Hewlett-Packard

Electronic Materials Measurement Seminar

Measurement Fundamentals

Kobe Instrument Division

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Hewlett-Packard

ELECTRONIC MATERIALS
MEASUREMENT
SEMINAR

Hewlett-Packard Electronic Materials Measurement Seminar

Agenda

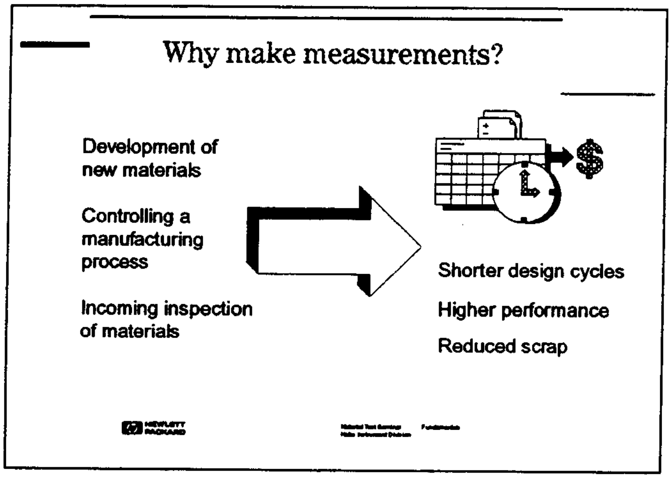
- Fundamentals
- LF and RF Parallel Plate Measurement Technique for Dielectric Substrates
- Lunch
- RF and MW Network Analyzer Measurement Technique for Dielectric Substrates
- Bulk Material Measurements
- Permeability (Magnetic) Measurements

The seminar starts with a review of fundamentals of making electronic material measurements. Then we will focus on LF/RF and RF/MW Dielectric Substrate measurements. The seminar will conclude with presentations on Bulk and Magnetic material measurements.

Objectives

- Provide basic education on Electronic Material measurements
- Increase awareness of the measurement solutions available from HP and third parties
- Provide guidance in choosing the best measurement technique for a given application
- Give practical information for improving measurements

The objective of the seminar is to provide a tutorial on electronic material measurements, to increase awareness of measurement solutions, to recommend guidelines for choosing the best technique, and to share best measurement practices.



Why make measurements?

Development of new materials

Controlling a manufacturing process

Incoming inspection of materials

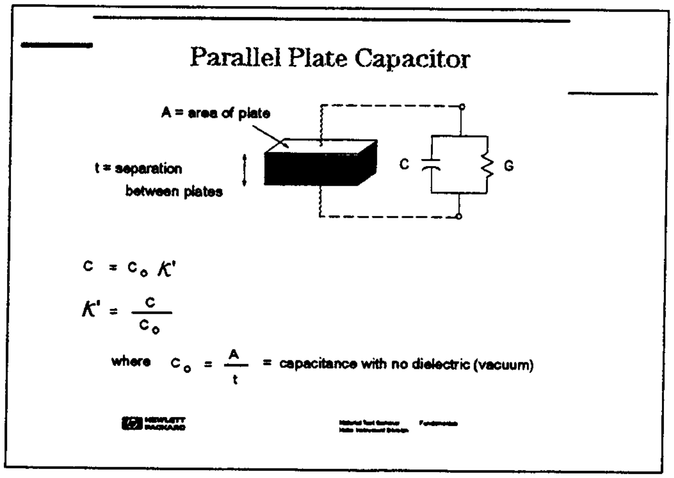
Shorter design cycles

Higher performance

Reduced scrap

4

Every material has a unique set of electrical characteristics. Accurate measurements of these properties can provide scientists and engineers with valuable information to properly incorporate the material into its intended application for more solid designs or to monitor a manufacturing process for improved quality control



Parallel Plate Capacitor

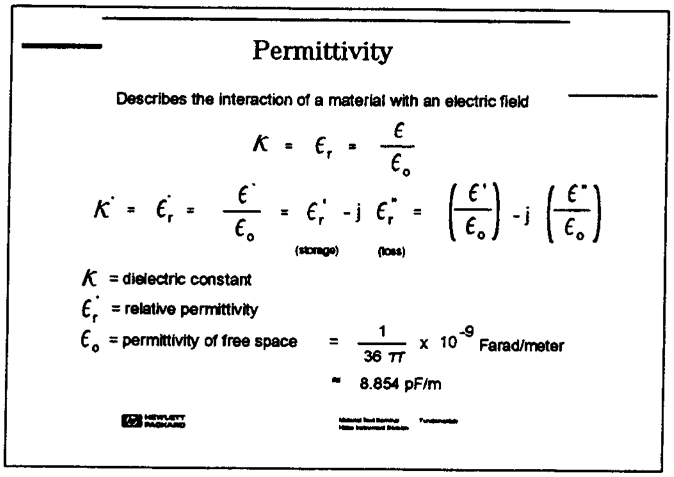
$C = C_o \kappa'$

$\kappa' = \frac{C}{C_o}$

where $C_o = \frac{A}{t}$ = capacitance with no dielectric (vacuum)

5

A material is classified as dielectric if it has the ability to store energy when an external electric field is applied. If a DC voltage source is placed across a parallel plate capacitor, more charge is stored when a dielectric material is between the plates than if no material (a vacuum) is between the plates. The capacitance with the dielectric material is related to dielectric constant.



Permittivity

Describes the interaction of a material with an electric field

$$\kappa = \epsilon_r = \frac{\epsilon}{\epsilon_o}$$

$$\kappa^* = \epsilon_r^* = \frac{\epsilon^*}{\epsilon_o} = \underset{\text{(storage)}}{\epsilon_r'} - j\,\underset{\text{(loss)}}{\epsilon_r''} = \left(\frac{\epsilon'}{\epsilon_o}\right) - j\left(\frac{\epsilon''}{\epsilon_o}\right)$$

κ = dielectric constant

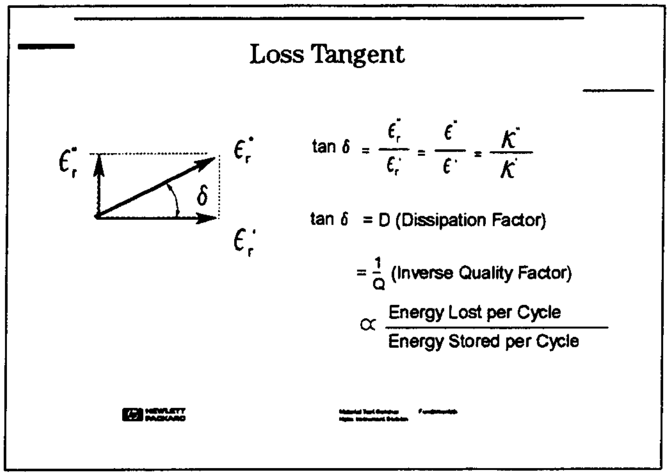
ϵ_r^* = relative permittivity

ϵ_o = permittivity of free space $= \frac{1}{36\pi} \times 10^{-9}$ Farad/meter

$\approx$ 8.854 pF/m

6

Permittivity (ε) describes the interaction of a material with an electric field. Dielectric constant (κ) is equivalent to relative permittivity (ε_r) or the absolute permittivity (ε) relative to the permittivity of free space (ε_o). The real part of permittivity (ε_r') is a measure of how much energy from an external electric field is stored in a material. The imaginary part of permittivity (ε_r'') is called the loss factor and is a measure of how dissipative or lossy a material is to an external electric field.



Loss Tangent

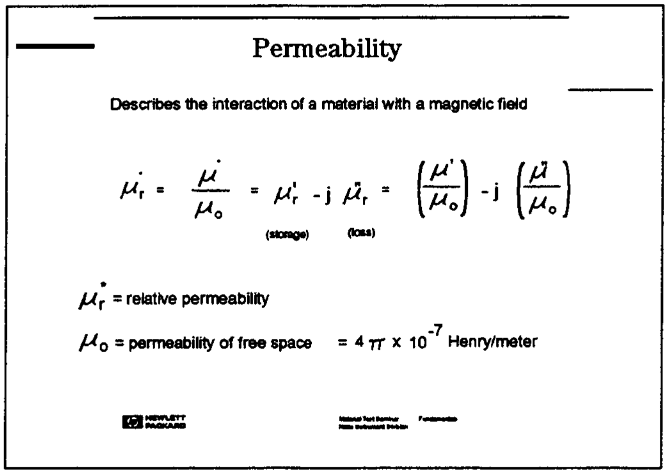
$$\tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'} = \frac{\varepsilon''}{\varepsilon'} = \frac{\kappa''}{\kappa'}$$

$\tan\delta$ = D (Dissipation Factor)

$= \frac{1}{Q}$ (Inverse Quality Factor)

$\propto \frac{\text{Energy Lost per Cycle}}{\text{Energy Stored per Cycle}}$

When complex permittivity is drawn as a simple vector diagram, the real and imaginary components are 90 degrees out of phase. The vector sum forms an angle δ with the real axis (ε_r'). The relative "lossiness" of a material is the ratio of the energy lost to the energy stored.



