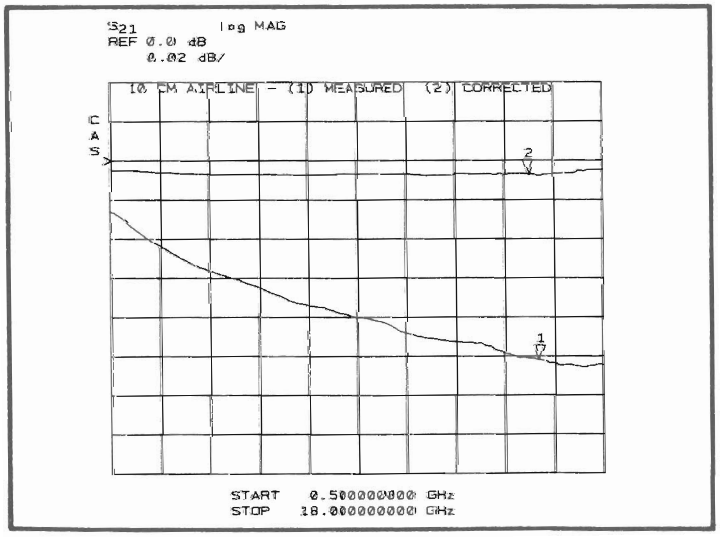
To illustrate this technique, let's look at a simple example. The figure shows the measurement setup for insertion loss of a 10 cm coaxial airline. In a fixtured measurement, the loss and phase of the coaxial line represents the error we would like to remove from the measured data. For a corrected transmission measurement, the standard definition for the "through" standard would be modified to include the length and loss of the airline. For this example, the definition of the 7 mm zero length "Through" was modified to have an offset delay of -333.6 pS and a loss of 800 Gigohms/second at 1 Gigahertz (.003 dB/cm at 1 GHz).



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The actual measured response of the airline and the residual response is shown here. Note that the effective loss of the airline is reduced from about .12 dB at 18 GHz to less than .01 dB. The phase shift (not shown) is reduced from about 6 full wavelengths to about 5 degrees.

CASE 2
EXISTING CALIBRATIONS

Fixture exhibits complex response due to multiple discontinuities, dispersive phase, etc...

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Another approach used for characterizing systematic effects uses other existing calibration techniques. These methods are useful for characterizing fixtures that exhibit complex responses that cannot be simply measured or assumed. Most microwave fixtures fall into this category.

Common features of these techniques are: the attempt to represent repeatable errors through a virtual network (the networks may differ in topology), and reliance on simple idealized standards for which the response is assumed or postulated.[5]

CLOSED FORM CALIBRATION TECHNIQUES

- 3 Reflections, 1 Transmission
- TSD (Through-Short-Delay)
- 1 Short, 3 Offsets
- Other

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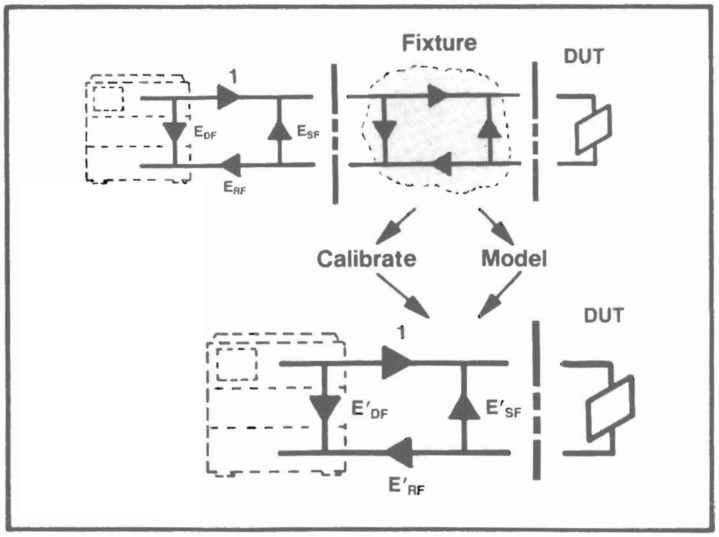
In an overview of existing calibration techniques,[6] the following methods listed here were included. Each of these techniques has a specific set as assumptions which may limit their applicability for general use. However, mathematically closed-form solutions have been developed.[1,6,7]

