Hewlett-Packard

Electronic Materials Measurement Seminar

Bulk Material Measurements

Kobe Instrument Division

HEWLETT
PACKARD

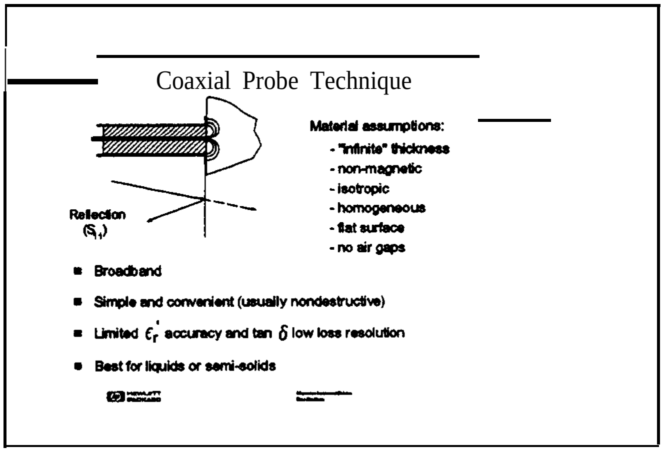
Electronic Materials Measurement Seminar

Bulk Material Measurements

Broadband Techniques

- Coaxial probe
- Transmission line
- **Free** space

We will be focussing on three broadband techniques.



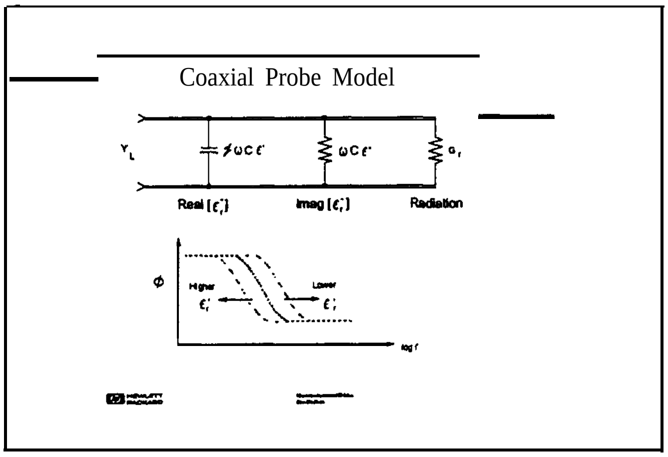
Coaxial Probe Technique

Material assumptions:

- "infinite" thickness
- non-magnetic
- isotropic
- homogeneous
- flat surface
- no air gaps

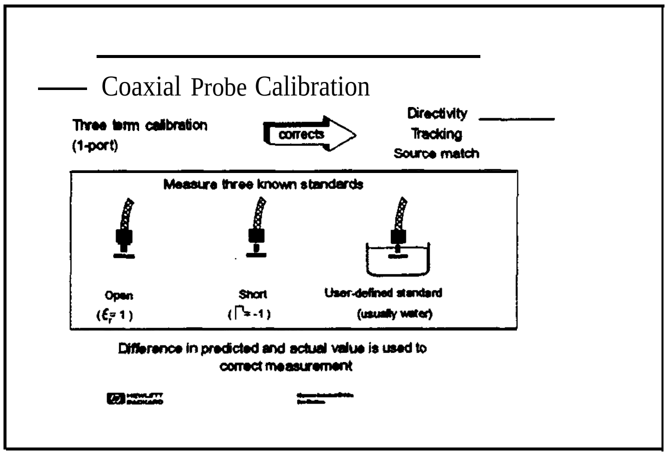
- Broadband
- Simple and convenient (usually nondestructive)
- Limited ϵ_r' accuracy and tan δ low loss resolution
- Best for liquids or semi-solids

The coaxial probe is a convenient and broadband technique for lossy liquids and semisolids. The MUT is assumed to be "infinite" in thickness, uniform throughout, nonmagnetic and to have uniform orientation. The probe can be used for pliable solids if no air gap is present between the probe and sample. A coaxial probe fixture connects to a vector network analyzer that measures the reflection from the MUT which is then converted to permittivity.



Coaxial Probe Model

The coaxial probe geometry can be modeled with a simple circuit, where the total admittance, Y, is composed of a pure capacitance (phase change) that can be related to $_r$' and a conductance (magnitude change) that can be related to $_r$". An additional conductance represents radiation losses which limits the probe sensitivity especially at higher frequencies.



Coaxial Probe Calibration

Three term calibration
(1-port)

Directivity
Tracking
Source match

Measure three known standards

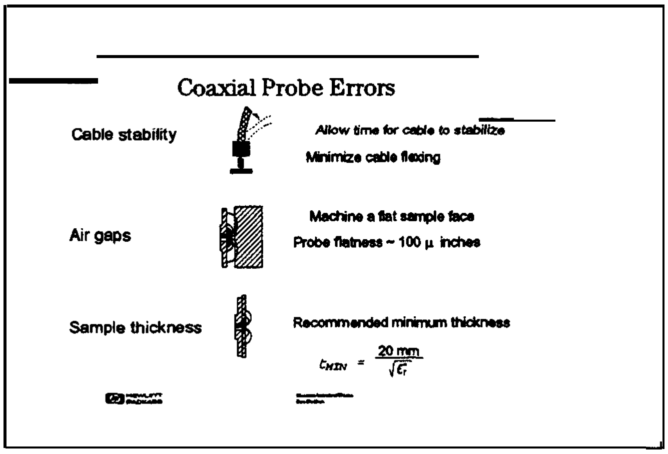
Open ($\varepsilon_r = 1$)

Short ($\Gamma = -1$)

User-defined standard (usually water)

Difference in predicted and actual value is used to correct measurement

A three term calibration corrects for the direct.ivity, tracking and source match errors that can be present in a reflection measurement. In order to solve for these three ***error*** terms, three well known standards are measured and the difference between the predicted and actual values are used to remove the systematic (repeatable) errors from the measurement. The three known standards are air, a short circuit and water.



Coaxial Probe Errors

Cable stability

Allow time for cable to stabilize
Minimize cable flexing

Air gaps

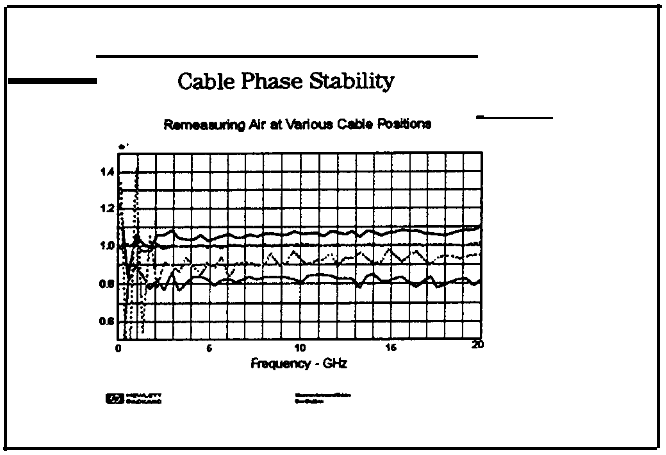
Machine a flat sample face
Probe flatness ~ 100 µ inches

Sample thickness

Recommended minimum thickness

$$t_{MIN} = \frac{20\text{ mm}}{\sqrt{\varepsilon_r}}$$

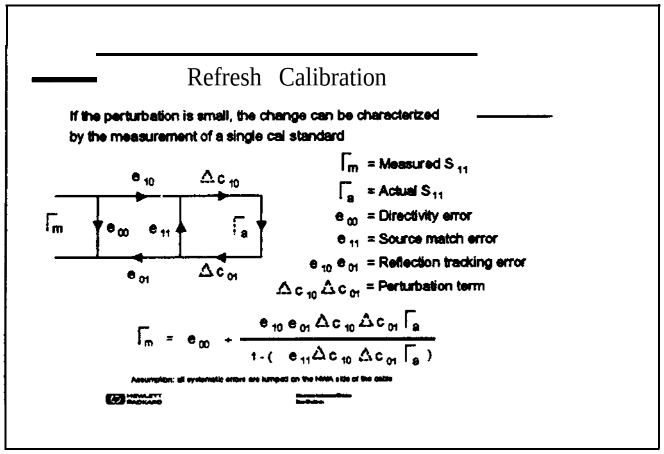
Even after calibrating the probe, there are additional sources of error that can affect the accuracy of a measurement. It is important to allow enough time for the cable (that connects the probe to the network analyzer) to stabilize before making a measurement and to be sure that the cable is not flexed between calibration and measurement. For solid materials, air gap between the probe and sample can be a significant source of error unless the sample face is machined to be at least as flat as the probe face. The sample must also be thick enough to appear “infinite” to the probe.



Cable Phase Stability

Remeasuring Air at Various Cable Positions

If the cable is moved or flexed after a calibration, the resulting measurement can vary **significantly**, causing measurement repeatability to be sacrificed. Instead of moving the probe to the sample, it is best to fix the probe and cable in one position while bringing the sample to the probe. The same result would be seen if a change in temperature **occurred** after a calibration.



Refresh Calibration

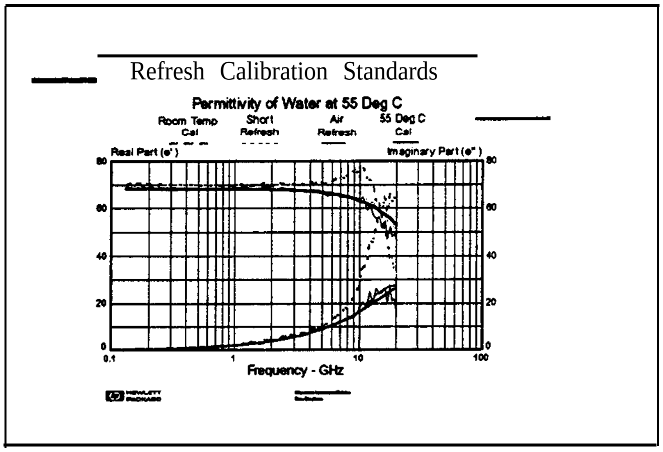
If the perturbation is small, the change can be characterized by the measurement of a single cal standard

Γ_m = Measured S_{11}
Γ_a = Actual S_{11}
e_{00} = Directivity error
e_{11} = Source match error
$e_{10}\,e_{01}$ = Reflection tracking error
$\Delta c_{10}\,\Delta c_{01}$ = Perturbation term

$$\Gamma_m = e_{00} + \frac{e_{10}\,e_{01}\,\Delta c_{10}\,\Delta c_{01}\,\Gamma_a}{1-(e_{11}\,\Delta c_{10}\,\Delta c_{01}\,\Gamma_a)}$$

Assumption: all systematic errors are lumped on the NWA side of the cable

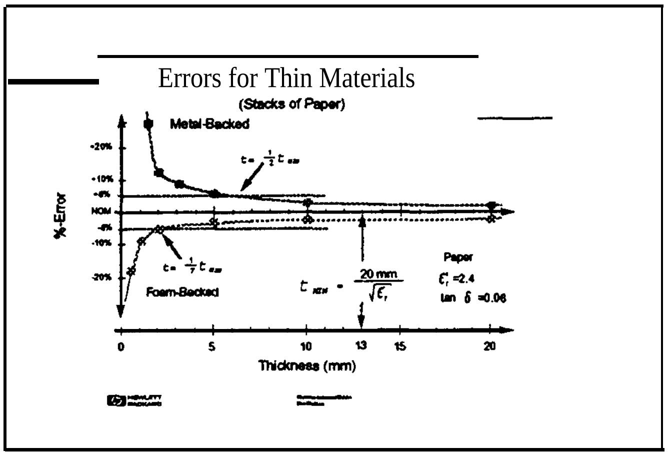
If the change in the measurement (due to cable movement or temperature change) is small enough, it may be possible to characterize that small change by measuring a single calibration standard, rather than the three standards required for a normal calibration. A refresh calibration modifies an existing calibration by remeasuring just one standard. This simplifies measurements that must be made at several different temperatures or measurements where the cable must be moved.