Permeability

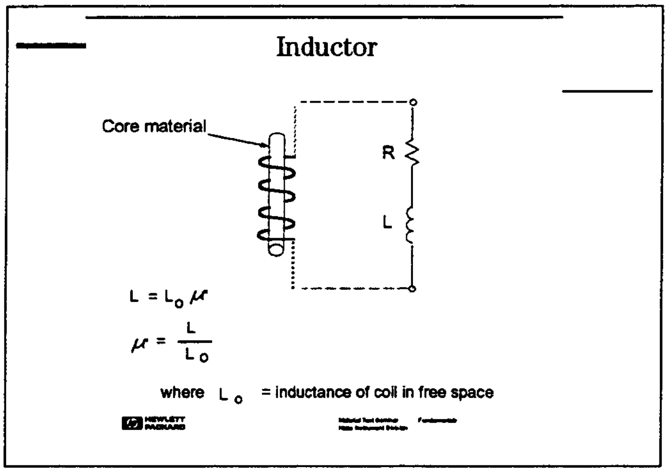
Describes the interaction of a material with a magnetic field

$$\mu_r^* = \frac{\mu^*}{\mu_0} = \underset{\text{(storage)}}{\mu_r'} - j\,\underset{\text{(loss)}}{\mu_r''} = \left(\frac{\mu'}{\mu_0}\right) - j\left(\frac{\mu''}{\mu_0}\right)$$

μ_r^* = relative permeability

μ_0 = permeability of free space = $4\pi \times 10^{-7}$ Henry/meter

Permeability (μ) describes the interaction of a material with a magnetic field. A similar analysis can be performed for permeability using an inductor with resistance to represent core losses in a magnetic material. If a DC current source is placed across an inductor, the inductance with the core material can be related to permeability.



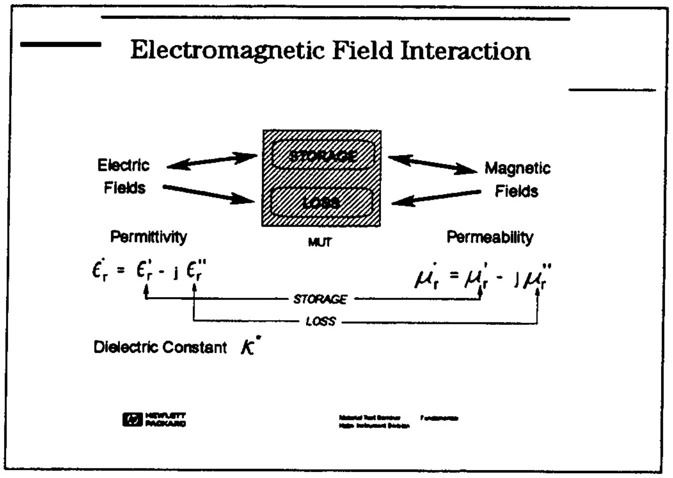
Inductor

$L = L_0 \mu$

$\mu = \frac{L}{L_0}$

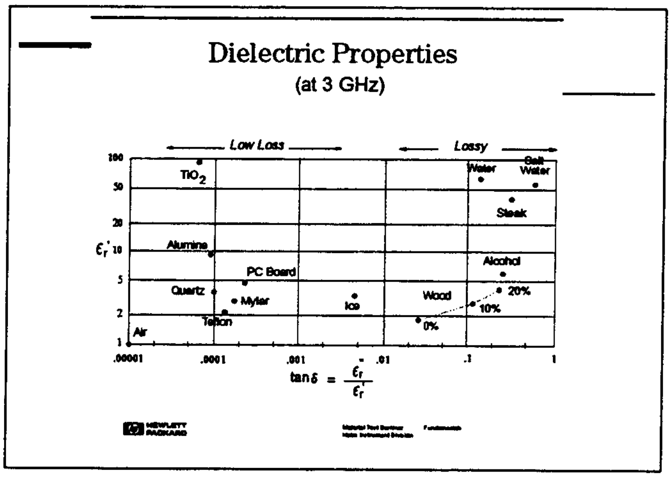
where L_0 = inductance of coil in free space

The complex permeability (μ^*) consists of a real part (μ') that represents the energy storage and a an imaginary part (μ'') that represents the energy loss term. Relative permeability (μ_r) is the absolute permeability (μ) relative to the permeability of free space (μ_0). Some materials such as iron (ferrites), cobalt, nickel and their alloys have appreciable magnetic properties; however, many materials are non-magnetic. All materials, on the other hand, have dielectric properties.



Electromagnetic Field Interaction

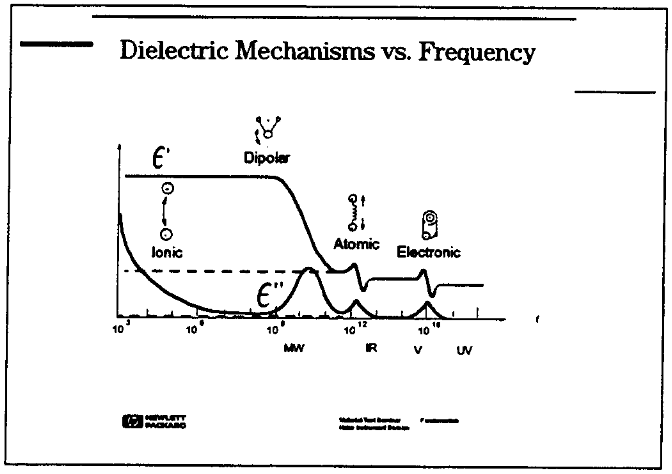
Permittivity (or dielectric constant) describes the interaction of a material with an external electric field. Permeability describes the interaction of a material with an external magnetic field. Both are complex values that have a real part that corresponds to the storage and an imaginary part that corresponds to the loss.



Dielectric Properties

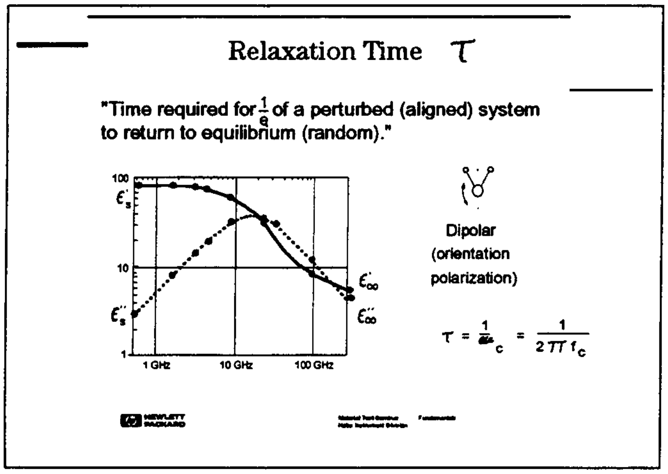
(at 3 GHz)

Materials for electronics applications, such as cable insulators or PC boards, tend to be grouped on the low loss side of the chart. Organic materials, such as foods, tend to be grouped on the lossy side of the chart. It is important to note that these measurements were made at a single frequency (3 GHz). Dielectric constant can change versus frequency, temperature, pressure, humidity, etc.



Dielectric Mechanisms vs. Frequency

A material may have several dielectric mechanisms that contribute to its overall permittivity. Each dielectric mechanism effect has a characteristic resonant frequency or relaxation frequency. As the frequency increases, the slower mechanisms drop out, leaving the faster ones to contribute to the storage (ϵ_r'). The loss factor (ϵ_r'') will correspondingly peak at each critical frequency.



