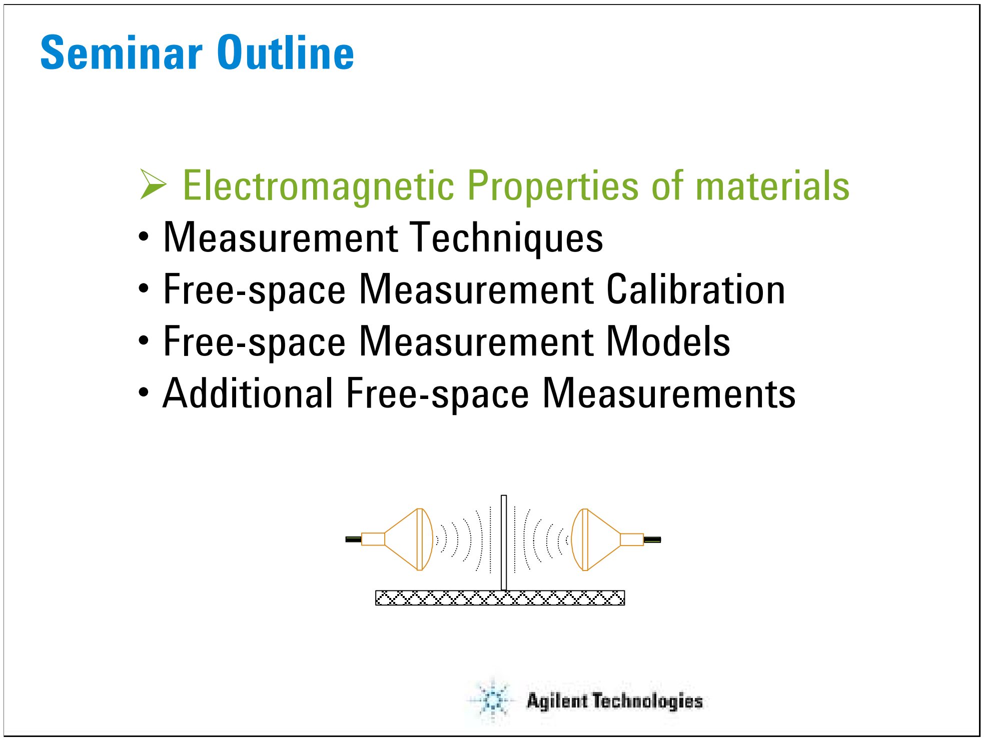
Free Space Materials Measurement Seminar

Agilent Technologies

June 2005

In the mid 1980s, Agilent Technologies developed several products that measure the electromagnetic properties of material samples. At that time Agilent Technologies was a part of the Hewlett-Packard Company. These products were developed to meet the needs our customers involved in the development of electronic components, circuits and systems as well as by Department of Defense contractors involved in the design and development of low observables, radome, and absorbing materials.. Since then many advancements have been made. Today’s seminar will highlight some of them.



Seminar Outline

- ➢ Electromagnetic Properties of materials
- Measurement Techniques
- Free-space Measurement Calibration
- Free-space Measurement Models
- Additional Free-space Measurements

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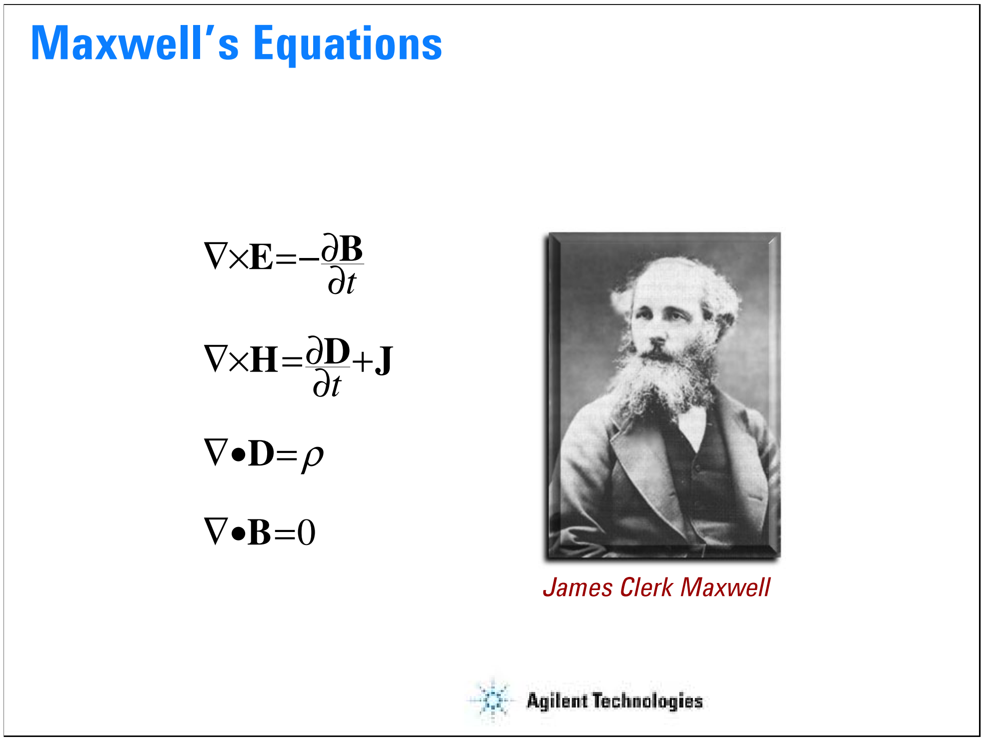

Maxwell's Equations

$$\nabla\times\mathbf{E}=-\frac{\partial\mathbf{B}}{\partial t}$$

$$\nabla\times\mathbf{H}=\frac{\partial\mathbf{D}}{\partial t}+\mathbf{J}$$

$$\nabla\bullet\mathbf{D}=\rho$$

$$\nabla\bullet\mathbf{B}=0$$

James Clerk Maxwell

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Everything we are going to talk about today, starts here. I'm sure you all recognize Maxwell and his famous equations. We won't go into detail, but due diligence demands we at least give mention.

The solution of Maxwell's equations determines how microwave energy propagates through a material. Maxwell's equations can be expressed in many equivalent forms. Its most general form is listed here.

Where:

J is the current density

E is the electric field intensity

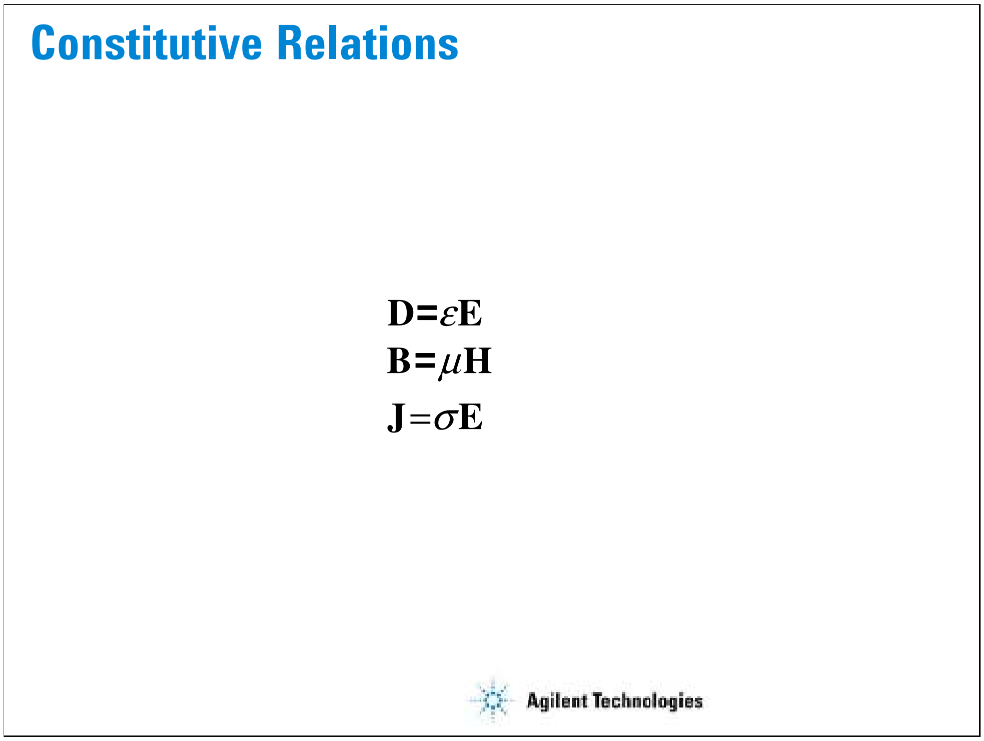
D is the electric flux density

H is the magnetic intensity field

B is the magnetic flux density

p is the charge density

These equations are based on Faraday's law and Ampere's law. These equations are always satisfied.