Refresh Calibration Standards

Permittivity of Water at 55 Deg C

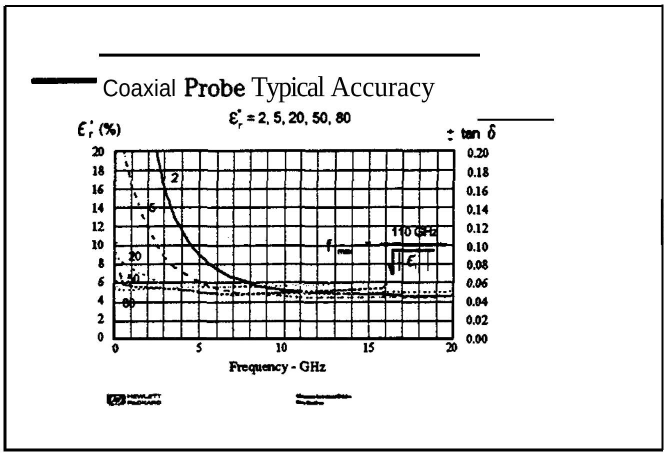
A measurement of 55” C water shows that a room temperature calibration introduces errors into the measurement. But when a short circuit or air is used to refresh the calibration it accomplishes **almost the** same results as a full calibration made **at 55°C.**



Errors for Thin Materials

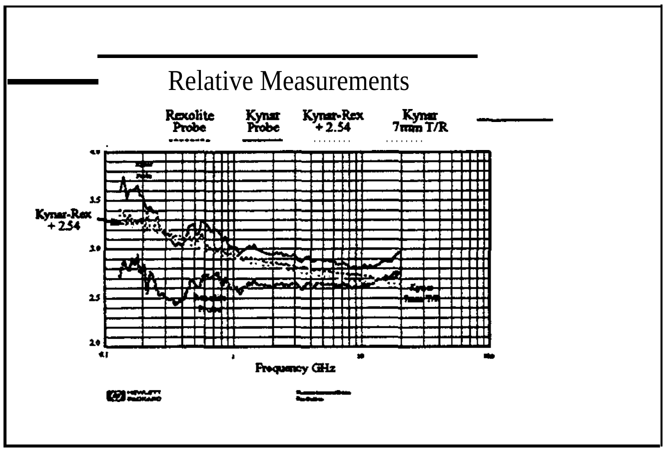
(Stacks of Paper)

The sample size must be chosen such that any reflections from boundaries are not detected by the probe. The effects of sample thickness are shown by the measurement of paper that has been stacked to various thicknesses. In one case the paper is backed by metal and in the other case by foam. At the recommended minimum sample thickness (t_{min}) the error from nominal is less than 5%.



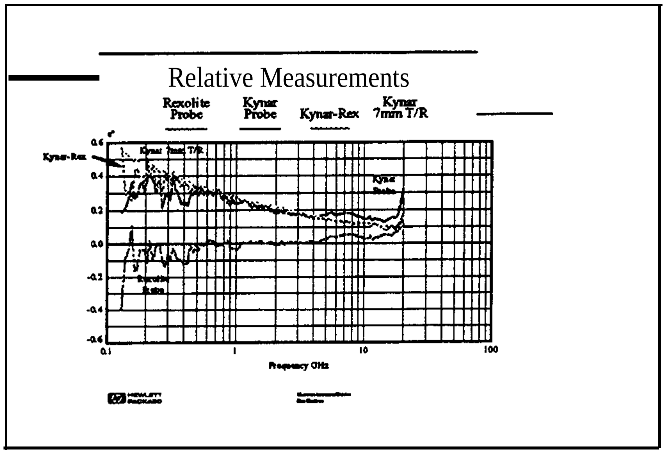
Coaxial **Probe** Typical Accuracy

The typical accuracy of a measurement made with a coaxial probe is dependent on both frequency and dielectric constant. In general, the probe is more accurate at higher frequencies, although there is a maximum frequency limit. The probe is also more accurate for higher permittivities. At best the accuracy in$_r$' is 5% and tan is 0.05.



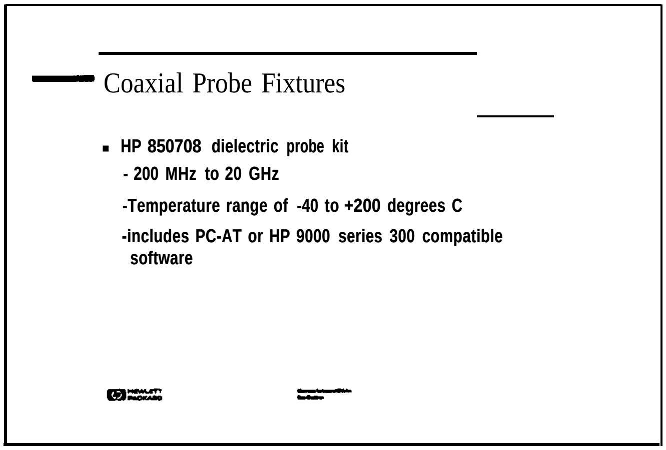
Relative Measurements

Although the absolute accuracy of a probe measurement may be limited, it does exhibit good measurement repeatability. Therefore, it can make very good relative measurements provided a known reference can be found. In this example kynar is measured with the probe and with a more accurate transmission line (T/R) technique. Rexolite, which is known to have a permittivity of 2.54, is then measured with the probe. A more accurate measurement of kynar is produced by making a measurement relative to rexolite and then adding a value of 2.54 to the difference.



Relative Measurements

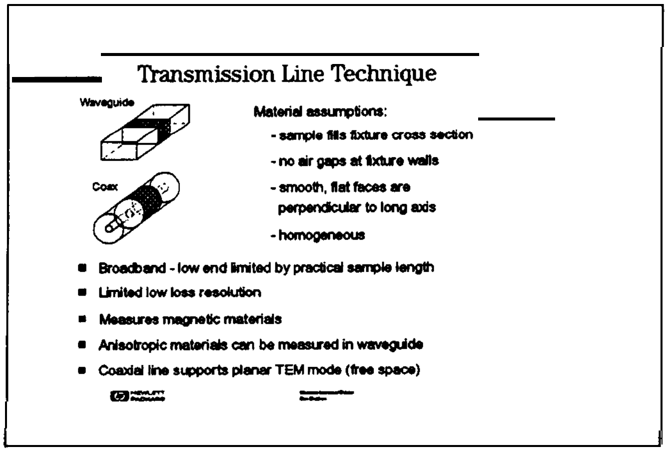
A similar measurement of the loss factor (ε_r'') of kynar relative to rexolite can be made.



Coaxial Probe Fixtures

- HP 850708 dielectric probe kit
  - 200 MHz to 20 GHz
  -Temperature range of -40 to +200 degrees C
  -includes PC-AT or HP 9000 series 300 compatible software

The HP 85070B dielectric probe covers a broad 200 MHz to 20 GHz frequency range and withstands high temperatures and corrosive chemicals with its hermetic glass to metal seal. It is compatible with a wide range of HP vector network analyzers. The software to control the network analyzer and convert the measured S-parameter to permittivity is included with the probe kit.



Transmission Line Technique

Material assumptions:
- sample fills fixture cross section
- no air gaps at fixture walls
- smooth, flat faces are perpendicular to long axis
- homogeneous

- Broadband - low end limited by practical sample length
- Limited low loss resolution
- Measures magnetic materials
- Anisotropic materials can be measured in waveguide
- Coaxial line supports planar TEM mode (free space)

The transmission line is a broadband technique for machineable solids. The MUT is assumed to completely fill the cross section of the fixture with no air gaps, have smooth flat faces and to be uniform throughout. Coaxial airline fixtures are broadband, but the samples are more difficult to machine. Waveguide fixtures extend to the mm-wave frequencies and the samples are simpler to machine, but their frequency coverage is banded. A transmission line fixture connects to a vector network analyzer that measures the reflection and transmission from the MUT which are then converted to permittivity and permeability.

Transmission Line Algorithms

Algorithm	Measured	Optimum Length	Results
Nicolson-Ross u&e (PN 8510-3)	$S_{11}, S_{21}, S_{12}, S_{22}$ (or S_{11}, S_{21})	$\lambda_g/4$	ϵ_r^* & μ_r^*
Precision e (NIST)	$S_{11}, S_{21}, S_{12}, S_{22}$	$n\lambda_g/2$	ϵ_r^*
Fast e	$S_{11}, S_{21}, S_{12}, S_{22}$ (or S_{11}, S_{21})	$n\lambda_g/2$	ϵ_r^*
Short-back e	S_{11}	$\lambda_g/2$	ϵ_r^*
Arbitrary-back e	S_{11}	$\lambda_g/2$	ϵ_r^*

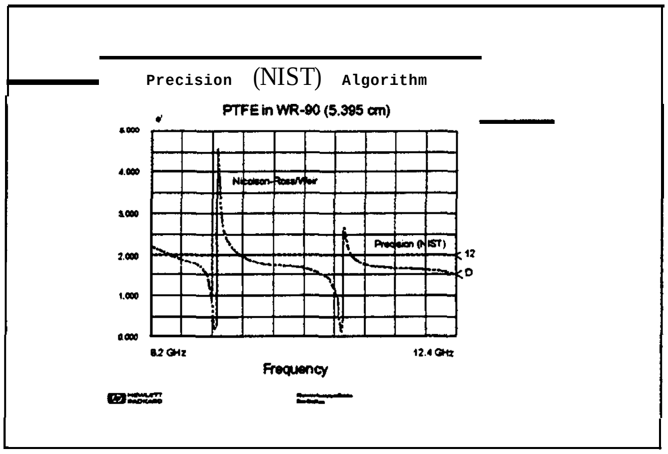
These are examples of algorithms that may be used to convert the measured S-parameters to permittivity or permeability. The first three require a two-port fixture. The last two require a one-port fixture which may be better for liquids or powders where a shorted waveguide section can be turned on end and filled. One-port fixtures may also be better for measurements at high temperatures where one end of the waveguide can be heated while cooling mechanisms keep the network analyzer cool.

Algorithm Selection

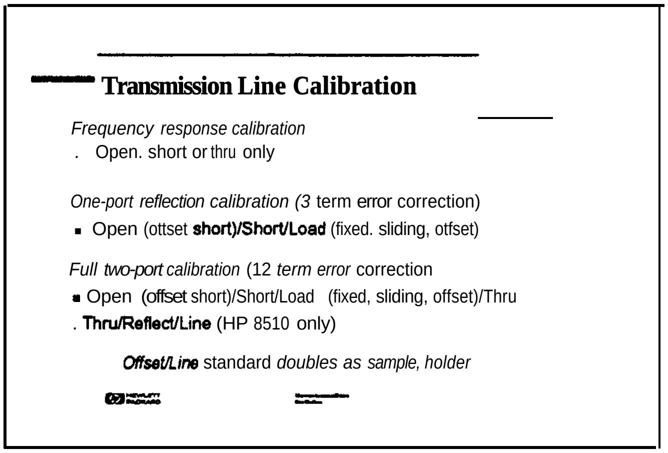
Algorithm	Best fit for:
Nicolson-Ross u&e	Magnetic, short or lossy MUTs. Fastest computation speed.
Precision e	Long, low loss MUTs. Highest accuracy with no discontinuities.
Fast e	Long, low loss MUTs. Similar to Precision but faster and better for lossy MUTs.
Short-backed e	Liquids, powders
Arbitrary-backed e	Thin films

The Nicolson-Ross algorithm is best for magnetic materials. The Precision algorithm is best for the highest accuracy. The Fast algorithm is similar to the Precision, but it is faster. The Short-backed algorithm is best for liquids or powders. The Arbitrary-backed algorithm is best for thin films.

Precision (NIST) Algorithm


PTFE in WR-90 (5.395 cm)

The Nicolson-Ross algorithm suffers from periodic dropouts at every half wavelength when the reflection from the front face of the sample cancels out the reflection from the back face. The Precision and Fast algorithms do not suffer from these discontinuities.