Relaxation Time τ

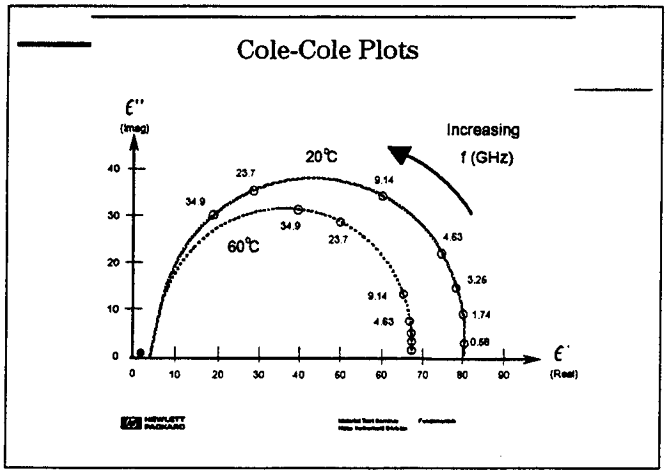
"Time required for $\frac{1}{e}$ of a perturbed (aligned) system to return to equilibrium (random)."

Dipolar (orientation polarization)

$$\tau = \frac{1}{\omega_c} = \frac{1}{2\pi f_c}$$

13

A molecule is formed when atoms combine to share one of more of its electrons. This rearrangement of electrons may cause an imbalance in charge distribution creating a permanent dipole moment. These moments are arranged in a random manner in the absence of an electric filed so that no polarization exists. Under the effect of an electric filed, the dipoles rotate to align with the electric field causing orientation polarization to occur. The dipole rotation causes a variation in both ε_r' and ε_r'' at the relaxation frequency which usually occurs in the microwave frequency range.

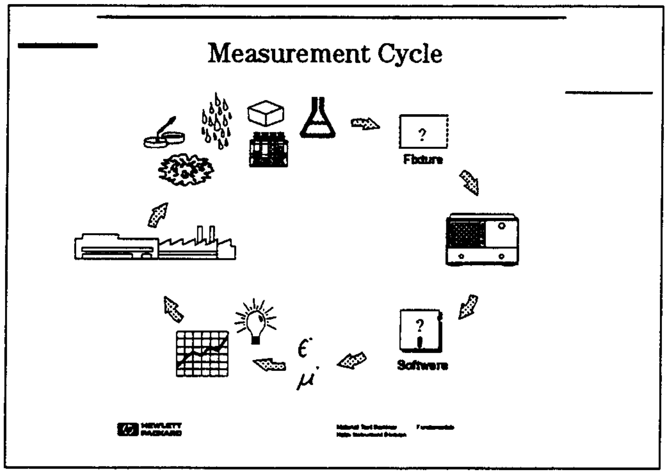


Cole-Cole Plots

Increasing f (GHz)

14

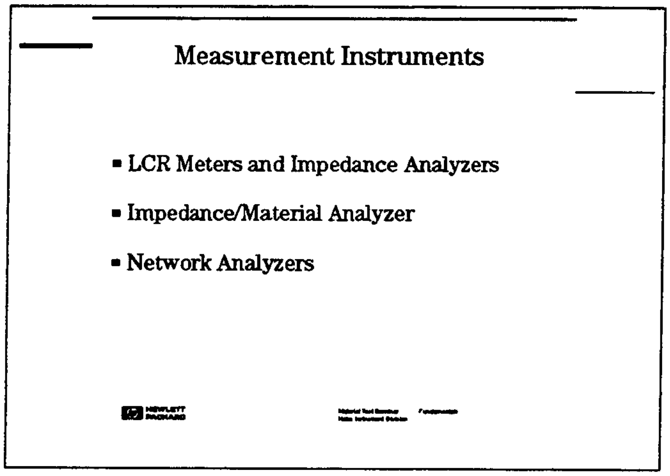
The complex permittivity may also be shown on a Cole-Cole diagram by plotting the imaginary part (ε_r'') on the vertical axis and the real part (ε_r') on the horizontal axis with frequency as the independent parameter.



Measurement Cycle

15

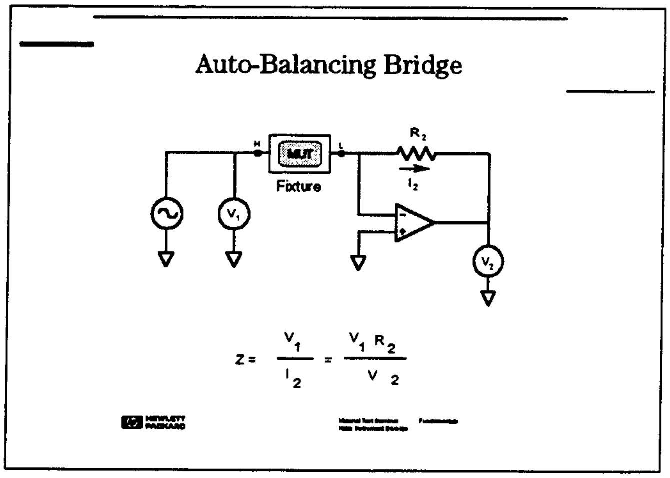
A complete measurement system requires a measurement instrument such as an impedance or network analyzer, a fixture to connect to the material under test (MUT), and a computer/software to convert the measured value (impedance or Sparameters) to permittivity or permeability.



Measurement Instruments

- LCR Meters and Impedance Analyzers
- Impedance/Material Analyzer
- Network Analyzers

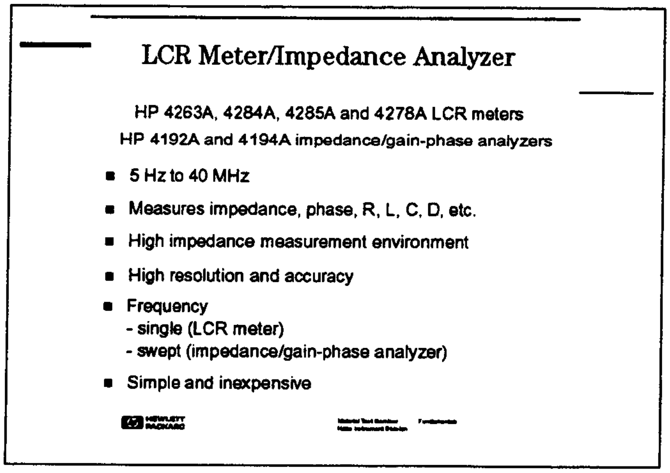
There are many types of instruments that may be used to measure materials. Hewlett-Packard has a variety of LCR meters, impedance analyzers, Impedance/Material analyzers, and network analyzers.



Auto-Balancing Bridge

$$Z = \frac{V_1}{I_2} = \frac{V_1 R_2}{V_2}$$

LCR meters and impedance analyzers use the autobalancing bridge technique to measure the impedance of materials. The material is stimulated with an ac source and the actual voltage across the material is monitored between the high (H) and low (L) terminals. The low terminal is driven to 0 V by a virtual ground of the op amp. The output voltage is proportional to the current through the material. Material test parameters are derived by knowing the dimensions of the material and by measuring the capacitance and dissipation factor.



LCR Meter/Impedance Analyzer

HP 4263A, 4284A, 4285A and 4278A LCR meters
HP 4192A and 4194A impedance/gain-phase analyzers

- 5 Hz to 40 MHz
- Measures impedance, phase, R, L, C, D, etc.
- High impedance measurement environment
- High resolution and accuracy
- Frequency
  - single (LCR meter)
  - swept (impedance/gain-phase analyzer)
- Simple and inexpensive

Hewlett-Packard offers a complete family of LCR meters and impedance analyzers that provide accurate capacitance and low dissipation factor measurements between 5 Hz and 40 MHz. Measurements are made in a high impedance measurement environment. LCR meters make measurements at a single frequency, while impedance analyzers measure over a swept frequency.

photo: HP 4284A LCR meter

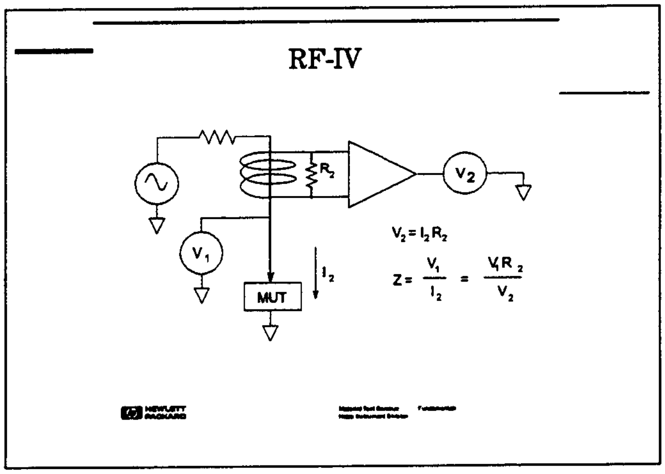
19

The HP 4284A offers the highest accuracy and resolution over an operating frequency range of 20 Hz to 1 MHz.

photo: HP 4194A Impedance Analyzer

20

The HP 4194A makes swept frequency measurements from 100 Hz to 40 MHz.



