HEWLETT PACKARD

Designing and Calibrating RF Fixtures for Surface-Mount Devices

David Ballo

Hewlett-Packard Company
Microwave Instruments Division
1400 Fountaingrove Parkway
Santa Rosa, California 95403
U.S.A.

1996 Device Test Seminar

Effective Test Methods for Today's RF Devices

Abstract

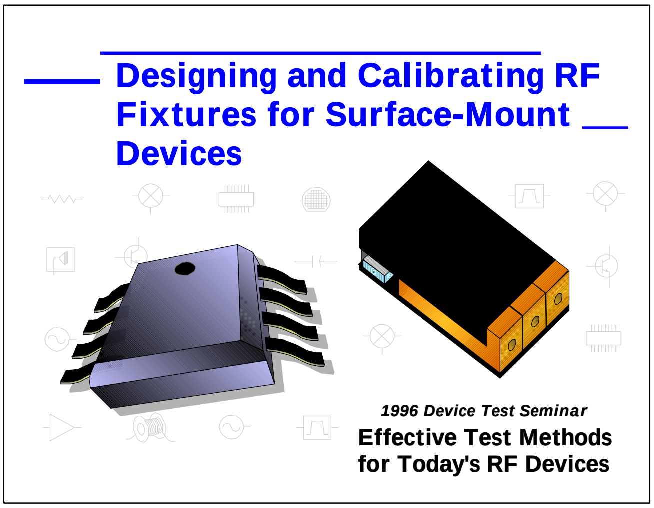
Many devices in today's communications systems are contained in leaded or leadless surface-mount packages, without coaxial connectors. Measuring these devices requires a test fixture in order to interface to coaxial-based test equipment. This paper covers techniques to design high-quality RF fixtures and the calibration standards needed for accurate measurements. These techniques are useful for both leaded and leadless components, from simple two-port devices such as filters, up to more complex multiport RFICs. Calibration alternatives will be discussed and methods will be presented to verify the raw and corrected performance of the fixtures. Included is a case study documenting the fixture-design process for a 947 MHz leadless dielectric-resonant filter.

Author

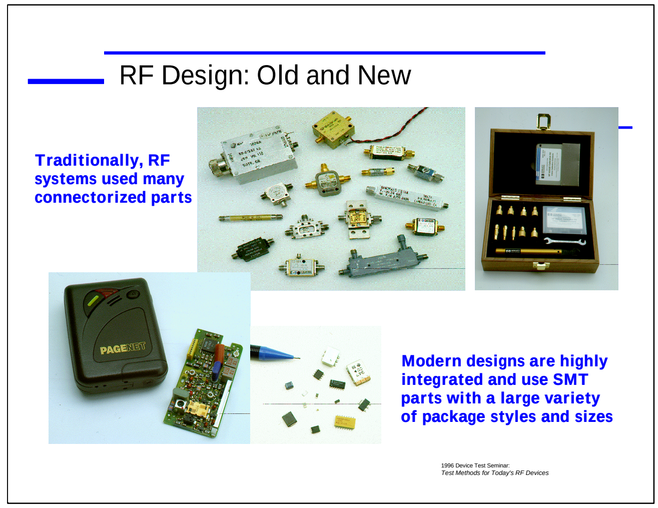
David Ballo is currently a Market Development Engineer for Hewlett-Packard's Microwave Instruments Division in Santa Rosa, California. David has worked for HP for over 15 years, where he has acquired extensive RF and microwave measurement experience. After getting a BSEE from the University of Washington in Seattle in 1980, he spent the first ten years in R&D doing analog and RF circuit design on a variety of Modular Measurement System (MMS) instruments. He followed that with a year in manufacturing. For the past four years, he has worked in the marketing department developing application notes, magazine articles, and seminar papers on topics including TWT amplifier test, group delay and AM to PM conversion of frequency- translating devices, adjacent-channel power measurements, and efficient test of multiport devices.

Designing and Calibrating RF Fixtures for Surface-Mount Devices

Slide #1



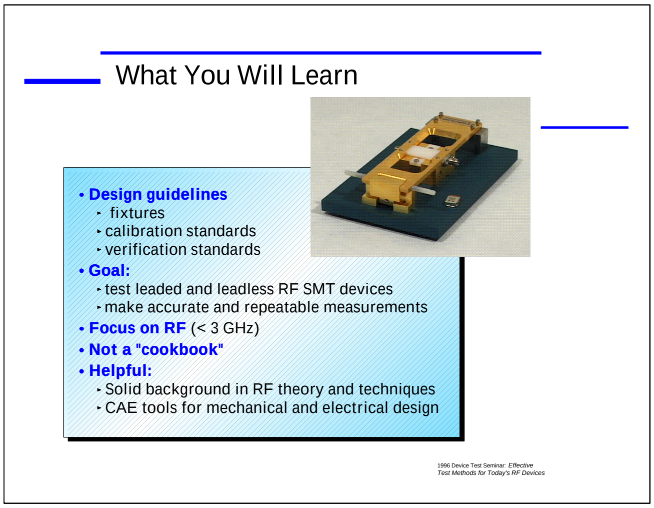
Slide #2



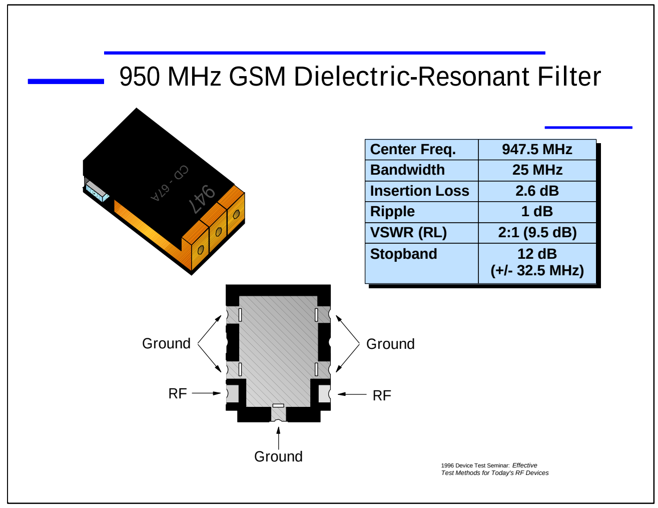
Due to the rapid growth of consumer RF products such as cellular and cordless telephones, a fundamental shift has occurred in the way RF devices and components are made and used. Surface-mount technology (SMT) is pervasive in RF design and manufacturing, requiring new strategies for measurement of SMT 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, and tuned and tested during manufacturing to ensure that performance specifications are met.

It wasn't that many years ago that most RF systems consisted of connectorized components, both passive and active, that were bolted together to form the final system. When printed-circuit boards (PCBs) were used, they consisted mostly of discrete 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.

Slide #3



Slide #4

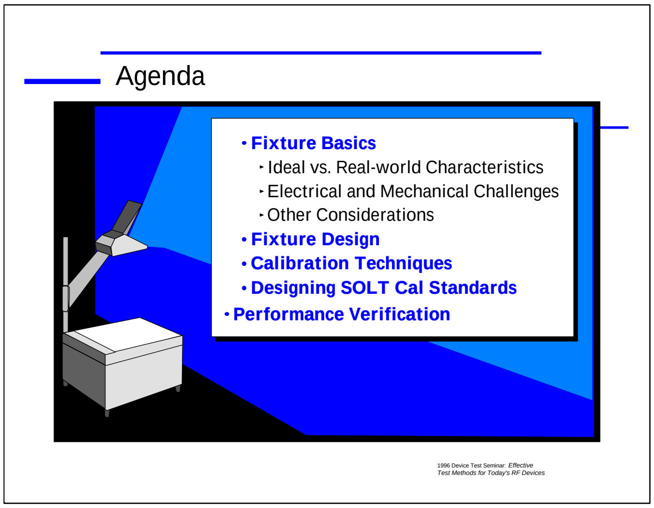


Making quality RF measurements on devices with standard coaxial connectors is relatively easy. Very accurate measurements can be made using commercial calibration kits and standard error-correction routines found in most network analyzers. Performing accurate measurements on devices with non-standard connectors is a little harder, requiring adapters and often custom calibration standards. Devices without connectors are the hardest 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.

The goal of this paper is to offer guidelines for designing effective RF fixtures and calibration standards that will yield repeatable and accurate measurements of surface-mount devices. We will discuss many concerns and issues that must be addressed as part of the fixture-design process. We will focus on applications below 3 GHz, though much of what will be covered is can be extended to higher frequencies. We will not attempt to offer a comprehensive design "cookbook", as most surface-mount parts have unique sets of attributes requiring custom fixture designs. A solid background in RF theory and techniques is very helpful for designing high-quality test fixtures. Access to modern computer-aided engineering (CAE) tools for mechanical and electrical design is also very valuable.

This paper features a case study of a 947 MHz dielectric-resonant filter (DRF) intended for GSM applications, and contained in a leadless surface-mount package. This particular part was chosen as a typical representative of current applications, and will be used as an example throughout the paper. Two different fixtures were designed to test this part. One is an internal HP design done expressly for this paper, and the other was designed by Inter-Continental Microwave (ICM) of Santa Clara, California, a commercial supplier of standard and custom RF and microwave fixtures. Both fixtures had to address the same set of problems, and as we will see, they exhibit both similarities and differences. As we explore the different aspects of fixture design, we will show how the design approaches of our sample DRF fixtures attempted to solve the various problems.

Slide #5

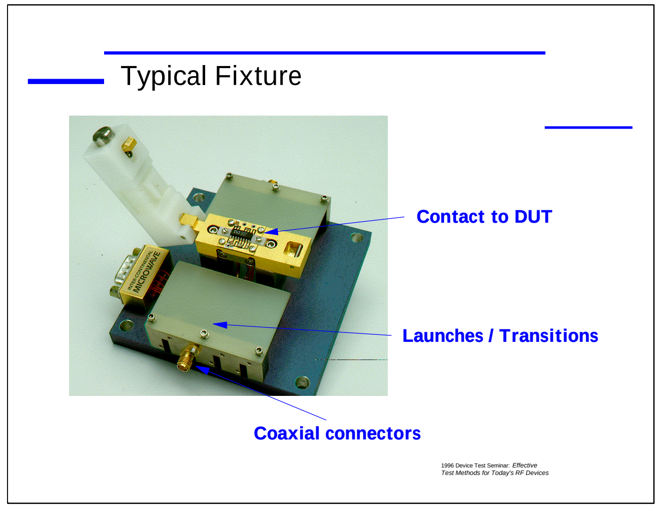


We will start out discussing fixturing basics, including the goal of fixtures and what separates an ideal fixture from one that can be achieved in the real world. We will cover both electrical and mechanical challenges of designing fixtures, as well as other considerations that must be taken into account before finally deciding on the optimum design approach.

Next, we will cover various aspects of fixture design such as part insertion, alignment, and clamping, making good transitions between different transmission-line types and sizes, minimizing discontinuities, making electrical contact, and if necessary, providing matching elements and bias.

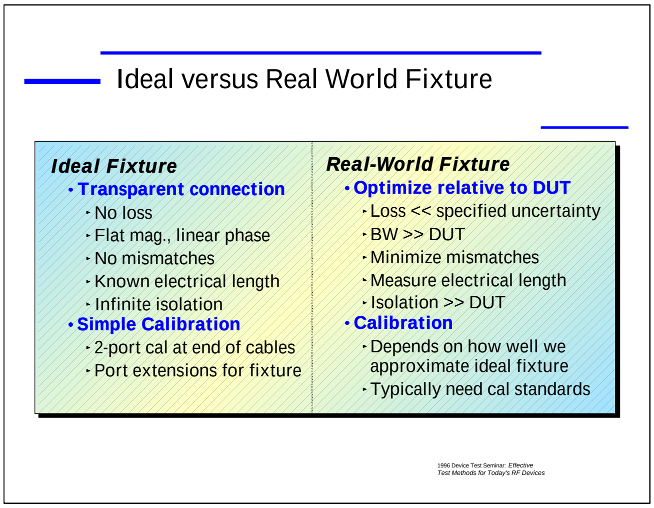
Following that will be a discussion of the various calibration strategies available, and then a section on designing in-fixture calibration standards to achieve the highest levels of accuracy. Finally, we will discuss ways to verify corrected performance and estimate error residuals, which can then be used to compute measurement uncertainty.

