Hewlett-Packard

Electronic Materials Measurement Seminar

RF and MW Network Analyzer Measurement Techniques for Dielectric Substrates

Kobe Instrument Division

HEWLETT PACKARD

Electronic Materials Measurement Seminar

RF and MW Network Analyzer Measurement Techniques for Dielectric Substrates

1

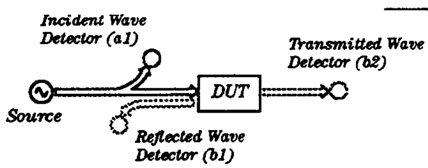
Microwave Material Measurement Techniques

- Vector Network Analyzer Review
  - error sources
  - calibration
- Substrate materials
  - resonant techniques
  - microstrip/stripline patterns
- Bulk materials
  - coaxial probe
  - transmission/reflection techniques
  - free space techniques

The microwave techniques for measuring permittivity and permeability presented will use network analyzers. A brief overview of network analyzer measurements will be presented followed by various measurement techniques. There is some crossover in applicability of the various methods but the discussion of the methods will proceed as outlined.

2

Network Analyzer Block Diagram



Reflection Coefficient $\Gamma = \frac{b1}{a1}$

Transmission Coefficient $T = \frac{b2}{a1}$

A network analyzer consists of a source, signal separation device and detectors. The signal separation device allows the forward and reverse traveling waves to be sensed independently. The reflection coefficient is the ratio of the reflected voltage wave over the incident voltage wave. The transmission coefficient is the ratio of the transmitted voltage wave over the incident voltage wave. Network analyzers with full s-parameter test sets can measure the reflection and transmission coefficients in both directions.

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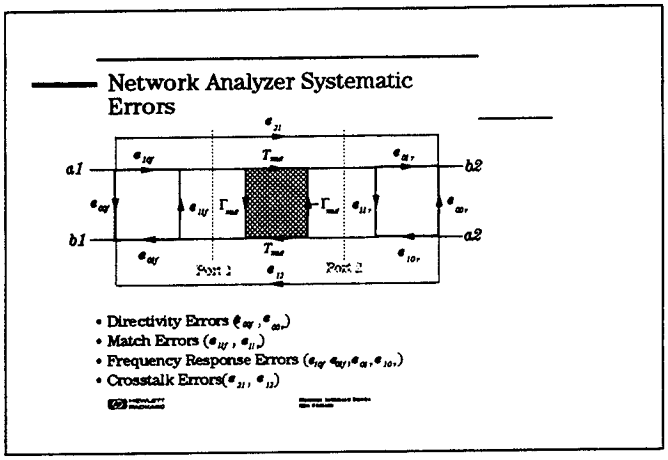

The systematic errors are repeatable non-ideal characteristics of the network analyzer. The frequency response terms arise from the path loss, phase delay, and detector response. Directivity errors are due to leakage signals that are sensed at the reflected wave detector that have not reflected off the DUT. Crosstalk errors are due to leakage signals that are sensed at the transmitted wave detector without passing through the DUT. Match errors arise from multiple reflections off the DUT that are not sensed at the incident wave detector.

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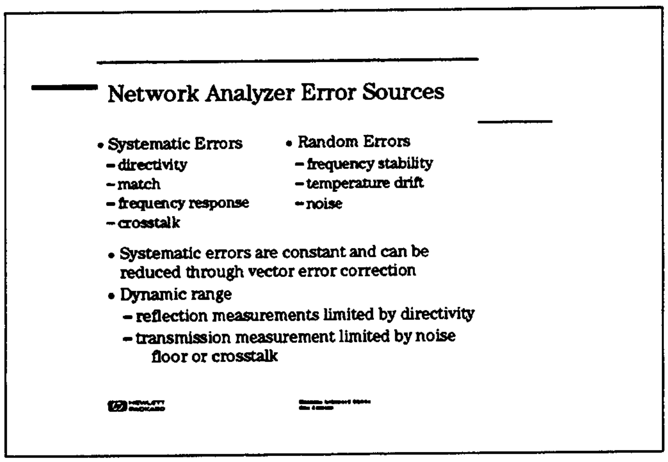

With vector network analyzers the systematic errors can be corrected through a calibration process known as vector error correction. This process computes the various systematic errors from measurement on known reference standards. When subsequent measurements are made the effects of the systematic errors are mathematically removed from the measurement. Frequency stability can be improved by using a synthesized source with the measurements.

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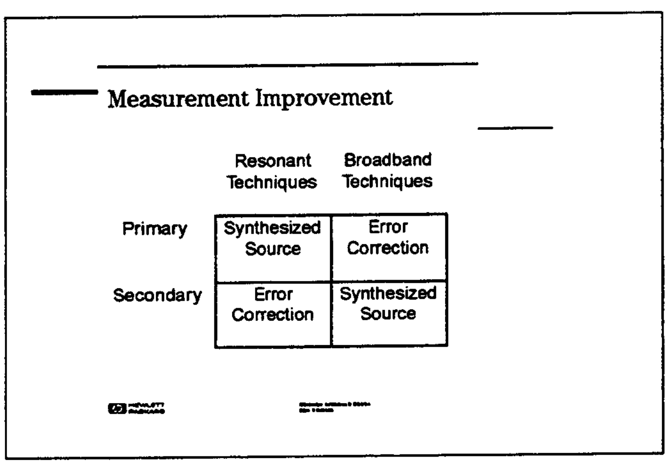

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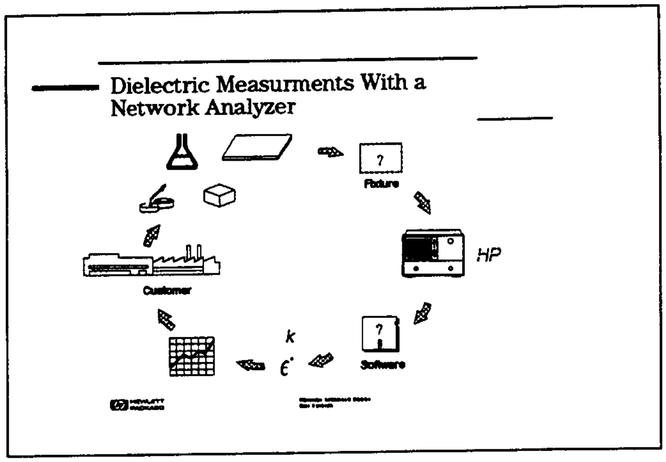
There are two classes of material measurements used with network analyzers--resonant techniques and broadband techniques. The resonant techniques provide a higher impedance environment and can yield better resolution on loss measurements than broadband techniques. The broadband techniques provide measurements over a range of frequencies rather than the isolated frequencies available with resonant techniques. For resonant measurements frequency stability is more important than vector error correction. With short cables the systematic error terms vary slowly with frequency and can be assumed constant over the narrow frequency ranges of concern with resonant techniques. With broadband measurements the importance is reversed. Error correction provides a greater benefit.



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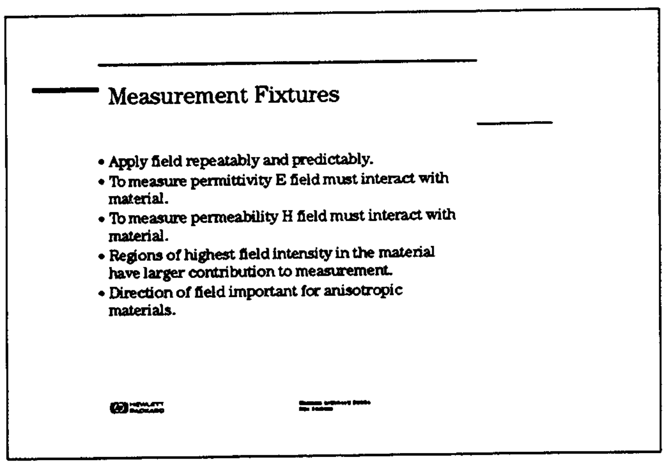
Hewlett-Packard network analyzers can be used to measurematerials over the RF and microwave frequency range. A fixture is often required to adap the materialto the coaxial ports of the network analyzer. Additionally, software may be required to convert the measurd S-parameters to dielectric constant.