Constitutive Relations

$$\mathbf{D}=\varepsilon\mathbf{E}$$
$$\mathbf{B}=\mu\mathbf{H}$$
$$\mathbf{J}=\sigma\mathbf{E}$$

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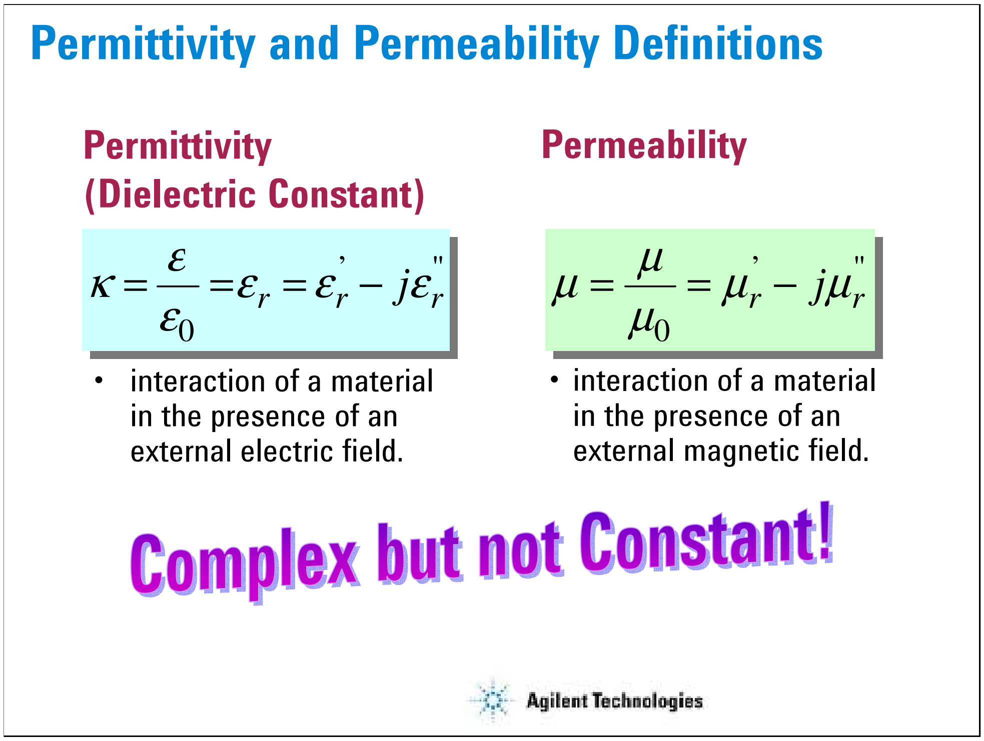
Other factors that make the solution unique to a particular situation are the boundary conditions and the satisfaction of the following constitutive relations. **e**, **u**, and **s** are, respectively, the permittivity, permeability and conductivity of the media. These are commonly referred to as the electromagnetic properties of the material. Many materials are non-magnetic. The consequence of this is that **μ** is known. At high frequencies, the effect of **σ** can be ignored. This is because its effect varies inversely with frequency. This is true for most non-conductive materals. The exception is for metals.



Permittivity and Permeability Definitions

Permittivity (Dielectric Constant)

$$\kappa = \frac{\varepsilon}{\varepsilon_0} = \varepsilon_r = \varepsilon_r' - j\varepsilon_r''$$

- interaction of a material in the presence of an external electric field.

Permeability

$$\mu = \frac{\mu}{\mu_0} = \mu_r' - j\mu_r''$$

- interaction of a material in the presence of an external magnetic field.

Complex but not Constant!

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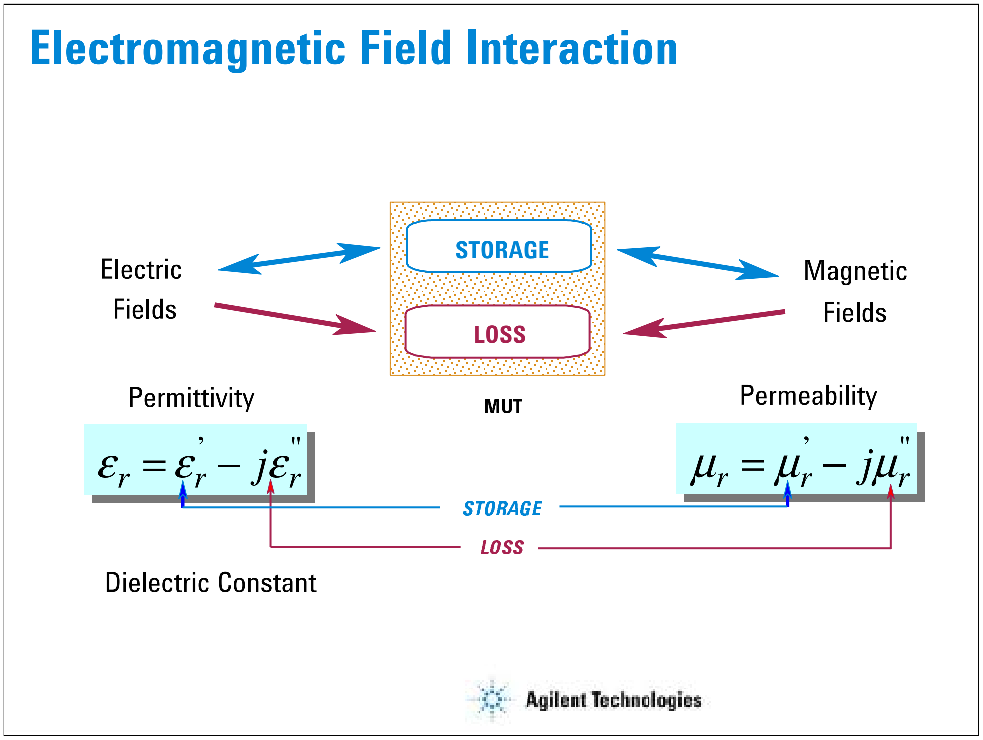
Permittivity (e), also called dielectric constant, describes the interaction of a material with an electric field. Dielectric constant (k) is equivalent to relative permittivity (e_r) or the absolute permittivity (e) relative to the permittivity of free space (e_0). The real part of permittivity (e_r’) is a measure of how much energy from an external electric field is stored in a material. The imaginary part of permittivity (e_r”) is called the loss factor and is a measure of how dissipative or lossy a material is to an external electric field.

Its fundamental dimensions are $T^2Q^2M^{-1}L^{-3}$ where T, Q, M and L are time, charge, mass and length respectively. Normally this is expressed as farad per meter (capacitance per distance).

Dielectric “Constant” is not constant over frequency or temperature!

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

Electric Fields

STORAGE

LOSS

MUT

Magnetic Fields

Permittivity

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$$

Permeability

$$\mu_r = \mu_r' - j\mu_r''$$

STORAGE

LOSS

Dielectric Constant

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When electric and magnetic fields pass through a material, each can interact with that material in two ways:

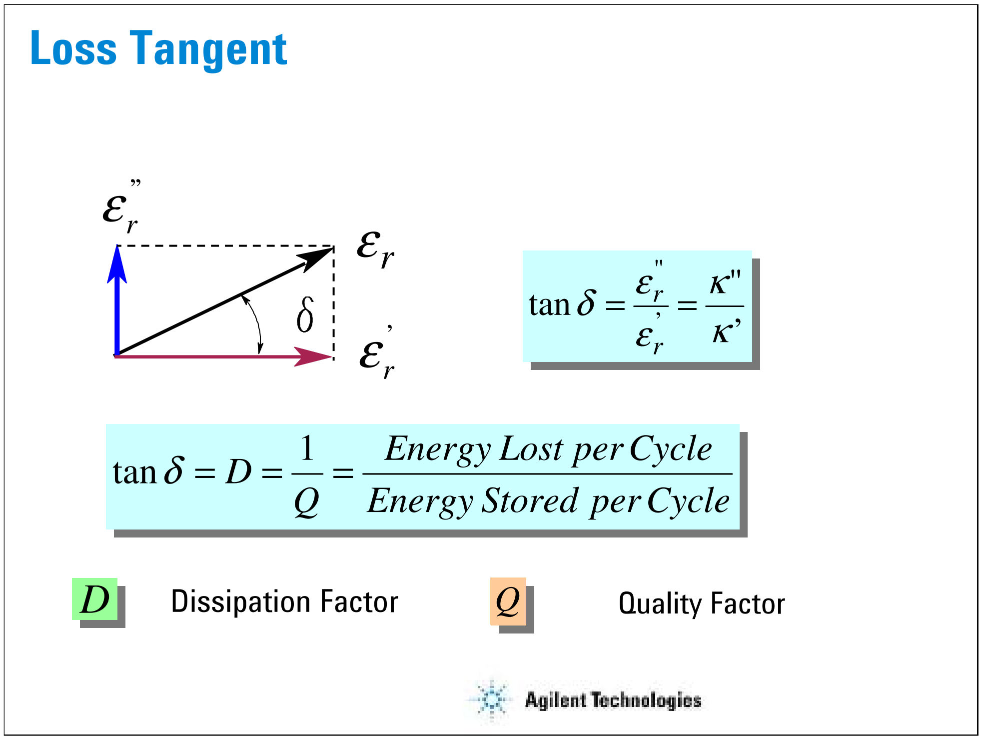
Storage: Energy may be exchanged between the field and the material, in a bi-directional (lossless) manner

Loss: Energy may be permanently lost from the field, and absorbed in the material (usually as heat)

The electric interactions are quantified by permittivity (e_r), also called dielectric constant (k). The magnetic properties are described by permeability (m_r). These are complex numbers with real and imaginary parts:

- ***Real Part:*** Represents storage term; denoted with ‘
- ***Imaginary Part:*** represents loss term; denoted with “.