Slide #6



The goal of any RF fixture is to provide some or all of the following objectives. First of all, the fixture must provide coaxial connectors to allow interfacing to test cables. For RF applications, SMA or Type-N connectors and cables seem to be the most common type. Often what follows is some sort of transition or launch from the coaxial connector to a noncoaxial transmission line such as microstrip. Along the way, there may be other transitions before the signal conductor arrives at the DUT. The fixture must then make electrical contact with the DUT. If the impedance of the DUT is not the same as the system reference impedance, then matching elements may be needed for proper measurements. Finally, active parts need bias current and voltages supplied to the proper pins or ports.

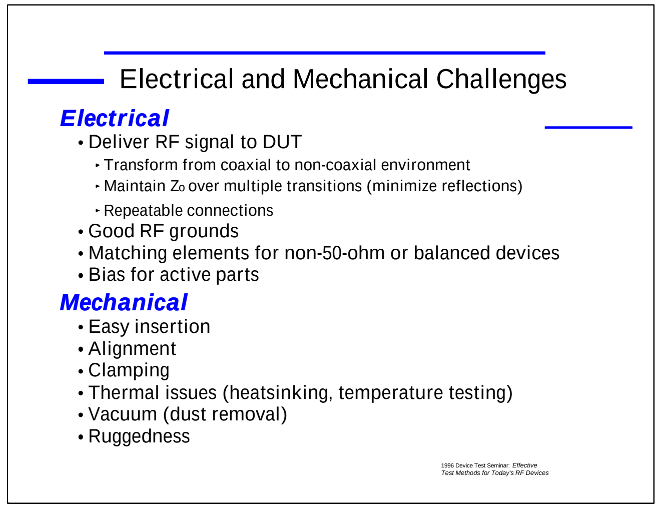
Slide #7



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.

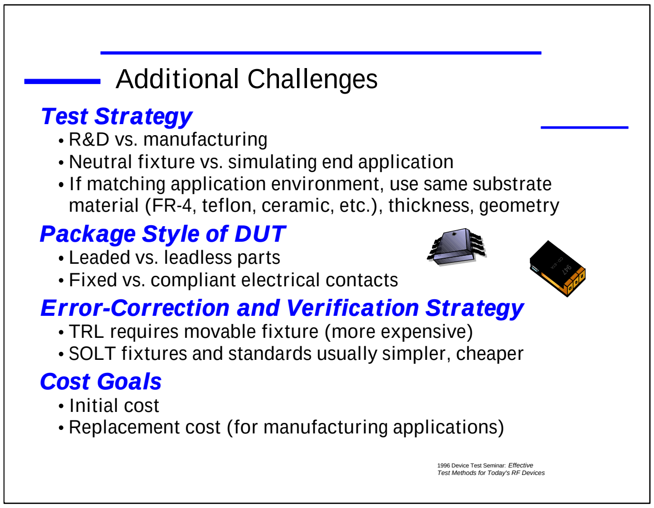
Since it is impossible to make an ideal fixture in the real world, we can only hope to approximate the ideal case as best as possible. We can do this by optimizing the performance of the test fixture relative to the performance of the DUT. We can try to make the loss of the fixture smaller than the specified 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. 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 #8

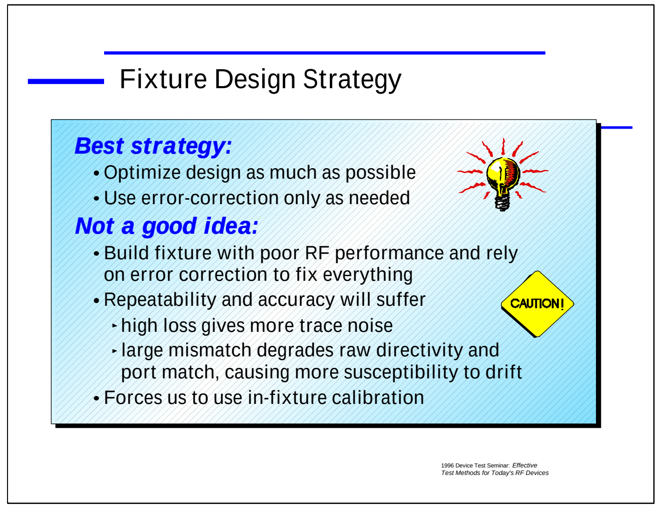


Now that we know how our real-world fixture should behave, let's consider some of the electrical and mechanical challenges that the fixture must address. We'll start with the electrical challenges. The fixture must deliver an RF signal to the DUT, which means converting from a coaxial to a non-coaxial environment at some point. The system reference impedance Z_o (usually 50 ohms) must be maintained over multiple transitions to provide a good match. The fixture must provide good RF grounds and eliminate spurious ground paths. Fixtures designed to test non-50-ohm or balanced devices may need matching elements. For example, we may need to transform up to a high-impedance passive device like an IF SAW filter, or transform down to a low-impedance active part like a transistor. Bias is required for active parts. Perhaps most importantly, it is essential that we have repeatable connections to the DUT, often for thousands and thousands of insertions.

The mechanical challenges of a good fixture are by no means trivial either. The fixture has to allow easy insertion of the DUT, with proper alignment. For repeatability, a clamp is generally desirable. For most applications, non-destructive contacting is essential. Thermal concerns must also be considered, such as the need for adequate heatsinking of power devices. Or perhaps the fixture needs to provide heating or cooling for environmental testing. In manufacturing applications where it is necessary to grind the resonator dielectric to tune the filter (ceramic duplexers for example), a vacuum dust-removal system may be required as part of the fixture design. Finally, the fixture should be rugged to withstand repeated use, particularly in manufacturing environments.



Slide #9

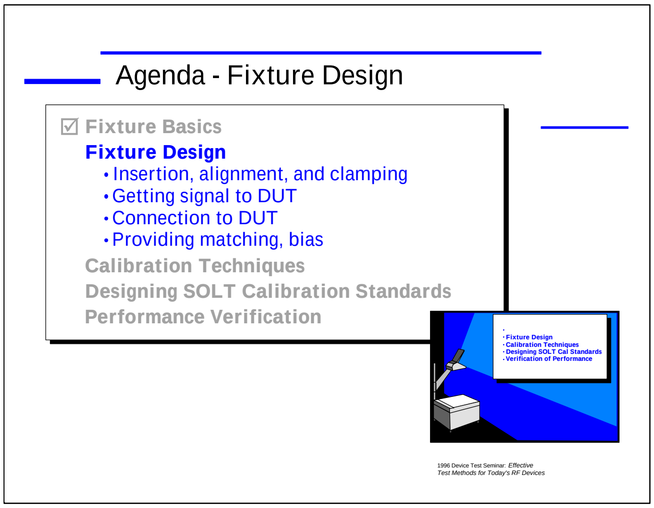


There are additional considerations that must be evaluated before we can begin to develop a fixture design strategy. The first step is to define our test strategy. Are we only going to measure a few parts in R&D or are we expecting to measure many parts in manufacturing? Are we trying to measure the DUT with a neutral fixture, or will the fixture simulate the end application? If we want to match the application environment exactly, the fixture and the end application should share the same substrate material, thickness, and pad geometry.

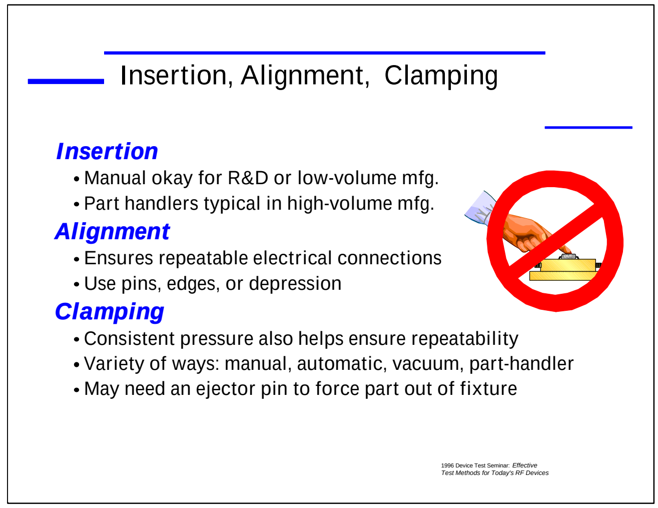
The package style of our DUT will also affect our design considerably. Fixtures for leaded surface-mount parts are often easier to design since the leads themselves can absorb the non-flatness of the fixture or lead geometry. Leadless (and sometimes leaded) parts require compliant contacts to ensure good RF signal and ground connections.

We must also consider our error-correction and verification strategy before undertaking the design of the fixture. If we intend to use thru-reflect-line (TRL) calibration, we will require a separable fixture capable of accepting center sections of different length. This type of fixture and the corresponding calibration standards are often more expensive to build. Alternately, we may wish to use short-open-load-thru (SOLT) calibration, which generally means simpler and therefore less expensive fixtures and standards. Knowing our cost goals from the beginning is very important. It may be sufficient for some applications to have a simple, inexpensive fixture, where other times a more flexible and robust (and therefore more expensive) fixture is desired. For manufacturing applications, the cost of replacing all or part of the fixture due to wear must also be considered.

Slide #10



Slide #11

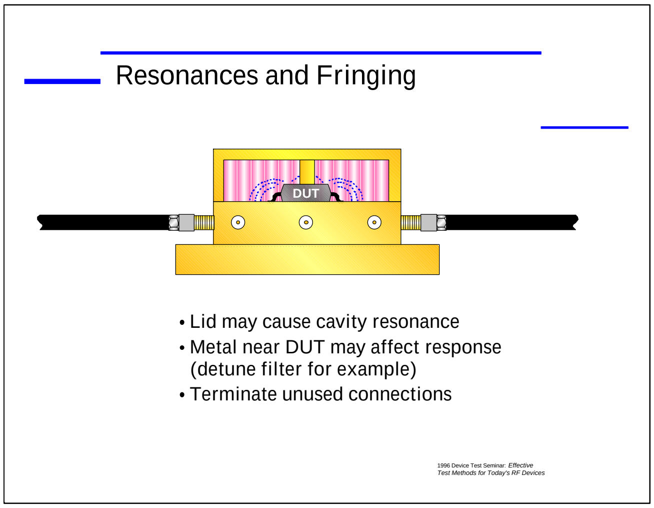


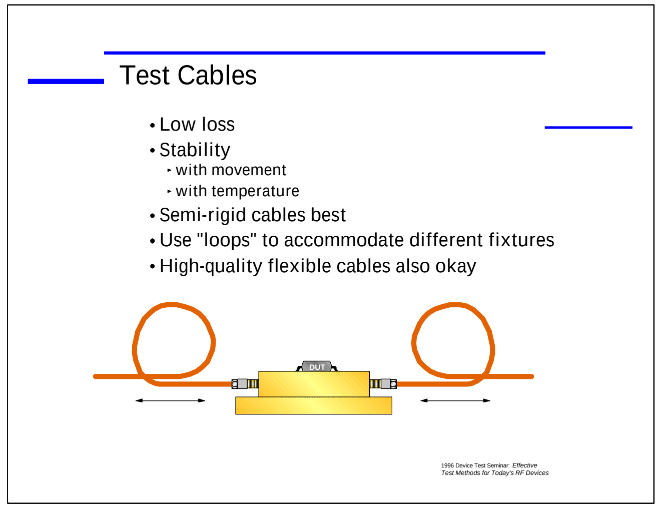
Once we have evaluated all of the previously discussed considerations, we can go about designing the fixture for our particular application. The best strategy is to optimize the fixture design as much as is practically possible, and then, if our application demands it, use some form of error-correction to remove the remaining errors. Building a poor fixture and expecting calibration to fix everything is not a good idea, as measurement repeatability and accuracy will suffer. For example, a fixture with a lot of loss causes degradation of measurement signal-to-noise-ratio, resulting in more trace noise and therefore greater measurement uncertainty. Fixtures with excessive mismatch severely degrade the raw directivity and port matches of the overall test system, resulting in greater susceptibility of measurement uncertainty due to drift. Furthermore, fixtures with poor RF performance usually force us to take the time and cost penalty of in-fixture calibration, in order to make decent measurements.

On the other hand, if we design a good fixture with performance that is significantly better than the specifications of the DUT, we may be able to get away without any in-fixture error correction, using only coaxial calibration at the ends of the test cables and perhaps port extensions. Components with more demanding specifications will often require more advanced error-correction techniques such as de-embedding or calibration using physical standards.