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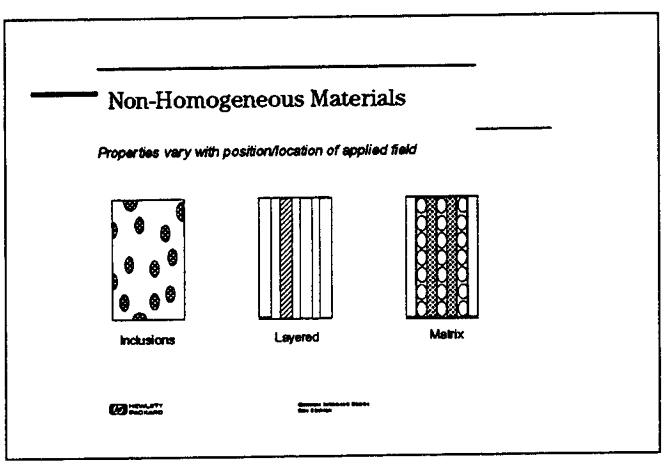
Measurement fixtures are necessary to apply the E field (for permittivity) and/or H field (for permeability) to the material in a predictable and repeatable manner. In order to measure permittivity a non-zero E field must be present in the material. The indicated permittivity will be a weighted average proportional to the field intensity in the material. If the material is anisotropic the direction of the electric field is also an important consideration. Similar considerations apply to permeability and H-fields.



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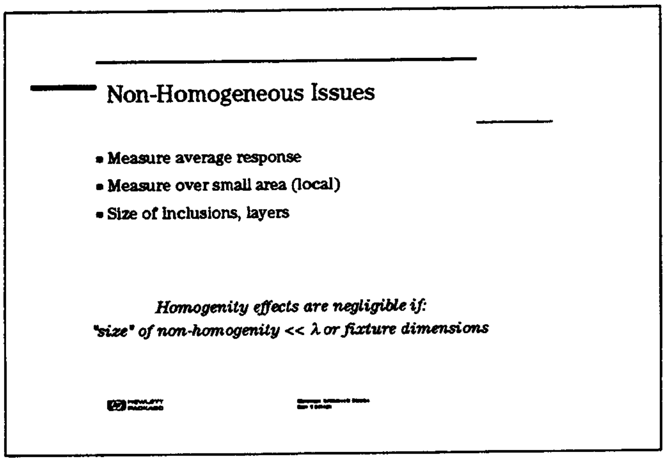
Many materials are not homogeneous or uniform, therefore their properties vary depending on the position and location of the applied electric or magnetic field.



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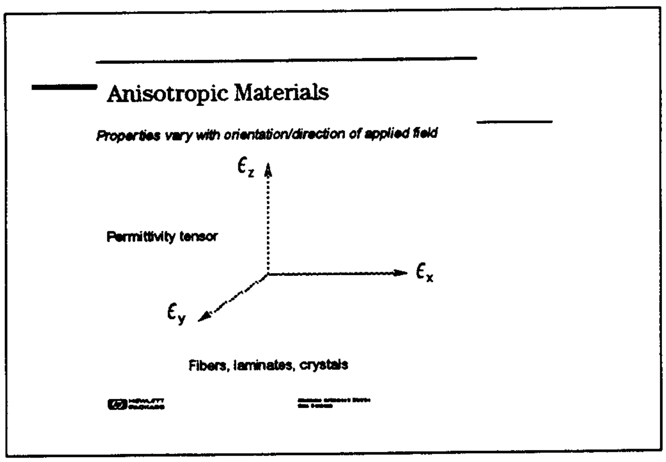
If the material is not uniform, the measured result will depend on the size of the inhomogeneity. In general, if the size of the nonhomogeneity is much less than the wavelength of the fixture dimensions, the material is assumedto be homogeneous.



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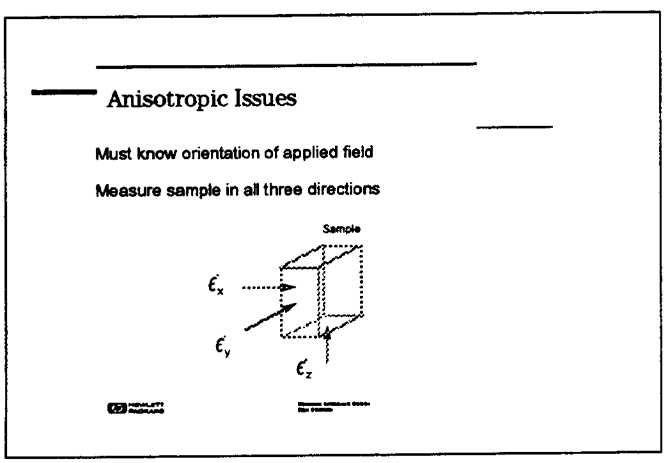
A material is anisotropic if its properties vary with different orientations and directions of the applied electric or magnetic field.



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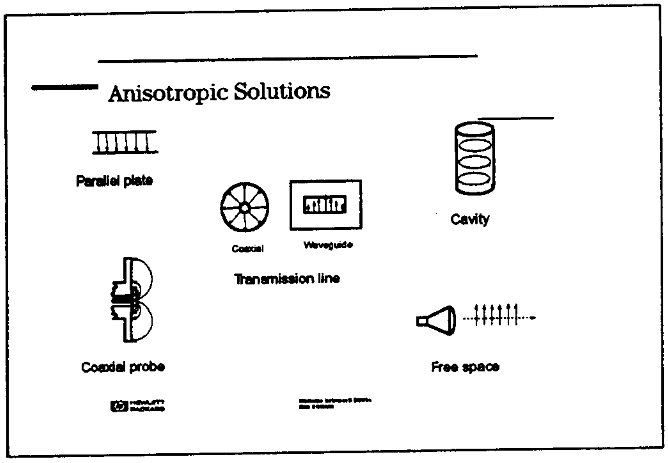
In order to measure an anisotropic material, the orientation of the applied field must be known and the sample must then be measured in all three orientations to determine the permittivity tensor.



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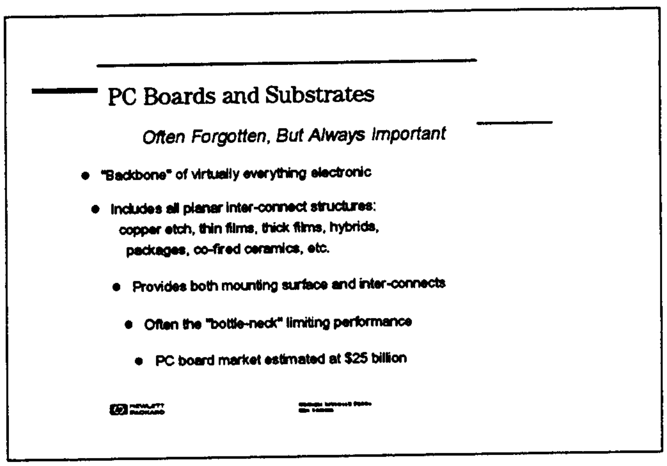
The field orientation will depend on the technique that is being used and the fixture.



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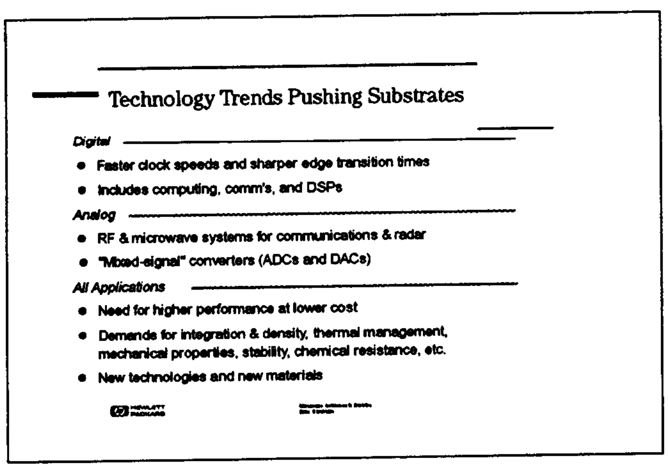
PC boards and substrates are an integral part of almost any electronic product. This category of materials includes any structure that provides a mounting surface or interconnect for electronic devices. As applications become more complex, th materials themselves become the limiting factor in overall performance