The three reflection technique used by the HP 8510A and HP 8753A is built into the instrument's firmware. We have noted previously that the ANA calibration scheme could not be used to characterize the effects of dispersive transmission media. Methods such as TSD (Through-Short-Delay) allow for the use of dispersive device-like standards, since their exact phase response is not required to compute the systematic effects. These techniques which involve characterization through direct measurement utilize fixture standards which are more likely to exist or can be easily fabricated.



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The closed-form calibration methods for fixture characterization rely completely on direct measurement. However, in many instances, the required set of device-like standards may not exist. An alternate approach for fixture characterization would be to develop an equivalent circuit model that represents the actual response of the mounting fixture. Considered as a series of real world elements with established responses, the equivalent fixture response can be characterized as the combined response of a series of known elements.

CASE 3
FIXTURE MODELING

- CAE Tools
- Observation
- Iterative

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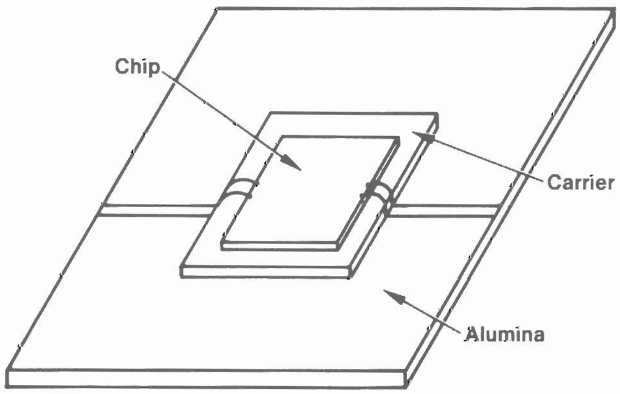
The emergence of commercially-available Computer-Aided Engineering tools (examples are Touchstone,[R] Super Compact[R]) for the designer has provided another approach which is useful in characterizing fixtures. These CAE tools can compute the precise S-parameter characteristics of an element or series of elements.

Observation of the physical structure of the fixture and assumptions are needed to develop the initial element values and topology.



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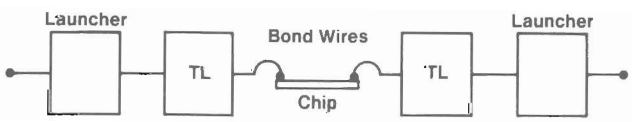
For example, consider the configuration shown here. The semiconductor chip is mounted on a carrier on a microstrip substrate. Although it would be conceptually possible to devise a set of calibration standards, there would be difficulties due to the inherent non-repeatability of the bond wires.



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An alternative approach would be to think of the fixture as a series of elements. The S-parameter response of these individual elements can be combined through analysis to represent the response of the complete fixture. These model elements were postulated through physical observation. However, CAE tools may be used to optimize the simulated response of the fixture model with the measured response of the fixture with any known device installed. An example of this process will be shown later.