This section of the paper will discuss the various aspects of fixture design that are needed to build high-quality RF fixtures. We will start with the task of getting the DUT physically into the fixture, with proper alignment and clamping. We will then cover ways of getting the test signal to the DUT while minimizing mismatch, and how to electrically and mechanically connect to the leads or pads of the DUT. We will also briefly cover some considerations about providing bias for active parts and matching for non-50 ohm devices.

Slide #12



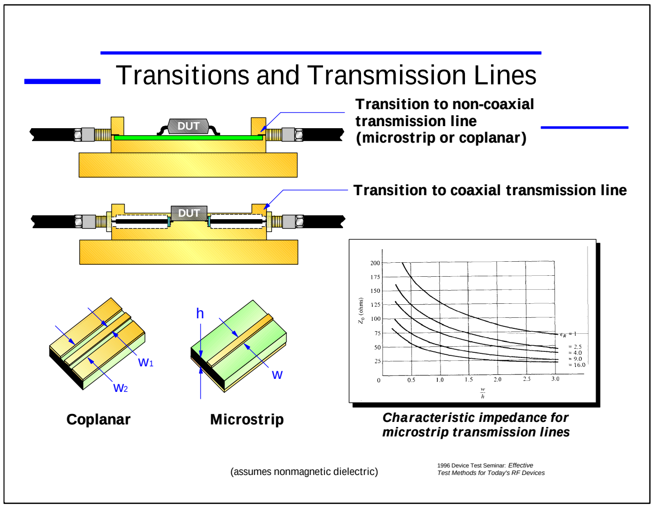


The first step in measuring a surface-mount device is to physically insert it into the test fixture. The part can be placed by hand in an R&D or low-volume manufacturing environment, or be inserted with an automated part handler. The fixture must provide some way of aligning the part to ensure that electrical contact is made to the proper pads or leads. The alignment of the part should be very consistent to ensure good measurement repeatability. Small shifts in DUT alignment can cause electrical paths to vary, which can result in significant measurement uncertainty. One way to achieve alignment is to place a pin in the fixture that is keyed to a notch or edge on the part. Another way is to use a depression in the fixture that matches the dimensions of the DUT.

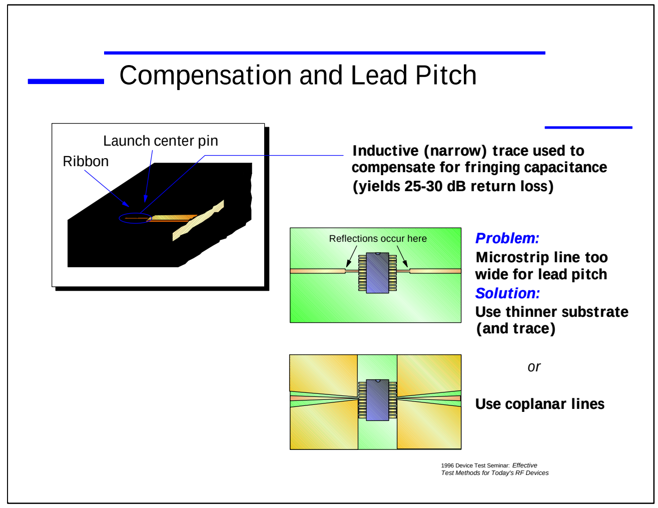
Clamping the part in place is critical because controlled, consistent pressure is key to making good, repeatable electrical measurements. While "finger pressure" may be okay in the R&D lab, it is generally not suitable for use in manufacturing applications. The clamp must provide just the right amount of mechanical travel to ensure proper electrical contact without putting undue flex on leads or contacts, or forcing the part to bottom-out in the fixture. Consistent pressure is important since contact resistance between DUT and fixture can vary with pressure. A clamp might consist of a simple hand clamp as our example fixtures use, or a more sophisticated clamp that might allow faster throughput for high-volume manufacturing. Other options include using a part handler to provide the clamping function, or a fixture with a vacuum-based clamp. After the part is tested, some fixtures employ a release mechanism that pops the part out of the fixture, making for easy retrieval.

Designing and Calibrating RF Fixtures for Surface-Mount Devices

Slide #13



Slide #14



Ideally, the mechanical attributes of the fixture will have no impact on the electrical performance. However, sometimes electrical resonances occur, especially at frequencies above 3 GHz or so. For example, a cavity resonance can occur when a lid is placed over the fixture. This problem can usually be solved by proper placement of a lossy substance, such as polyiron, or by not using a lid in the first place. Another cause of resonances can be adjacent contact pins or transmission lines. To avoid unwanted reflection or crosstalk, unused connections should be properly terminated.

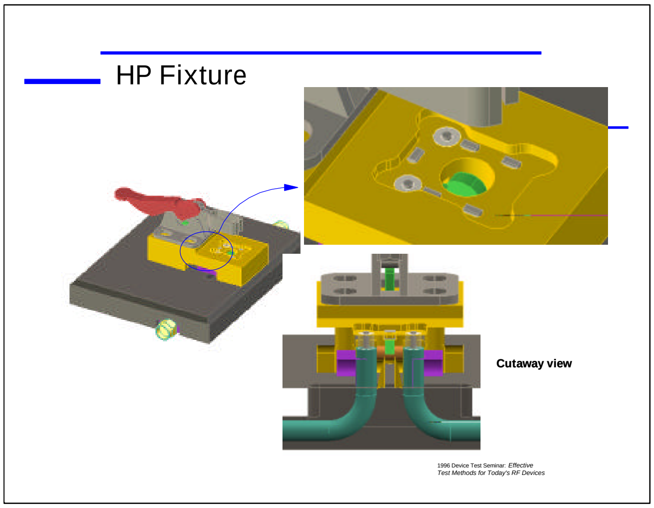
Another potential problem is excess electrical fringing between the DUT and the fixture. This can cause electrical performance of the DUT to be different in the fixture than in the end application. The problem can happen if the DUT will not be near any metal on the PCB, but metal parts of the fixture get too close during test. For example, a metal clamp or alignment pin could cause filter resonators to be detuned or exhibit lower Q. In general, it is best that any non-electrical contact to the DUT be made with nonmetallic parts.

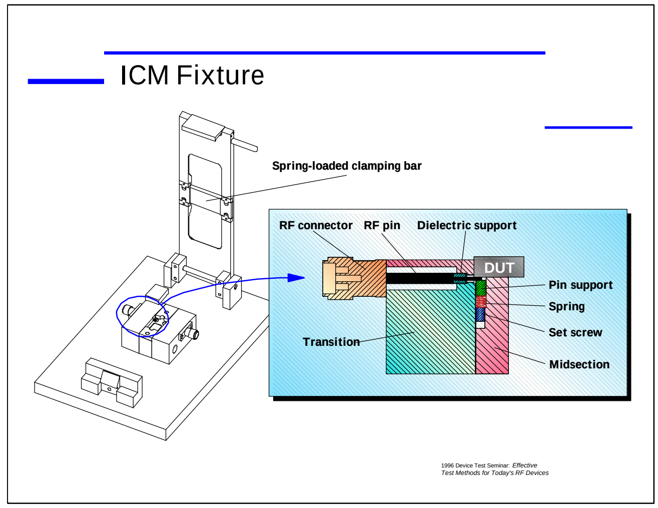
Before we begin discussion on the electrical aspects of fixture design, it is worthwhile to talk about the test cables used between the network analyzer and the fixture. They should exhibit low loss over the frequency range which we want to measure. The stability of these test cables also needs to be good to get repeatable measurements. Inexpensive cables can give different results even with minimal movement, particularly when doing phase measurements. This phenomenon gets worse at higher measurement frequencies. The test cables also need to be stable over temperature. Normal temperature fluctuations can be a significant source of random errors if poor test cables are used.

The best choice for test cables is semi-rigid coax. Loops can be added to allow for some variation in fixture width if multiple fixtures will be used at a given test station. High-quality flexible test cables, while more expensive, also have excellent repeatability.

Designing and Calibrating RF Fixtures for Surface-Mount Devices

Slide #15





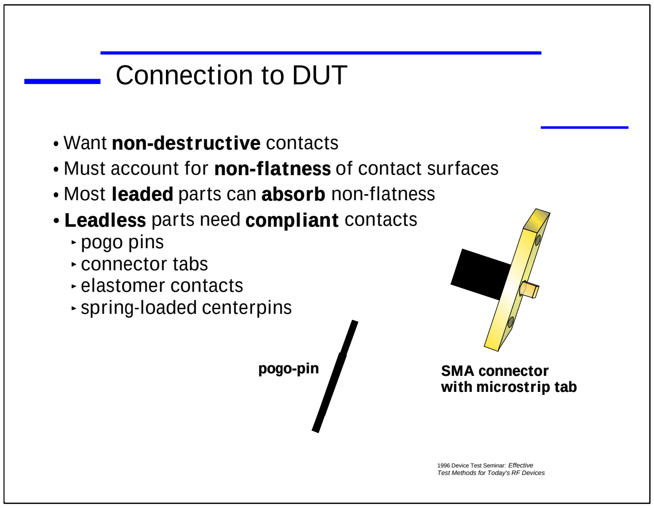
One of the most challenging aspects of fixture design is to provide a good RF path between the test cables and the DUT. The goal is to maintain Z_o (usually 50 ohms) across different transmission line media, while minimizing reflections at discontinuities.

The first step in the RF path is the coaxial connector. For the RF range, type-N or APC 3.5 connectors are the best choices (since cal standards are available in those connector styles), but SMA connectors are also acceptable. What follows will be a transition to some sort of transmission line. For leaded parts, non-coaxial lines are usually used as it is easy to make contact between the transmission line and the DUT. For leadless parts (when compliant contacts are needed), coaxial lines often make more sense.

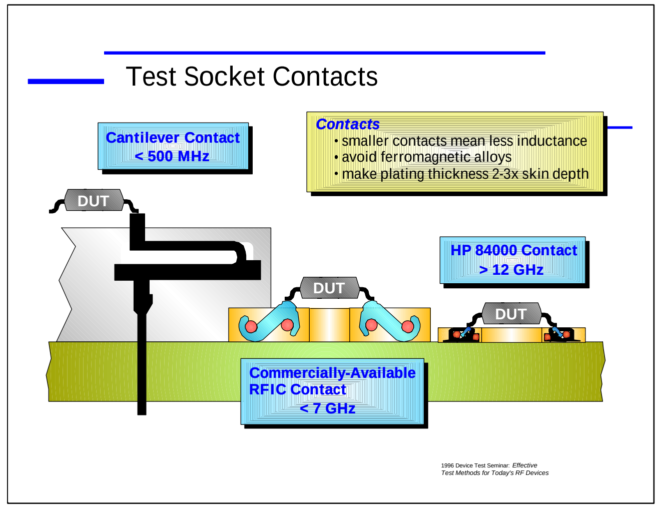
Microstrip is the most common non-coaxial transmission line for RF applications. It is easy to make a connector-substrate launch, as the center pin or tab of the connector can directly touch the microstrip line. The bottom of the microstrip substrate can have direct contact to the fixture, providing a solid RF ground. The graph above shows the width/height ratio versus line impedance for different substrate dielectric-constants.

Another common transmission medium is coplanar line, consisting of a center conductor with ground surfaces on either side. This is more common for microwave applications as it is convenient for probing (the probes can use the standard ground-signal-ground layout). For non-probe applications, it is harder to properly ground a coplanar substrate to the fixture. Both microstrip and coplanar lines allow easy placement of discrete components for matching, supply bypassing, etc.

Slide #16



Slide #17



Providing a low-reflection transition between the centerpin of a bulkhead connector and the signal trace of a non-coaxial transmission line can be challenging. Typically the diameter of the centerpin is not the same as the width of the trace, causing some fringing capacitance. HP solved this problem with its HP 83040 series of modular microcircuit packages (now obsolete) by using inductive compensation at this transition. The center conductor of the microstrip line was briefly narrowed to look inductive, effectively canceling the fringing capacitance. The centerpin was also bonded to the microstrip line with a wrap-around gold mesh, to ensure consistent electrical connection. Return loss of 25-30 dB or better was obtained in this manner.