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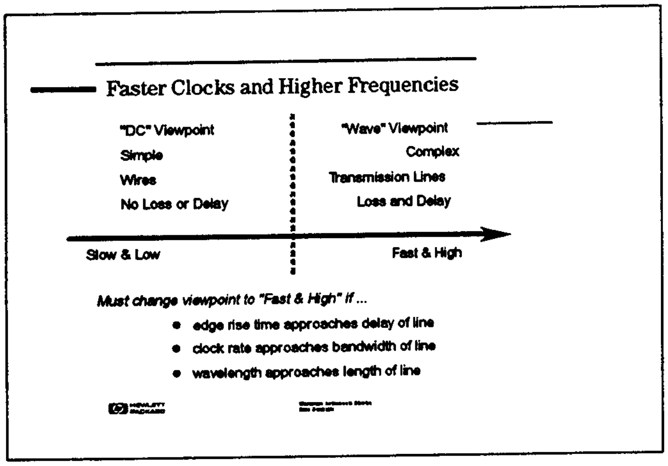
Current market trends are pushing substrate technology to higher and higher levels. Digital applications require faster clock speeds and sharpe edge transition times. Analog applications require higher performance and are incorporating more digital/analog converters. All applications demand higher performance, reliability and reproducibility, more miniaturization and integration, and lower cost. This drives the need for new and improved materials.



As digital circuits reach higher clock speeds and faster edges, interconnects can no longer be treate as "wires" without delay or loss. A simple DC analysis must give way to a more complex transmission line analysis at higher frequencies. As a rule of thumb, the transition to a high frequency "viewpoin t" must be made if the edge rise time approaches the delay of the line, if the clock rate approaches the bandwidth of the line, or if the wavelength approaches the length of the line.

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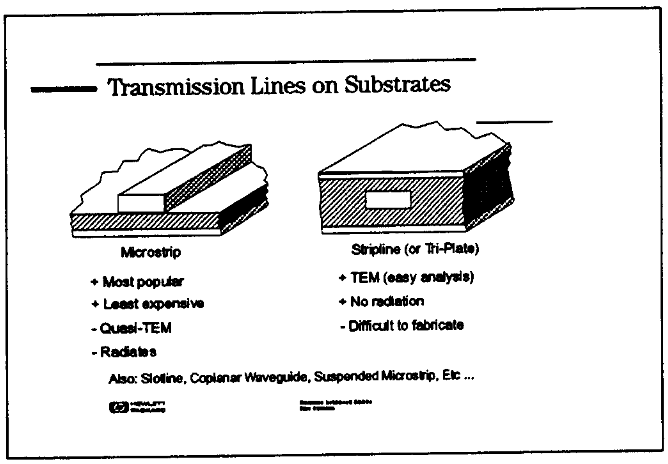

A microstrip transmission line consists of a strip conductor that lieson layer of dielectric material with a ground plane below which serves as a substrate. Microstrip is the most common and leas expensive type of transmission line but supports quasi-TEM waves and radiates. A stripline consists of a conducting strip thatlies between two conducting planes. The region between the strip and planes is filled with a uniform dielectric. Stripline is more difficult to manufacture but can support a TEM wave and does not radiate. Other types of media include slotline, coplanar waeguide and suspended microstrip.

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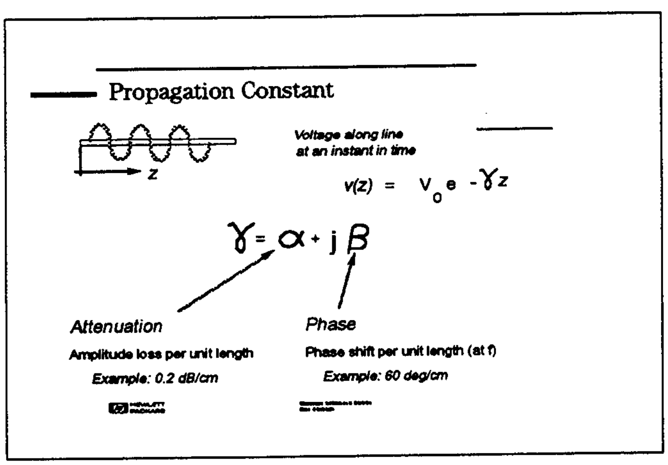


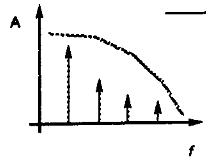
As an electromagnetic wave is propagated down a transmission line, it is attenuated by the lossy elements of the line. The instantaneous voltage along the line is described by the propagation constant. The propagation constant is made up of an attenuationconstant (amplitude loss per unit length) and a phase constant (phase shift per unit length at a given frequency).

18

Why Worry About Propagation?

Attenuation

- Bandwidth
- Pulse Distortion
- Rise Time & Clock Speeds



Phase

- Velocity
- Delay Time, Time-of-Flight
- Pulse Distortion (non-linear phase vs frequency)
- Matching Elements, Tuning Stubs

The amount of attenuation and phase will affect th performance of the transmission line by changing the propagation of the electromagnetic wave. Attenuation reduces the magnitude of the wave which can change the bandwidth of the signal, distort the pulse shape, or change the rise time and clock speed. Phase shift impacts the velocity of the signal or the delay time and can also introduce pulse distortion. These equations emphasize the impact of dielectric constant.

19

Propagation and Dielectric Constant

Attenuation

Dielectric Losses: $\alpha\ (\text{dB/cm}) = 0.9\ f(\text{GHz})\ \frac{\epsilon_r''}{\epsilon_r'}\sqrt{\epsilon'_{eff}}$

(plus losses in conductors)

Phase

$$\beta\ (\text{rad/cm}) = \frac{2\pi\ f(\text{GHz})\ \sqrt{\epsilon'_{eff}}}{30}$$

Velocity: $V\ (\text{cm/ns}) = 30\ \frac{1}{\sqrt{\epsilon'_{eff}}}$

The attenuation constant and phase constant are a function of the microstrip geometry, the electrical properties of the dielectric substrat and conductors, and the frequency.

20

Impedance

Z_O The characteristic impedance is the instantaneous ratio of V over I of a uniform infinitely-long transmission line.

Conceptually: $Z_O = \frac{V}{I} = \frac{V^2}{P} = \frac{P}{I^2}$

... but these are not strictly true for non-TEM transmission lines.

The characteristic impedance of a TEM transmission line is the ratio of the instantaneous voltage and current along the line. For non-TEM transmission lines (i.e. microstrip) a different approach must be used.

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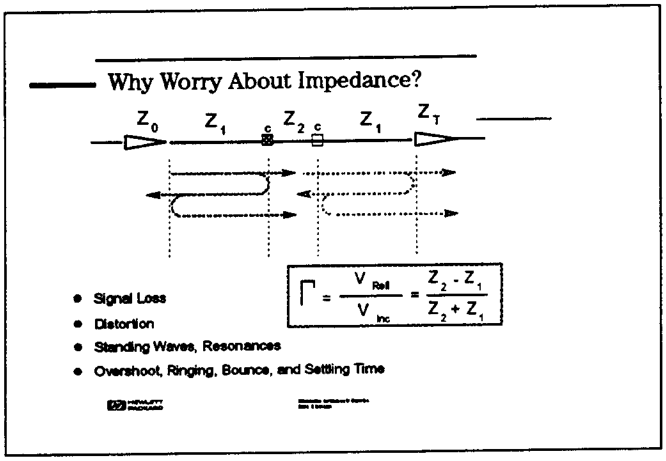
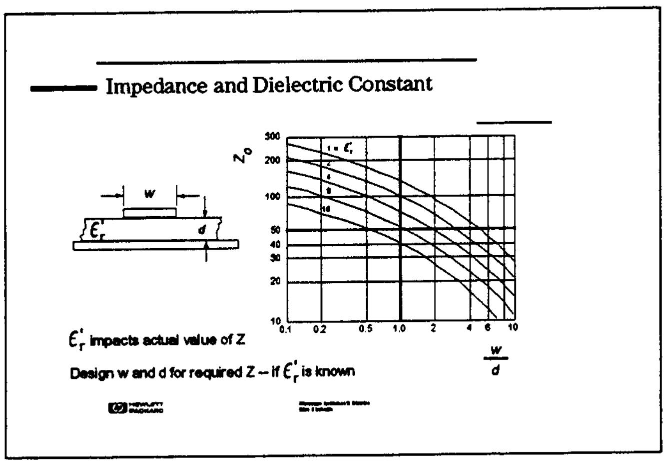


$$\Gamma = \frac{V_{Ref}}{V_{Inc}} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

22

Changes in impedance along a transmission line (mismatches) cause part of a traveling wave to be reflected backwards. This leads to signal loss, distortion, standing waves, overshoot and ringing. In order to avoid unpredictable behavior, it is important to design transmission lines with a known (and preferably constant) impedance.