RF-IV

$V_2 = I_2 R_2$

$Z = \frac{V_1}{I_2} = \frac{V_1 R_2}{V_2}$

21

The HP 4291A Impedance/Material Analyzer uses the RF-IV technique for measuring impedance of material from 1 MHz to 1.8 GHz. An unknown impedance Z is calculated from measured voltage (V1) and current (I2) values. The current is calculated using a low-loss transformer.

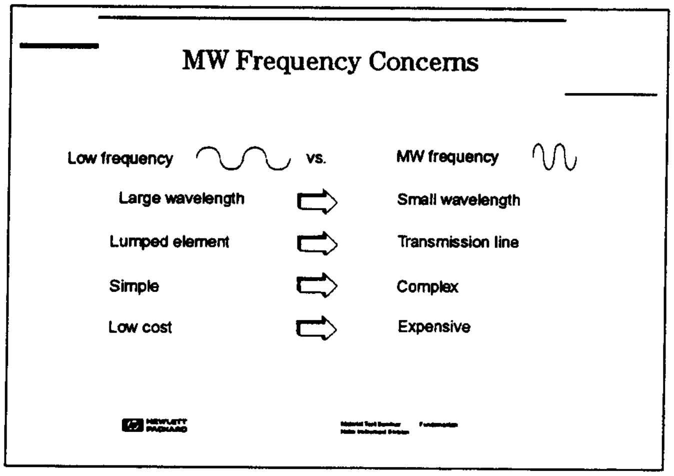
Impedance/Material Analyzer
HP 4291A

- 1 MHz to 1.8 GHz
- Calculates and Displays Material Parameters (ε,μ) vs frequency, temperature
- Measure Impedance, phase, R, L, C, D, etc.
- High Resolution and Accuracy
- Ease of Use

The HP 4291A is the only product from HP that uses the RF-IV technique. The HP 4291A with opt 002 (Material Parameters) can calculate and display dielectric and magnetic parameters. The parameters can be displayed vs. frequency or temperature or others (dc bias, ac signal level). The basic accuracy is ε_r = +/- 8% at ε_r < 10, tan δ : +/- 0.003. The HP 4291A has a built-in disk drive and is menu driven.

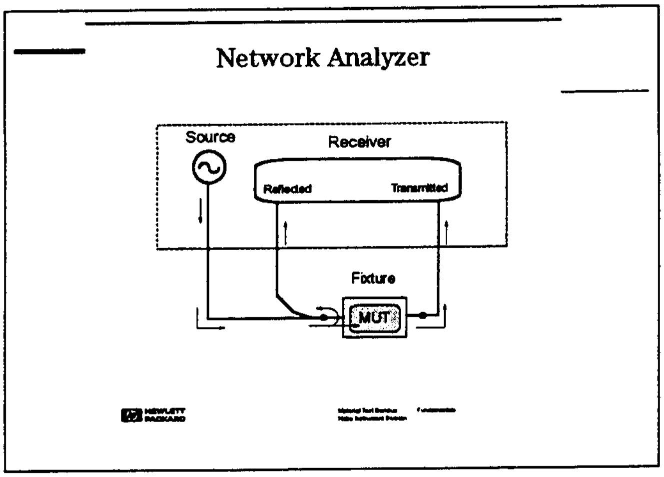
photo: HP 4291A Impedance/Material Analyzer

MW Frequency Concerns



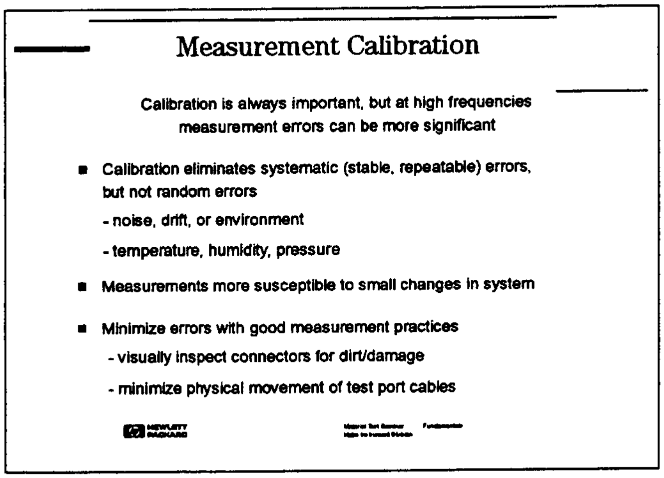
Low frequency	vs.	MW frequency
Large wavelength	⇨	Small wavelength
Lumped element	⇨	Transmission line
Simple	⇨	Complex
Low cost	⇨	Expensive

Simple components and connecting wires that perform well at low frequencies behave differently at high frequencies. At microwave frequencies wavelengths become small compared to the physical dimensions of the devices such that two closely spaced points can have a significant phase difference. Low frequency lumped-circuit element techniques must be replaced by transmission line theory to analyze the behavior of devices at higher frequencies. Additional high frequency effects make microwave circuits more complex and expensive.



Network Analyzer

A measurement of the reflection from and/or the transmission through a material along with a knowledge of its physical dimensions provides the information to characterize the permittivity and permeability of the material. A vector network analyzer consists of a signal source, a receiver and a display. The source launches a signal at a single frequency to the MUT. The receiver is tuned to that frequency to detect the reflected and transmitted signals from the material. The source is then stepped to the next frequency and the measurement is repeated to display the reflection and transmission measurement response as a function of frequency.

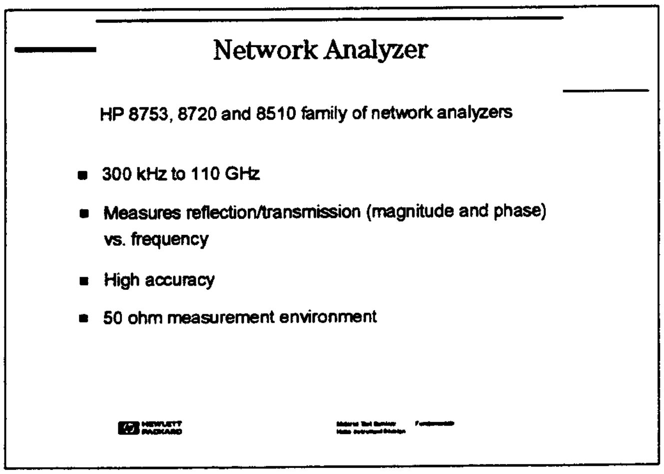


Measurement Calibration

Calibration is always important, but at high frequencies measurement errors can be more significant

- Calibration eliminates systematic (stable, repeatable) errors, but not random errors
  - noise, drift, or environment
  - temperature, humidity, pressure
- Measurements more susceptible to small changes in system
- Minimize errors with good measurement practices
  - visually inspect connectors for dirt/damage
  - minimize physical movement of test port cables

It is too time consuming and costly to try to design a perfect microwave network analyzer. Instead a measurement calibration is used to eliminate the systematic (stable and repeatable) measurement errors caused by the imperfections of the system. Random errors due to noise, drift or the environment cannot be removed with a measurement calibration. This makes a microwave measurement susceptible to errors from small changes in the measurement system. These errors can be minimized by adopting good measurement practices such as visually inspecting all connectors for dirt or damage, and by minimizing any physical movement of the test port cables after a calibration.