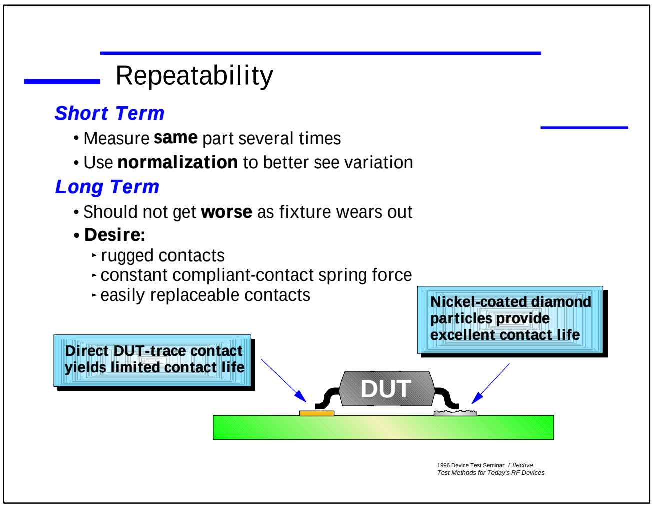
When dealing with multi-leaded RFICs, lead pitch can be a problem. A wide microstrip trace might have to narrow considerably to match the size of a pad or lead. This discontinuity will cause some reflection to occur. One alternative is to use a thinner substrate, resulting in a microstrip line with a smaller width. A coplanar design can easily accommodate this problem since transmission lines can gradually get narrower and still maintain the proper Z_o. If discontinuities occur, it is desirable to place them as far away from the DUT as possible so time-domain gating can easily separate the reflections from the DUT and the fixture (more discussion on this later).

An alternative to having a coaxial-connector launch to a microstrip or coplanar line is to use a coaxial transmission line structure right up the DUT. This approach was taken by both the HP and ICM fixture designs for the example GSM filter. The HP fixture uses pieces of 0.141" semi-rigid cable with SMA connectors on one end and flush cuts at the other end. Small pieces of conductive cylindrical elastomer are used for electrical and mechanical contact between the semi-rigid cables and the DUT. A 50-ohm environment is maintained around each elastomer piece. This design provides a low-cost transition with reasonably good RF performance. Our approach from the beginning was to design a low-cost fixture for manufacturing use. We felt this approach was a good way to achieve an economical fixture with an easy way to replace the contacts to the DUT should they wear out.

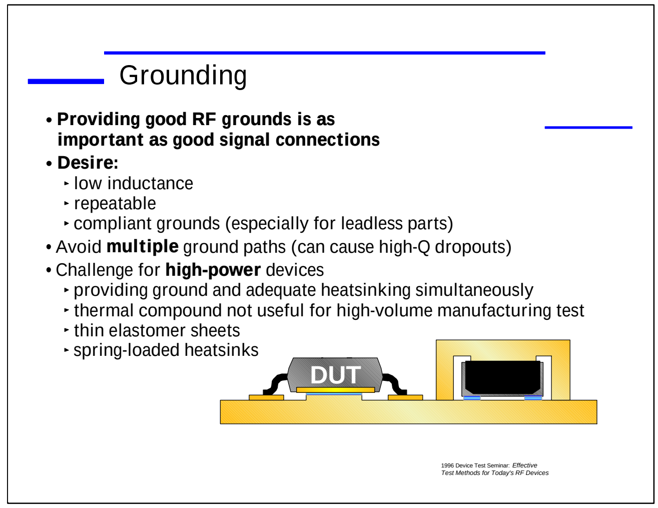
While the use of elastomer contacts to the DUT works well for RF, it may not be suitable for DUTs requiring high-current DC connections, as the elastomer contacts can have excessive DC resistance for this application.

Designing and Calibrating RF Fixtures for Surface-Mount Devices

Slide #18



Slide #19



Instead of using semi-rigid cable, the ICM fixture uses suspended coaxial transmission lines. The middle of the centerpin is suspended in air. One end is supported with a plastic dielectric insert, and the other end is inserted into a flange-mounted SMA connector. To maintain a constant impedance over the length of the transmission line, the ratio of diameters of the centerpin and the hollow cylinder in which it rests must remain constant. When the centerpin steps to a larger or smaller size, the outer conductor wall must step accordingly. If this constraint is not followed, significant reflections would occur at the transitions. The end of the center conductor nearest the DUT is extended slightly beyond the coax structure in order to make contact with the DUT. The contact end is pushed upward slightly by a spring-loaded dielectric dowel in order to provide a compliant contact to the DUT.

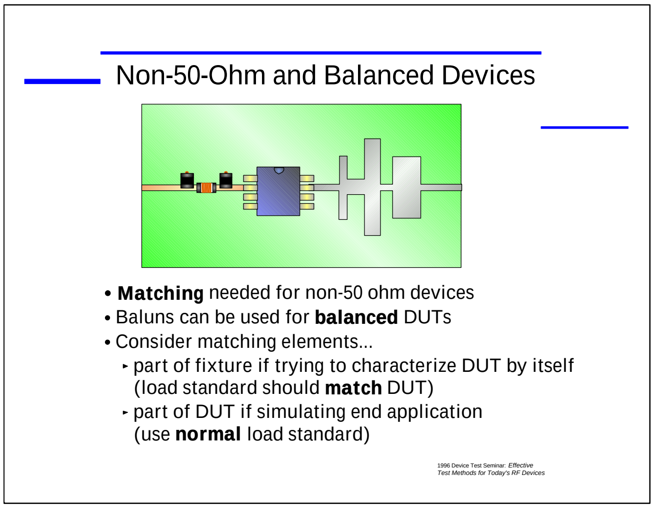
As one can see from the above and previous illustrations, using modern CAE tools (such as HP's ME-30) for fixture design is extremely helpful as considerable mechanical detail is necessary to achieve an effective design.

Providing a good electrical contact to the DUT is one of the most important aspects of fixture design. For manufacturing (and often for R&D), non-destructive pressure connections are desirable, so many parts can be quickly and easily measured. Soldering parts into the fixture is not a viable option for manufacturing test.

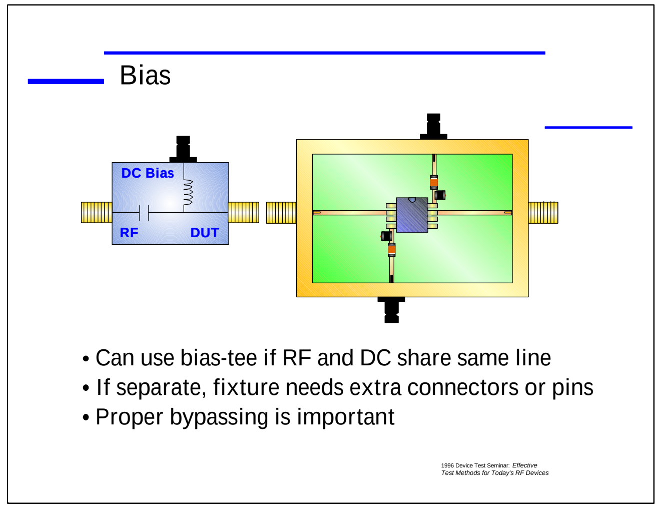
Making good pressure connections requires that non-uniformity of the DUT contact surface be considered. For example, a leadless package cannot simply rest directly on the fixture substrate, because signal or ground pads may not make good contact due to non-uniform part flatness. Some sort of contact compliance is needed, supplied either by the spring-force of the DUT leads, or by compliant contacts in the fixture. Some manufacturers require compliant fixture contacts even for devices in leaded packages, to avoid undue flexing of the leads or because lead stiffness is too great to overcome their contact unevenness.

There are several different ways to make compliant electrical connections. We have seen two approaches already. Another choice is to use "pogo-pins", which are spring-loaded metal pins that contact the pad of the part. They must be incorporated into a transmission-line structure of some sort. One very simple approach used by some device manufacturers are flange-mounted SMA connectors with microstrip tabs on the launch end of the connector (rather than the more-common extended centerpin). The contact pads of the DUT are placed directly on these tabs, which provide the necessary spring force for compliant connections.

Slide #20



Slide #21



For automated semiconductor test systems, the contact to the DUT is often made with a compliant test socket integrated onto a larger test board. Standard commercial test sockets designed for digital test use a cantilever technology which is only useful to around 500 MHz. For RFIC test, shorter contacts with lower inductance are essential. Commercial test sockets are readily available that work well to around 7 GHz.

For the HP 84000 series of custom RFIC test systems, a very low-inductance, compliant contact was designed with excellent performance to above 12 GHz. The spring force for these contacts is provided by conductive elastomers. Special alloys are used to provide good electrical conductivity with low friction between moving parts. Individual contacts can easily be replaced. This technology is only available in the HP 84000 test systems, and is not sold separately.

Some care must be taken when choosing alloys or plating material for compliant contacts. Materials that exhibit ferromagnetic properties (such as iron or steel) should be avoided as they can actually increase intermodulation distortion, especially at high power levels. Another concern is that at very-high frequencies, "skin effect" starts to be significant (current travels near the surface of the contact). For plated contacts used above 1 GHz or so, the plating thickness should be several times the skin depth. Gold is commonly used to plate contacts as it yields excellent contact life and can be applied over a variety of metals such as beryllium copper, aluminum, or brass.

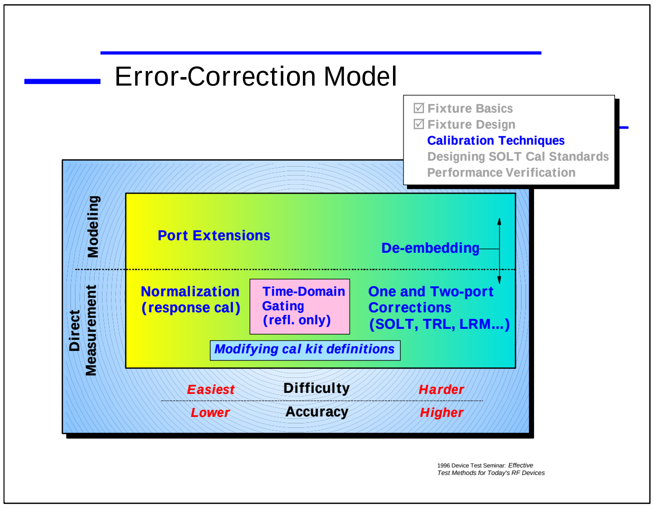
One very important aspect of fixture performance is repeatability. Inserting and measuring the same part several times gives a good indication of how much measurement uncertainty to expect due to part alignment, contact pressure, and grounding variations. The first measurement can be used as a reference for normalization. Subsequent measurements will then directly display measurement uncertainty.

Long-term repeatability is a big consideration for fixtures intended for manufacturing applications. The fixture should continue to give repeatable and accurate measurements even after repeated insertions and connections have been made. Spring force should remain fairly constant over the life of the contacts. The contacts should be easily replaceable as well, so the entire fixture does not have to be discarded after the contacts wear out. While the elastomer contacts use in the HP fixture are easily replaceable, an evaluation would have to be undertaken to determine how many connections could repeatably be made before new contacts should be inserted. Fixtures with spring-loaded metal contacts like the one designed by ICM have been shown to provide reliable contacts for several hundred thousand connections before needing replacement of the center pin.

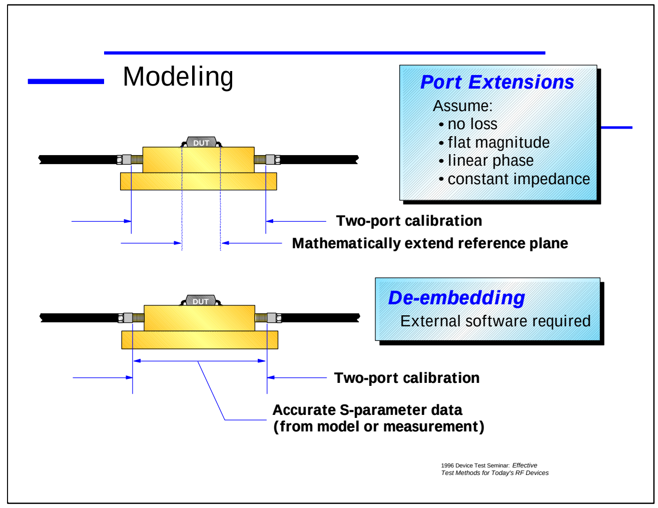
For fixtures that rely on direct contact to leaded parts (without compliant contacts), one contact technology that can be used is nickel-plated diamond particles. These particles are bonded directly to the PCB during the fabrication process, and provide a rugged contact surface capable of many 100's of thousands of contacts. Using direct contact between the lead of the part and the PCB is not a good solution for manufacturing test, as contact life is very limited.