FIXTURE MODELING

- ANA Error Adapter
- Fixture Error Adapter

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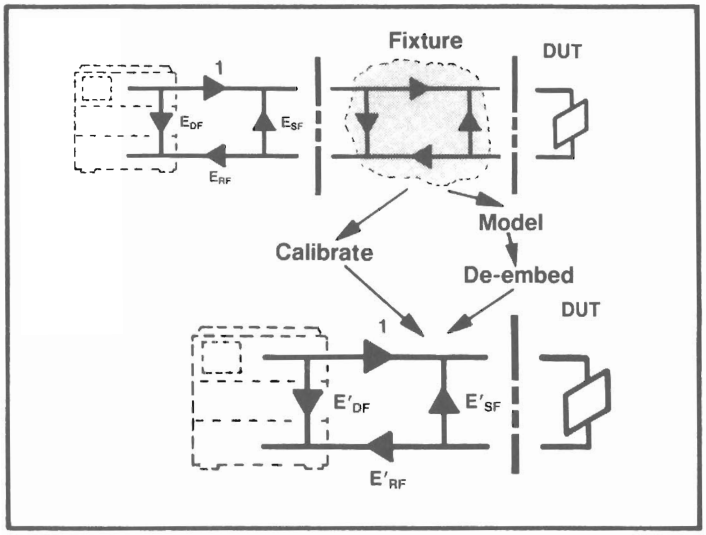
In the interest of minimizing the elements of a fixture model, one would attempt to use conventional ANA calibration techniques to characterize the coaxial portion of the measurement system. The computed S-parameter response of the fixture model for the specified measurement frequencies would generate the fixture error adapter.

Some method is needed to combine the error adapters from the ANA and the fixture model. (Some CAE tools can effectively subtract the fixture's S-parameter response from the measured data.) Previously, a technique called de-embedding was developed which allows for the inclusion of a fixture error adapter into the error model[2,3] of an ANA.



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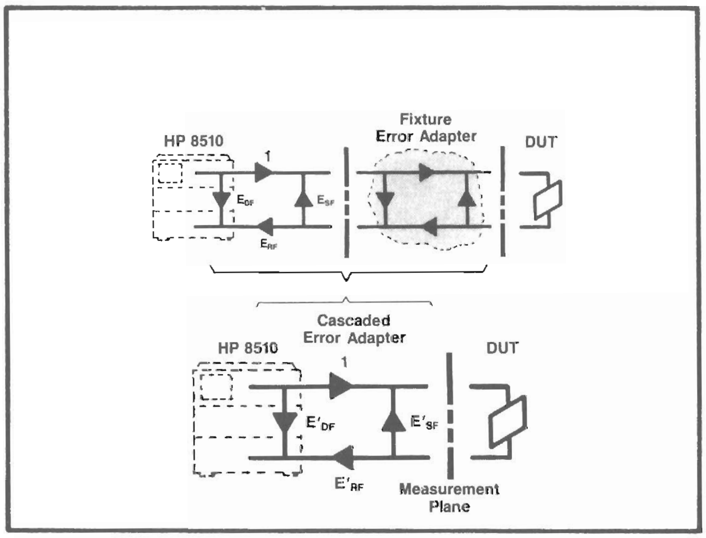
De-embedding allows an ANA to display calibrated data as if it had been directly calibrated at the device interface.



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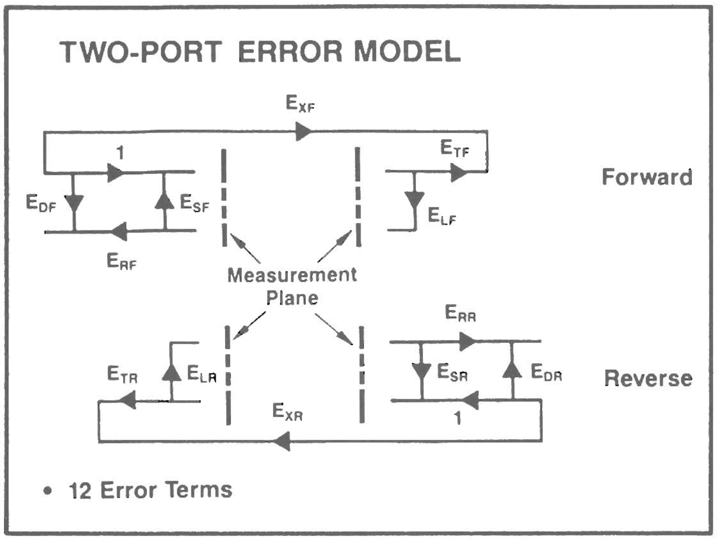
Once the S-parameter response of the fixture's element model has been generated, it can be combined with the error adapter of the ANA to create a "cascaded error adapter," which then can be reloaded into the instrument. The effective measurement plane, although different than the calibration plane, is at the DUT interface.