Transmission Line Calibration

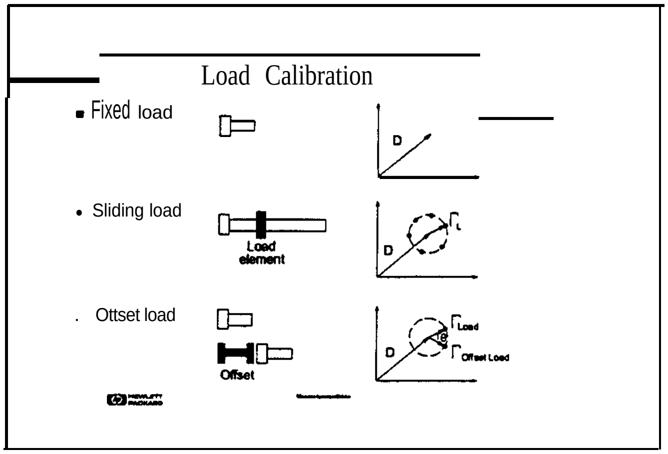
Frequency response calibration
- Open. short or thru only

One-port reflection calibration (3 term error correction)
- Open (offset **short)/Short/Load** (fixed. sliding, offset)

Full two-port calibration (12 *term error* correction
- Open (offset short)/Short/Load (fixed, sliding, offset)/Thru
- **Thru/Reflect/Line** (HP 8510 only)

Offset/Line standard *doubles as sample, holder*

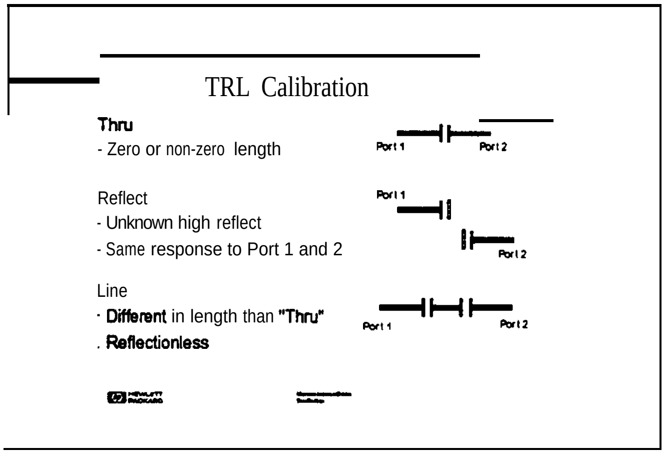
The network analyzer must be calibrated before making a measurement to remove the systematic errors from the system. The simplest calibration is a frequency response calibration because it requires only one calibration standard. One-port fixtures require a one-port calibration to compensate for all three error terms in a reflection measurement. Two-port fixtures require a more time-consuming two-port calibration for the greatest accuracy in removing all twelve error terms in a transmission and reflection measurement.



Load Calibration

- Fixed load
- Sliding load
- Offset load

There are three types of loads that can be used in a calibration to solve for the directivity error term. The simplest is a fixed load where the directivity error is directly related to the measurement of the load. A sliding load traces out a circle around the point of the directivity vector as the load element is moved along the airline and the center of the circle is calculated. An offset load requires two measurements, one with a fixed load and the second with the same fixed load offset by a specific length. By knowing two points and the angle between them, the center of the directivity circle can be calculated.



TRL Calibration

Thru
- Zero or non-zero length

Reflect
- Unknown high reflect
- Same response to Port 1 and 2

Line
- **Different** in length than **"Thru"**
- **Reflectionless**

A TRL or Thru-Reflect-Line calibration is the most accurate type of two-port calibration. The Thru can be a zero length or non-zero length Thru that connects port 1 to port 2. The Reflect can be any unknown high reflection device as long as it presents the same high reflection to port 1 and port 2. The Line must be different in length from the Thru and is assumed to be reflectionless.

TRL Calibration Residual Errors

- Fewer known standards required
- Simple standards (especially for non-coaxial media)
- Highest precision

Residual Errors	Fixed Load	Sliding Load	offset Load	TRL
Directivity	-40 dB	-52 dB	-60 dB	-60 dB
Match	-35 dB	-41 dB	-42 dB	-60 dB
Tracking	0.1 dB	0.047 dB	0.035 dB	0 dB

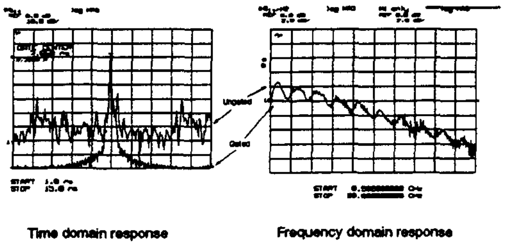
A TRL calibration requires fewer standards which do not have to be well known. It offers the highest precision of any network analyzer calibration. The HP 85 10 is the only network analyzer that has a true TRL calibration. The HP 8720 has a modified version of TRL called TRL* that is not recommended for the transmission line technique since it requires a well matched device.

Time Domain Gating

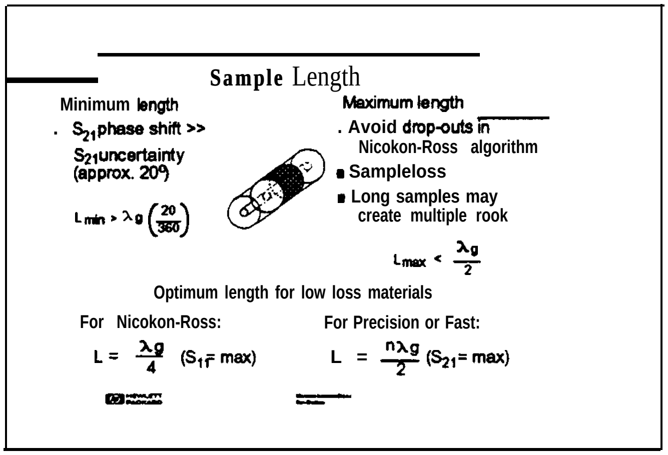
- Remove mismatches or w-reflections
- Calibrate when no calibration standards are available
  1. Calibrate in a known connector type
  2. Connect cable or adapters
  3. Connect SHORT
     Apply time domain gate to SHORT response
  4. Normalize with TDR gate ON
     Add phase offset of 180 degrees
  5. For transmission, normalize to THRU response

Time domain is available as Option 010 on HP vector network analyzers. Rather than viewing data in the frequency domain it can be converted to the time domain using an inverse fast Fourier transform. Time domain gating can be equated to a bandpass filter in time that removes mismatches or re-reflections outside of the gate. This can also be a valuable tool when calibration standards are not available.

Time Domain Gating



When no calibration standards are available, first calibrate in a known connector type then connect the needed cables or adapters. Connect a short circuit at the reference plane and place the time domain gate around it. In the frequency domain normalize to the gated response and offset the phase by 180 degrees.



Sample Length

Minimum length

- S_{21} phase shift >> S_{21} uncertainty (approx. 20°)

$L_{min} > \lambda g \left(\frac{20}{360}\right)$

Maximum length

- Avoid drop-outs in Nicokon-Ross algorithm
- Sampleloss
- Long samples may create multiple rook

$L_{max} < \frac{\lambda g}{2}$

Optimum length for low loss materials

For Nicokon-Ross: $L = \frac{\lambda g}{4}$ (S_{11}= max)

For Precision or Fast: $L = \frac{n\lambda g}{2}$ (S_{21}= max)

Choosing the optimum sample length will improve the accuracy of a measurement. The minimum length of the sample is limited by the phase uncertainty of the network analyzer. The maximum sample length is limited by the l/2 wavelength dropouts with the Nicolson-Ross technique, the sample loss and by the fact that long samples may lead to multiple roots. The optimum sample length depends on the chosen algorithm.

Wavelength Equations

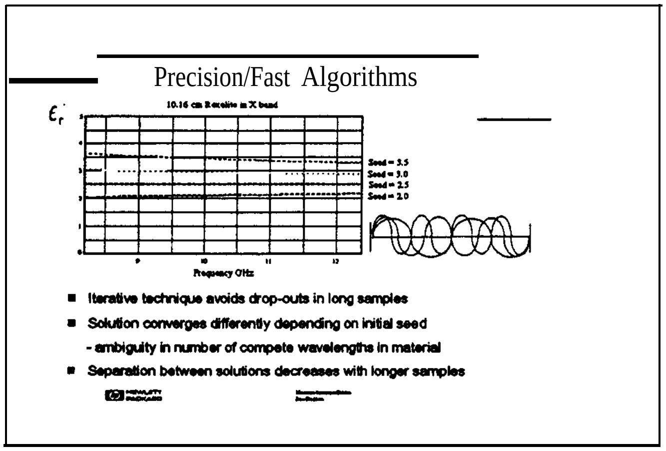
Wavelength of free space $\lambda_o = \frac{c}{f} = \frac{30\text{ cm}}{f\text{ (in GHz)}}$

Guide wavelength $\lambda_g = \frac{1}{\sqrt{\frac{\varepsilon_r' \mu_r'}{\lambda_o} - \frac{1}{\lambda_c}}}$

XC = cutoff frequency for waveguide

Phase shin A0 = $\frac{L}{\lambda_g}$ (360°)

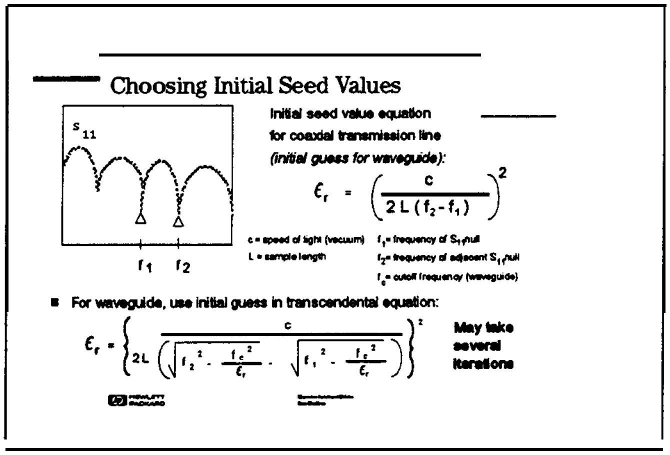
The wavelength in free space is dependent on the speed of light divided by the frequency. The wavelength in the transmission line media is dependent on the permittivity and permeability of the sample, the wavelength in free space and the cutoff wavelength (neglect for coaxial). The phase shift through the sample is dependent on the length of the sample divided by the guide wavelength.



Precision/Fast Algorithms

- Iterative technique avoids drop-outs in long samples
- Solution converges differently depending on initial seed
  - ambiguity in number of compete wavelengths in material
- Separation between solutions decreases with longer samples

The Precision and Fast algorithms are iterative techniques that do not have the l/2 wavelength dropout problem of the Nicolson-Ross model. However, it may be possible for the solution to these algorithms to converge differently if there is an ambiguity in the number of complete wavelengths that might be present in the sample length.



Choosing Initial Seed Values

Initial seed value equation for coaxial transmission line *(initial guess for waveguide):*

$$\epsilon_r = \left(\frac{c}{2L(f_2 - f_1)}\right)^2$$

c = speed of light (vacuum)
L = sample length
f_1 = frequency of S_{11} null
f_2 = frequency of adjacent S_{11} null
f_c = cutoff frequency (waveguide)

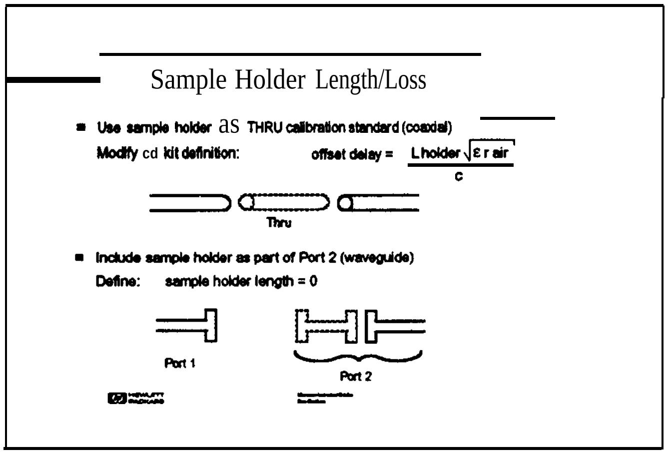
- For waveguide, use initial guess in transcendental equation:

$$\epsilon_r = \left\{\frac{c}{2L\left(\sqrt{f_2^2 - \frac{f_c^2}{\epsilon_r}} - \sqrt{f_1^2 - \frac{f_c^2}{\epsilon_r}}\right)}\right\}^2$$

May take several iterations

Iterative algorithms require an initial seed value. The equation to compute an initial seed value for coaxial fixtures can be determined by locating the nulls in the S_{11} frequency response. This same equation can be used as an initial guess for waveguide fixtures. That initial guess can then be used in the transcendental equation (which may take several iterations to converge).