Network Analyzer

HP 8753, 8720 and 8510 family of network analyzers

- 300 kHz to 110 GHz
- Measures reflection/transmission (magnitude and phase) vs. frequency
- High accuracy
- 50 ohm measurement environment

Hewlett-Packard offers a complete family of network analyzers covering a 300 kHz to 110 GHz frequency range. Network analyzers measure the reflected or transmitted signals as a function of frequency. Measurements are very accurate and are made in a 50 ohm measurement environment.

photo: HP 8753 RF Network Analyzers

28

The HP 8752 family of RF network analyzers have an integrated source and transmission/reflection test set and cover the frequency range of 300 kHz to 1.3 or 3 GHz. The HP 8753C family of RF network analyzers cover the frequency range of 300 kHz to 3 or 6 GHz. An Sparameter or transmission/reflection test set must be selected to complete the system. New features of the HP 8753C include built-in capabilities for mixer tests and swept harmonic tests of amplifiers and a choice of an optional solid state switch.

photo: HP 8720 Microwave Network Analyzers

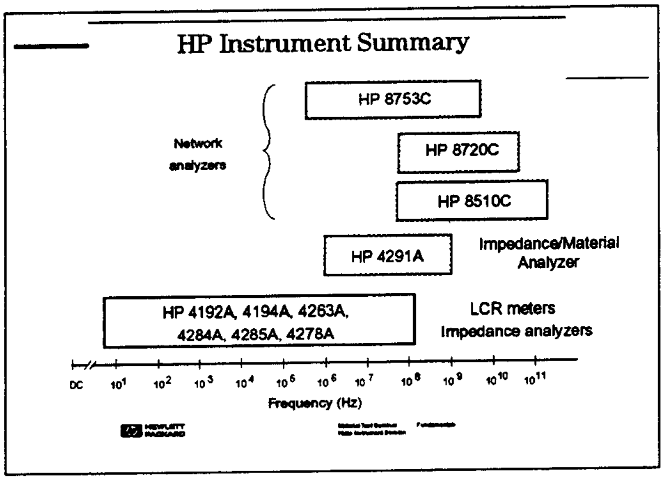
29

The HP 8720C family of microwave network analyzers have an integrated source and S-parameter test set and cover the frequency range of 50 MHz to 13.5, 20 or 40 GHz. New features of the HP 8720C include higher output power, 100 dB of wide dynamic range, power sweep capability for measuring amplifier gain compression, TRL* calibration and choice of an optional solidstate switch.

photo: HP 8510 Microwave Network Analyzers

30

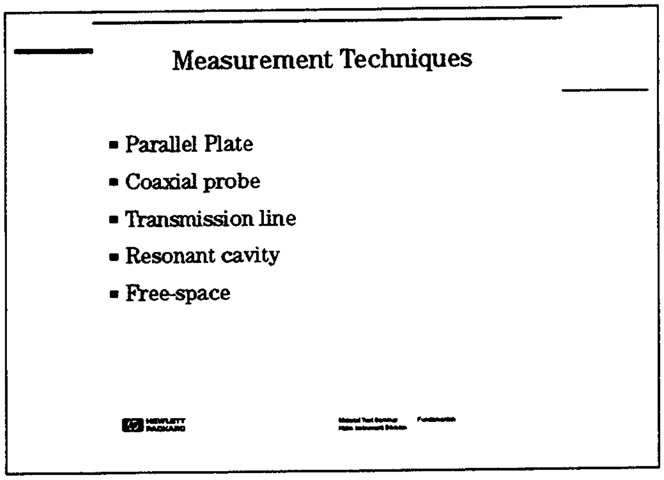
The HP 8510 family of microwave and millimeterwave network analyzers provides the highest performance and most versatility with frequency coverage from 45 MHz to 110 GHz (depending on the source and test set selected). An HP 8510C system may be configured by selecting a source and test set to match the needs of the application. New features of the HP 8510C include a color CRT, internal disk drive, four Sparameter display, five marker readouts, and test port power flatness for amplifier testing.



HP Instrument Summary

31

Hewlett-Packard offers a wide range of measurement instruments for testing the electronic properties of materials. Select the frequency coverage, price and performance that is required for your application.

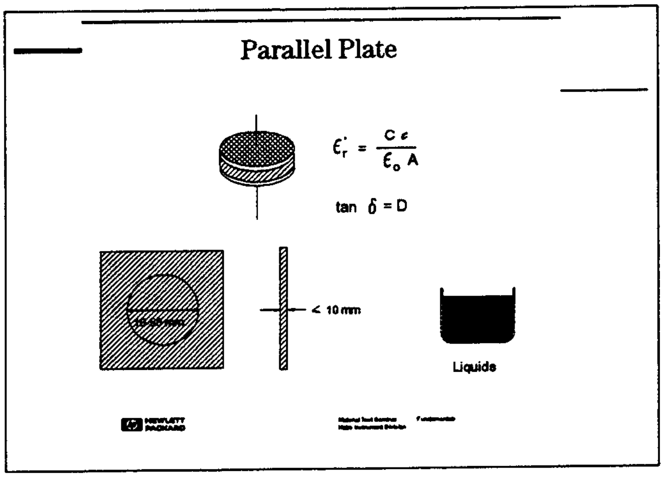


Measurement Techniques

- Parallel Plate
- Coaxial probe
- Transmission line
- Resonant cavity
- Free-space

32

Before the material properties can be measured with these instruments, a measurement fixture is required to apply the electromagnetic fields in a predictable way and to allow connection to the instrument. The type of fixture required will depend on the chosen measurement technique and the physical properties of the material. There are five common measurement techniques that are used.



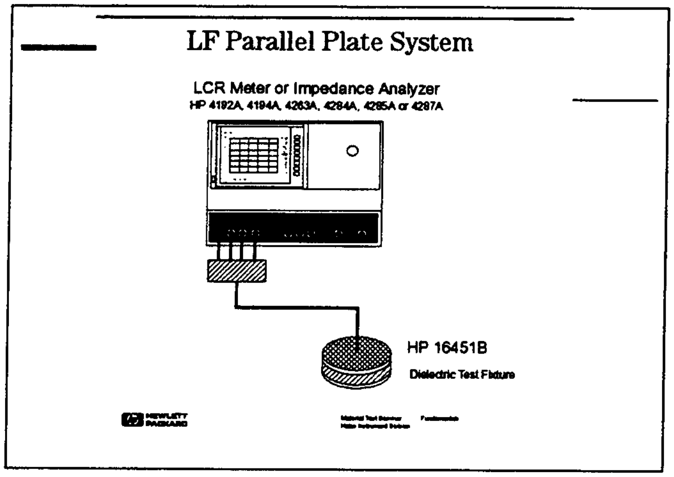
Parallel Plate

$$\epsilon_r' = \frac{C\,t}{\epsilon_0 A}$$

$\tan\delta = D$

33

The parallel plate method involves sandwiching a thin sheet of material or liquid between two electrodes to form a capacitor. An LCR meter or impedance analyzer is used to measure the loaded fixture. ε,' is computed from the measurement of capacitance and ," is computed from the measurement of dissipation factor (D).



LF Parallel Plate System

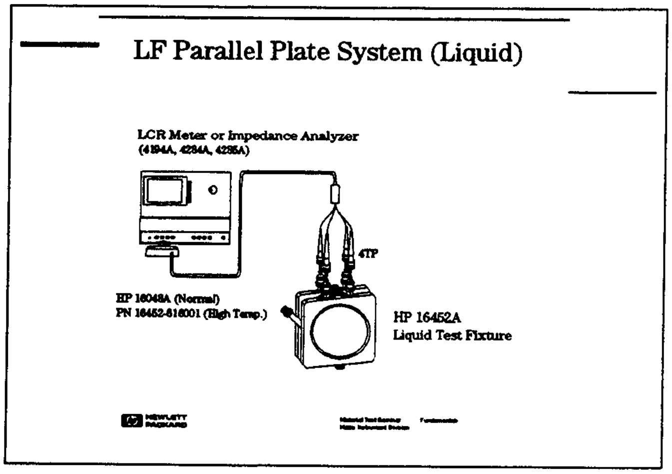
LCR Meter or Impedance Analyzer
HP 4192A, 4194A, 4263A, 4284A, 4285A or 4287A

HP 16451B
Dielectric Test Fixture

A typical LF parallel plate system for measuring dielectric substrates consists of an LCR meter or impedance analyzer and a parallel plate fixture. A computer and software may be required to convert the measured impedance to dielectric constant.

photo: HP 16451B Parallel Plate Fixture

The HP 16451B dielectric test fixture connects to HP LCR meters or impedance analyzers. It operates up to 30 MHz and comes with four types of electrodes. When used with the HP 4194A impedance analyzer, no external computer or software is required.