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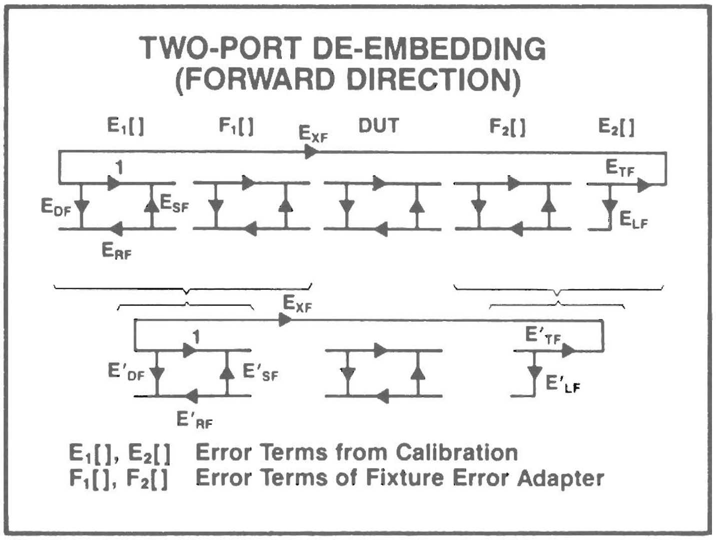
The one-port ANA error adapter has been used up to this point for simplicity. Now let's look at the full two-port error model.

The goal of the de-embedding process is to provide error terms for an error adapter which includes the fixture errors along with the error terms obtained from the calibration process. These terms must be in the same form as the calibration error terms so that the ANA can properly correct the raw data.



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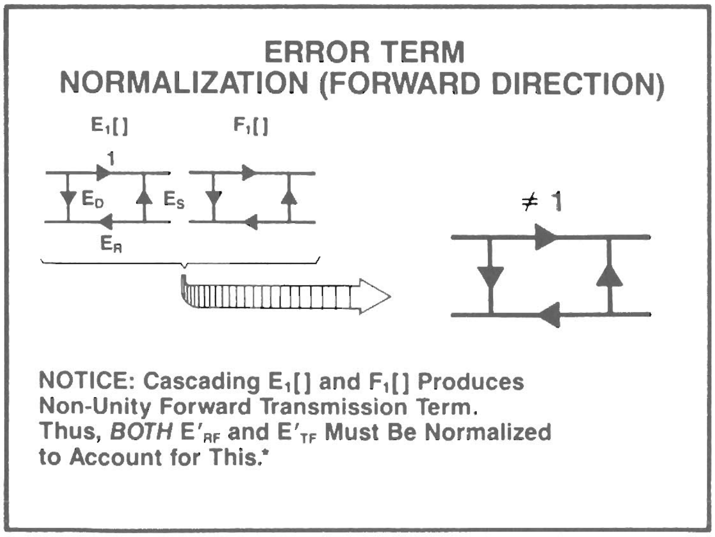
This figure shows the original calibration terms E_1[] and E_2[] being cascaded with the fixture error model terms, F_1[] and F_2[] to provide new error terms, E'[], for the ANA.