This presentation focuses on permittivity, since most of the common materials are completely non-magnetic.



Loss Tangent

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

$$\tan\delta = D = \frac{1}{Q} = \frac{Energy\ Lost\ per\ Cycle}{Energy\ Stored\ per\ Cycle}$$

D	Dissipation Factor	Q	Quality Factor

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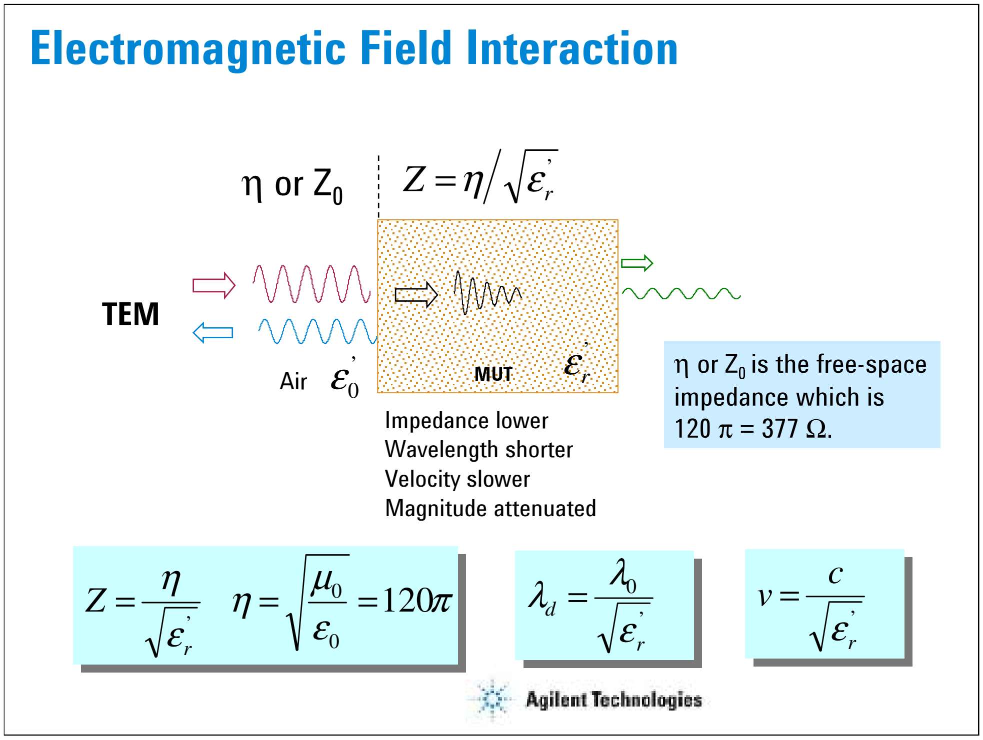
Another term will talk about is loss tangent. When complex permittivity is drawn as a simple vector diagram, the real and imaginary components are 90^{o} out of phase. The vector sum forms an angle d with the real axis (e_r'). The relative "lossiness" of a material is the ratio of the energy lost to the energy stored.

Here: tand = loss tangent = tan delta = tangent loss = dissipation factor

In some cases is used the term "quality factor or Q-factor" with respect to an electronic microwave material.



Electromagnetic Field Interaction

η or Z_0

$Z = \eta / \sqrt{\varepsilon_r'}$

TEM

Air ε_0'

MUT ε_r'

Impedance lower
Wavelength shorter
Velocity slower
Magnitude attenuated

η or Z_0 is the free-space impedance which is 120 π = 377 Ω.

$$Z = \frac{\eta}{\sqrt{\varepsilon_r'}} \qquad \eta = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 120\pi$$

$$\lambda_d = \frac{\lambda_0}{\sqrt{\varepsilon_r'}}$$

$$v = \frac{c}{\sqrt{\varepsilon_r'}}$$

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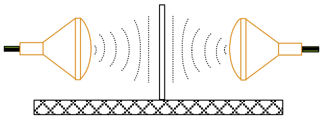
Let's use the "optical view" of dielectric behavior. Consider a flat slab of material in space, with a wave incident on its surface. We will have incident, reflected and transmitted waves. Since the impedance of the wave in the material is different (lower) from the free space impedance, there will be impedance mismatch and this will create the reflected wave. Part of the energy will penetrate the sample. Once in the slab, the wave velocity is slower and the wavelength is shorter according the equations above. Since the material will always have some loss, there will be attenuation or insertion loss. For simplicity the mismatch on the second border is not considered.

Seminar Outline

- Electromagnetic Properties of materials

➢Measurement Techniques

- Free-space Measurement Calibration
- Free-space Measurement Models
- Additional Free-space Measurements



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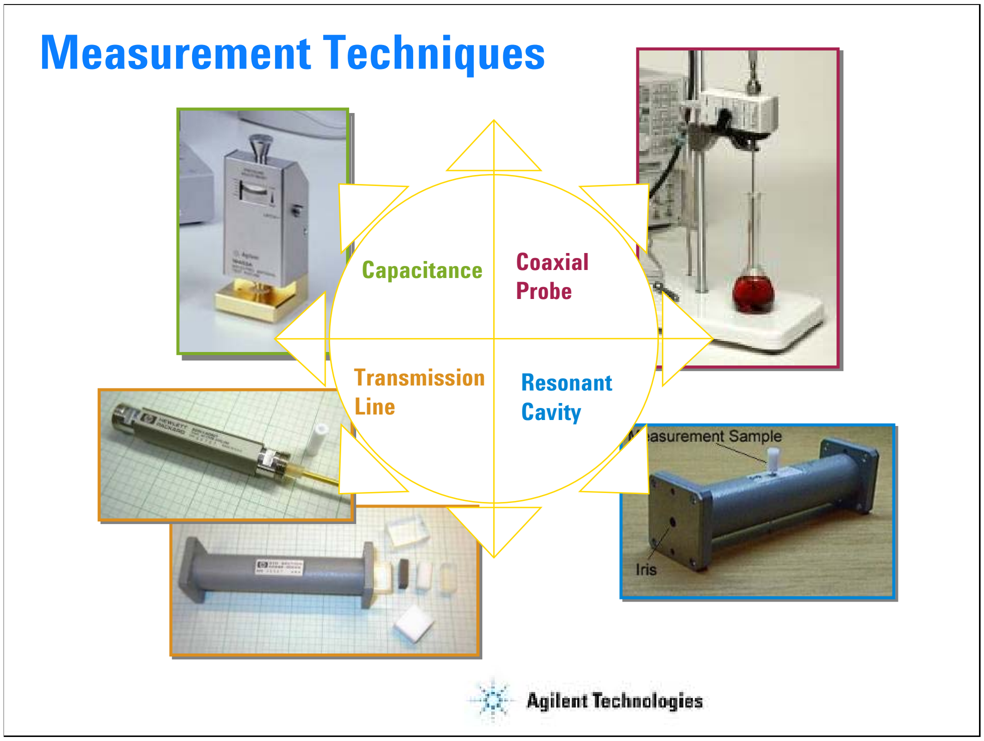

Measurement Techniques

Capacitance

Coaxial Probe

Transmission Line

Resonant Cavity

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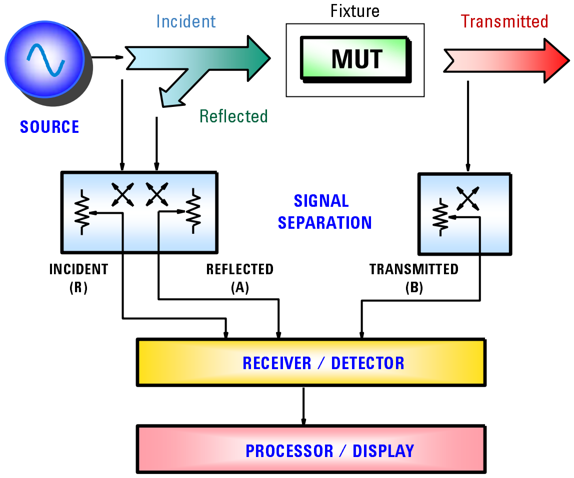
Here’s a quick look at some methods and fixturing used to measure dielectric properties of materials. Clockwise from the upper left.