28



Sample Holder Length/Loss

- Use sample holder as THRU calibration standard (coaxial)

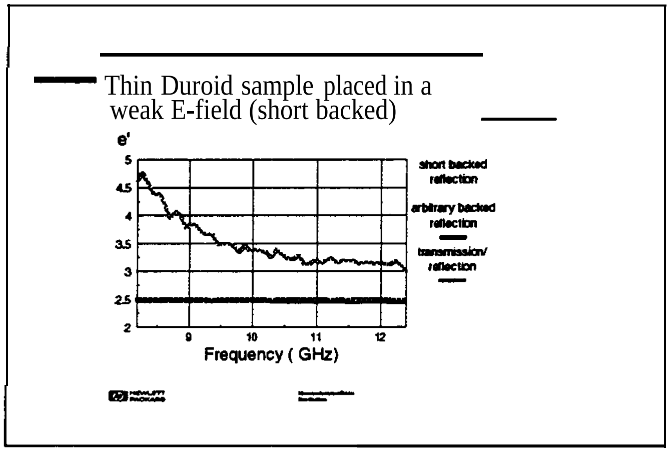
Modify cd kit definition: offset delay = $\frac{L_{holder}\sqrt{\varepsilon_{r\,air}}}{c}$

- Include sample holder as part of Port 2 (waveguide)

Define: sample holder length = 0

The accuracy of a measurement can be improved by accounting for the loss of the sample holder which is assumed negligible. For coaxial fixtures, the sample holder can be defined as part of the Thru standard by modifying the offset delay in the calibration kit definition. For waveguide fixtures, the sample holder can be included as part of port 2 during the calibration, such that the calibration standards are inserted between port 1 and the sample holder. In this case the sample holder length must be defined to have zero length.

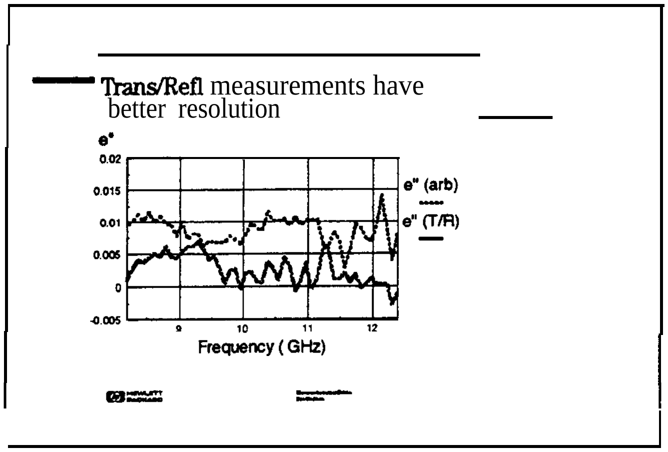
29



Thin Duroid sample placed in a weak E-field (short backed)

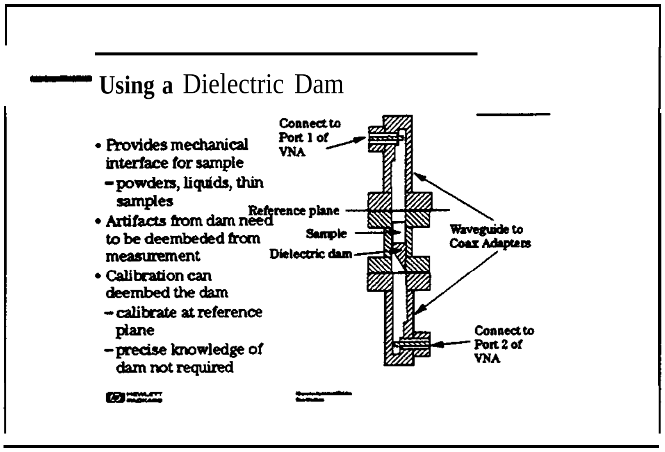
Measurements of 59.3 mil Duroid: In a short-backed l-port transmission line, the E-field must approach zero near the short. Therefore, thin samples have a small impact on the reflection coefficient, causing large errors in permittivity. More flexible algorithms permit the sample to be positioned against an arbitrary impedance, allowing the user to maximize the E-field in the sample. Measurement of the same sample offset from the short by a Teflon spacer (arbitrary backed reflection) closely matches that of a transmission/reflection measurement.

30



Trans/Refl measurements have better resolution

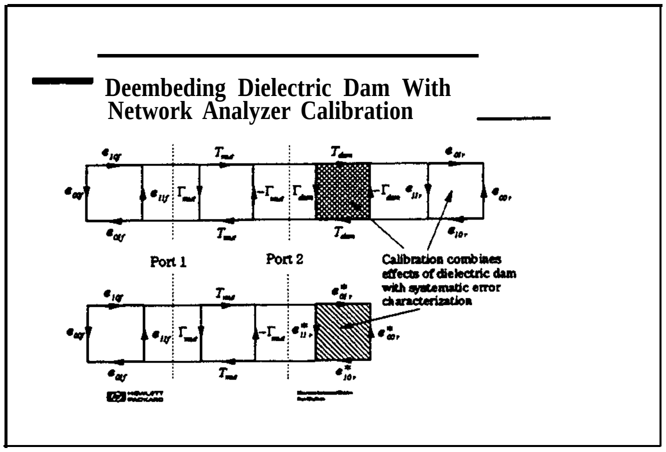
Transmission/Reflection measurements provide better resolution than reflection measurements alone. This graph shows the loss factor measurement of the 59.3 mil Duroid sample. Better resolution is obtained with a transmission/reflection measurement. The dynamic range of a reflection measurement is limited by the directivity (about 40-50 dB in this case) while the dynamic range of a transmission measurement is limited by the crosstalk (about 100 dB in this case).



Using a Dielectric Dam

- Provides mechanical interface for sample
  - powders, liquids, thin samples
- Artifacts from dam need to be deembeded from measurement
- Calibration can deembed the dam
  - calibrate at reference plane
  - precise knowledge of dam not required

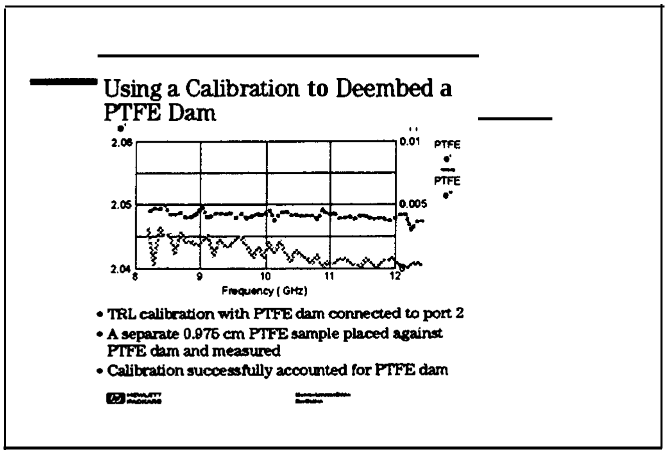
Short backed measurement fixtures are often used for the measurement of liquids and powders because their structure is ideally suited for sample containment. A dielectric dam can be used with transmission/reflection measurements to provide the physical containment of the sample. The reflections and transmission loss and delay of the dielectric dam must be deembeded or removed from the transmission and reflection measurement before the sample permittivity and permeability can be calculated.



Deembeding Dielectric Dam With Network Analyzer Calibration

Calibration combines effects of dielectric dam with systematic error characterization

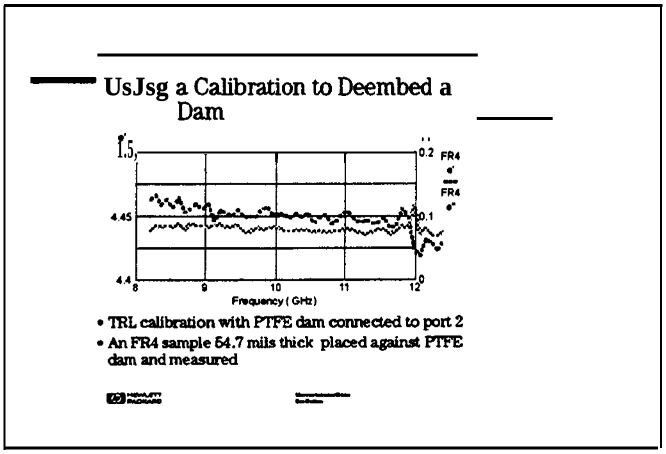
If the characteristics of the dam (permittivity and dimensions) are accurately known they can be mathematically removed or deembeded. It is also possible to deembed the effects of the dam without knowing the permittivity or dimensions of the dam. This can be done by having the dam present during the calibration. The s-parameters of the dam required for deembeding will be combined with the systematic error terms during the vector error correction resulting in the appropriate deembeding for subsequent measurements.



Using a Calibration to Deembed a PTFE Dam

- TRL calibration with PTFE dam connected to port 2
- A separate 0.975 cm PTFE sample placed against PTFE dam and measured
- Calibration successfully accounted for PTFE dam

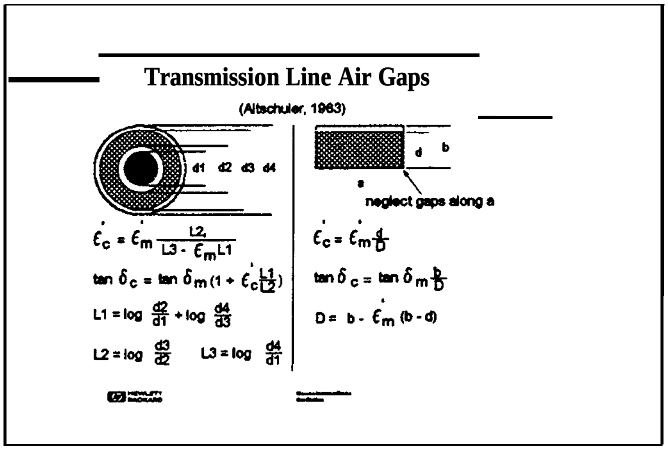
The effectiveness of using a dielectric dam is demonstrated with this measurement. A PTFE dam is present during the network analyzer calibration. After calibration another piece of PTPE is placed against the dam and measured. Physically there will not be a reflection from the sample/dam interface because they are the same material but mathematically there is a reflection at the sample/dam interface which enables the data reduction algorithm to correctly determine the permittivity of the measurement sample.



UsJsg a Calibration to Deembed a Dam

- TRL calibration with PTFE dam connected to port 2
- An FR4 sample 54.7 mils thick placed against PTFE dam and measured

A thin sample was placed against the Teflon dam and measured. The dam insured that the sample was perpendicular to the longitudinal axis. This technique has also been useful in measuring powders and semi-solids.