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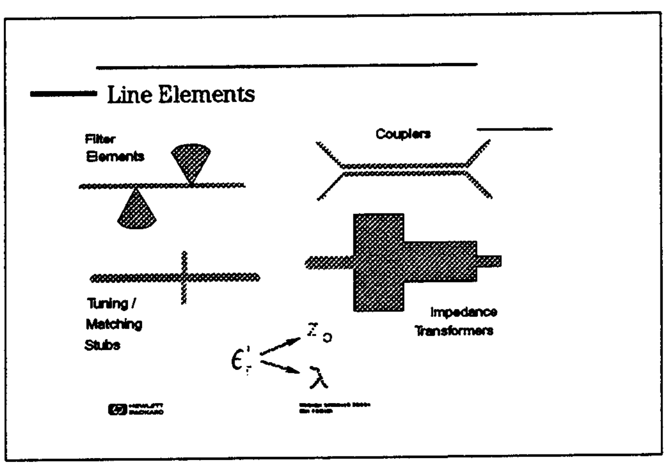
The impedance of a microstrip transmission line is determined by the dielectric constant and the ratio of the trace width (w) to the dielectric thickness (d). If the dielectric constant can be measured accurately, it can be used to select appropriate microstrip dimensions for a given impedance.



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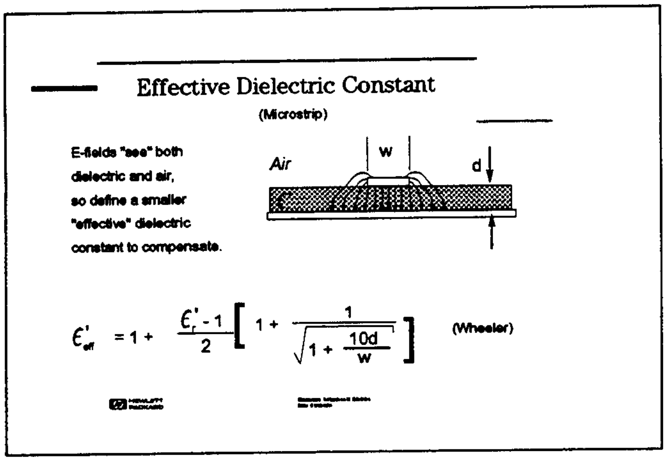
At high frequencies, circuit elements and components are sometimes constructed exclusively with transmission lines. These designs require an exact knowledge of impedance and wavelength.



In microstrip the electromagnetic fields are quasiTEM such that the electric fields are partially in the substrate and partially in air. Wheelers formula expresses the "effective dielectric constant" that is required to account for the nonTEM nature of the fields.

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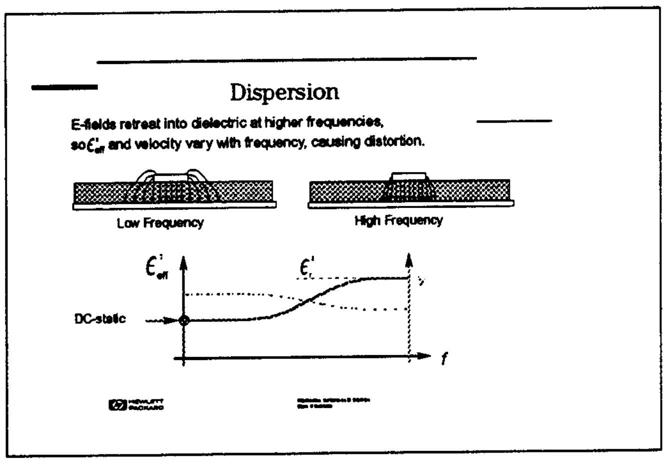

As frequency increases, the electric field on a microstrip line shifts down into the substrate. The effective dielectric constant and velocity vary with frequency causing a form of ditortion called dispersion. As the effective dielectric constant increases with frequency, the phase velocity decreases.

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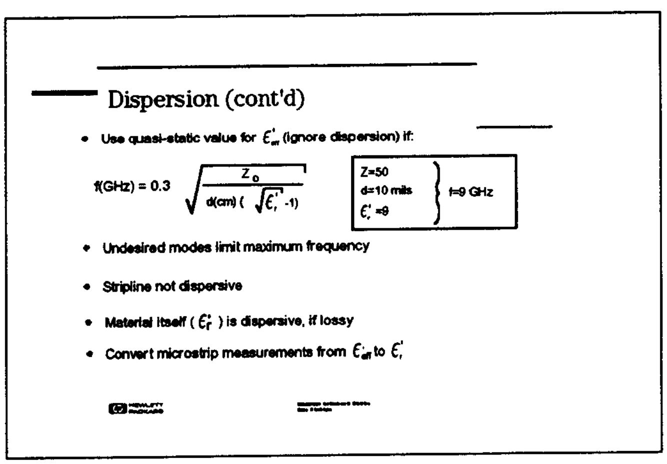
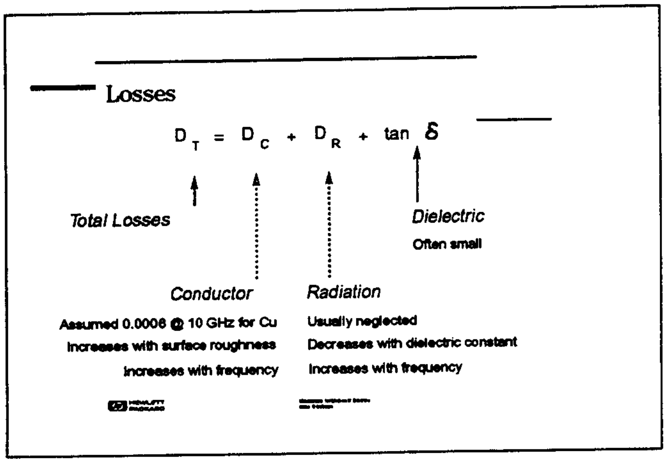


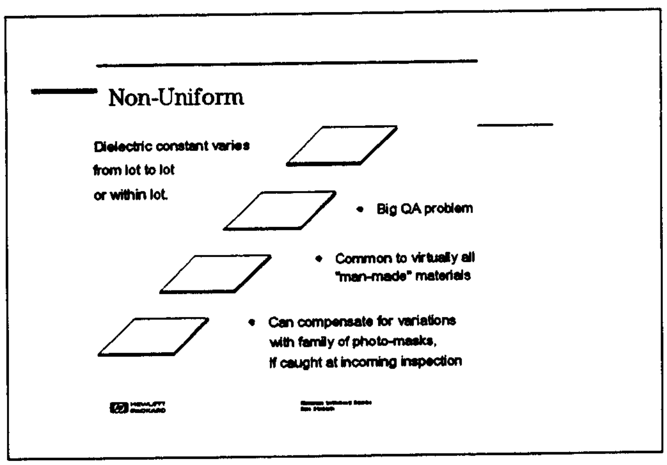
As a rule of thumb, the frequency below which microstrip dispersion may be neglected is given by the equation. Dispersion is usually associated with microstrip lines (stripline is not dispersive) at higher frequencies, although higher order modes will lim it the maximum frequency. It is important to convert microstrip measurements from effective dielectric constant using Wheeler's formula or some other form of compensation.

27



28

The total loss in a microstrip line consists of ohmic skin loss in the conductor, radiation losses and dielectric substrate losses. Conductor losses normally dominate and increase with frequency. Radiation losses are often ignored. Dielectric losse are usually smaller than conductor losses, but may be significant for some materials and designs.