1. Capacitance: Uses a parallel plate capacitor, with the material sandwiched between. This method uses an impedance analyzer. It is typically used at the lower frequencies, below 1 GHz.
2. Coaxial probe: This method uses an open ended coaxial probe, usually with a network analyzer. It is the easiest method to use for liquids, or soft semi-solids, although very flat hard solids can be measured as well. Agilent offers probes in the RF to microwave frequencies, 200MHz to 50GHz.
3. Resonant Cavity: This method uses a resonant cavity for the sample holder, and a network analyzer to measure the resonant frequency and Q of the cavity, both empty and with the sample present. From this, permittivity can be calculated. This method has the best loss factor resolution.
4. Transmission Line: This method can use a variety transmission “lines” for sample holders with a network analyzer. Lines can be coaxial, waveguide and even free-space is considered a transmission line technique. It is useful for a broad frequency range, from the low microwave region to mm-wave.

Network Analyzer Block Diagram



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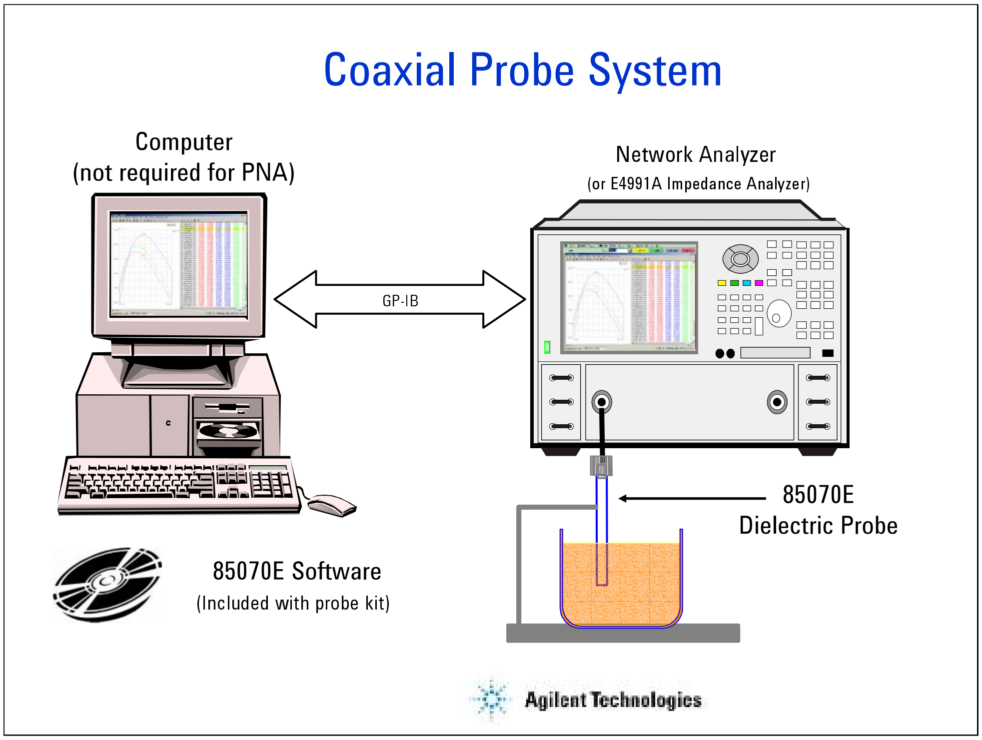
Here is a generalized block diagram of a network analyzer, showing the major signal-processing sections. In order to measure the incident, reflected and transmitted signal, four sections are required:

- Microwave signal source for stimulus
- Signal-separation devices
- Receivers that down convert and detect the signals
- Processor/display for calculating and reviewing the results

A reflection measurement is the ratio of the Reflected signal detected at A, over the Incident signal detected at R. A transmission measurement is the ratio of the Transmitted signal detected at B, over the Incident signal detected at R. Ratioed measurements reduce errors caused by imperfections in the source. Errors caused by differences in these signal paths or any leakage signals within the network analyzer can be calibrated out by the user before measurements are made.. Calibration is typically a simple procedure where three known standards are measured.



Coaxial Probe System

Computer
(not required for PNA)

GP-IB

Network Analyzer
(or E4991A Impedance Analyzer)

85070E
Dielectric Probe

85070E Software
(Included with probe kit)

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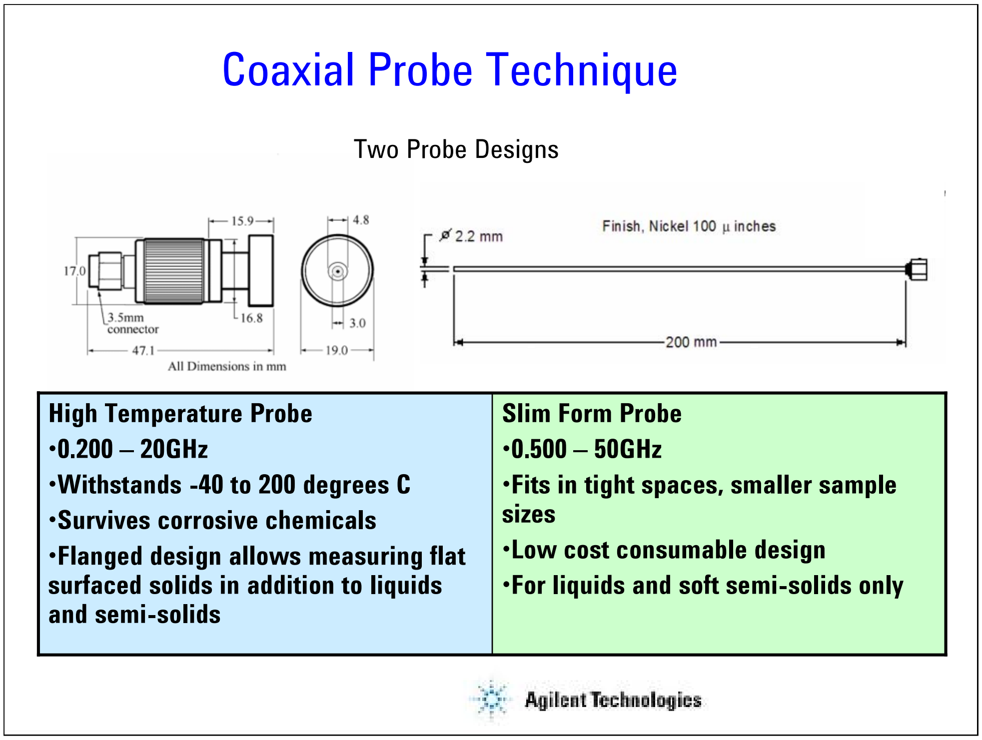
A typical coaxial probe system consists of a vector network analyzer, a coaxial probe, an external computer with HP-IB card and software. For the PNA series network analyzers, a computer is not required because the software can be run directly on the instrument.

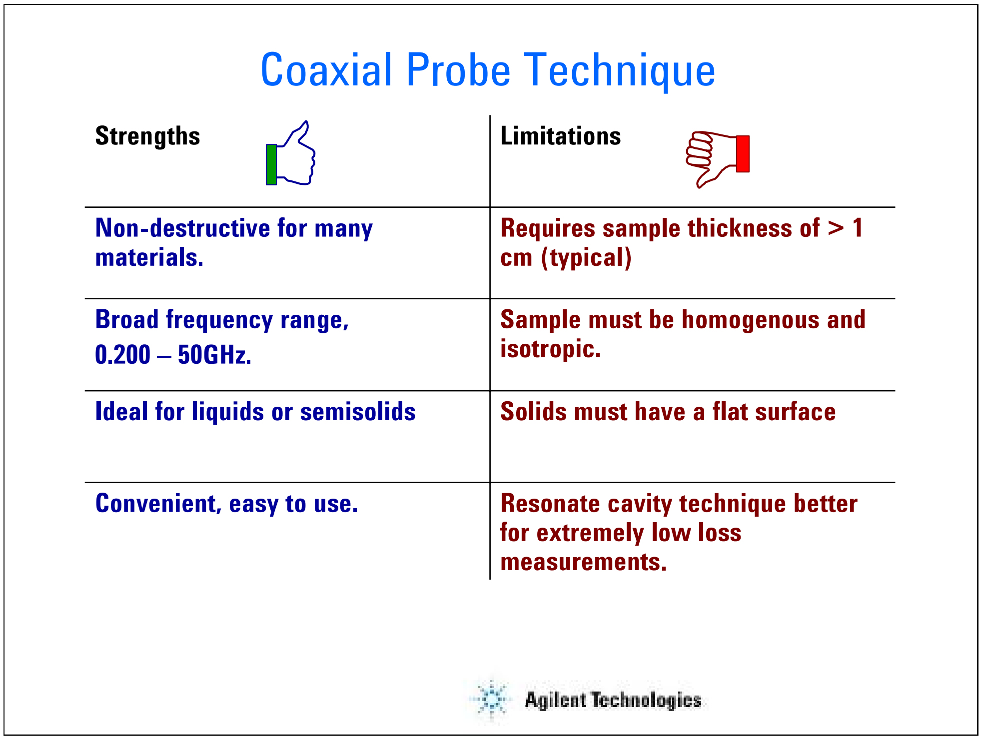


Coaxial Probe Technique

Two Probe Designs

High Temperature Probe	**Slim Form Probe**
•0.200 – 20GHz **•Withstands -40 to 200 degrees C** **•Survives corrosive chemicals** **•Flanged design allows measuring flat surfaced solids in addition to liquids and semi-solids**	**•0.500 – 50GHz** **•Fits in tight spaces, smaller sample sizes** **•Low cost consumable design** **•For liquids and soft semi-solids only**

The coaxial probe technique is best for liquids and semi-solid materials. For hard solid materials one flat surface is required. Special precautions should be taken to avoid air gaps between the sample and the probe (this may be air bubble in the case of liquid). Since only the s_{11} parameter is measured, only the dielectric properties can be calculated, and the MUT should be non magnetic. The underlying theory presumes infinite sample. In reality the sample should be “thick enough”. The method is simple, convenient, nondestructive (no special sample is needed in most of the cases) and with one measurement we can sweep up to 50 GHz. The disadvantages of the method are the limited accuracy compared with other methods (transmission method 85071E, resonator methods) and the limitation of the thickness of the sample.