Transmission Line Air Gaps

(Altschuler, 1963)

$$\epsilon'_c = \epsilon'_m \frac{L2}{L3 - \epsilon'_m L1}$$

$$\tan \delta_c = \tan \delta_m \left(1 + \epsilon'_c \frac{L1}{L2}\right)$$

$$L1 = \log \frac{d2}{d1} + \log \frac{d4}{d3}$$

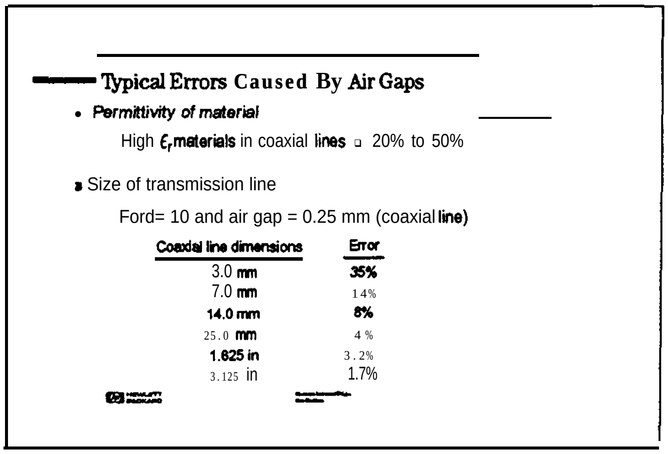
$$L2 = \log \frac{d3}{d2} \qquad L3 = \log \frac{d4}{d1}$$

$$\epsilon'_c = \epsilon'_m \frac{d}{D}$$

$$\tan \delta_c = \tan \delta_m \frac{b}{D}$$

$$D = b - \epsilon'_m (b - d)$$

Air gap between the fixture walls and the sample can be one of the largest sources of error in a transmission line measurement. For coaxial fixtures, the air gap along the center conductor wall has a much bigger effect than the air gap along the outer conductor wall. Likewise, for waveguide fixtures, the air gap along the long wall has a much bigger effect than the air gap along the short wall. Air gap correction algorithms can improve the accuracy of a measurement **if** the air gap is uniform and can be precisely measured.

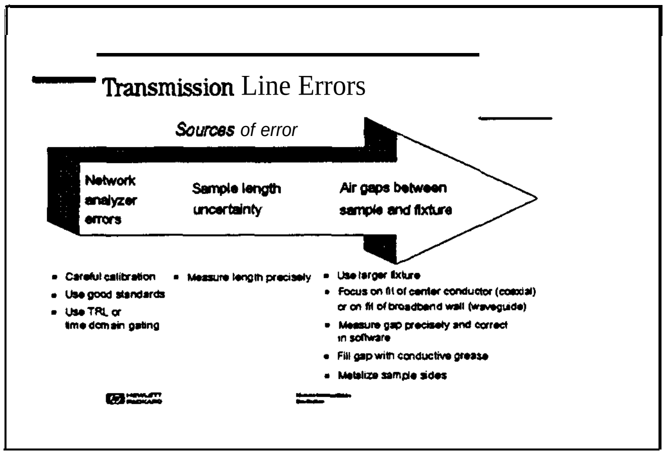


Typical Errors Caused By Air Gaps

- ***Permittivity of material***
  - High ϵ_r **materials** in coaxial **lines** □ 20% to 50%
- Size of transmission line
  - Ford= 10 and air gap = 0.25 mm (coaxial **line)**

Coaxial line dimensions	**Error**
3.0 mm	**35%**
7.0 mm	14%
14.0 mm	**8%**
25.0 mm	4%
1.625 in	3.2%
3.125 in	1.7%

Materials with higher permittivities and smaller diameter transmission lines will be more susceptible to error from air gap.



Transmission Line Errors

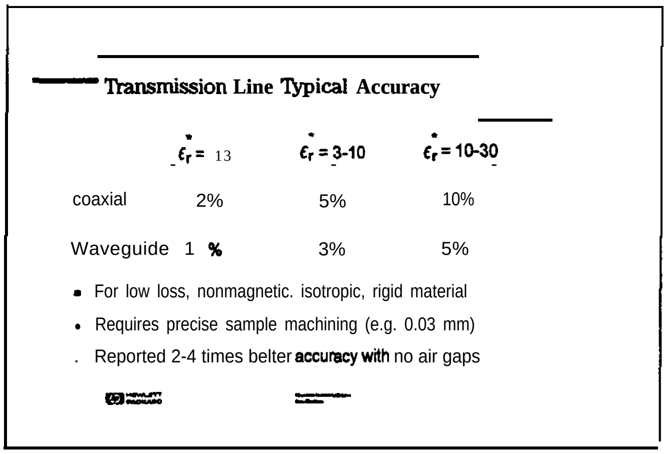
Sources *of error*

Network analyzer errors
- Careful calibration
- Use good standards
- Use TRL or time domain gating

Sample length uncertainty
- Measure length precisely

Air gaps between sample and fixture
- Use larger fixture
- Focus on fit of center conductor (coaxial) or on fit of broadband wall (waveguide)
- Measure gap precisely and correct in software
- Fill gap with conductive grease
- Metalize sample sides

Even after calibrating the network analyzer there is additional measurement uncertainty introduced by sample length uncertainty and air gap between the sample and fixture walls. These effects can be minimized but never completely removed.

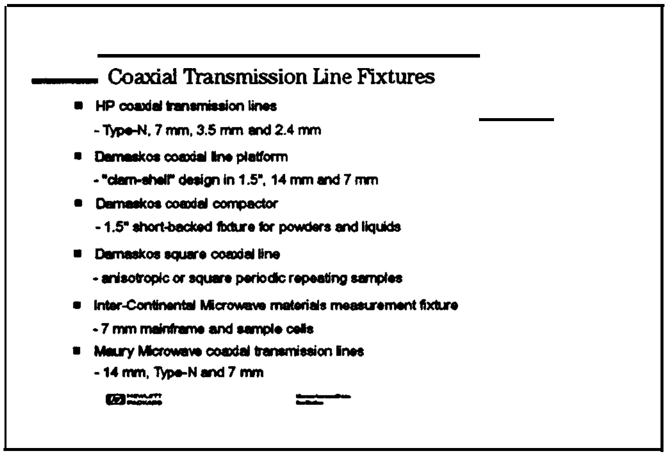


Transmission Line Typical Accuracy

	ϵ_r = 13	ϵ_r = 3-10	ϵ_r = 10-30
coaxial	2%	5%	10%
Waveguide	1 %	3%	5%

- For low loss, nonmagnetic. isotropic, rigid material
- Requires precise sample machining (e.g. 0.03 mm)
- Reported 2-4 times belter **accuracy with** no air gaps

The typical accuracy of a transmission line measurement ranges from 1% to 10% or higher depending on the MUT and how well it is machined.

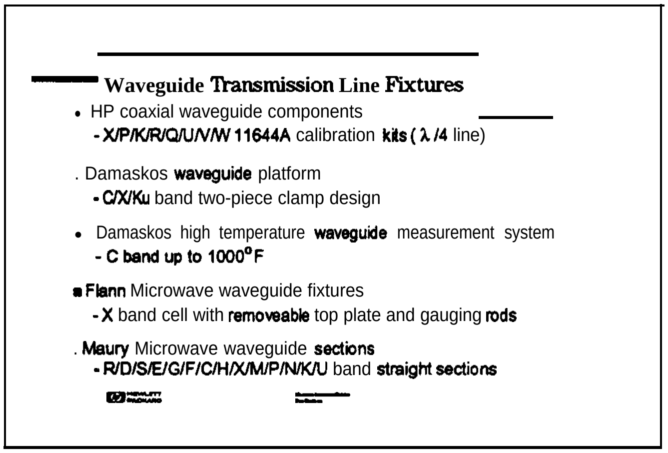


Coaxial Transmission Line Fixtures

- HP coaxial transmission lines
  - Type-N, 7 mm, 3.5 mm and 2.4 mm
- Damaskos coaxial line platform
  - "clam-shell" design in 1.5", 14 mm and 7 mm
- Damaskos coaxial compactor
  - 1.5" short-backed fixture for powders and liquids
- Damaskos square coaxial line
  - anisotropic or square periodic repeating samples
- Inter-Continental Microwave materials measurement fixture
  - 7 mm mainframe and sample cells
- Maury Microwave coaxial transmission lines
  - 14 mm, Type-N and 7 mm

40

The HP **8505X-series** coaxial verification kits contain airlines that can also be used as sample holders. There are several third party suppliers of coaxial transmission lines that provide fixtures for a wide variety of applications.

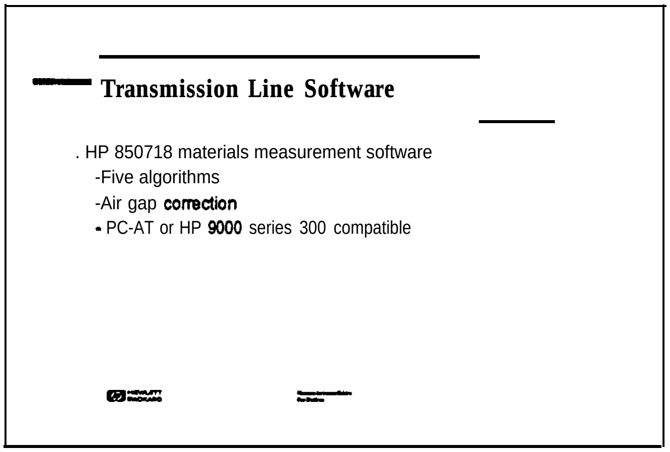


Waveguide Transmission Line Fixtures

- HP coaxial waveguide components
  - X/P/K/R/Q/U/V/W 11644A calibration kits (λ/4 line)
- Damaskos waveguide platform
  - C/X/Ku band two-piece clamp design
- Damaskos high temperature waveguide measurement system
  - C band up to 1000°F
- Flann Microwave waveguide fixtures
  - X band cell with removeable top plate and gauging rods
- Maury Microwave waveguide sections
  - R/D/S/E/G/F/C/H/X/M/P/N/K/U band straight sections

41

The HP 11644A-series waveguide calibration kits contain a l/4 wavelength line and a straight section that can also be used as sample holders. There are several third party suppliers of waveguide transmission lines that provide fixtures for a wide variety of applications.

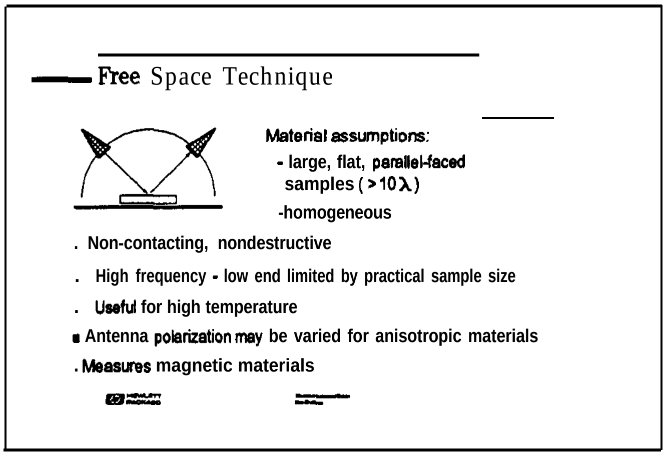


Transmission Line Software

- HP 850718 materials measurement software
  - Five algorithms
  - Air gap correction
  - PC-AT or HP 9000 series 300 compatible

42

The HP 85071B materials measurement software controls the network analyzer and converts the measured S-parameters to permittivity and permeability. It has five different algorithms to choose from (one-port and two-port) and has an air gap correction algorithm. The software is compatible with a wide variety of HP vector network analyzers.