LF Parallel Plate System (Liquid)

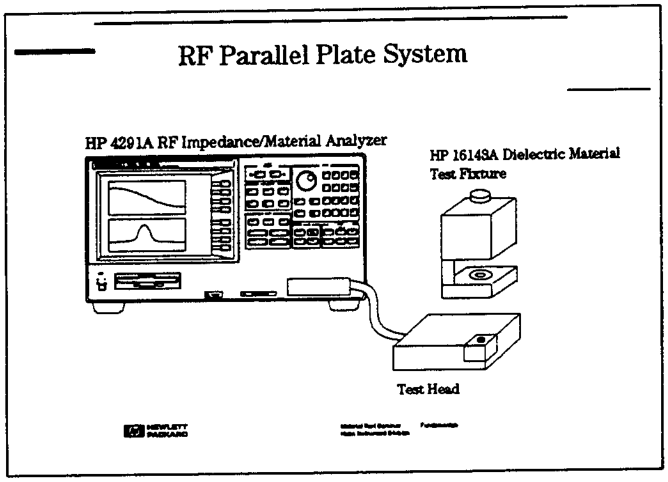
LCR Meter or Impedance Analyzer
(4194A, 4284A, 4285A)

4TP

HP 16048A (Normal)
PN 16452-616001 (High Temp.)

HP 16452A
Liquid Test Fixture

Liquid materials can be measured from 20 Hz to 30 MHz using the HP 16452A Liquid Test Fixture and HP 4284A LCR Meter, 4285A LCR Meter and HP 4194A Impedance Analyzer. High temperature test cables are available (P/N 16452-616001).

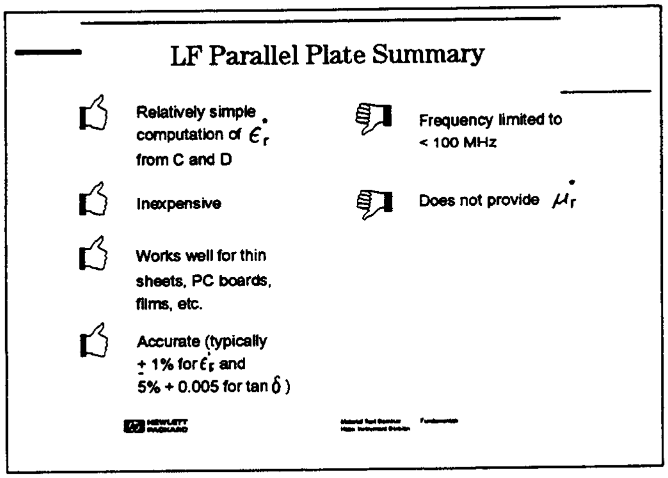


RF Parallel Plate System

The RF Parallel Plate System consists of the HP 4291A Impedance/Material Analyzer and the HP 16143A Dielectric Material Test Fixture. The HP 4291A opt 002 includes built-in dielectric and magnetic material test parameters (these parameters are calculated and displayed).

photo: HP 16453A Dielectric Material Test Fixture

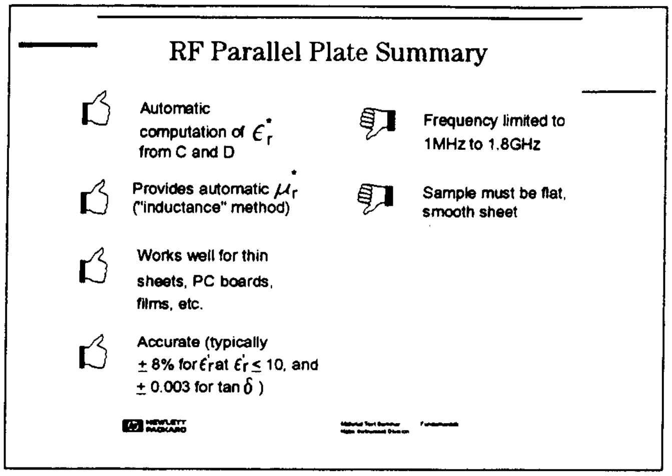
The HP 16453A employs the contacting electrode method. Its upper electrode has a spring inside and pushes the material for a good contact with the electrodes. There is no need to adjust for flatness of the electrode.



LF Parallel Plate Summary

- 👍 Relatively simple computation of ϵ_r^* from C and D
- 👍 Inexpensive
- 👍 Works well for thin sheets, PC boards, films, etc.
- 👍 Accurate (typically ± 1% for ϵ_r and 5% + 0.005 for tan δ)
- 👎 Frequency limited to < 100 MHz
- 👎 Does not provide μ_r^*

The parallel plate method works best for accurate, low frequency measurements of thin sheets or liquids. It does not measure materials with magnetic properties.

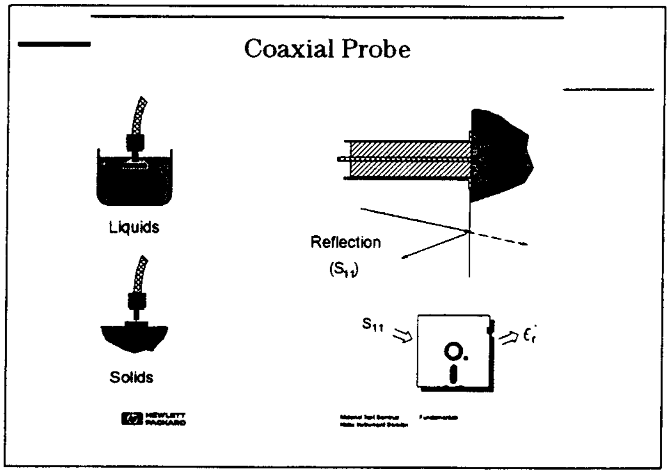


RF Parallel Plate Summary

- 👍 Automatic computation of ϵ_r^* from C and D
- 👍 Provides automatic μ_r^* ("inductance" method)
- 👍 Works well for thin sheets, PC boards, films, etc.
- 👍 Accurate (typically ± 8% for ϵ_r' at $\epsilon_r' \le 10$, and ± 0.003 for tan δ)
- 👎 Frequency limited to 1MHz to 1.8GHz
- 👎 Sample must be flat, smooth sheet

40

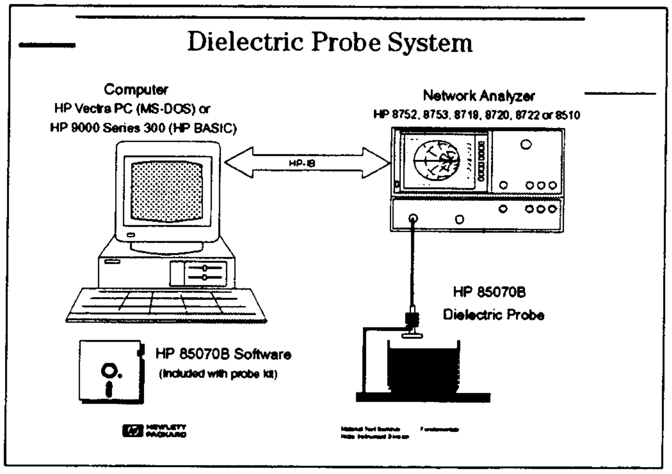
RF Parallel Plate provides ease of use and good accuracy for both dielectric and magnetic materials (use "inductance" measurement method to measure permeability).



Coaxial Probe

41

The open-ended coaxial probe is a cut off section of transmission line. The material is measured by touching the probe to a flat face of a pliable solid (plastic) or immersing it into a liquid or semisolid. The fields at the probe end "fringe" into the material and change as they come into contact with the MUT. The reflected signal (S_{11}) can be measured and related to ε_r*.



Dielectric Probe System

Computer
HP Vectra PC (MS-DOS) or
HP 9000 Series 300 (HP BASIC)

Network Analyzer
HP 8752, 8753, 8719, 8720, 8722 or 8510

HP 85070B Dielectric Probe

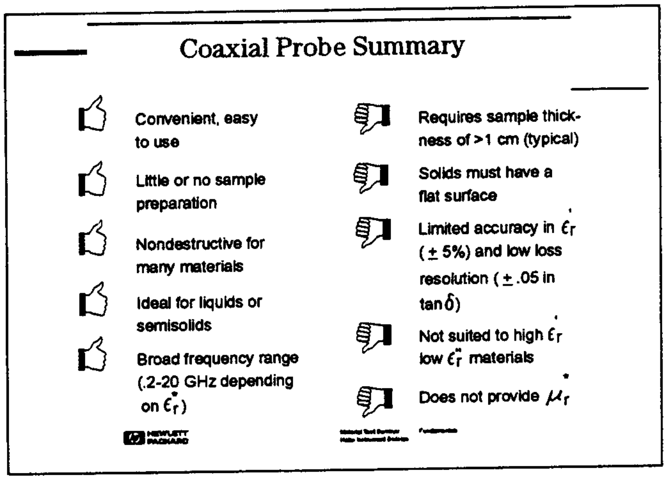
HP 85070B Software
(Included with probe kit)

42

A typical coaxial probe system consists of a vector network analyzer, a coaxial probe and an external computer and software.

photo: HP 85070B Dielectric Probe

The HP 85070B is a coaxial probe that measures the complex dielectric constant of liquids and semisolids from 200 MHz to 20 GHz. The HP 85070B probe kit includes a probe and software to convert the measured S-parameter to permittivity.