Coaxial Probe Technique

Strengths	Limitations
Non-destructive for many materials.	Requires sample thickness of > 1 cm (typical)
Broad frequency range, 0.200 – 50GHz.	Sample must be homogenous and isotropic.
Ideal for liquids or semisolids	Solids must have a flat surface
Convenient, easy to use.	Resonate cavity technique better for extremely low loss measurements.

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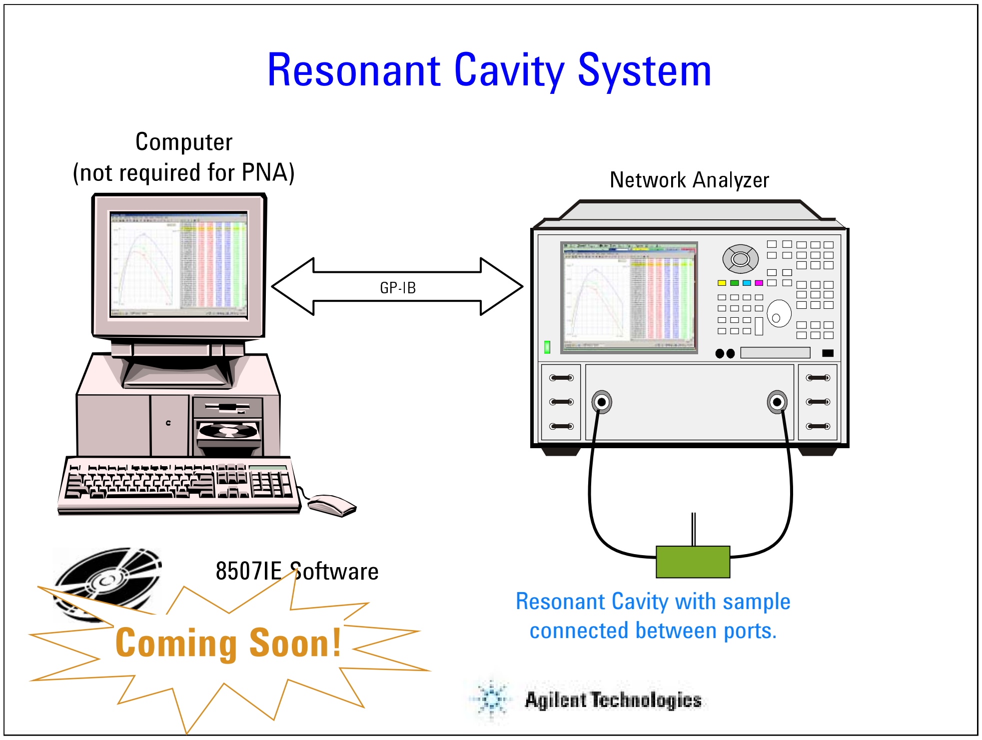
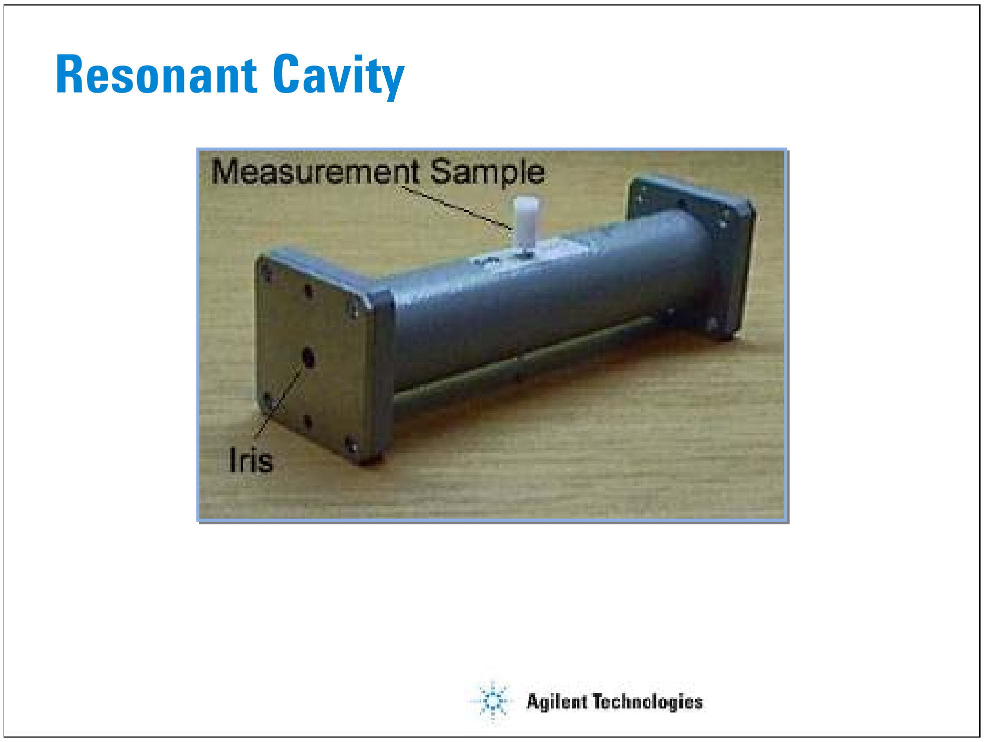
The coaxial probe method is convenient and operates over a wide, 200 MHz to 50 GHz, frequency range. It is not well suited to low loss materials, magnetic materials or where high accuracy is desired.



Resonant Cavity System

Resonant Cavity with sample connected between ports.

The resonant cavity system consists of a resonant cavity connected between two ports of a network analyzer with coax cables. The dielectric properties can be calculated from the transmission response of the cavity, measured empty and then with the sample. The calculation can be performed manually, or from user written software controlling the network analyzer over LAN or GPIB.



Resonant Cavity

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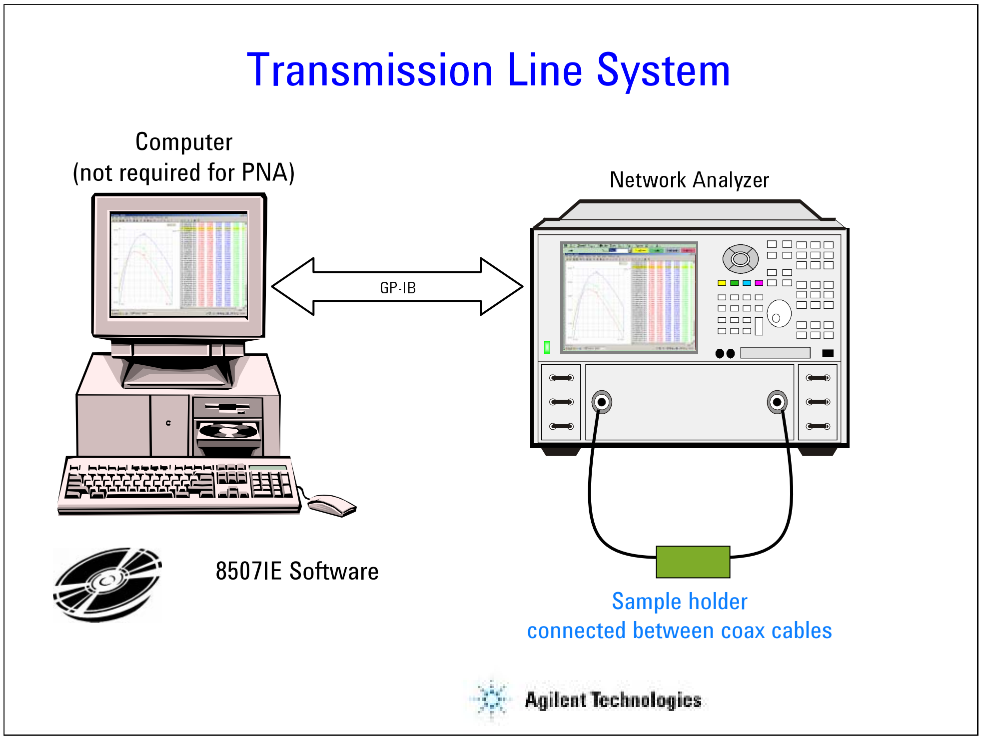
Free space measurements offer a means of making permittivity measurements without contacting the material sample. The sample is placed between two antennas. This picture shows a clear sheet of plastic, approximately 1/8th inch thick, being measured.