Designing and Calibrating RF Fixtures for Surface-Mount Devices

Slide #22



Slide #23



Providing low-impedance repeatable RF grounds is just as important as providing good signal connections. Ground connections that are not part of the expected grounding scheme of the DUT should be avoided. Multiple ground paths can cause small, discrete discontinuities (high-Q dropouts) in the measured response, as the phase of the various paths vary versus frequency. Inductive grounds can also cause measurement impairment, such as degraded stopband isolation or poor return loss. As with signal lines, compliant ground contacts can be useful to ensure consistent ground connections. For example, the HP-designed fixture uses small rectangular pieces of conductive elastomer that sit in recesses in the fixture. These flexible contacts align with the ground pads of the filter.

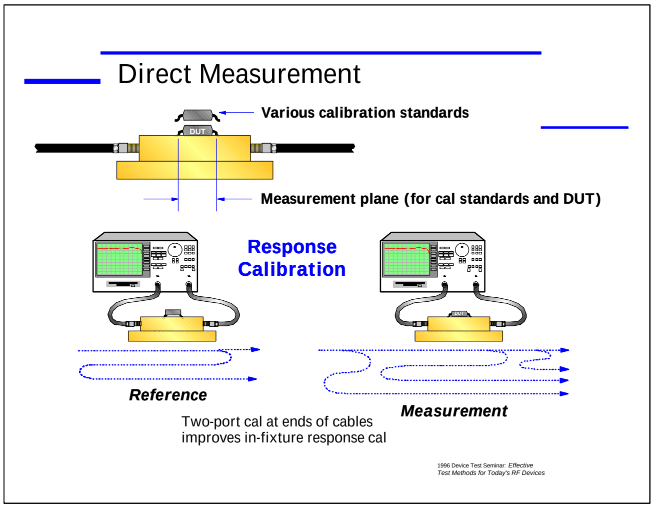
One challenge when testing high-power devices is providing good RF grounding and adequate heatsinking simultaneously. While a thermal compound can be used during R&D characterization and during assembly, it is generally not suitable for high-volume manufacturing test. A thin elastomer sheet with high electrical and thermal conductivity has been successfully used by some transistor manufacturers. Another successful solution used for SOIC devices is to use a spring-loaded heatsink which contacts the underside of the DUT.

When testing non-50-ohm devices, sometimes a matching network is needed to make good measurements. Matching elements include discrete inductors and capacitors, baluns and other types of transformers, and transmission line stubs and steps. Baluns can be used to test balanced parts such as differential-input amplifiers or balanced filters.

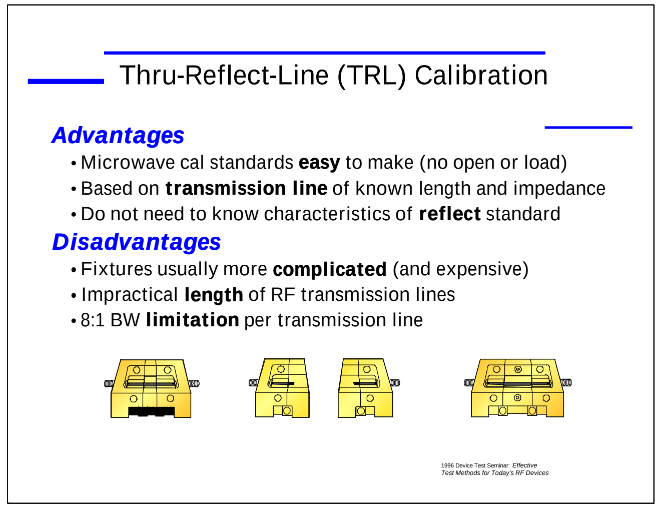
There are two different in-fixture calibration strategies that can be used when testing non-50 ohm or balanced parts. If we are trying to measure the performance of the DUT by itself, we must consider the matching elements as part of the fixture. This requires that our load standard be the same impedance as our DUT. If we are testing a balanced device, our load must also be balanced. This approach should be used if we are trying to determine the optimum matching network based on the performance of our DUT.

If we already know what our matching circuit will look like in the end application and we want to characterize the combined network (DUT plus matching elements), we can consider the matching network part of the DUT. In this case, we should use a 50-ohm load standard before the matching circuitry. The fixture design must somehow allow us to break the connection before the matching elements in order to perform a calibration. The matching elements should be located as close to the DUT as possible.

Slide #24



Slide #25



Making in-fixture measurements of active parts requires that DC bias be supplied along with the RF signal. Traditionally, when bias was needed for testing transistors, external bias tees were used in the main RF signal path. This approach is still valid today. However, most packaged amplifiers and RFICs require that DC power be supplied on separate pins. This means the fixture must provide extra connectors or DC-feedthroughs for the necessary bias.

Just as with matching elements, discrete elements can be place directly on the fixture near the DUT to provided proper RF bypassing and isolation of the DC supply pins. Good RF bypassing techniques can be essential as some amplifiers will oscillate if RF signals couple onto the supply lines. As was previously mentioned, bias connections to the DUT should present a low DC impedance.

Now that we have looked at the various aspects of making good RF fixtures, let's examine our error-correction choices. The relative performance of our fixture compared to the specifications of the DUT 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.

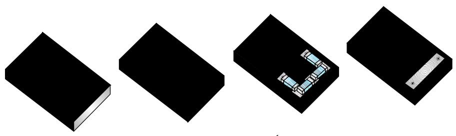
Direct measurement usually involves measuring physical calibration standards and calculating error terms. This method provides accuracy that is based on how precisely we know the characteristics of our calibration standards. The number of error terms that can be corrected varies considerably depending 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.

Time-domain gating is a special technique that can be used for making error-corrected reflection measurements on broadband devices. We will see later that time-domain gating can be a valuable tool to help us characterize the reflection performance of both our load and thru load standard.

Slide #26

Short-Open-Load-Thru (SOLT) Calibration

SOLT Cal is Attractive for RF Fixtures
- **Simpler** and less-expensive fixtures and standards
- Easy to make **broadband** calibration standards
- Cal standards must **match** pad geometry of DUT



How often should I calibrate? Depends on:
- **temperature** drift
- **wear** of fixture
- DUT **specifications**

Slide #27

Modifying Cal Kits

	Open	*Short*	*Load*	*Thru/Line*	*Arbitrary Impedance*
Capacitance	☑				
Inductance		☑			
Offset delay	☑	☑	☑	☑	☑
Offset Zo	☑	☑	☑	☑	☑
Offset loss	☑	☑	☑	☑	☑
Min/max frequency	☑	☑	☑	☑	☑
Coax/waveguide	☑	☑	☑	☑	☑
Fixed/sliding/offset			☑		
Terminal impedance					☑

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.

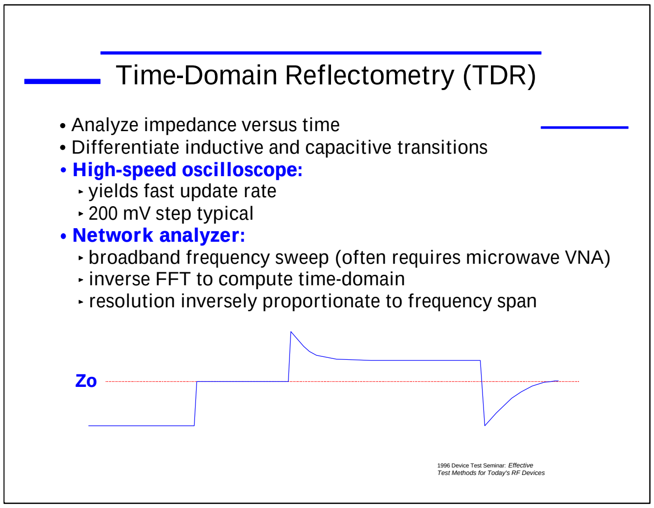
A more rigorous approach is to use de-embedding. De-embedding requires an accurate linear model of the fixture, or measured S-parameter data of the fixture. Computer-aided design (CAD) tools can help analyze and optimize the model of the fixture. In-fixture calibration standards may be used to help measure 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.

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 cal only requires one standard each for transmission (a thru) and reflection (a short or open).

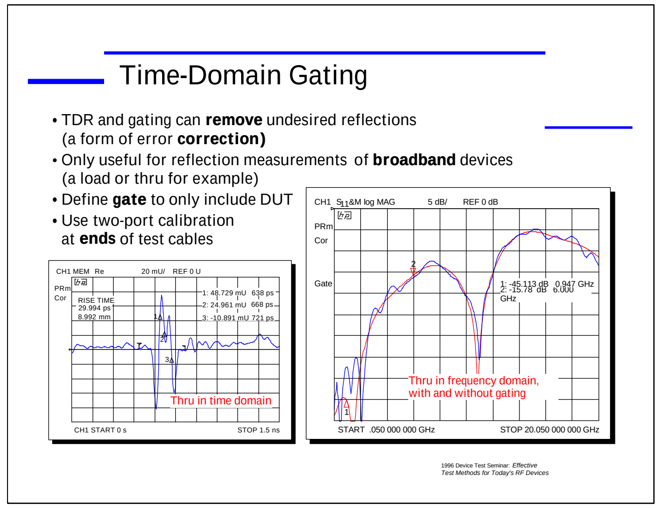
Response calibration has a serious inherent weakness because no correction can be done for errors due to source and load match. This is especially a problem for low-loss transmission measurements (such as measuring a filter passband or a cable) and for reflection measurements. Using response calibration for transmission measurements on low-loss devices can result in considerable measurement uncertainty in the form of ripple. Measurement accuracy will depend on the relative mismatch of the test fixture and network analyzer compared to the DUT. Response calibration is often acceptable for transmission measurements with significant loss in at least one direction (an amplifier for example), but is not a good idea for reflection measurements.

When response calibration is used for transmission measurements with fixtures, considerable measurement improvement can be made by first performing a two-port correction at the ends of the test cables. This will improve the effective source and load match of the network analyzer, thus helping to reduce the measurement ripple due to reflections from the fixture and the analyzer's test ports.

Slide #28



Slide #29



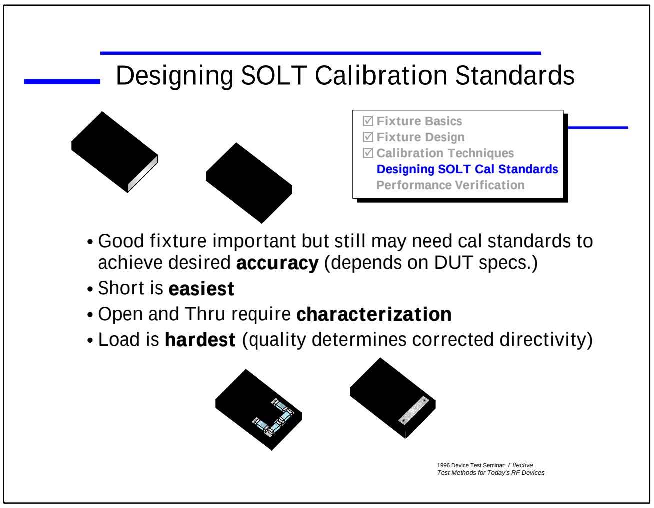
More advanced error correction than response/normalization is achieved with more measurements and more calibration standards. For example, a one-port open-short-load (OSL) calibration requires three measurements of three standards, while a two-port SOLT calibration requires twelve measurements on four standards. The most accurate calibration of a fixture is achieved by using a full set of calibration standards measured at the contact plane of the DUT. The two most common types of fixture calibrations based on physical calibration standards are TRL and SOLT. Each has its unique set of advantages and disadvantages, but if properly done, both yield excellent measurements.

The main advantage of TRL is that the cal standards are relatively easy to make and define. This is a big benefit for microwave applications, where it is difficult to build good open and load standards that are needed for an SOLT calibration. TRL uses a transmission line of known length and impedance as one standard. The only restriction is that the line needs to be significantly longer in electrical length than the thru line, which typically is of zero length. The general rule-of-thumb for the line standard is that it should be between 20 and 160 degree in length, which for our GSM filter at 947 MHz, would result in a transmission line between one and nine centimeters in length. TRL calibration also uses a high-reflection standard (usually a short or open) whose impedance does not have to be well characterized.

The biggest disadvantage of TRL is that the fixture is generally more complicated and expensive to manufacture compared to a fixture designed for SOLT standards. This is because a TRL-based fixture must be capable of being separated in half, to allow insertion of the long transmission lines. At RF, the transmission lines can get too long to be practical as well. Another drawback is that the transmission lines can only be used over an 8:1 bandwidth. For a broader calibrated bandwidth, additional line standards must be made.