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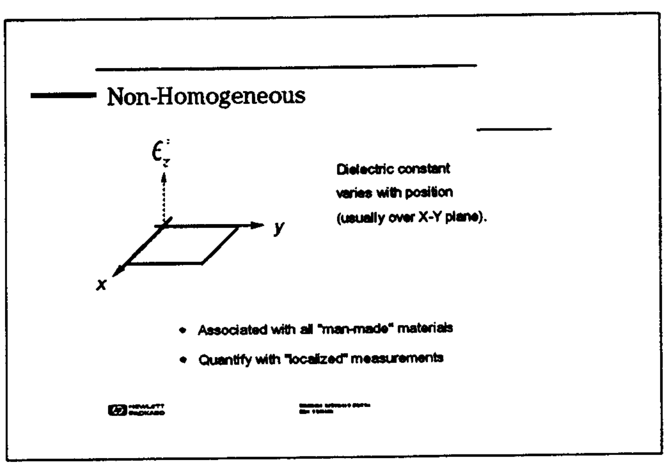
There are three ways that changes in dielectric constant cause trouble. The most common is substrate nonuniformitie from lot to lot or nonuniformities within the same lot. This is an especially important task at incoming inspection where designs may be affected by variations in substrates.



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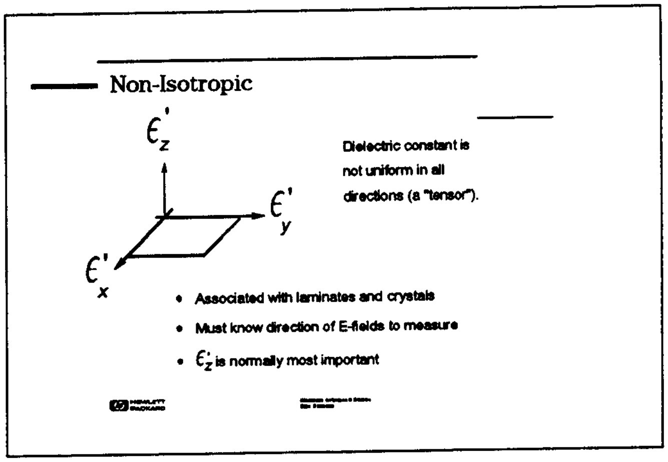
Dielectric constant can vary with position over the substrate sheet. The amount of nonhomogeneity can be quantified with a localized measurement over the xy plane.



Dielectric constant can vary with direction of the applied electric field resulting in a permittivity tensor quantity. This is commonly the case with laminates and crystals. Most of the electric field within a microstrip or stripline dielectric is in the zdirection perpendicular to the surface of the substrate. Only the fringing field has components lying in the xy plane of the sheet.

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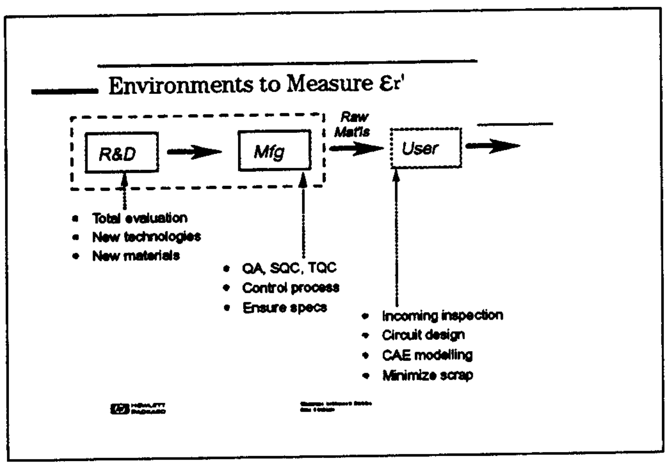
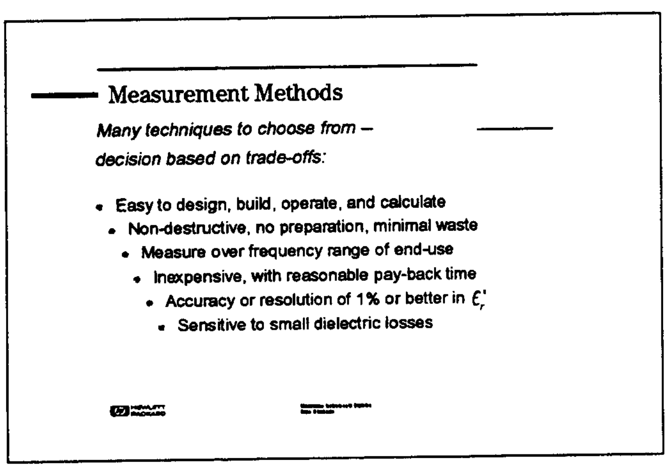


Measurements of dielectric constant might occur i several environments. In R&D, dielectric constant is crucial to the development and evaluation of ne materials. In manufacturing, dielectric constant can be used in quality control and process control to ensure that the end product meets its specifications. Users often measure the dielectric constant of incoming raw materials before integrating them into their circuit designs.

32



There are many techniques for making the actual measurement. The choice of measurement method is based on a number of factors. The frequency range of use often drives the choice. There is often a tradeoff between measurement accuracy and sensitivity and simplicity and convenience. And of course, cost is almost always a consideration when choosing a solution.

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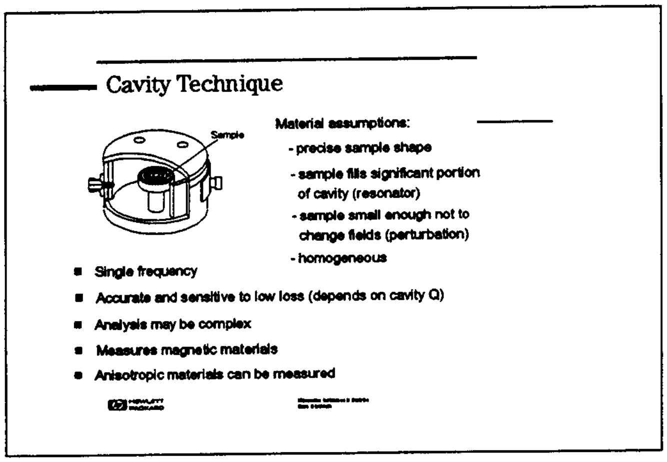
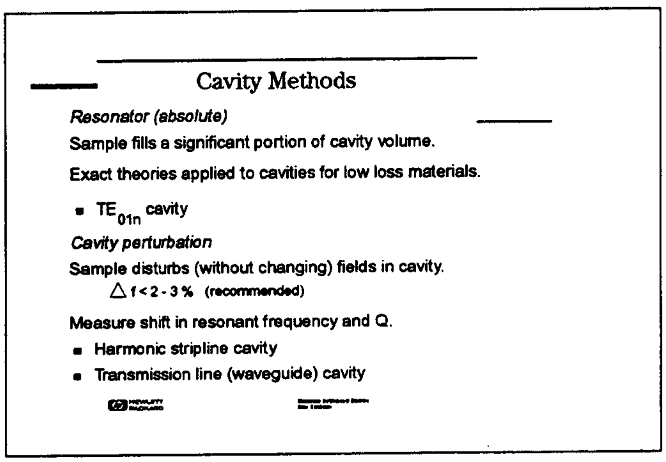


34

The resonant cavity is the most accurate technique available, especially for low loss materials. The MUT is assumed to be precisely shaped and uniform throughout. Measurements are made at a single frequency (not swept), although a cavity may resonate at several different frequencies. A cavity fixture connects to a network analyzer that measures the center frequency and Q of the MUT which are then converted to permittivity or permeability.