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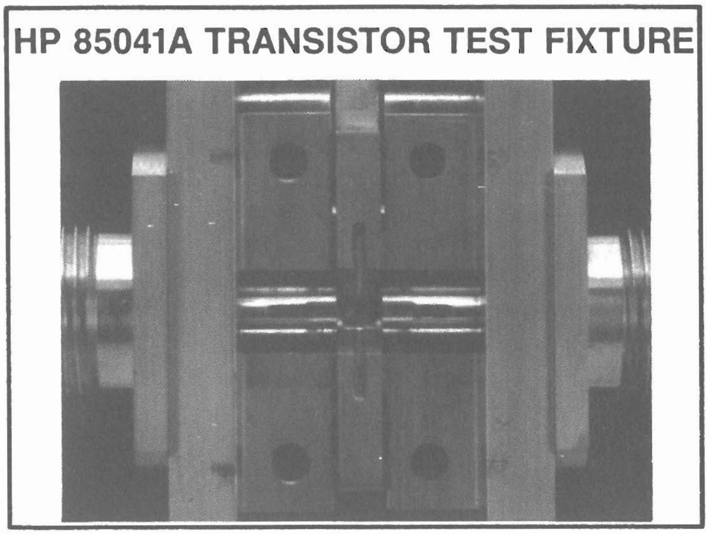
It should be noted that the result of the cascade of E_1[] (which has a unity forward transmission term) with the fixture Port 1 error model F_1[] produces a nonunity forward transmission term. This term must be normalized in order to satisfy the internal error model. This requires that the product of the cascaded transmission terms be put into E'_{rf}. Similarly, but possibly not so obviously, the forward transmission tracking term which resulted from the cascade of F_2[] and E_2[] must be multiplied by the forward transmission term which resulted from the cascading of E_1[] and F_1[] to normalize E'_{tf}.

The equations for de-embedding have been previously derived.[2,8] Further, the de-embedding equations have been implemented in the HP 85014A Active Device Measurements Application Pac.



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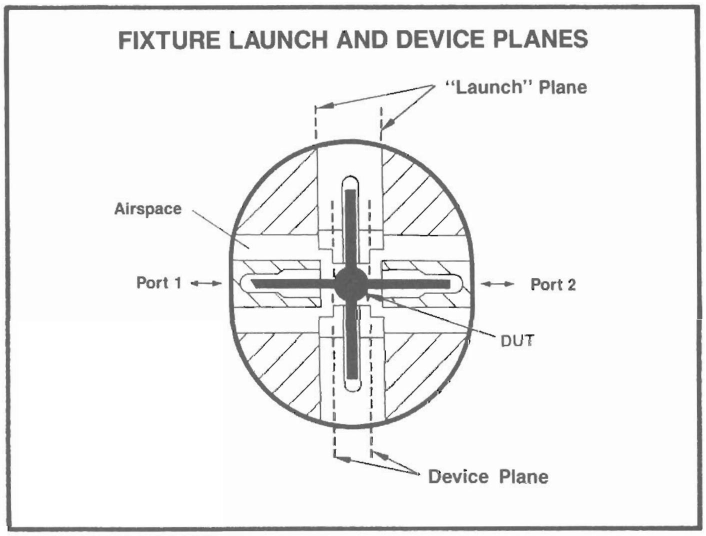
An example of a fixture that has characterized through modeling is the HP 85041A Transistor Test Fixture. Together with the HP 85014A software, de-embedded fixture measurements can be made on 0.07 and 0.10 inch diameter stripline microwave transistors.

This fixture was designed to make repeatable connections up to 18 GHz. Additionally, a device-like short circuit and a through-line were available for verification of the fixture's performance.



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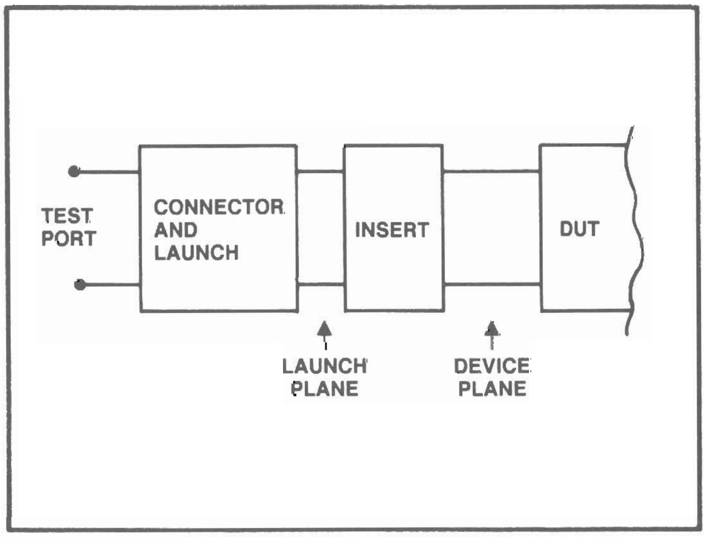
This figure illustrates the launch and device planes of the HP 85041A. Note that the fixture is primarily a 50 ohm coaxial line up to the launch plane. Initially a direct calibration approach at the launch plane was attempted, but the non-repeatability of the in-fixture calibration standards did not provide adequate characterization of the systematic effects. Since direct calibration did not meet the required performance, a more repeatable method was needed.