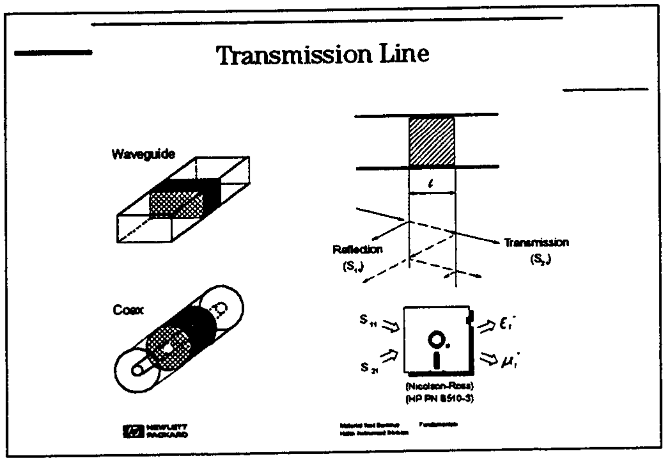
Coaxial Probe Summary

- 👍 Convenient, easy to use
- 👍 Little or no sample preparation
- 👍 Nondestructive for many materials
- 👍 Ideal for liquids or semisolids
- 👍 Broad frequency range (.2-20 GHz depending on ϵ_r^*)

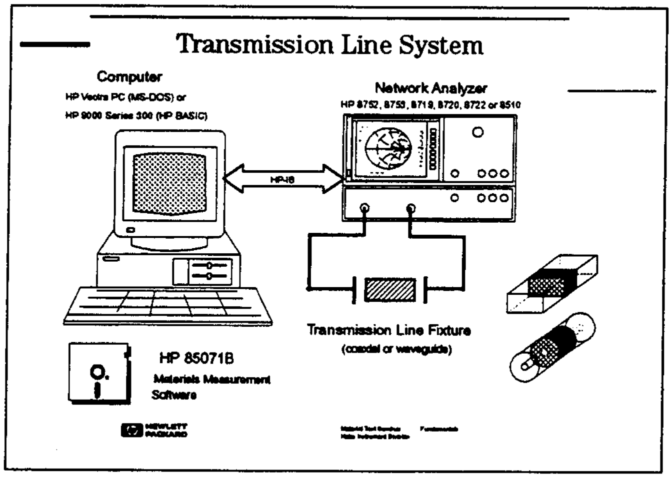
- 👎 Requires sample thickness of >1 cm (typical)
- 👎 Solids must have a flat surface
- 👎 Limited accuracy in ϵ_r^* (± 5%) and low loss resolution (± .05 in tanδ)
- 👎 Not suited to high ϵ_r^* low ϵ_r'' materials
- 👎 Does not provide μ_r^*

The coaxial probe method is convenient and operates over a wide 200 MHz to 20 GHz frequency range. It is not well suited to low loss materials, magnetic materials or where high accuracy is desired.

Transmission Line



Transmission line techniques involve placing the material inside a portion of an enclosed transmission line. The line is usually a section of rectangular waveguide or coaxial airline. Coaxial airlines are broadband, but the toroid shaped samples are more difficult to manufacture. Waveguide sections are banded, but the brick shaped samples are simpler to machine and measurements can be extended to the mm-wave bands. ε_r* and μr* are computed from the measurements of the reflected signal (S_{11} and S_{22}) and transmitted signal (S_{21} and S_{12}).

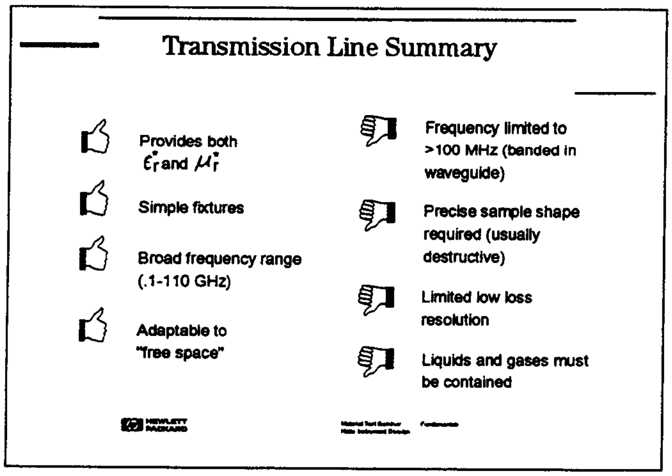


Transmission Line System

A typical transmission line system consists of a vector network analyzer, a coaxial airline or waveguide section and an external computer and software.

photo: HP 85071B Transmission Line Software

Coaxial and waveguide fixtures are available from HP and a variety of third party suppliers. The HP 85071B is a materials measurement software package that converts the measured Sparameters to permittivity and permeability.

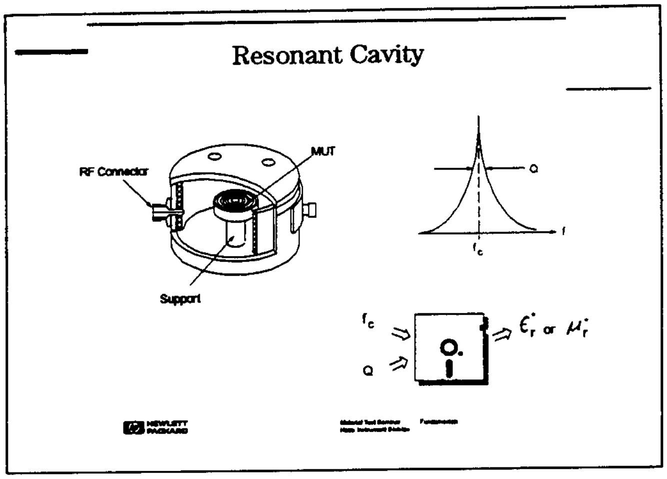


Transmission Line Summary

- 👍 Provides both ε_r^* and μ_r^*
- 👍 Simple fixtures
- 👍 Broad frequency range (.1-110 GHz)
- 👍 Adaptable to "free space"

- 👎 Frequency limited to >100 MHz (banded in waveguide)
- 👎 Precise sample shape required (usually destructive)
- 👎 Limited low loss resolution
- 👎 Liquids and gases must be contained

The transmission line method is best for solid materials that can be precisely machined to fit inside a coaxial or waveguide airline. Although it is more accurate that the coaxial probe technique, it is still somewhat limited in resolution for low loss materials.



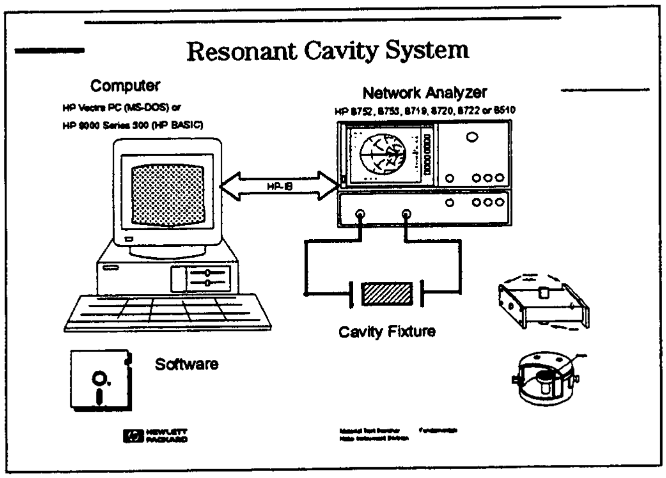
Resonant Cavity

Resonant cavities are high Q structures that resonate at certain frequencies. A sample of the material affects the center frequency (f_c) and quality factor (Q) of the cavity. From these parameters, the complex permittivity (ε_r*) or permeability (μ_r*) of the material can be calculated at a single frequency.

Cavity Summary

👍 Very accurate	👎 Does not provide broadband frequency data
👍 Very sensitive to low loss δ (to 10^{-6} for some cavities)	👎 Precise sample shape required (usually destructive)
	👎 Analysis may be complex

The cavity technique is the most accurate of the five techniques, especially for low loss materials. But measurement are made at single frequencies only and the analysis can be complex.