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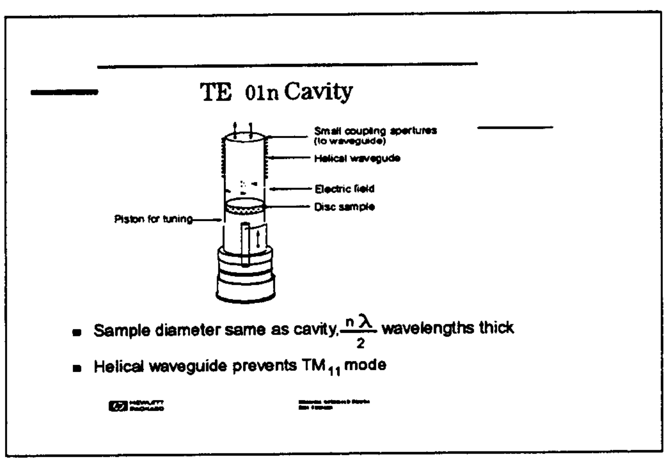
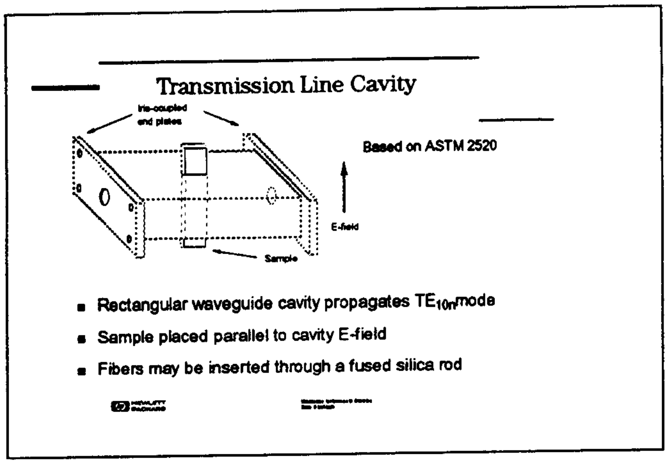
There are two cavity methods that can be employed. The most accurate is the resonator or absolute method which requires a sample that fills a large portion of the cavity and a very precise knowledge of the fields in the cavity. The simpler method is the perturbation method which requires a very small sample such that the fields in the cavity are only slightly disturbed to shift the measured resonant frequency and cavity Q.



36

The TE_{01n} cavity accepts a disc shaped sample that has the same diameter as the cavity and is a multiple of a half wavelength thick.



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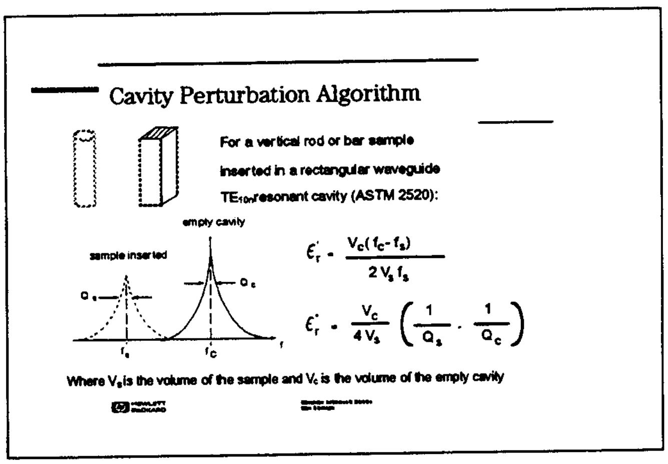
The simplest example of a cavity is made from a section of rectangular waveguide with iris coupled end plates. The sample is placed parallel to the electric field. The technique is based on ASTM standard D2520.



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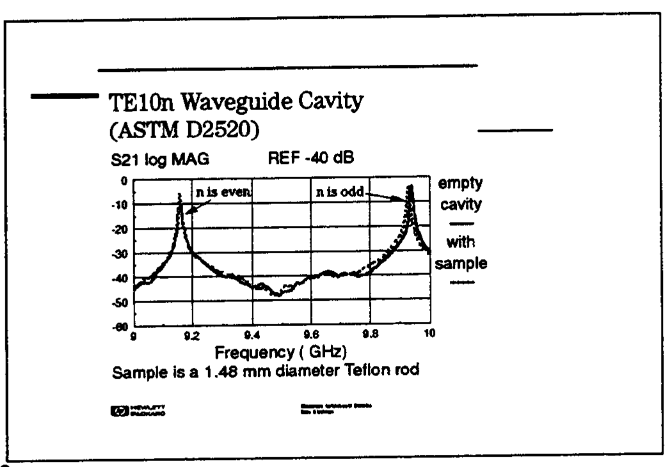
The algorithm to determine prmittivity is dependent on the center frequency and Q measure with and without the sample inserted. The volume of the empty cavity and sample are also required.



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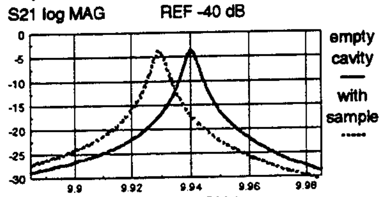
This graph shows two resonant responses for the waveguide cavity with and without a Teflon rod (1.48mm in diameter) placed through the center of the cavity. The even order modes have an E-field null at this point while the odd order modes have an E-Field maximum. Only the odd order modes are influenced by the introduction of the Teflon sample.

TE10n Waveguide Cavity (ASTM D2520)



Sample is a 1.48 mm diameter Teflon rod

40

This is a close up view of the odd order mode. The permittivity is calculated from the change in resonant frequency and Q due to the introduction of the measurement sample. The calculations are based on perturbation theory. The change in 3 dB bandwidth frequencies are much less than a percent so perturbation theory holds.

TE01n Cavity Calculations

f_c=9.9401 GHz $\quad$ f_s=9.92935 GHz

V_c=32516 cm^3 $\quad$ V_s=0.0175 cm^3

Q_c=2162 $\quad$ Q_s=2109

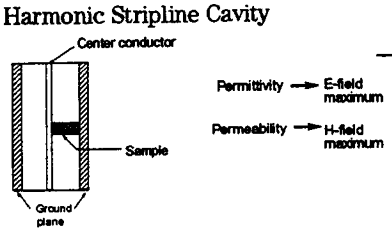
$$\varepsilon_r' = \frac{V_c(f_c - f_s)}{2V_s f_s} + 1 = 2.01$$

$$\varepsilon_r'' = \frac{V_c}{4V_s}\left(\frac{1}{Q_s} - \frac{1}{Q_c}\right) = 0.0054$$

41

The real part of permittivity for the Teflon sample is calculated to be 2.01 which agrees well with published values. The loss tangent is calculated to be 0.0054 which is greater than published values on the order of 0.000002. The Q of the resonator is the limiting factor in the loss tangent measurement. Better resolution would be available with a higher Q cavity. For this case the surface roughness and conductivity are the limiting factor for Q. In some cases the limiting factor will be the coupling into and out of the cavity–in those cases the Q can be improved by reducing the coupling. Vector network analyzers have a larger dynamic range than scalar network analyzers and will allow measurements to be made with less coupling. Techniques that take advantage of phase information as well as magnitude information (Q circles) can also be used to advantage.

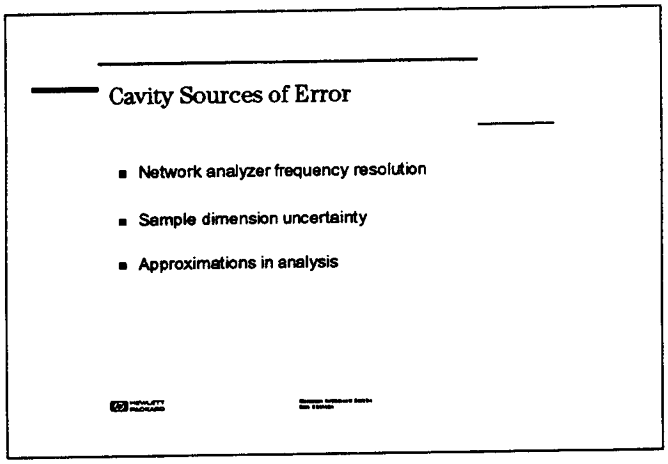
Harmonic Stripline Cavity



- Single frequency - Cavity size sets fundamental frequency (also resonates at integer multiples)
- Ideal for small, thin, rectangular solid samples

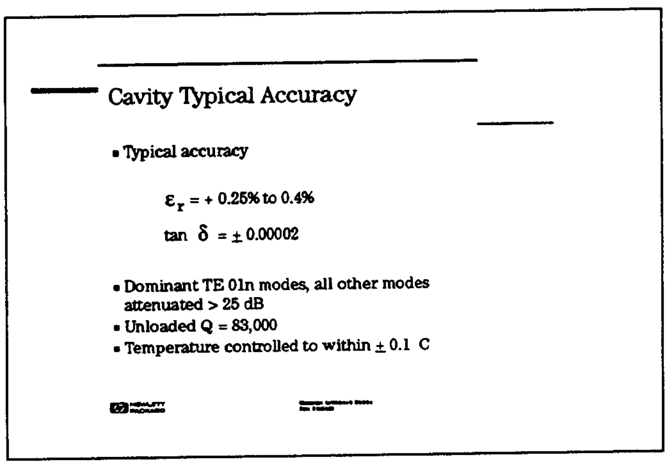
42

A harmonic stripline cavity has two outer ground planes with a center conductor in between. A small, thin sample is placed between the center conductor and ground plane in an electric field maximum (permittivity) or a magnetic field maximum (permeability).