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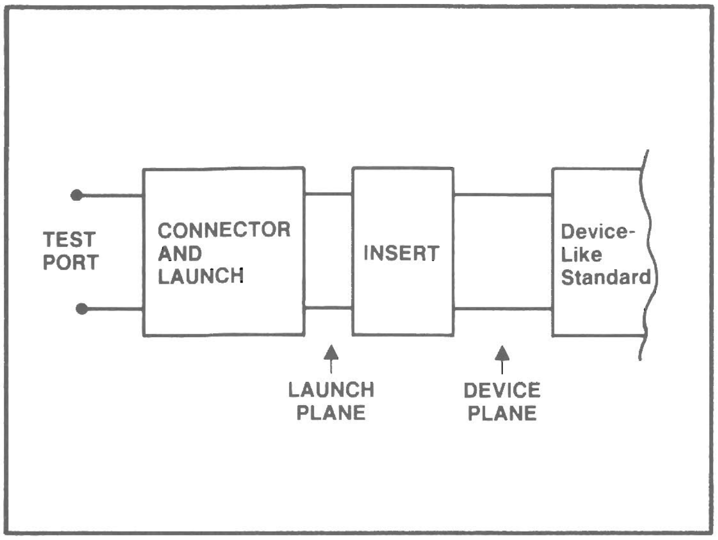
A coaxial calibration serves well to characterize the coaxial ANA test ports. A fixture model could then be used to represent the systematic effects up to the DUT.

The first step was to develop a first order model based on physical observation. The structure from the input connector up to the launch plane is primarily a 50 ohm airline. At the launch plane, we would expect a large discontinuity followed by a transmission line with characteristic impedance of a stripline transistor lead.



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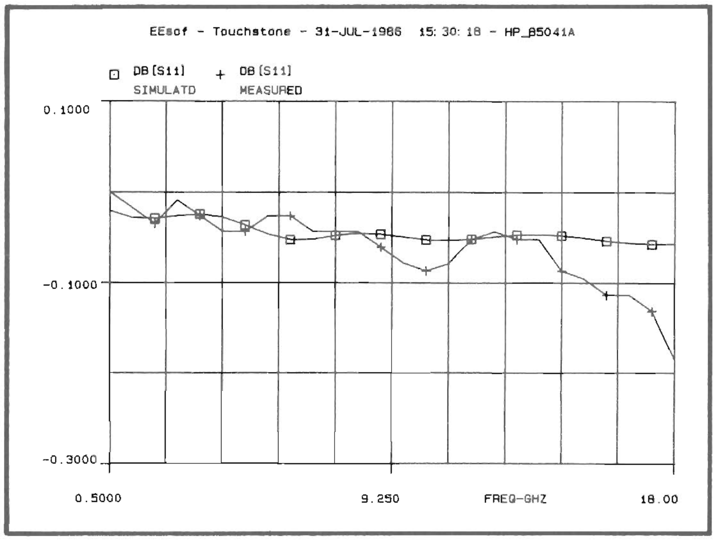
The next step would involve optimization of the fixture's modeled response with its measured response. Measurement of the device-like short circuit and through-line were used in the optimization.