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. SOLT calibration does not require the fixture to move. For electrical contact, the calibration standards have to match the pad geometry of the DUT. For mechanical insertion, the standards have to fit in the fixture with proper clamping, but it is not necessary that they match the DUT package exactly. Another advantage of SOLT calibration is that the standards generally work over a very broad bandwidth - calibration from DC to 3 GHz is easy to achieve.

How often will we be required to perform a calibration? It depends primarily on three factors. The first is the thermal stability of the test environment. As the instru- ment drifts due to temperature changes, calibration may be necessary depending on the magnitude of the change and the specifications of the DUT. The second factor is how mechanically stable the fixture is. As the fixture wears out, its characteristics might change slightly, requiring a new calibration. Finally, any changes in test-system performance must be compared to the specifications of the DUT to evaluate severity. In general, each application is unique and the user must determine the



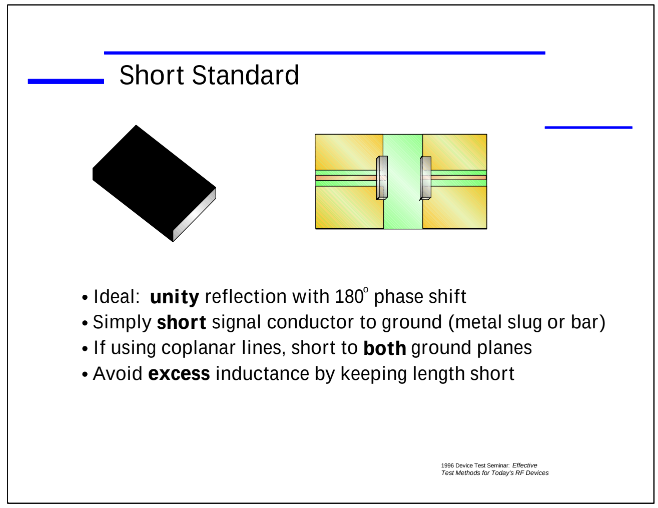
appropriate calibration interval.

Slide #30

Most high-performance network analyzers allow the user to modify the standard definitions for the calibration standards. This is very important for fixture-based measurements, since the in-fixture calibration standards rarely will have the same attributes as any of the standard coaxial-based cal kits.

For normalized transmission measurements, we can achieve a little better accuracy by modifying the definition of the thru to include loss and electrical length. Two-port calibration requires proper definition of all of the reflection and transmission standards. This includes terms such as offset delay and loss, impedance, and fringing capacitance (for opens). The resulting definition of the in-fixture calibration standards can be stored in the analyzer as a custom user-cal kit. Coming up with the proper definitions of the standards is crucial for accurate measurements, and will be covered in more depth later.

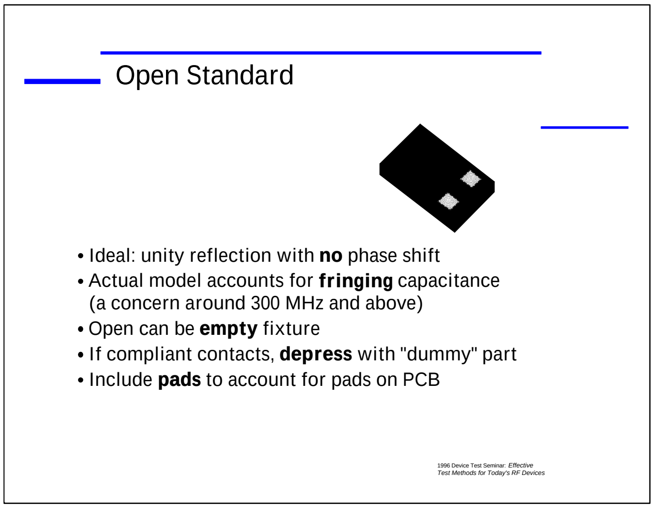
Slide #31



Once the fixture has been designed and fabricated, we can use time-domain reflectometry (TDR) to effectively evaluate how well we minimized reflections. As long as individual transitions can be discerned, TDR can show us which ones need more optimization. TDR can also help evaluate and improve the quality of our load and thru standards.

There are two basic ways to perform TDR measurements. One way is accomplished by generating a high-speed step function (usually a few hundred millivolts in amplitude) and measuring it with a high-speed oscilloscope. This technique provides measurements with a high update rate, which allows real-time tweaking. It is very easy to determining which transition is which, as the designer can place a probe on a transition and look for the spike on the TDR trace. However, in general, oscilloscopes cannot display data in the frequency domain as can a network analyzer.

The second technique uses a network analyzer making normal frequency-domain swept measurements. The inverse-Fourier transform is used to transform the frequency-domain data to the time domain, yielding TDR measurements. While the update rate is much slower, the advantage is that one instrument can be used to provide both time and frequency-domain 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



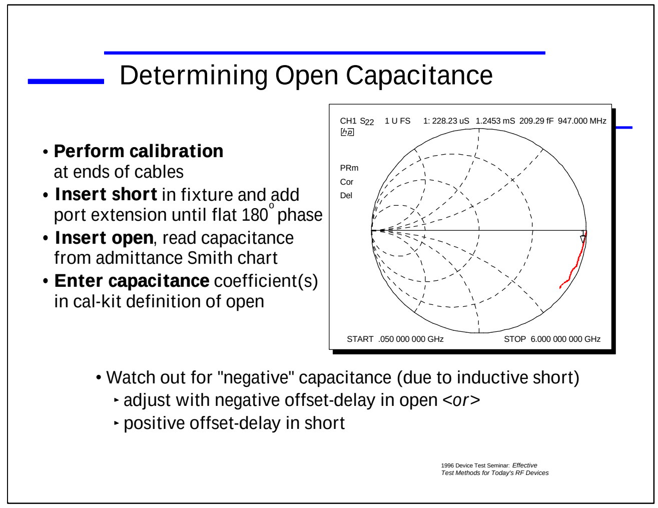
characterization, but can result in very large fixtures.

Slide #32

Gating can be used in conjunction with time-domain measurements to isolate the reflections of the DUT from those of the fixture. This is a form of error correction. For time-domain gating to work effectively, the time domain responses need to be well-separated in time (and therefore distance). There are two ways to use time-domain gating. The simpler method corrects for mismatch errors, but not for fixture loss or phase shift. The procedure involves calibrating at the ends of the test cables with a standard cal kit, connecting the fixture containing the DUT, making a time-domain measurement, and defining the gate to exclude reflections occurring before and after the DUT.

There is also a more accurate way to use time-domain gating, which can correct for loss and phase shift as well as mismatch. As before, the reflection of the launch and other transitions must be distinguishable in the time domain from the reflection of an open or short in the fixture. If the fixture is small, a broad frequency sweep will be needed to provide the necessary resolution. To use this method, begin by calibrating at the ends of the test cables with a standard cal kit. Connect the fixture with a short (or open) loaded instead of the DUT. Look at the time-domain response and use gating to remove all except the response of the short (or open). Return to the frequency domain and perform a normalization with the time-domain gating still on. Now the DUT can be inserted and measured in the fixture. Gating removes mismatch effects, while normalization removes the loss and phase shift of the fixture.

The plots above show the performance of our thru



standard (without normalization). We see about a 7 dB improvement in return loss at 947 MHz using time-domain gating, resulting in a return loss of 45 dB.

Slide #33

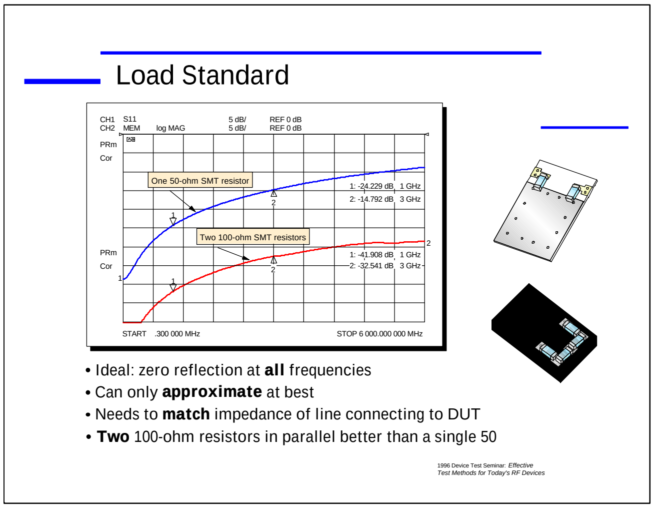
Designing a good fixture solves a large portion of our component-test problem, but we may need a set of quality in-fixture calibration standards before we can make accurate enough measurements on our DUT. Fortunately, making good SOLT standards is not a difficult task in the RF range.

The short is the simplest standard to make, giving ideal reflection. The open, while not difficult to "make" (it is usually the fixture containing no part or a dummy part), it is harder to characterize for our cal kit definition because we have to account for fringing capacitance. The load is the hardest standard to make well. The quality of the load will determine our corrected system directivity which in turn determines how much uncertainty we will have for reflection measurements. For the thru standard, we need to accurately know the impedance and length of the transmission line. These values must then be incorporated into the cal-kit definition of the thru.

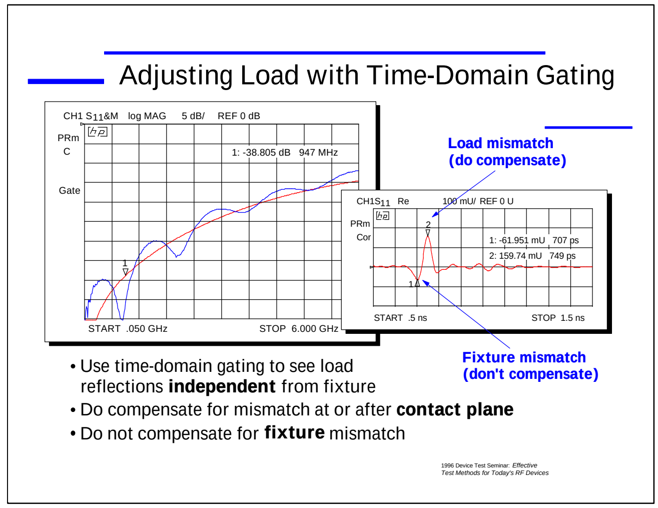
Let's examine each standard in a little more detail.

Designing and Calibrating RF Fixtures for Surface-Mount Devices

Slide #34



Slide #35



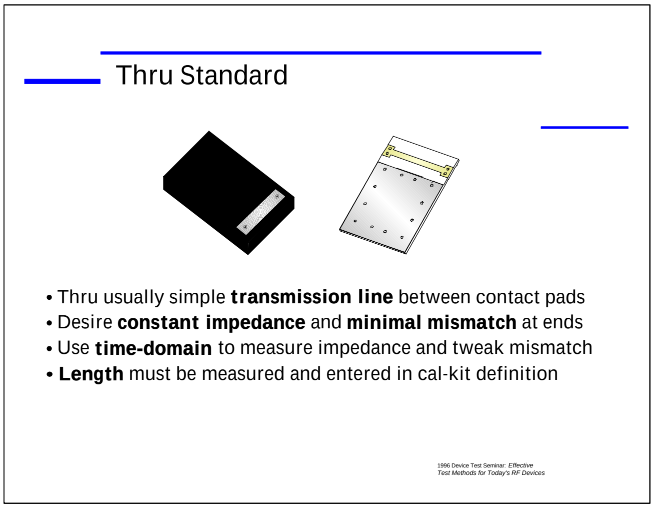
The electrical definition of an ideal short is unity reflection with 180 degrees of phase shift. This means all of the incident energy is reflected back to the source, perfectly out of phase with the reference. A simple short-circuit from signal conductor to ground makes a good short standard. For example, the short can be a metal slug or bar, similar in shape to the DUT. 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 as part of the user-cal kit definition (in terms of electrical delay).