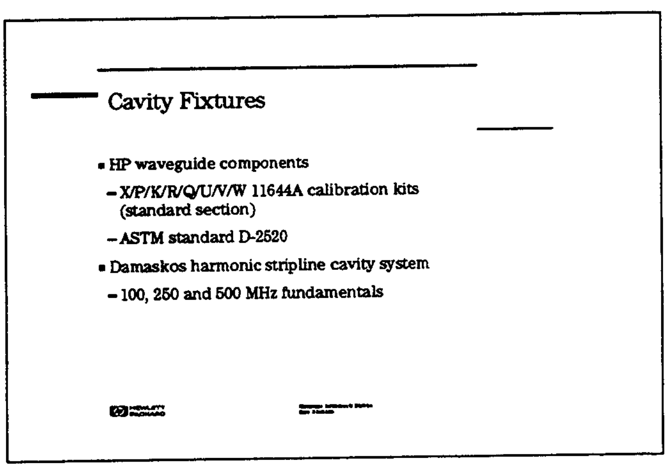
Although a resonant cavity technique is extremely accurate, it is still subject to errors. The network analyzer must have excellent frequency resolution (1 Hz) to measure the very small changes. The sample dimensions must be known precisely. And there is additional error due to approximations in the analysis.

43



The National Institute of Standards and Technology TE_{01n} resonator cavity is accurate to less than 1% and is extremely sensitive to low loss materials.

44



The waveguide cavity can be made by using one of the standard sections from the HP 11644A calibration kits. A third party supplier of harmonic stripline cavities provides models with various fundamental frequencies.

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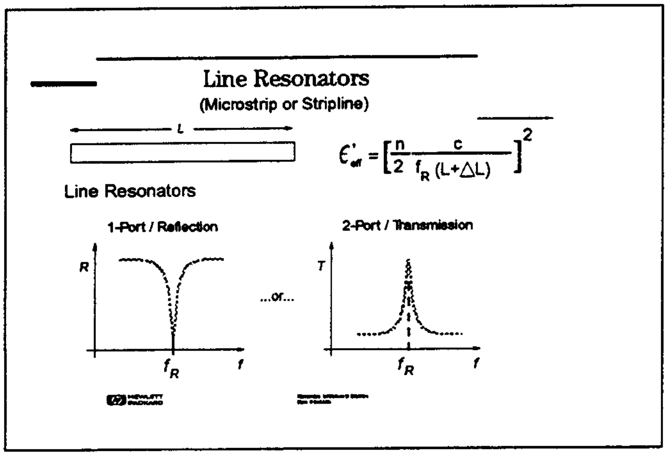
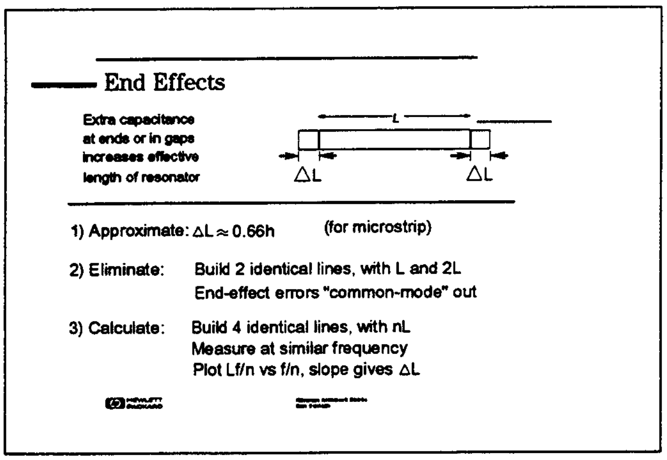


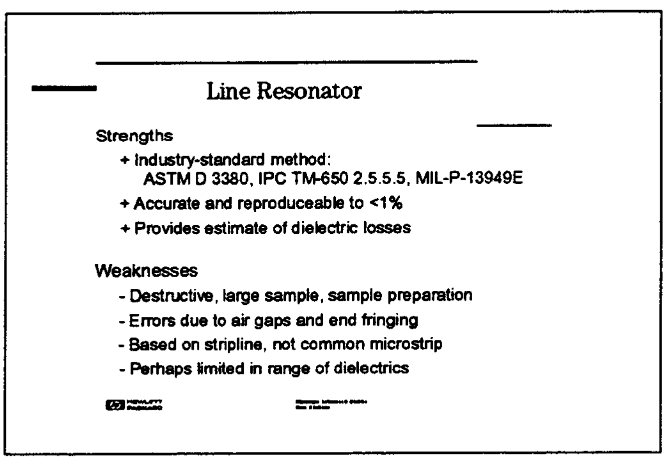
The most popular techniques for substrate measurements use a circuit etched on the substrate itself. The line resonator is a simple technique that requires the resonant frequency measured by a network analyzer to compute the effective dielectri constant. n is the number of wavelengths along the resonator, L is the resonator length, and L is the fringing correction that can be approximated or empirically determined.

46



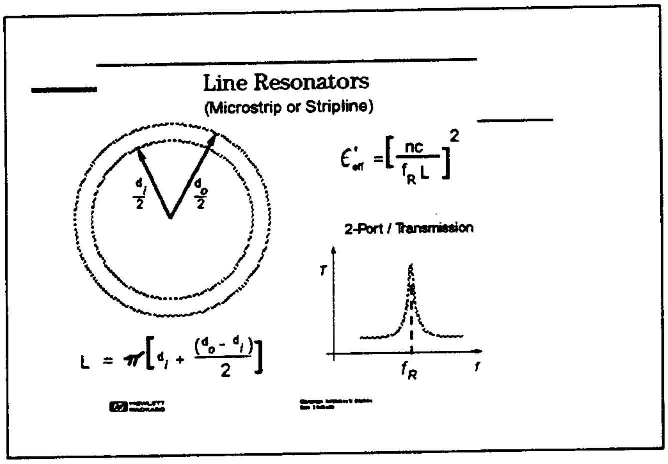
The added capacitance from the fringing effect at the ends of the line increase the effective length of the line. One way to compensate for the end effect is to approximate the effective length. The end effect can be eliminated by creating two lines of different lengths to commonmode out the effects. The end effect can also be calculated by measuring four lines of different lengths to empirically arrive at a value for the effective length.

47



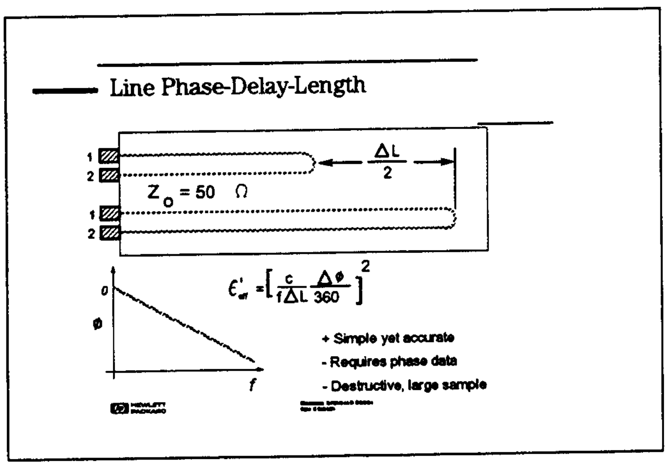
The line resonator technique is well documented and accurate to 1% (typically). It is a destructive technique that requires some sample preparation and compensation for end effects.