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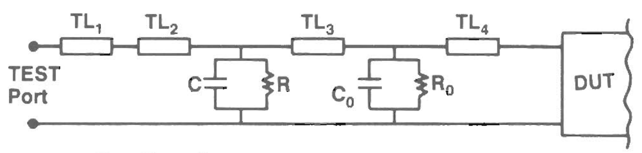
The plot shows the optimized S11 response of a first order fixture model compared to the measured response of the fixture with a short circuit installed. Further decisions must be made, such as whether to alter the topology of the model and how closely to constrain the element values of the model to approach the measured response of the fixture.

As with direct calibration techniques, assumptions about the response of the device-like standards will result in an erroneous characterization.



$R = R_0 = 0$

$C = 13.7$ fF

$C_o = 120$ fF

T_1	1	2	3	4	Units
$_z0$	50.0	51.4	50.5	140	ohms
l	1.56	0.35	0.25	0.03	Cm
α	.003	.005	.003	.064	dB/cm

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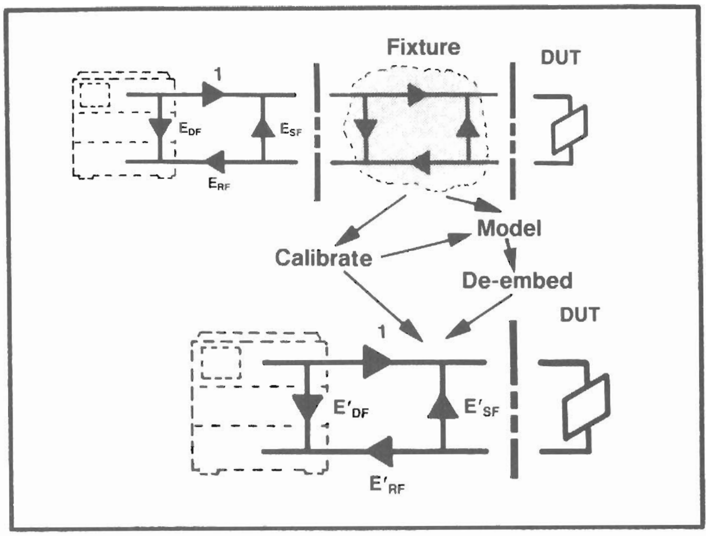
The model shown includes the final topology and element values. The transmission lines are specified in terms of characteristic impedance, length and loss.

With the HP 85014A software pac, the S-parameter response of this model is computed, cascaded with the HP 8510 error adapter, and then stored. De-embedded measurements can then be displayed in real-time by the HP 8510.



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This characterization example illustrates one more relationship for our fixtured measurement diagram. In the real world, solutions to difficult measurement problems are often the result of a combination of different techniques. While we established that calibration and modeling are indeed separate approaches to characterization, in practice both may be used together to arrive at a solution that neither alone could solve.

SUMMARY

- Simple Techniques
- Existing Calibrations
- Modeling/De-embedding

5277

Up to this point, methods for fixture characterization and correction have been presented. The purpose was not to detail any one of the techniques, but to provide an insight into how currently available tools might be applied.

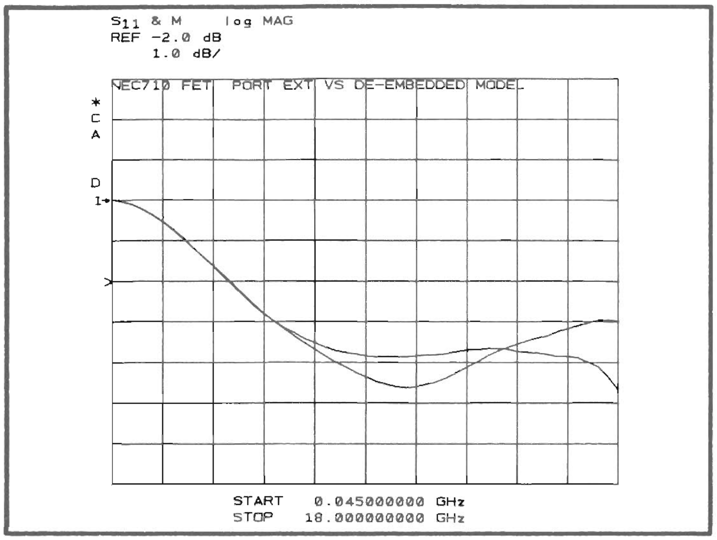
Finally, let's review these techniques once more focusing on the advantages and limitations of each.