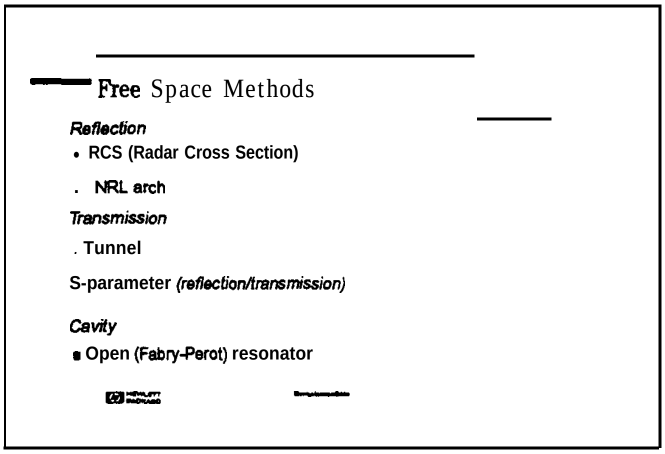


Free Space Technique

Material assumptions:
- large, flat, parallel-faced samples (> 10λ)
- homogeneous

- Non-contacting, nondestructive
- High frequency - low end limited by practical sample size
- Useful for high temperature
- Antenna polarization may be varied for anisotropic materials
- Measures magnetic materials

Free space is best for high temperature measurements since the sample is not enclosed in any kind of fixture. The MUT is assumed to be large, flat and uniform throughout. The free space antennas are connected to a vector network analyzer that measures the reflection and transmission from the MUT which are then converted to permittivity and permeability.



Free Space Methods

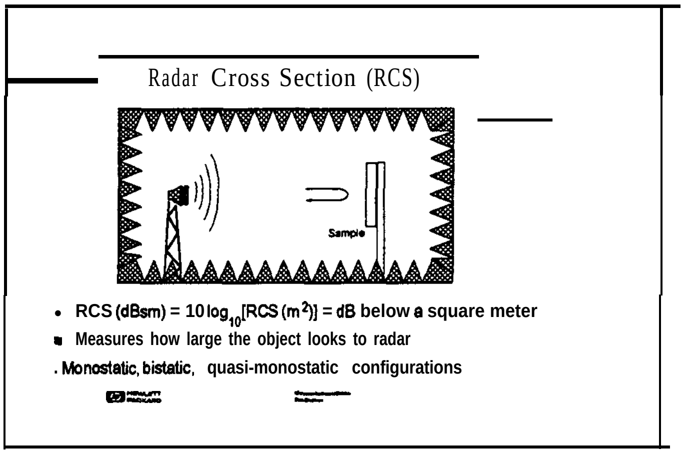
Reflection
- RCS (Radar Cross Section)
- NRL arch

Transmission
- Tunnel

S-parameter *(reflection/transmission)*

Cavity
- Open (Fabry-Perot) resonator

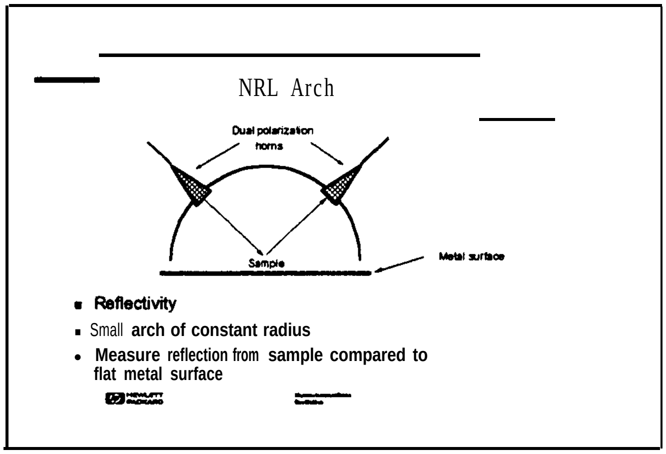
There are many free space measurement methods available to choose from.



Radar Cross Section (RCS)

- RCS (dBsm) = 10 $\log_{10}$[RCS (m^2)] = dB below a square meter
- Measures how large the object looks to radar
- Monostatic, bistatic, quasi-monostatic configurations

Radar cross section measurements determine how large an object looks to a radar.

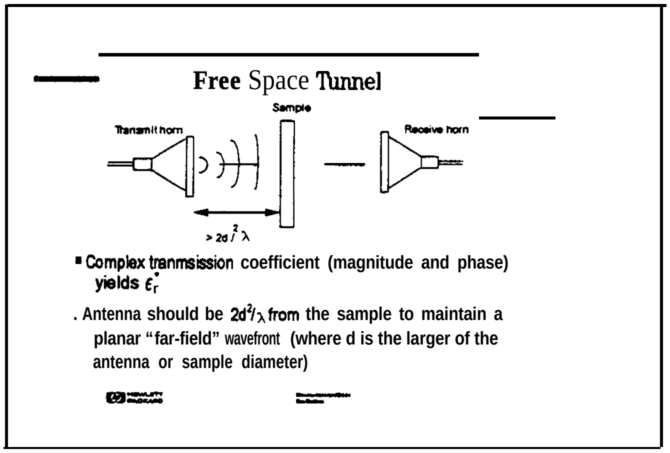


NRL Arch

- **Reflectivity**
- Small **arch of constant radius**
- **Measure** reflection from **sample compared to flat metal surface**

46

An NRL arch measures the reflectivity of a sample.

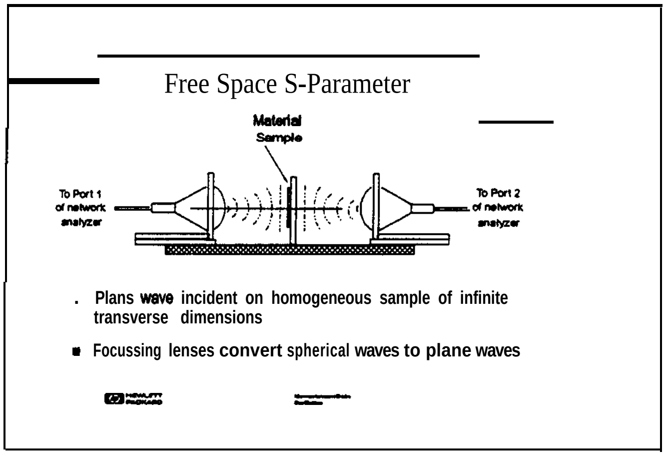


Free Space **Tunnel**

- **Complex tranmsission coefficient (magnitude and phase) yields ϵ_r^***
- **Antenna should be $2d^2/\lambda$ from the sample to maintain a planar "far-field"** wavefront **(where d is the larger of the antenna or sample diameter)**

47

For a free space tunnel, the sample is placed between the transmit horn and the receive horn. The received signal is measured and converted to permittivity. The antenna should be placed at least **$2d^2/$** away from the sample to ensure a planar far-field wavefront at the sample.

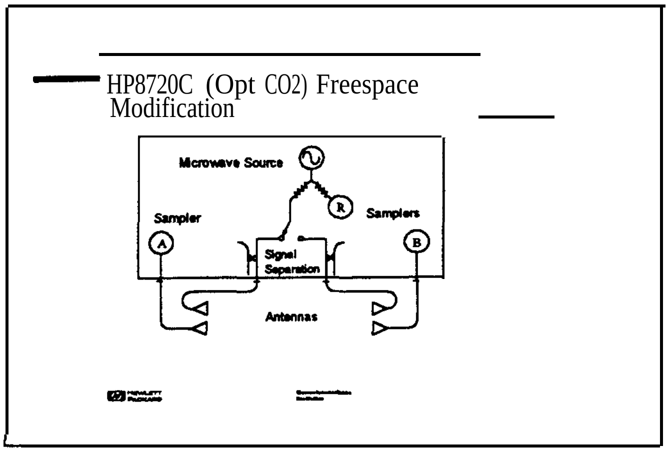


Free Space S-Parameter

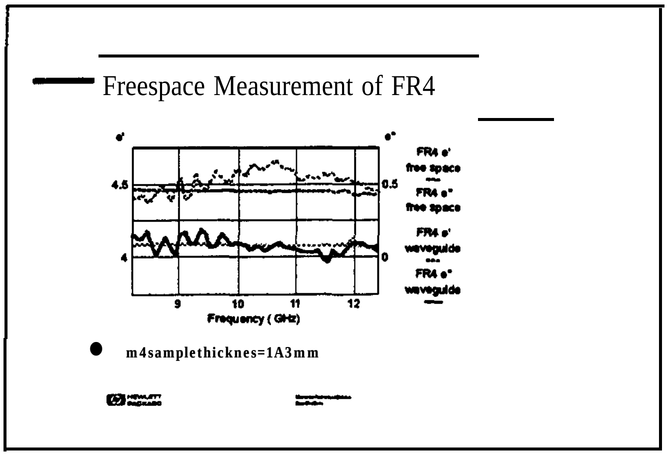
- **Plans wave incident on homogeneous sample of infinite transverse dimensions**
- **Focussing lenses convert** spherical **waves to plane waves**

48

An S-parameter configuration offers several advantages in the area of calibration to provide a more accurate measurement. By measuring all four S-parameters, a TRL (Thru-Reflect-Line) or TRM (Thru-Reflect-Match) calibration can be used. Some systems incorporate focusing lenses into the antenna that convert spherical waves to plane waves. This allows the antenna spacing to be closer and the sample size to be smaller.

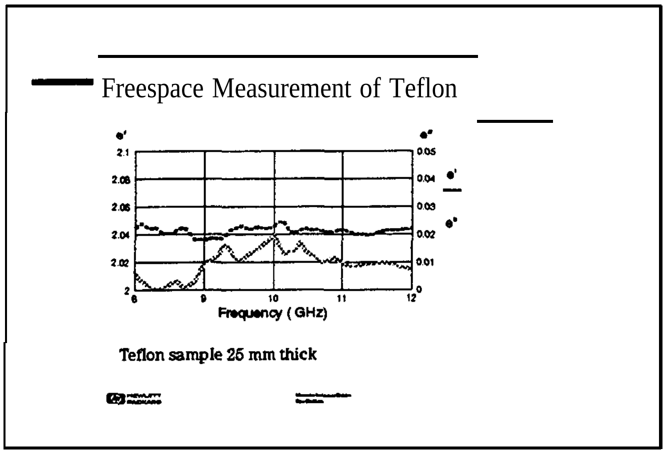

HP8720C (Opt C02) Freespace Modification

Using the same antenna for transmit and receive degrades directivity, particularly if non-focused antennas are used. The internal reflections can easily dominate the desired signal if the same antenna is used for transmission and reception. Using separate transmit and receive antennas overcomes this problem yielding better directivity. The HP872OC option CO2 provides front panel access to the samplers allowing a full s-parameter test set to be constructed in free space. This allows the transmission/reflection algorithms in the HP8507 1B to be used directly with the free space setup.


Freespace Measurement of FR4

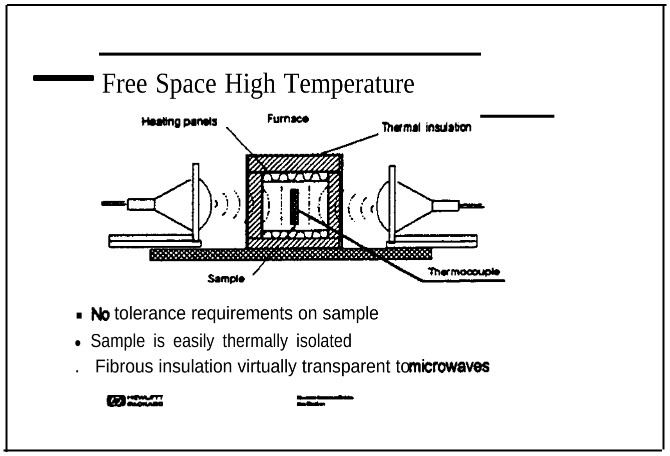
- m4samplethicknes=1A3mm

This plot shows measured ***results*** on FR4 (1.43 mm thick) using both the free space and waveguide techniques. The residual systematic errors after calibration are still lower in the waveguide measurement.