Transmission Line System

Computer
(not required for PNA)

GP-IB

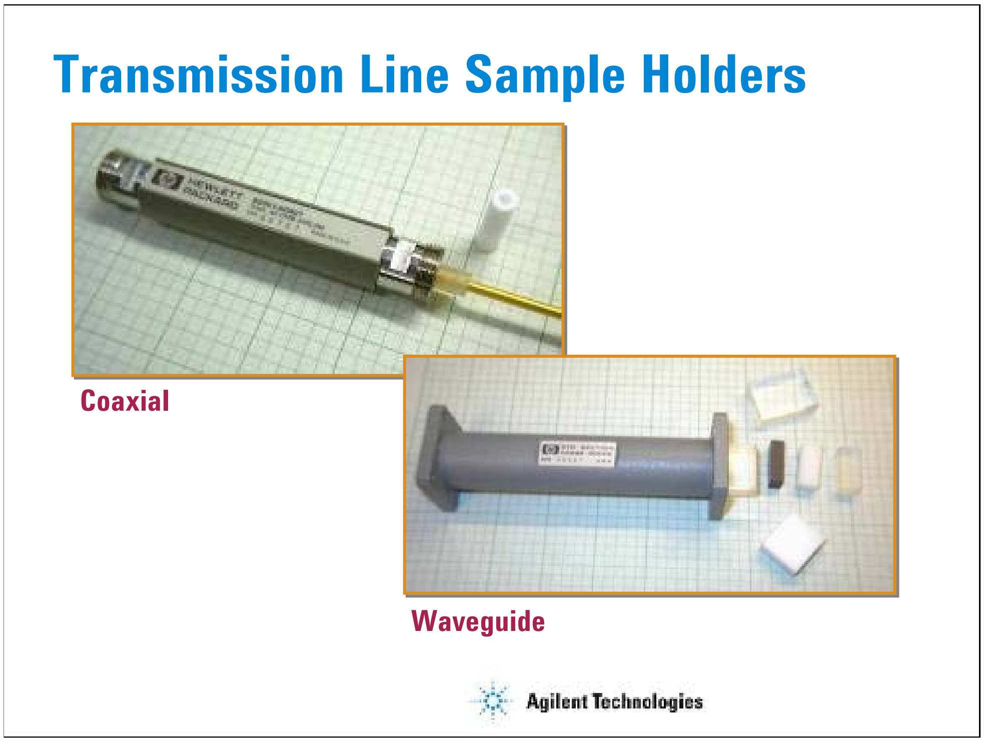
Network Analyzer

8507IE Software

Sample holder
connected between coax cables

Agilent Technologies

A typical transmission line system consists of a vector network analyzer and a sample holder connected between the two network analzyer ports.. Agilent provides software that converts the reflection and transmission coefficients to dielectric properties.   For the PNA series network analyzers, a computer is not required as the software can be run directly on the instrument.. For all other network analyzers, an external computer with HP-IB card is required.



Transmission Line Sample Holders

Coaxial

Waveguide

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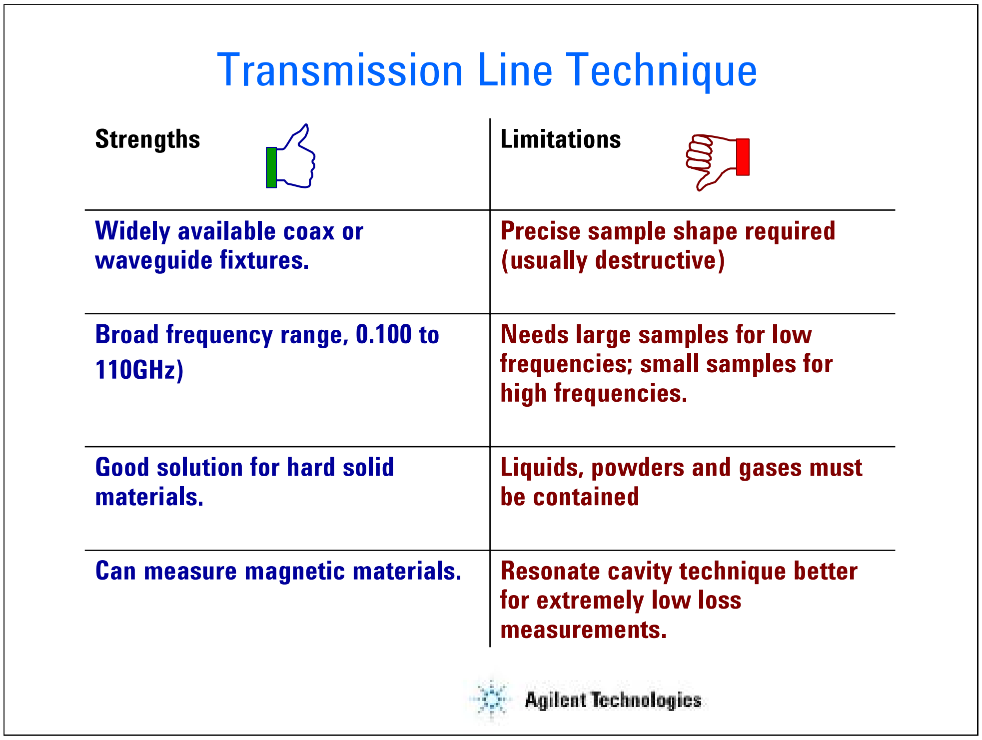
The open-ended coaxial line offers a convenient, nondestructive means of measuring permittivity over a broad frequency range. It is well suited for liquids, semi-solids and powders. It can also be used to measure solids as long as the solid has a flat surface. Precaution should be taken to avoid air gaps between the sample and the probe (this may be air bubble in the case of liquid). The underlying theory presumes infinite sample. In reality the sample should be “thick enough”.



Transmission Line Technique

Strengths 👍	**Limitations** 👎
Widely available coax or waveguide fixtures.	Precise sample shape required (usually destructive)
Broad frequency range, 0.100 to 110GHz)	Needs large samples for low frequencies; small samples for high frequencies.
Good solution for hard solid materials.	Liquids, powders and gases must be contained
Can measure magnetic materials.	Resonate cavity technique better for extremely low loss measurements.

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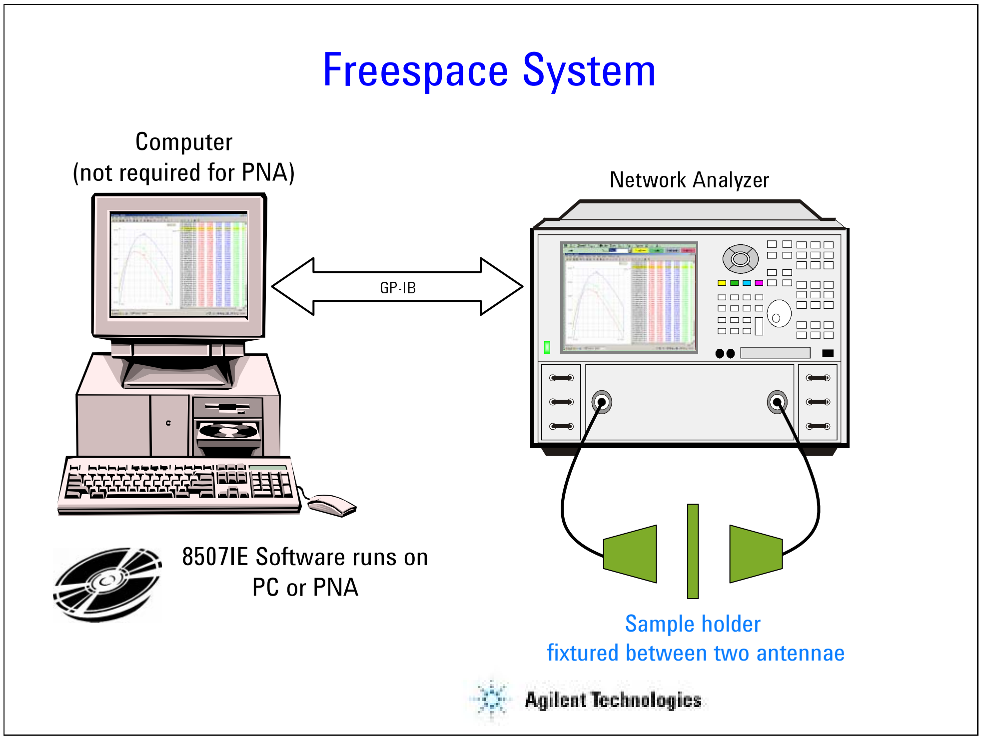
The transmission line method is best for solid materials that can be precisely machined to fit inside a coaxial or waveguide airline. Although it is more accurate that the coaxial probe technique, it is still somewhat limited in resolution for low loss materials.