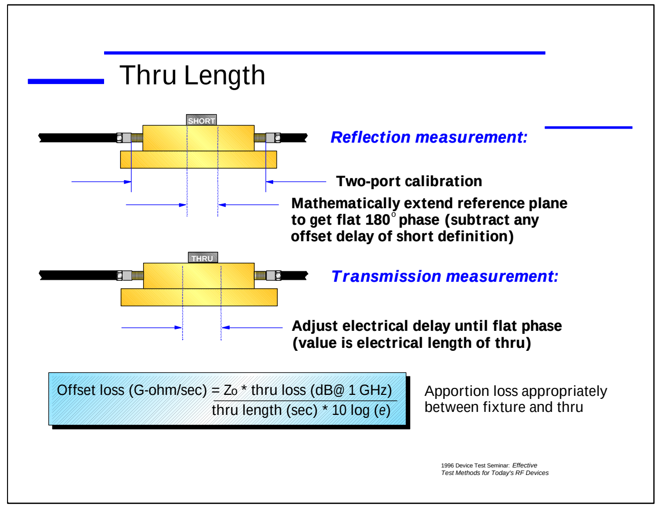
The electrical definition of an ideal open is unity reflection with no phase shift. The actual model for the open, however, does have some phase shift due to fringing capacitance. The open can simply be the fixture with no part in place. When compliant pins are used, it is best to depress the pin with a non-metallic "dummy" part shaped like the DUT, to avoid excess pin length affecting the fringing capacitance. The part can be made out of a small piece of PCB, ceramic substrate, or plastic. It may be desirable to include a small pad on the dummy part to account for the capacitance of the PCB pads used in the actual circuit.

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 (e.g., APC 3.5 for an SMA fixture). Next, connect the fixture and insert the short standard. Set the port extension to get a flat 180^o phase response. To fine-tune the value of port extension, set the reference value of the trace to 180^o 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. Now, remove the short, insert 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 - 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.

Slide #36



Slide #37



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.

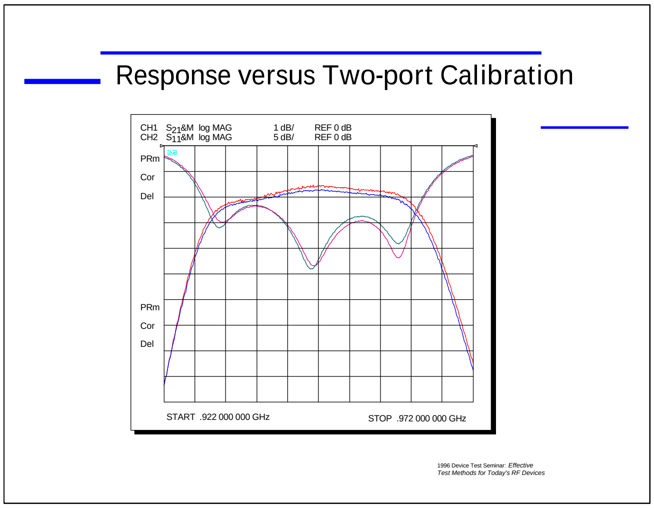
When measuring the fringing capacitance, a problem can arise if the short standard is electrically longer than the open standard. The impedance of the open circuit will appear to be the result of a negative capacitor. This is indicated by a trace that rotates backwards (counter-clockwise) on the Smith 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. 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.

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. The load standard should match the impedance of the signal line at the contact plane of the DUT. Typically this is 50 ohms, but could be different if matching is used.

At RF, we can build a good load using standard surface-mount resistors. Sometimes it is better to use two 100 ohm resistors in parallel instead of a single 50 ohm resistor, as parasitics are decreased. 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 about a 20 dB better match than a single 50 ohm resistor.

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).

Slide #38

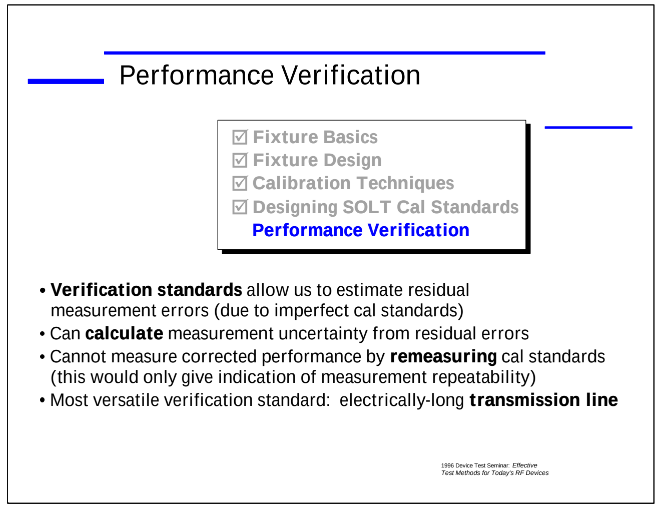


It is possible to adjust our load standard to compensate for unavoidable parasitics that degrade the reflection response. It is important that we only compensate for mismatch at or after the DUT contact plane (e.g., due to an imperfect load or contact mismatch), but not before contact plane (i.e., reflections from the fixture itself). If we compensate our load to counteract fixture mismatch, we will be *adding* reflection error during calibration instead of *removing* it. However if the contact area has mismatch (due to a pad, for example) and it is representative of the contact in the end application, compensating the load to account for mismatch is good. Now if the device is tuned in the fixture for optimum return loss, the effect of the pad mismatch will also be tuned out. Compensation may take the form of a shunt capacitance or series inductance for example. Techniques for adding or subtracting small amounts of reactance include adding excess solder, cutting traces or pads, and adding wire mesh or adhesive-backed copper tape.

Time-domain gating is an excellent tool for helping to determine the proper compensation. We can easily see if mismatch is inductive or capacitive. When switching from a frequency-domain display of reflection (in log-magnitude format) to a time-domain display, be sure to change the data display to real format.

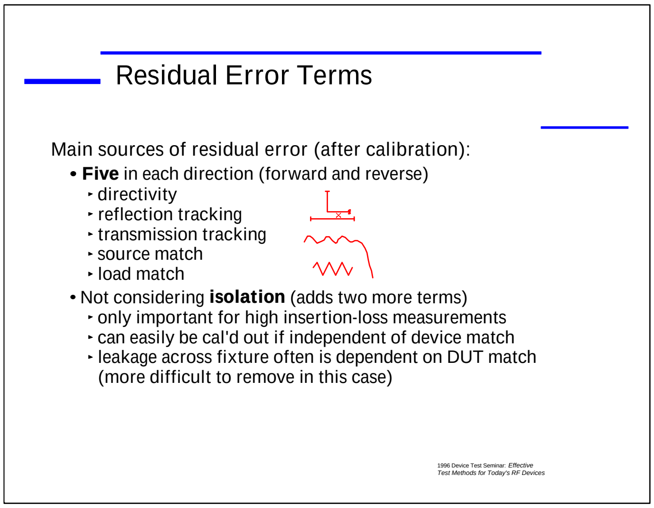
In the above plot, we see that our load standard looks somewhat inductive. This is most likely due to excessive length of our feed-throughs, which could be shortened if we reduced the thickness of the PCB. Even with the inductive nature of the load, we measure a respectable return loss (using time-domain gating) of 39 dB at 947 MHz. The capacitive dip just prior to the load is part of the fixture itself. The effect of this dip is removed when using two-port error correction.

Slide #39



The thru standard is usually a simple transmission line between the appropriate input and output pins or pads of the fixture. A good thru should have small mismatches at the input and output contacts, and maintain a constant impedance over its length (which is generally the case). Nominally, the impedance of the thru is the same as the reference impedance of the system. Even if the geometry of the thru is slightly off, resulting in an impedance value that is say 51 ohms instead of 50, we can correct for this by changing the user-cal kit definition to the measured value. Time-domain tools are an excellent way to measure the impedance of the thru standard. As we just discussed with the load, compensation should be made for input and output contact mismatch (at either end of the thru), but not for any fixture mismatches.

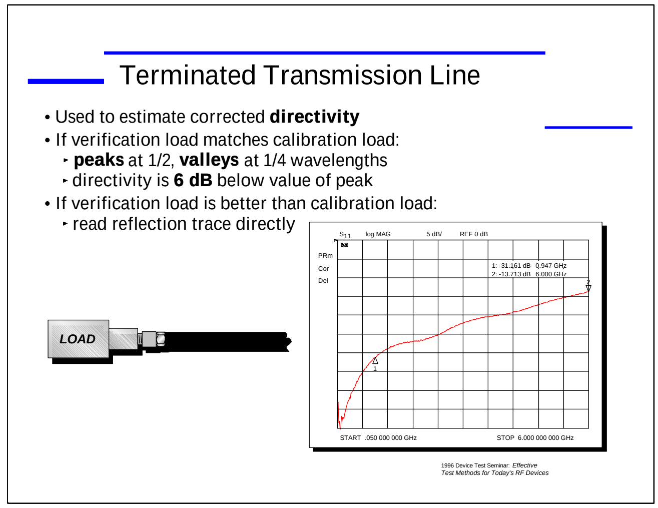
Slide #40



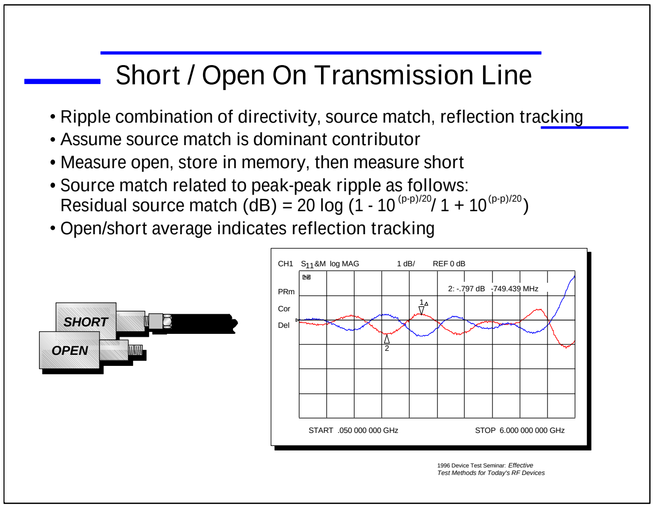
We also need to know the electrical length of the thru standard. Most default cal-kit definitions assume a zero-length thru, whereas SOLT-based fixtures require a finite length thru. We can measure the electrical length of the thru quite easily as follows: first perform a two-port calibration at the ends of the test cables using standard coaxial standards. Connect the fixture and insert the short standard. Using a reflection measurement, set the value for port extension to remove delay up to the contact plane (remember to subtract any offset delay built into the short definition). Repeat for the other side of the fixture. Now the thru can be inserted and measured with a transmission measurement. Measure group delay or adjust electrical delay until the phase response is flat. The value for the delay is the electrical length of the thru, which we can now enter in the cal-kit definition as offset delay.

For short thru-standards, it is usually not necessary to account for any loss since it is likely to be very small. However, if desired, a value for the loss of the thru can be entered in the cal-kit definition as offset loss. Offset loss accounts for loss due to skin effect, which increases as the square-root of frequency. Offset loss (in G-ohms/sec) can be computed from the measured loss at 1 GHz as follows: $\frac{Zo * loss(dB@1GHz)}{electrical\text{–}length(\mathrm{sec}) * 10\log(e)}$

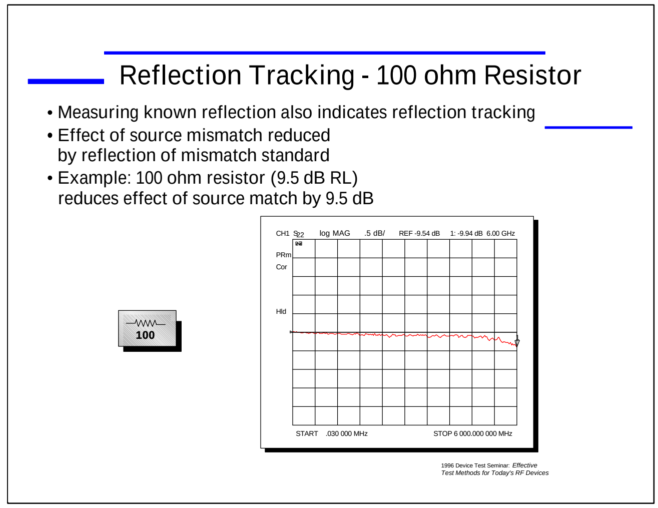
If offset-loss is accounted for, the overall measured loss of the fixture and thru must be properly apportioned. One easy way to accomplish this is to scale based on length. For example if the port extension is 100 ps on one port, 150 ps on the other, and the length of the thru line is 750 ps, then 75% of loss is due to the thru. Use engineering judgment if the thru is significantly more or less lossy than the fixture (e.g., the thru is on PCB, and the fixture uses a ceramic substrate).