Freespace Measurement of Teflon

Teflon sample 25 mm thick

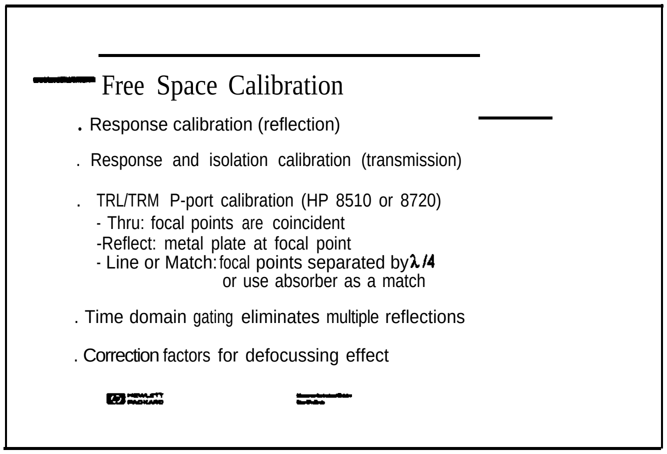
The effects of systematic errors are reduced for thicker materials. The results for 25mm thick Teflon are more consistent than the freespace results of the 1.43 mm thick FR4. Measurement of thicker samples “distributes” the systematic errors because the systematic error becomes a lower percentage of the sample response.



Free Space High Temperature

- No tolerance requirements on sample
- Sample is easily thermally isolated
- Fibrous insulation virtually transparent to microwaves

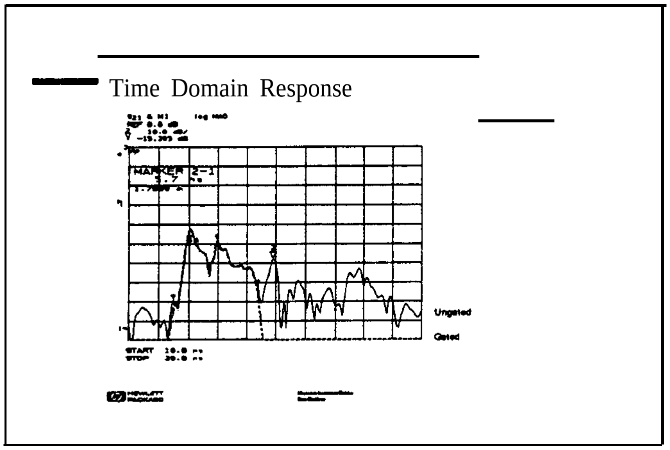
High temperature measurements are not a problem in free space since the sample is never touched or contacted. The sample can be heated by placing it within a furnace that has "windows" of insulation material that are transparent to microwaves.



Free Space Calibration

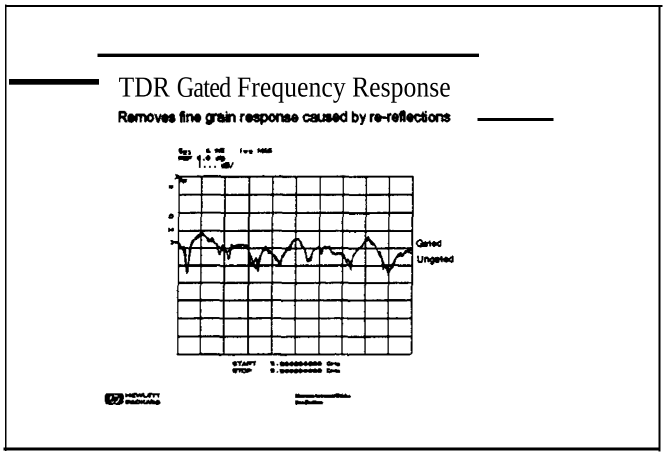
- Response calibration (reflection)
- Response and isolation calibration (transmission)
- TRL/TRM P-port calibration (HP 8510 or 8720)
  - Thru: focal points are coincident
  - Reflect: metal plate at focal point
  - Line or Match: focal points separated by $\lambda/4$ or use absorber as a match
- Time domain gating eliminates multiple reflections
- Correction factors for defocussing effect

Free space calibration standards present special problems since they are "connectorless". A calibration can be as simple as a response calibration to a full two-port calibration depending on the convenience and accuracy desired. A TRL (Thru-Reflect-Line) or TRM (Thru-Reflect-Match) calibration may actually be easier than other calibration techniques in free space. Time domain gating is often used to take the place of or supplement an existing calibration.



Time Domain Response

A time domain response shows the mismatch effects which may be degrading the quality of a free space measurement. If a time domain gate is applied around the signal of interest, many of the unwanted re-reflections can be eliminated.



TDR Gated Frequency Response

Removes fine grain response caused by re-reflections

Comparing the gated versus nngated response in the frequency domain shows how mismatch effects can add unwanted fine grain ripple to a free space measurement.

Free Space Sources **of Error**

- sample
  - -finite size
  - -contact with conducting backplane
- . Non-plane wave illumination
- . Accuracy/calibration of microwave receiver
- . Mechanical stabitty/alignment of sample and antennae
- . Quality of at-echoic environment

Free space measurements are susceptible to errors due to finite sample size and non-plane wave illumination. Care should be taken to minimize these effects.

Free **Space Typical Accuracy**

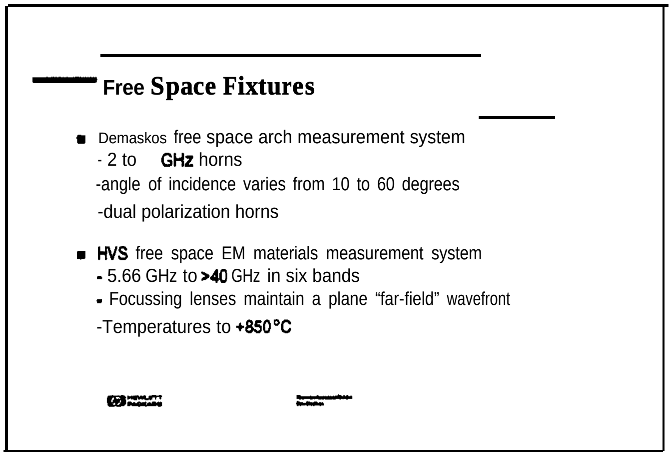
- Typical acccuracy

  $\epsilon_r' = \pm 1 - 5\,\%$

  $\tan\delta = \pm 0.005$

- Difficult to measure loss of thin (< 1 l) and **low loss (tan $\delta < 0.01$) samples**

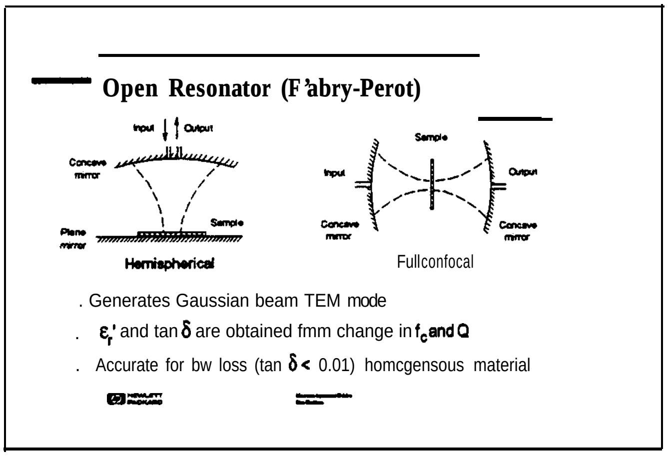
The typical accuracy that can be achieved with a free space measurement is under 5%. It is still difficult to measure very thin and low loss samples.



Free Space Fixtures

- Demaskos free space arch measurement system
  - 2 to GHz horns
  - angle of incidence varies from 10 to 60 degrees
  - dual polarization horns
- HVS free space EM materials measurement system
  - 5.66 GHz to >40 GHz in six bands
  - Focussing lenses maintain a plane "far-field" wavefront
  - Temperatures to +850°C

There are several third party suppliers that provide free space antennas and hardware that can be used with HP **network analyzers.**



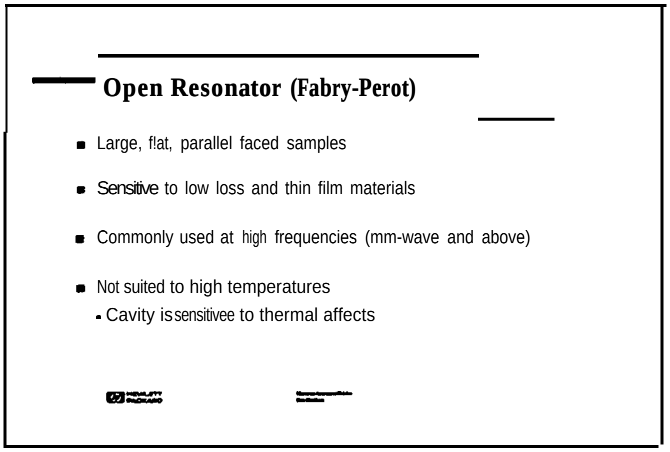
Open Resonator (F'abry-Perot)

. Generates Gaussian beam TEM mode

. ε_r' and tan δ are obtained fmm change in f_c and Q

. Accurate for bw loss (tan $\delta < 0.01$) homcgensous material

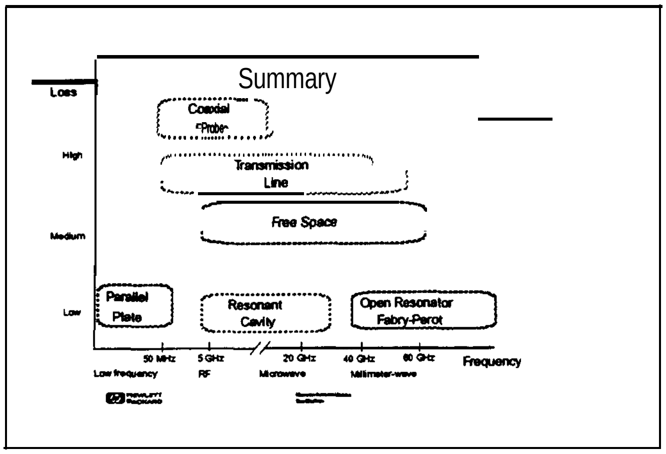
An open resonator (often called the Fabry-Perot technique) is best for measurements at very high frequencies and is very accurate especially for low loss materials.



Open Resonator (Fabry-Perot)

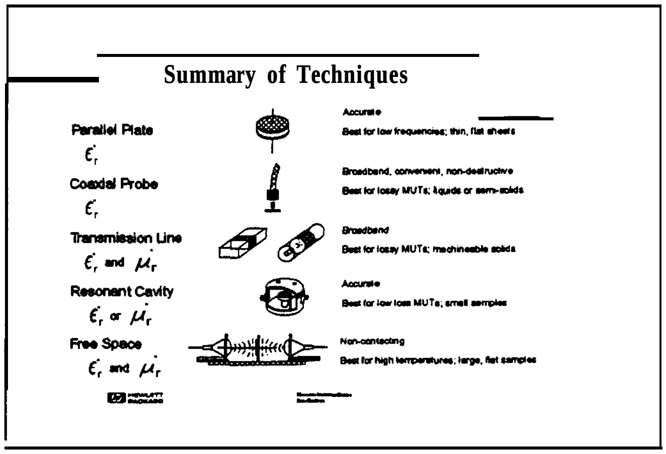
- Large, flat, parallel faced samples
- Sensitive to low loss and thin film materials
- Commonly used at high frequencies (mm-wave and above)
- Not suited to high temperatures
  - Cavity issensitivee to thermal affects

The open-resonator is a combination of a free space and cavity technique. It measures large, flat samples with greater accuracy at higher frequencies.



Summary

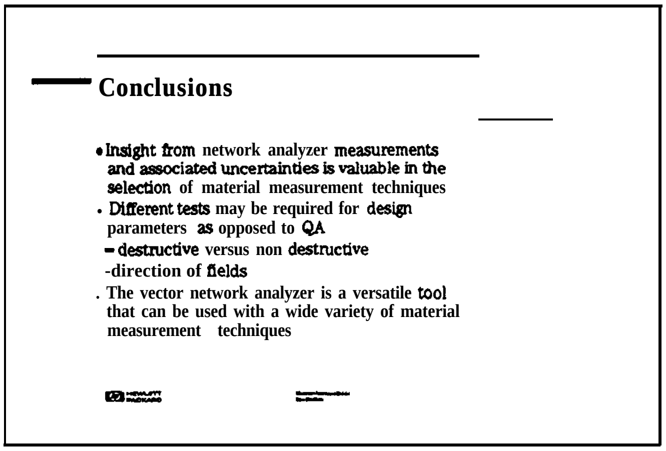
The different measurement techniques are mapped out according to frequency range of operation and suitability to the MUT. lossiness.