Resonant Cavity System

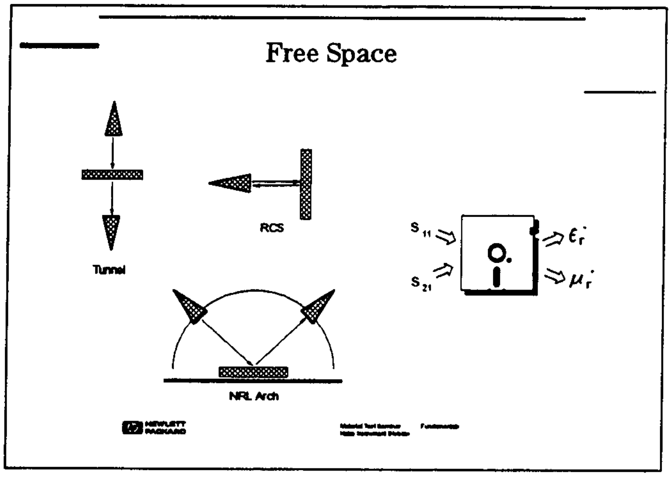
Computer

HP Vectra PC (MS-DOS) or
HP 9000 Series 300 (HP BASIC)

Network Analyzer

HP 8752, 8753, 8719, 8720, 8722 or 8510

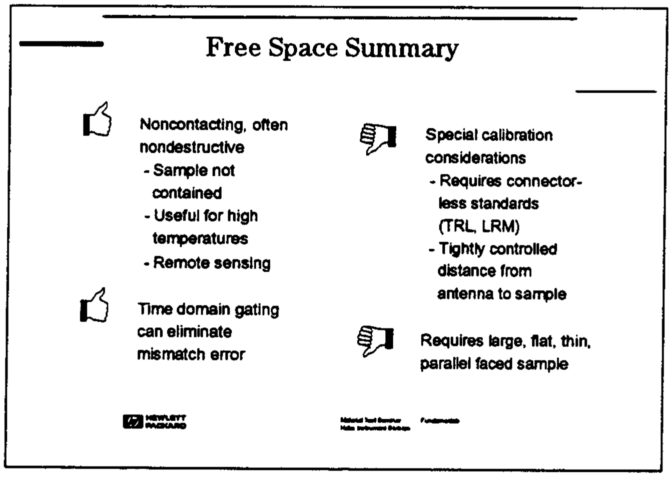
A typical resonant cavity system consists of a network analyzer, cavity fixture and an external computer and software. Cavity fixtures and software are available from third party suppliers.



Free Space

52

Free space techniques use antennas to focus microwave energy at a through a slab of material without the need of a test fixture. The same algorithms that are used for the transmission line technique can be applied to free space.



Free Space Summary

👍 Noncontacting, often nondestructive
- Sample not contained
- Useful for high temperatures
- Remote sensing

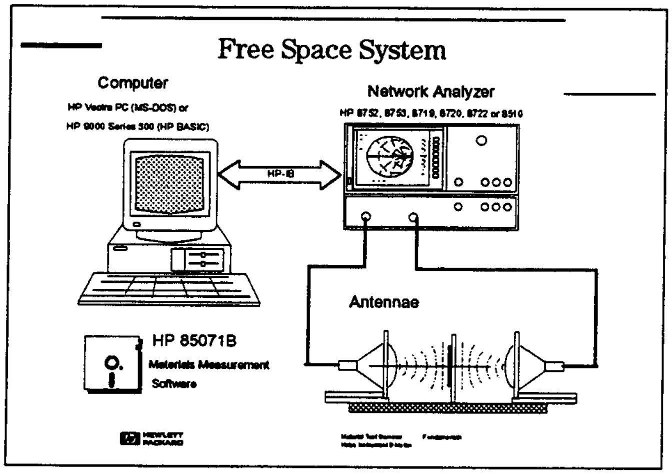
👍 Time domain gating can eliminate mismatch error

👎 Special calibration considerations
- Requires connector-less standards (TRL, LRM)
- Tightly controlled distance from antenna to sample

👎 Requires large, flat, thin, parallel faced sample

53

Free space techniques are best for large, flat samples that cannot be easily fixtured or that must be tested under high temperature conditions. It is a noncontacting technique that is usually nondestructive; however, special considerations must be taken for the calibration since "connectorless" standards must be used.



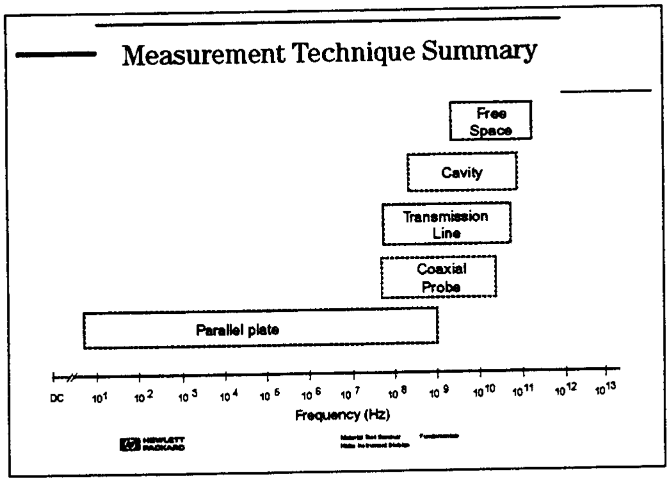
Free Space System

54

A typical free space system consists of a vector network analyzer, antenna hardware and an external computer and software.

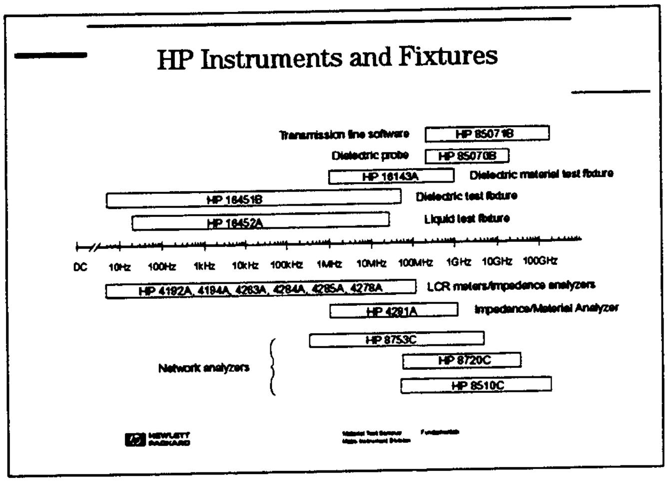
photo: Free Space System

Antenna hardware is available from third party suppliers. The HP 85071B materials measurement software can be used to convert the measured S-parameters to permittivity and permeability.



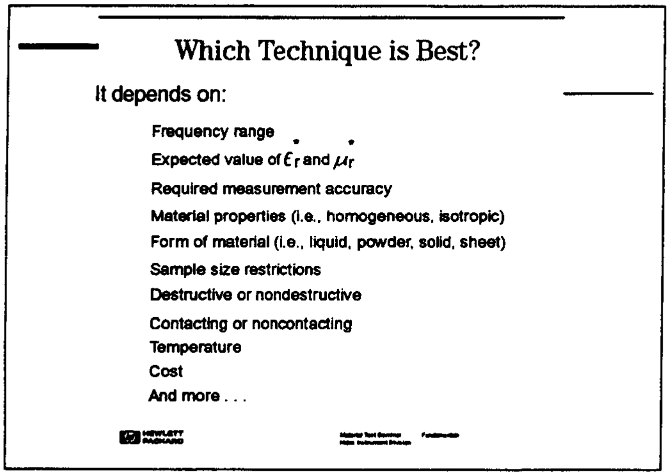
Measurement Technique Summary

One way to select a measurement technique is by frequency range. The techniques discussed previously range in frequency from dc to over 100 GHz.



HP Instruments and Fixtures

Hewlett-Packard has a wide range of fixtures and measurement instruments for measuring the dielectric properties of materials. Additional fixtures and software are available from third party suppliers.



Which Technique is Best?

It depends on:

- Frequency range
- Expected value of ϵ_r^* and μ_r^*
- Required measurement accuracy
- Material properties (i.e., homogeneous, isotropic)
- Form of material (i.e., liquid, powder, solid, sheet)
- Sample size restrictions
- Destructive or nondestructive
- Contacting or noncontacting
- Temperature
- Cost
- And more . . .

Choosing the best technique for a given application is not always easy since it is dependent upon many factors. The application sessions will focus more specifically on choosing the best technique for a substrate material measurement or an absorber/insulator material measurement.