48



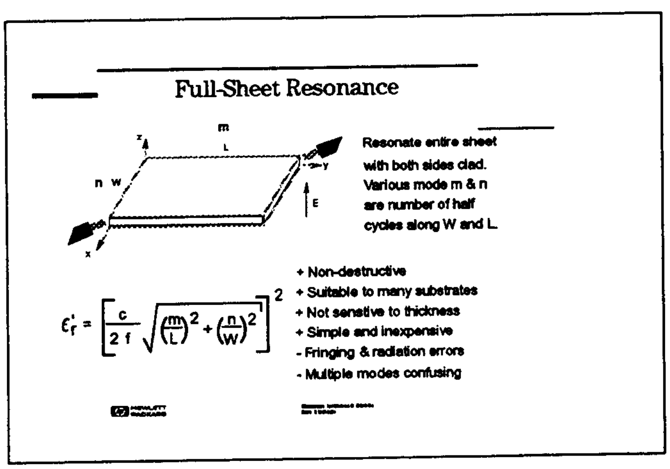
49

The ring resonator technique requires a microstrip line that is etched such that the circumference is a multiple of an integral number of full wavelengths. Like the line resonator technique, the resonant frequency measured by a network analyzer is used to compute dielectric constant. The ring resonator is not subject to errors from end effects. The ring i loosely coupled to transmission lines that are separated about the circumference by 180 degrees to minimize coupling around the ring.



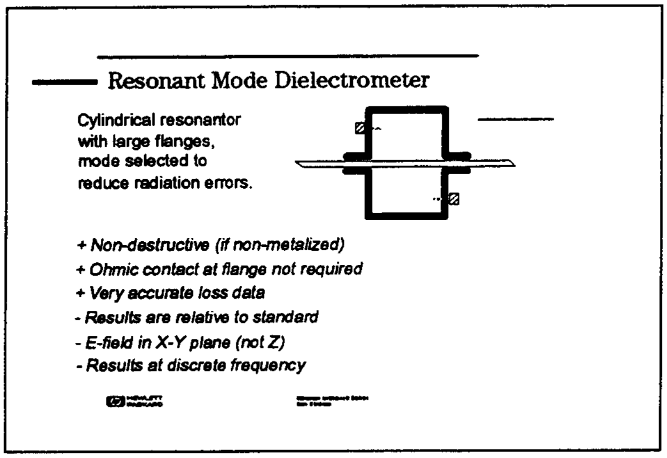
50

The line phase-delay-length technique is simple yet accurate. The phase difference between two etched lines is measured by a network analyzer and used to compute dielectric constant, via the propagation velocity. Too lines are used so that the errors due t connectors will common-mode out.



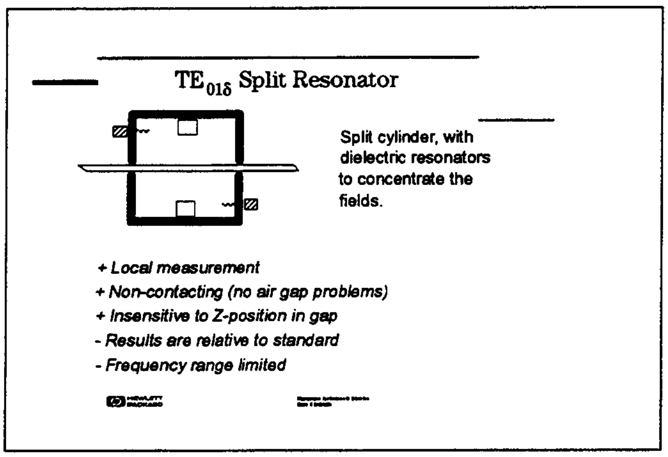
51

The full sheet resonance technique requires a metallized rectangular substrate to create a "parallel plate dielectric-loaded waveguide resonator". It is inexpensive and nondestructive but subject to fringing and radiation errors and complex multiple modes. The resonant frequency measured by a network analyzer is used to comput dielectric constant at the m order of transverse resonance and the n order of longitudinal resonance.



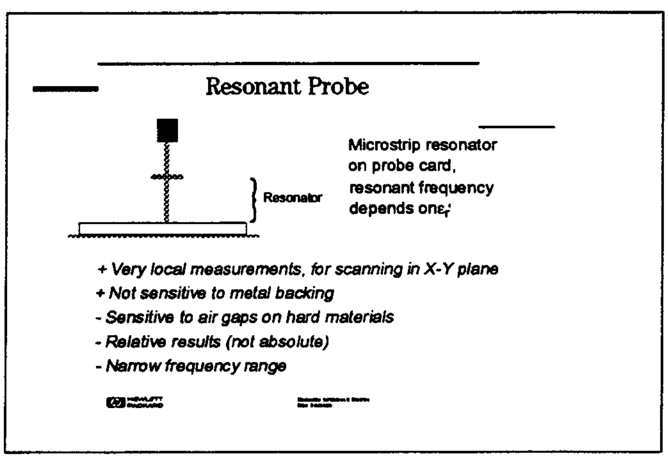
The resonant mode dielectrometer is a cylindrical cavity resonator that accepts a wide range of nonmetallized substrates. The resonant frequency measured by a network analyzer is used to comput dielectric constant. Since there is no component of the electric field normal to the surface of the sample, ohmic contact between the specimen and the sides of the slot is not required but measurements are made in the xy plane only. The measurements are nondestructive and provide accurate loss but are made relative to a standard at single frequencies.

52



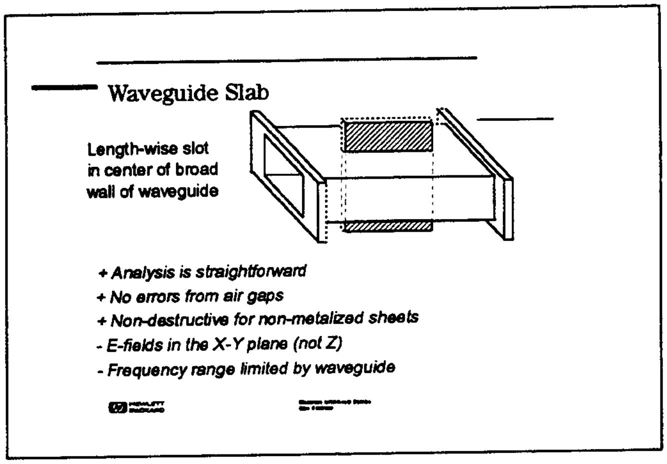
The $TE_{01\delta}$ split resonator is made up of two dielectri rod resonators that support the $TE01\delta$ mode enclosed in a split metal cavity. The resonant frequency measured by a network analyzer is used to compute the dielectric constant. The measurement is localized, noncontacting and is not sensitive to the zposition of the sample. The measurements are relative and limited in frequency range.

53



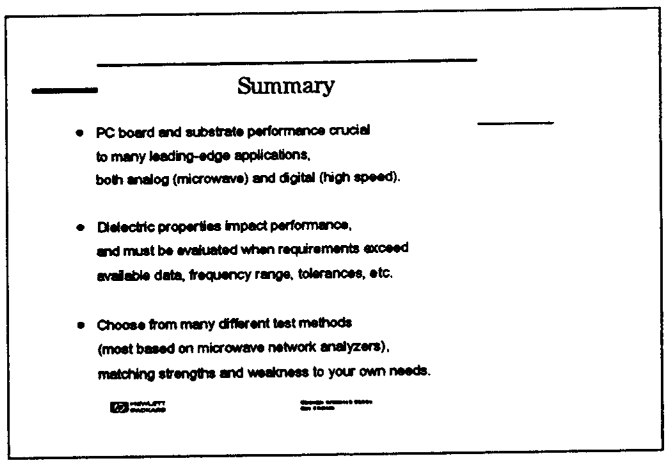
The resonant probe technique is based on the fact that when a material is lightly coupled to a microwave resonant structure, the resonant frequency is perturbed. The change in resonant frequency measured by a network analyzer is used to compute dielectric constant. This technique allows localized relative measurements with narrow resolution and shallow depth. An air gap between the probe and sample can add additional error.

54



55

The waveguide slab technique requires a nonmetallized sample that is inserted into a longitudinal slot that is centered on the broadwalls of a rectangular waveguide. The measured reflecte and transmitted signals are used to compute dielectric constant. The results are along the xy plane of the sample.



56

PC boards and substrates are critical to the design of almost any electronic product and are important in digital as well as analog designs. Dielectric properties must often be measured when existing data is not available. Many of the available measurement mehods are based on RF or microwave network analyzers.