Summary of Techniques

Parallel Plate	ϵ_r^*	Accurate Best for low frequencies; thin, flat sheets
Coaxial Probe	ϵ_r^*	Broadband, convenient, non-destructive Best for lossy MUTs; liquids or semi-solids
Transmission Line	ϵ_r^* and μ_r^*	Broadband Best for lossy MUTs; machineable solids
Resonant Cavity	ϵ_r^* or μ_r^*	Accurate Best for low loss MUTs; small samples
Free Space	ϵ_r^* and μ_r^*	Non-contacting Best for high temperatures; large, flat samples

Other factors such as accuracy, convenience and the material shape and form are also factors in selecting a measurement technique.



Conclusions

- Insight from network analyzer measurements and associated uncertainties is valuable in the selection of material measurement techniques
- Different tests may be required for design parameters as opposed to QA
  - destructive versus non destructive
  - direction of fields
- The vector network analyzer is a versatile tool that can be used with a wide variety of material measurement techniques

Insight gamed *from* and understanding of network analyzer and associated uncertainties is valuable in the design and selection of material measurement techniques. The technique chosen depends on a variety of factors and may differ depending on the intended use of information. For example, it would be important to insure that the field directions matched the final application when measuring anisotripic materials with the intent of obtaining design parameters. If the intent is to check for consistency field direction may be less important. The wide variety of techniques presented can all be implemented using a vector network analyzer.

References

Literature Cross Refemces

Topic	**Author**	**Comments**
Basics	HP Ap Note 1217-1 01yphant Bahl Cascade Microtech Ramo, Whinnery, Van Duzer Wheeler Gupta	Background on Dielectrics Microwave, MIC Microwave Applications Digital Applications Stripline, Microstrip Microstrip Design Microstrip Design
Cavity Resonator	Kent ASTM D 2520, Dube Hill Nishikawa (MuRata)	 Split, Non-Destructive
Coax Probe	HP 85070 Fan, Misra	 Metal-Backed
Dispersion	Gonzalez York	 Evaluation, Review
Full Sheet Resonance	Woolaver York Howell Napoli Ladbrooke	 Closed Edges Original Method (1971) Error Analysis & Correction
Lumped Capacitance	Iskander	
Resonant Probe	Wang	Non-Destructive, Localized
Review of Methods	York 01yphant	
Standard Method Strip Lines	ASTM D3380, IPC 650 Das Peterson Riedell	
Strip Resonators	ASTM D3380, IPC 650 Bogatin Mayercik Gipprich Tanaka	2-Port Sttipline l-Port Microstrip, Time Domain Ring Ring, 2-Port Line Stripline, Loss Measurements
Waveguide Slab	York Bahl	
Q Circles	Oldfield Estin	Cavity Measurements

Reference Literature

1. ASTM D 2520-86; “Test Methods for Complex Permittivity (Dielectric Constant) of Solid Electrical Insulting Materials at Microwave Frequencies and Temperatures to 1650 deg **C";** American Society for Testing and Materials [waveguide transmission line and cavity perturbation methods, using HP 415E and sweeper]
2. ASTM D 3380-90; “Standard Test Method for Relative Permittivity and Dissipation Factor of Polymer-Based Microwave Substrates”; American Society for Testing and Materials [standardized method, using discrete HP 415E and sweeper, see IPC TM-650, based on MIL-P-13949E]
3. Bahl, I. et al; “Modern Microwave Substrate Materials”; State-of-the-Art Reference, Microwave Journal, 1990
4. Bogatin, E.; “Closed Form Analytical Model for the Electrical Properties of Microstrip Interconnects”, IEEE CHMT-13 (2), **June** 1990 [time-domain l-port microstrip resonators]
5. Cascade Microtech; High Speed Digital Microprobing **--** Principles and Applications”; Mar 91
6. Cascade Microtech; “Product Overview: High Frequency Measurement Tools and Solutions”; Nov 199 1
7. Das, N. et al; “Two Methods for the Measurements of Substrate Dielectric Constant”; IEEE MTT-35 (7), July 1987 [phase difference from two microstrip lines and from over-layed layer, using HP 8510]
8. Dube, D. et al; “Dielectric Measurements on Substrate Materials at Microwave Frequencies Using a Cavity perturbation Technique”; J Appl Phys 63 (7), April 1988 [rectangular cavity perturbation at X-band, alumina and silica, using HP 8510]
9. Estin, Arthur J. (Cyberlink); Janesic, Michael B. (Nist); “Improvements in Dielectric Measurements with at Resonant Cavity”, IEEE IMTC-5 Conference Proceedings 1991. [Q circles]
10. Fan, S et al; “Study on Metal-Flanged Open Ended Coaxial Line Terminating in a Conductor-Backed Dielectric Layer”; IEEE IM-T/C Proc 1990 [metal-backed probe]
11. Gipprich, J. et al; “Microwave Dielectric Constant of a Low Temperature Cofired Ceramic (LTCC)“; IEEE CHMT-14 (4), Dec 1991 [microstrip ring and end-coupled 2-port resonators, **e'=8,** f<14 GHz, using HP 85 10 and 8757]
12. Gonzalez, G.; ‘Microwave Transistor Amplifiers”; Prentice-Hall
13. Gupta, K. et al; “Microstrip Lines and Slotlines”; Artech House, 1979
14. HP; “Basics of Measuring the Dielectric Properties of Materials”; Ap Note 1217-1, HP Lit No 5091-33OOE, March 92
15. HP; “Measuring Complex Permittivity and Permeability at RF and Microwave Frequencies”; Symposium Paper, HP Lit No 5952-2385(D), Sept 89
16. HP 85070B Dielectric Probe; Data Sheet, HP Lit No 5091-6247E, Jan 93
17. HP 85071B Materials Measurement Software; Data Sheet, HP Lit No 5091_6248E, Jan 93
18. Hill, G.; “Precise Determination of Dielectric Properties of Alumina”; IEEE lM-23 (4), Dec 1974 **[TM-0 In rectangular cavity perturbation method, 10 GHz]**
19. Howell, J.Q.; “Quick Accurate Method to Measure Dielectric Constant of Microwave Inegrated-Circuit Substrates”; IEEE MTT-21, p142, Mar 73 [parallel-plate cavity (FSR) with metalized edges to reduce radiation]
20. ICM (Inter-Continental Microwave); “Test Fixtures and Calibration Standards”; Catalog, HP Lit No 5091-0534E
21. IPC TM-650 2.5.5.5; “Stripline Test for Permittivity and Loss Tangent of X-Band (for PC Boards)“; Nov 87 [see ASTM D 3380]
22. Iskander, M. (advisor); “Nondestructive Measurement of the Complex Permittivity of Substrates”; HP Engr Clinic, U of Utah, June 1988 [survey of methods, lumped-capacitance coax line approach]
23. Kent, G.; “Dielectrometer for Measurement of Substrate Permittivity”; Microwave Journal, Dec 1991 [resonant mode dielectrometer with closed ends]
24. Ladbrooke, P.H.; “Some Effects of Field Perturbation Upon Cavity-Resonance and Dispersion Measurements on MIC Dielectrics”; IEEE MlT-25 (1 l), Nov 77 [detailed analysis of resonator errors due to metal loss, fringing, coupling, and anisotropy, with correction formula]
25. Mayercik, M. (SGS-Thomson); “Resonant Microstrip Rings Aid Dielectric Material Testing”; Microwave & RF, April 1991 [microstrip ring resonator, f=3.7 GHz, **e'=10,** using scalar analyzer]

26. Napoli, L.S. et al; “Simple Technique for Accurate Determination of Microwave Dielectric Constant for Microwave Integrated Circuit Substrates”; IEEE MTI-19, p. 664, July 71 [parallel-plate resonator (FSR) with open edges]
27. Nishikawa, T. et al (MuRata Mfg Co); “Dielectric Resonator Method for Non-destructive Measurement of Complex Permittivity of Microwave Dielectric Substrates”, Euro Mic Conf, Sept 1990 or Conf of Precise EM Meas Proc, June 1988 [split resonator to measure local properties of sheet]
28. Oldfield, Laurence (Royal Signals and Radar Establishment); “An Automatic Network Analyzer (ANA) Technique for the Absolute Measurement of the Q-Factors of a Dissipatively Coupled Single Port Cavity”; copyright controller HMSO, London 1982 [Q Circles]
29. Olyphant, M. et al (3M); “Microwave Substrates Support MIC Technology”; Microwaves, Nov/Dec 1980 [strip resonators and chip cavities, with review of methods, many references]
30. Olyphant, M. (3M); “Practical Dielectric Measurement of Clad Microwave Substrates”; 3M Tech Note 8 [good overview, strip resonators, chip cavities, TE-011 cavity, many refs]
31. Peterson, M. (HP); “Electric Characterization of FR4 and Cyanate Ester PCB Substrate Materials”; (not published)[phase/magnitude difference between two striplines to 20 GHz, using HP 8510]
32. Quist, L.; “Measurement of PCB Characteristics”; Wireless Design Note 220 (not published) [long stripline, 1=52 cm, f=1 GHz, using HP 8720]
33. Riedell, H. et al; “Dielectric Characterization of Printed Circuit Substrates”; IEEE IM-39(2) April 1990 [parameter transformation of 2-port transmission line, using HP 85 10, plus review of methods]
34. Tanaka, H. et al; “Precise Measurements of Dissipation Factor in Microwave Printed Circuit Boards”; IEEE IM-38 (2), April 1989 [u-i-plate stripline resonator, emphasizing loss measurements]
35. Wang, M. et al; “High Spatial Resolution Dielectric Constant Uniformity Measurements Using Microstrip Resonant Probes”; IEEE MIT-S Digest, 1990 [microstrip resonant probe for small-area dielectric measurements over surface of substrate]
36. Wheeler, H.A.; “Transmission-Line Properties of a Strip on a Dielectric Sheet on a Plane”; IEEE MTT-25 (8), Aug 1977 [classic approximations for microstrip]
37. Woolaver, G. (Arlon); “Accurately Measure Dielectric Constant of Soft Substrates”; Microwaves & RF, Aug 1990 [full sheet resonance]
38. York, R; Microwave Measurement of Substrate Dielectric Constant and Microstrip Dispersion”; MS Thesis, Cornell (not published) [good review of methods, full sheet resonance and waveguide slab methods, verification of dispersion models]
39. York, RA. et al; “Automated Method for Dielectric Constant Measurements of Microwave Substrates”; Microwave Journal, March 1990 [waveguide slab method, using HP 8510]

Professional Societies

- ASTM (American Society for Testing and Materials)
  1916 Race St.
  Philadelphia
  PA 19103

- EIPC (European Institute of Printed Circuits)
  Via Marainin 17
  CH 6900 Lugano
  Switzerland
  +41-91-549-432 (Fax)

- IEPS (International Electronics Packaging Society, Inc.)
  114 North Hale St.
  Wheaton
  Illinois 60187-5513
  (708) 260-1044
  (708) 260-0867 (Fax)

- IEEE, CHMT Society (Components, Hybrids, and Manufacturing Technology)

- IPC (Institute for Interconnecting and Packaging Electronic Circuits)
  7380 N. Lincoln Ave.
  Lincolnwood
  IL 60646
  (708) 677-2850
  (708) 677-9570 (Fax)

- ISHM (International Society for Hybrid Microelectronics)
  1861 Wiehle Ave., Suite 260
  Reston
  VA 22090
  (703) 47 l-0066
  (703) 471-1937

- JPCA (Japan Printed Circuit Association)
  Toranomon-Kioyoshi Building
  3-10 Toranomon 4-chome
  Minato-ku
  Tokyo 105
  Japan
  +03-3436-4641 (Fax)

- PCIF (Printed Circuit Interconnection Federation)
  Exeter House
  48 Holloway Head
  Birmingham Bl 1NG
  United Kingdom
  +21-666-6316 (Fax)