Freespace System

Computer
(not required for PNA)

Network Analyzer

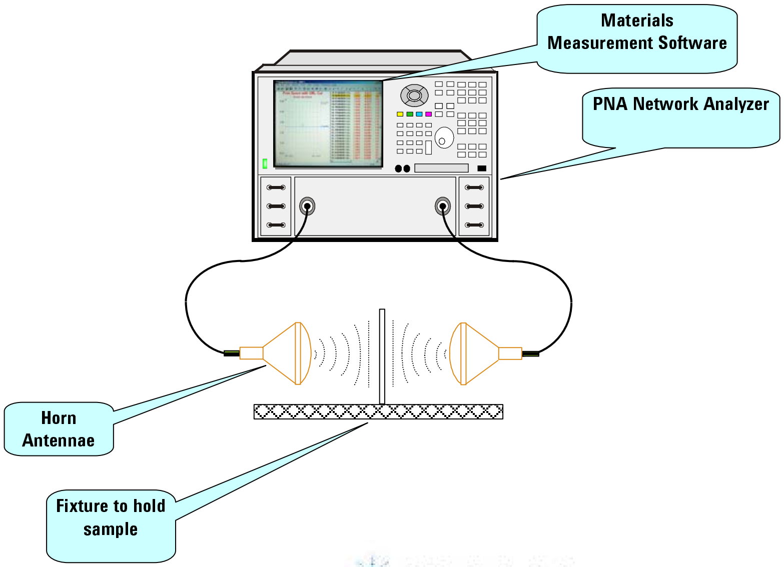
8507IE Software runs on PC or PNA

Sample holder
fixtured between two antennae

Agilent Technologies

A typical freespace system consists of a vector network analyzer, two antennae facing each other with a sample holder between them. Agilent provides software that converts the reflection and transmission coefficients to dielectric properties. For the PNA series network analyzers, a computer is not required as the software can be run directly on the instrument.. For all other network analyzers, an external computer with HP-IB card is required.

Free Space Transmission System



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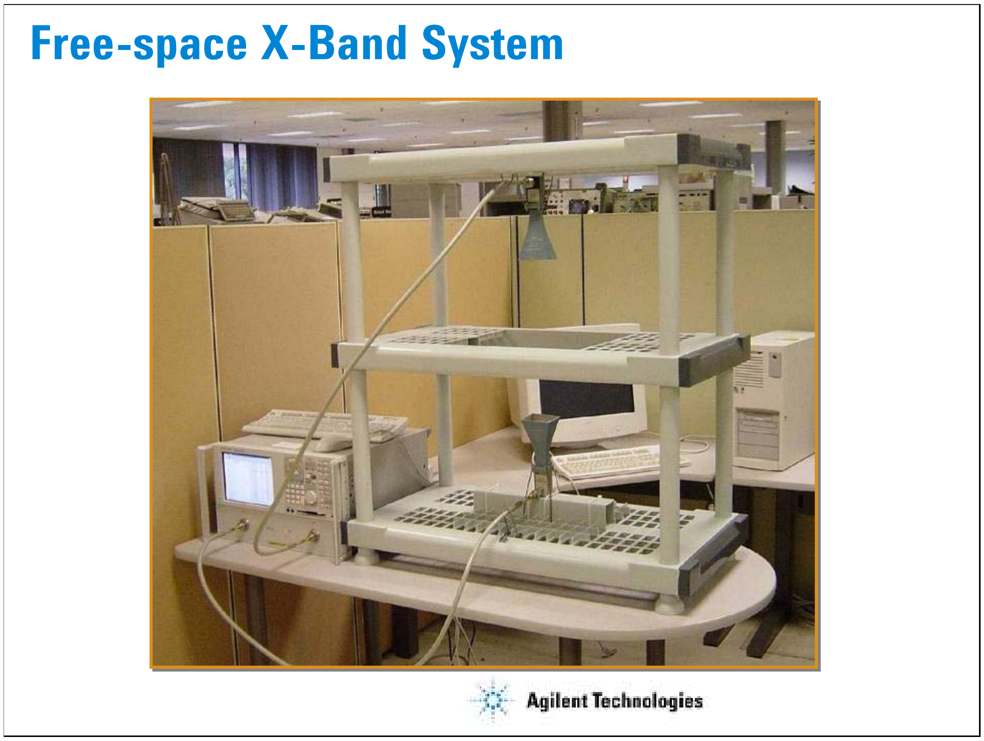
And, the focus of our talk today: Free space measurements offer a means of making permittivity measurements without contacting the material sample. The sample is placed between two antennas. Either the transmission thru and/or the reflection off the sample is used to calculate the permittivity.

The basic free space materials measurement system is simple. A network analyzer, in this case an Agilent PNA network analyzer. Two antennae and a fixture to hold the sample between them. Also useful is some software to calculate the dielectric properties from the network analyzers S parameter data. When using a PNA, the software can be run on the box itself, eliminating the need for an external computer, and interface card such as LAN or GPIB.



Free-space X-Band System

Here is a picture of a very simple and inexpensive X-band, 8.2 to 12.4GHz, free space system. The fixture is made from a shelving unit purchased at an office supply store. The antennae are held in place on the top and bottom shelf. The middle shelf had a hole cut out to serve as a sample holder. New calibration techniques we will discuss later correct for the reflections of the fixture, antenna and surrounding area, and fairly reasonable results were obtained. Care had to be taken, however, not to bump or move the system after calibration, as it was not very rigid.

Free Space W-band System

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Here is a photo of a W-band, 75-110GHz, measurement system. You can see the PNA mm-wave system includes and two mm-wave heads to multiply the frequency and an additional box to control the heads.

These w-band std-gain horns were purchased for less than $700 US, and the sample holder is made out of a few pieces of scrap plastic held together with some plastic screws and pink rubber bands. It’s clamped to the table with C-clamps so it doesn’t move.

Free Space W-band System

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Here is a closer look at the horns and sample holder. Obviously, more robust fixturing can be made for industrial use, but even with these easily made, simple fixtures, reasonable results were obtained, which you will see later in this presentation.

Free Space Quasi-Optical System

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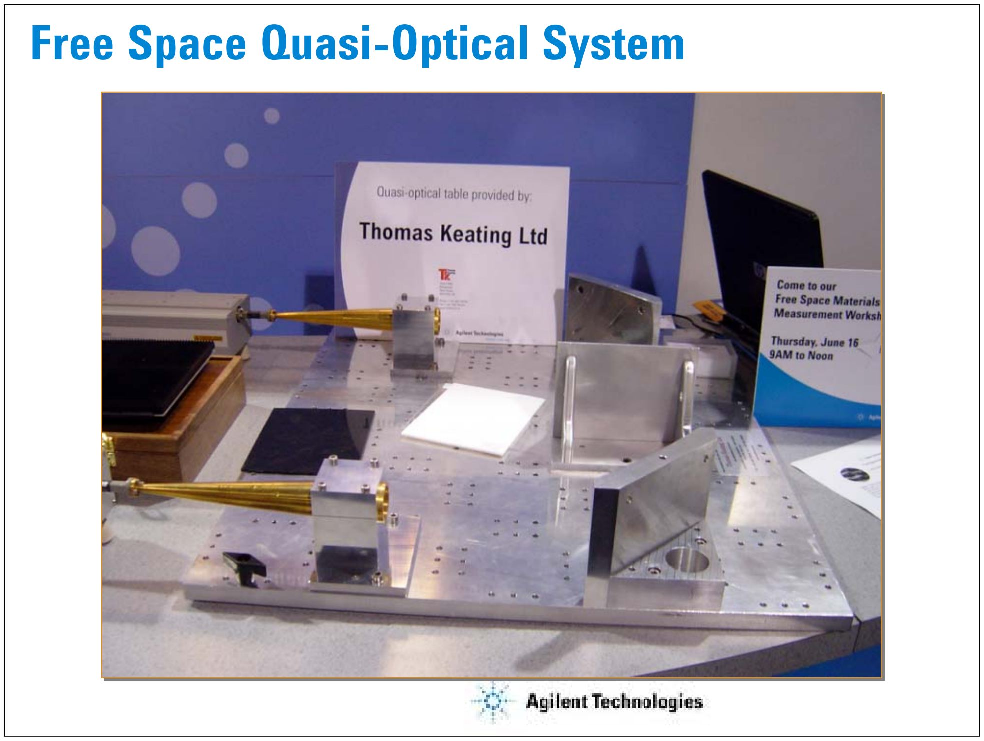
Here’s a look at another W-band setup, this time using mirrors to reshape and redirect the beam. More accurate results for e’ can be achieved.