Slide #41



Slide #42



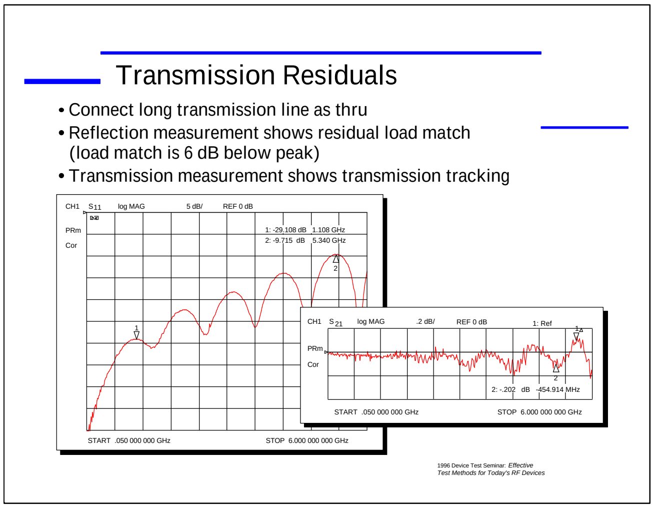
Now that we have covered the design of both fixtures and calibration standards, let's see how good a job we did with our fixture design. The above plot shows the passband performance of the 947 MHz GSM filter measured in the HP-designed fixture. In one case, a full in-fixture two-port calibration was done, and in the other, an in-fixture response calibration was done. The two sets of data are quite close, indicating that the raw performance of our fixture is very good, at least at these frequencies. Since this particular DUT does not have a very stringent return-loss specification, our fixture mismatch is small in comparison. If the return loss of the DUT were better, a response calibration may not yield enough measurement accuracy.

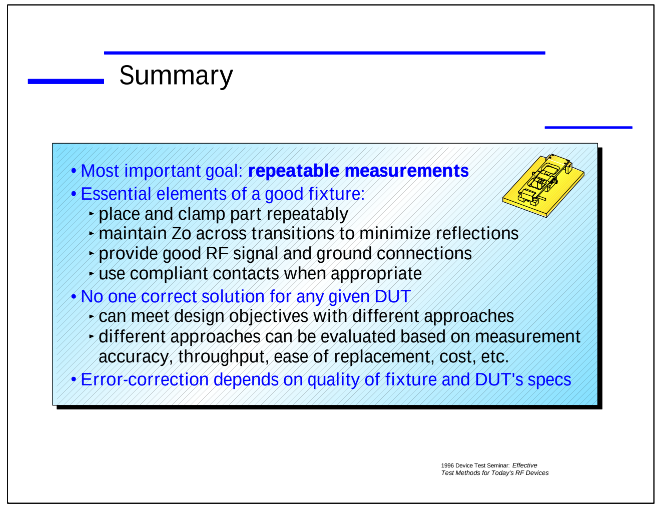
For this particular DUT, we have achieved our goal of designing a test fixture with good enough performance to eliminate the need for two-port calibration. A simple response calibration gives good results. However, had we not had the calibration standards to do a two-port calibration, we would not have been able to make this comparison. It is a good idea to have calibration standards available to characterize the performance of our fixture, even if they are not used for error-corrected measurements during the manufacture of our DUT.

Once our fixture and calibration standards have been fabricated and we have performed a two-port calibration, we may wish to confirm that we are making good measurements. This process is called verification, and involves further measurements on a set of passive devices called verification standards. Measuring these verification standards will give us a good indication of residual measurement errors, which are the result of slight imperfections in the calibration standards (it is impossible to make *perfect* calibration standards). Once we know the residual error terms, we can calculate measurement uncertainty for any particular measurement of an actual DUT. The verification standards are specifically designed to highlight the various effects of residual errors. We cannot measure our corrected performance simply by remeasuring the calibration standards, as this would only give an indication of our measurement repeatability.

The most versatile verification standard is an electrically-long length of transmission line. The line must be long so that systematic error terms become out-of-phase with respect to the error terms measured during calibration. OSL calibration standards are placed at the end of the line to highlight various residual error terms. Our approach to building long transmission lines was to use semi-rigid coaxial cable with an SMA connector on the end to allow different coaxial standards to be connected.

Slide #43





Let's briefly recall the major sources of residual measurement error that remain even after a one- or two-port calibration has been done. There are five main terms in each measurement direction (forward and reverse). Reflection and transmission tracking indicate how well two receiver channels track over frequency during ratioed measurements, which is important in reflection measurements such as return loss, VSWR, and impedance, and in transmission measurements such as gain or insertion loss, and isolation. Load and source match are indications of how close we have made our test ports to the system reference impedance (usually 50 ohms). Finally, directivity is the effective leakage term of our signal-separation devices, which are usually couplers or bridges that are integrated into the network analyzer. This term is critical for reflection measurements.

One additional source of error that we will not attempt to verify is crosstalk. Crosstalk is only important when making high-insertion loss transmission measurements, such as when measuring the stopband of high-rejection filters or when measuring amplifiers with extremely good isolation. Crosstalk can be effectively removed with calibration if it is independent of device match, for example, if direct source to receiver leakage occurs. If the crosstalk is dependent on the port matches of the DUT, then it is more difficult to remove. This can occur if there is radiation leakage in the fixture or some alternate propagation mode, both of which are generally dependent on the match presented by the DUT. Another source of match-dependent crosstalk can occur if high-level signals in the reflection receiver leak into the transmission receiver.

Slide #44

The first verification standard we will consider is a terminated transmission line. This will give us a good estimate of the corrected (residual) directivity of our test fixture and network analyzer. The transmission line should be the same impedance as the system reference and should be long enough to generate ripple over the frequency range of interest. A minimum of a quarter wavelength at the high end of the frequency range is required, but several wavelengths is better as it allows characterization to lower frequencies. The termination at the end of the line should match the calibration standard as closely as possible. We will now generate a ripple pattern in the reflection measurement with valleys occurring at frequencies that are odd numbers of quarter wavelengths of the line, and peaks occurring at integral numbers of half wavelengths. The value of the peak will be 6 dB above the actual return loss of the load. This is what determines our system directivity, as we can never measure better directivity than the return loss of the calibration termination. The effective system directivity is simply equal to the peak (in dB) minus six.

What happens if the load used as the verification standard is much better than the one used during calibration? Then our residual directivity can be read directly from the corrected reflection measurement. An example of this is shown above, where a coaxial load standard was used at the end of a long line. Our residual directivity is about 31 dB at 947 MHz, degrading to only 14 dB at 6 GHz. While we have plenty of directivity at the center frequency of our filter to perform accurate reflection measurements, we would have to improve the bandwidth of our load standard to make accurate measurements at 6 GHz.

Slide #45

The next verification standard is a short or open (or both) placed at the end of a transmission line. Again, the line should be long enough to generate ripples. This time, the reflection ripples will be caused by a combination of the residual directivity, source match, and reflection tracking. A good estimate of the residual source match can be achieved by assuming the ripple is primarily due to source match, as it is usually significantly worse than residual directivity. Reflection tracking generally gives an overall slope to the ripple pattern. With this assumption, the residual source match can never be better than the residual directivity, as we can never see the reflection effects of less signal than that which leaks through due to directivity.

The peak to peak ripples can be seen more easily if the we first measure the open and store the trace in memory, and then measure the short and display both traces. The envelope of the ripples represent the combined error. The average of the open and short ripples is a good estimation of residual reflection tracking. Any loss of the verification line, however, will be added (twice) to the residual reflection tracking.

Residual source match can be estimated (worst case) as follows:

Residual source match (dB) = $20\log(\frac{1-10^{-(p-p)/20}}{1+10^{-(p-p)/20}})$

For example, the above plot shows a peak-peak ripple of 0.797 dB around 2 GHz. This is equivalent to a worst case source match of $20\log(\frac{1-10^{(-0.797)/20}}{1+10^{(-0.797)/20}})$ or -26.8 dB.

Slide #46

Another good way to estimate reflection tracking is to measure a known reflection. This is easily accomplished by measuring the reflection of a single 100-ohm resistor for example, giving a SWR of 2:1 (a return loss of 9.54 dB). Here again, the ripple on the measurement is a combination of directivity, source match, and reflection tracking, but the effect of an imperfect source match is decreased by the reflection coefficient of the mismatch standard (9.54 dB in this case, or nearly 70%). For the worst case, we can assume that the trace ripple of this measurement is solely due to reflection tracking.

Slide #47

Now that we have looked at the major sources of residual reflection errors, let's look at the main transmission residuals. The first one we will consider is residual load match. Any mismatch of the thru standard used during calibration will contribute to residual load match. To verify this term, simply measure the reflection of a long transmission line connected as a thru across the fixture. This line should be a different length than the one used for the thru calibration, and should be greater than a quarter wavelength to generate sufficient ripple. The measurement is essentially identical to the one previously described for measuring residual directivity. In this case, the peak of the ripple is 6 dB above the residual load match. In our example above, we see a residual load match of about 35 dB (29 + 6) around 1 GHz.

Finally, let's check residual transmission tracking. We can use the same long transmission line, but we measure transmission instead of reflection. The peak-peak ripple in this measurement is residual transmission tracking, and is due to the raw source match times the residual load match plus the raw load match times the residual source match ($\rho_{s(raw)} * \rho_{l(resid)} + \rho_{l(raw)} * \rho_{s(resid)}$).

Slide #48

We have covered quite a bit of information on designing and calibrating high-quality test fixtures for SMT devices. The most important goal of fixture design is to ensure repeatable measurements. To this end, we must make sure that the part is placed and clamped in the fixture in a repeatable manner. Next, we have to maintain the proper Z_o between the coaxial connectors and the DUT, across any and all transitions, to minimize reflections. And, we have to provide good RF signal and ground connections, using compliant contacts when appropriate. Even within these parameters, we have seen that for any particular DUT, there are different design approaches that can be taken, all of which may yield acceptable results. The best approach will depend on the mechanical and electrical specifications of the part to be measured, the overall test goals (including the required measurement accuracy), and the cost to implement the fixture.

We discussed several forms of error-correction including time-domain techniques and using physical calibration standards. We showed how to make your own SOLT standards for calibration, and how to verify calibrated performance with verification standards. The appropriate level of calibration depends on the quality of the fixture and the DUT's specifications.

This paper attempted to provide enough tools and guidelines to allow anyone to make effective RF fixtures and calibration standards that will yield repeatable and accurate measurements of surface-mount devices. If your expertise is not in RF design or fixture fabrication, companies such as Hewlett-Packard and Inter-Continental Microwave can help solve your test-fixturing needs, from simple surface-mount devices, up to more complex RFICs.

Acknowledgments

The author wishes to acknowledge the expertise and efforts of Keith Howell of Hewlett-Packard and Werner Schuerch of Inter-Continental Microwave for the time and expense devoted to developing test fixtures and calibration standards for our case study. Thanks also go to Joel Dunsmore of Hewlett-Packard, who provided much of the material on building calibration and verification standards, and who readily supplied advice and guidance based on his extensive knowledge and experience with RF measurement theory and practice.

References

Calibrating for PC Board Fixtures and Probes, Joel Dunsmore, ARFTAG Proceedings, Spring 1995.

Techniques Optimize Calibration of PCB Fixtures and Probes, Joel Dunsmore, *Microwaves & RF*, October 1995, pp. 96-108, November 1995, pp. 93-98.

Accurate Measurement of Packaged RF Devices, Mirin Lew, *RF and Microwave Device Measurements for the '90's*, Hewlett-Packard 1995 Device Test Seminar paper (included in HP literature number 5963-5191E).

Automatic and Manual Test Fixtures and Calibration Standards, Inter-Continental Microwave product catalog (HP literature number 5962-9723E).

Specifying Calibration Standards for the HP 8510 Network Analyzer, Hewlett-Packard Product Note 8510-5A, (HP literature number 08510-90352, or HP literature number 5956-4352, February 1988).

In-Fixture Microstrip Device Measurements Using TRL* Calibration, Hewlett-Packard Product Note 8720-2, (HP literature number 5091-1943E, August 1991).

Calibration and Modeling Using the HP 83040 Modular Microcircuit Package, Hewlett-Packard Product Note 83040-2, (HP literature number 5952-1907E, May 1990).

Designing and Calibrating RF Fixtures for Surface-Mount Devices

Third-Party Companies

Fixtures:

Inter-Continental Microwave
1515 Wyatt Drive
Santa Clara, California 95054-1524
USA
Phone: (408) 727-1596
Fax: (408) 727-0105

Test Sockets:

Johnstech International
1100 New Brighton Boulevard
Minneapolis, MN 55413-1641
USA
Phone: (612) 378-2020
Fax: (612) 378-2030

Conductive Elastomer:

Chomerics, Inc.
77 Dragon Court
Woburn, MA 01888
Phone: (617) 935-4850
Fax: (617) 933-4318