CASE 1
SIMPLE TECHNIQUES

- Utilizes Existing ANA Calibration
- May be Useful for Low Frequency Applications
- Cannot Compensate for Fixture Parasitics and Dispersive Effects

5278

First, we considered some simple techniques that could be implemented with existing ANA features - Port Extension and modified standard model definitions. When the fixture's response is measured or assumed to be similar to a coaxial line, approximate DUT data can be displayed directly. This technique cannot remove complex responses due to fixture discontinuities and parasitics however, and consequently may only be useful for low frequency measurements and with simple fixture structures.



5306

This figure shows an impedance measurement of a .5 micron GaAs FET comparing two techniques. Measured data is shown using:

1) a de-embedded fixture model
2) Port Extensions equivalent to a lossless 2.5 cm coaxial line.

At frequencies below 6 GHz, the measured data tracks closely. At higher frequencies, only the de-embedded model can account for parasitics.

CASE 2
EXISTING CALIBRATIONS

- **Closed Form Solutions Available**
- **Compensates for Fixture Parasitics and Dispersion**
- **Characterizes Fixture at Time of Measurement**

5279

Existing calibration techniques have been developed that rely on characterization by direct measurement. Mathematical solutions have been published and can be implemented through a desktop computer and an ANA. These direct characterization methods can account for parasitics and dispersive effects without detailed knowledge of the fixture's structure. Further, any changes in the fixture's physical structure (design improvements) or long term drift are characterized at the time of measurement. That is, the characterization is always unique to that fixture, removing the fabrication requirement that a particular mechanical outline be precisely met.

CASE 2
EXISTING CALIBRATIONS

- **Requires Specified Set of Device-like Standards**
- **Accuracy Solely Dependent on Actual vs. Idealized Response of Standards.**

5280

These calibrations, however, require a specific set of idealized device-like standards. The ultimate accuracy of the corrected measurement rests entirely on how closely the actual response of the standards meet their idealized response. Further, we may have no way of separating systematic fixture effects from errors in specification of the standards. The frequency range over which this technique can be used is not only tied to the useable bandwidth of the fixture but also to the frequency range that the standards exhibit their idealized response.

With these calibration techniques, error correction is post-processed. That is, raw data is taken from the instrument and correction is done on the external computer. De-embedding to preserve real-time correction may or may not be feasible, depending on the topology of the error model.

CASE 3 MODELING/DE-EMBEDDING

- Does Not Require a Complete Set of Idealized Standards
- May Use Time Domain Response to Develop Model
- Uses Available CAE Tools
- Real-time Corrected Response

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Fixture characterization through modeling has become feasible through CAE tools. This technique is particularly useful when fixture standards do not exist or are difficult to use. As a cascade of simple elements, the response of complex fixtures can be characterized through observation, analysis and optimization. Measured time and frequency domain characteristics can be used directly (optimization) or indirectly (postulating network topology and element values).

De-embedding is a technique which allows ANA's to display real-time error corrected data. CAE tools are available which can perform de-embedding directly (HP 85014A) or through post-processing (Touchstone™).

CASE 3 MODELING/DE-EMBEDDING

- Modeling is an Iterative Process
- Requires Knowledge of Potential Fixture Parasitics
- Does Not Compensate for Long Term Drift of Fixture vs Model

5282

Fixture modeling, however, is an iterative process which depends on accurate postulation of representative elements and structure. The accuracy of this process is ultimately dependent on the expertise of the user - particularly, the ability to represent parasitics with an appropriate element.

Once a model has been established, it is assumed that the physical structure of the fixture remains constant. Long term (wear-out) and short-term (temperature) effects may not be accounted for.

OUTLINE

- The Measurement Problem
- Fixture Consideration
- Error Correction Techniques
- Summary

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