Free Space Quasi-Optical System

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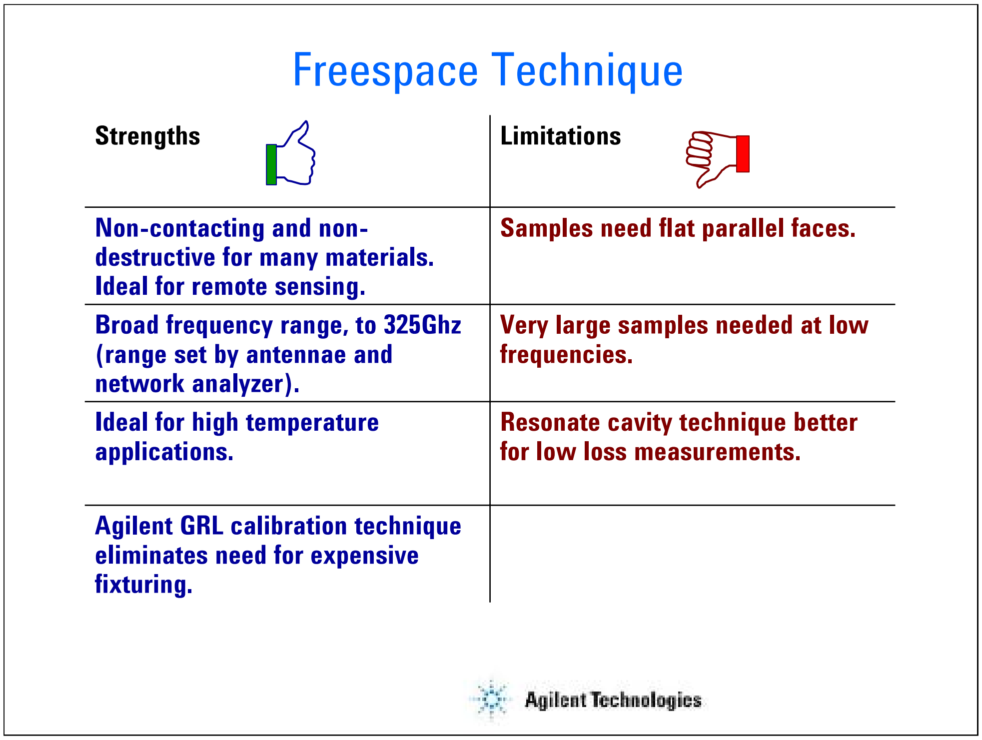

Freespace Technique

Strengths	Limitations
Non-contacting and non-destructive for many materials. Ideal for remote sensing.	Samples need flat parallel faces.
Broad frequency range, to 325Ghz (range set by antennae and network analyzer).	Very large samples needed at low frequencies.
Ideal for high temperature applications.	Resonate cavity technique better for low loss measurements.
Agilent GRL calibration technique eliminates need for expensive fixturing.	

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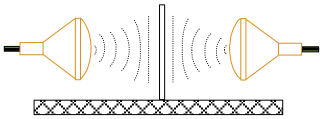
The freespace technique works well for sheet materials, powders, or liquids. Since it is a non-contacting technique, it is ideal for remote sensing and high temperature applications. Special ovens can be purchased with microwave “windows”. The sample is placed inside and the test equipment can remain safe outside. Agilent’s GRL (Gated Reflect Line) calibration technique eliminates the need for expensive fixturing needed with other calibration techniques.

Seminar Outline

- Electromagnetic Properties of materials
- Summary of Measurement Techniques
- ➢ Free-space Measurement Calibration
- Free-space Measurement Models
- Additional Free-space Measurements



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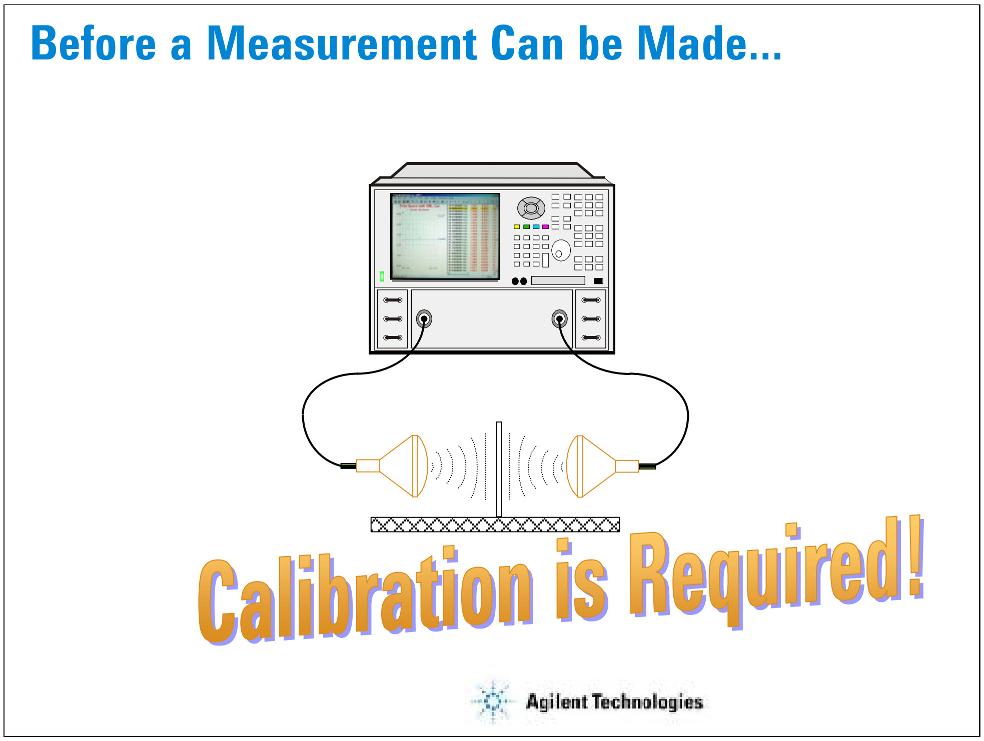

Before a Measurement Can be Made...

Calibration is Required!

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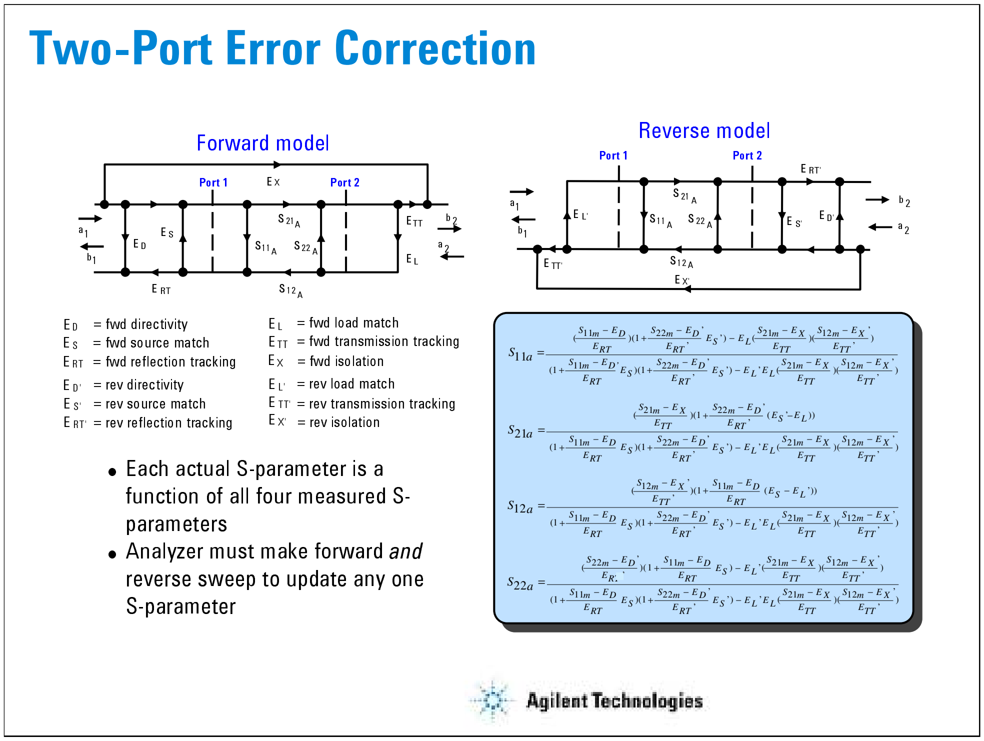
System errors must be corrected for before a measurement is made.



Two-Port Error Correction

E_D = fwd directivity
E_S = fwd source match
E_{RT} = fwd reflection tracking
$E_{D'}$ = rev directivity
$E_{S'}$ = rev source match
$E_{RT'}$ = rev reflection tracking

E_L = fwd load match
E_{TT} = fwd transmission tracking
E_X = fwd isolation
$E_{L'}$ = rev load match
$E_{TT'}$ = rev transmission tracking
$E_{X'}$ = rev isolation

- Each actual S-parameter is a function of all four measured S-parameters
- Analyzer must make forward *and* reverse sweep to update any one S-parameter

$$S_{11a} = \frac{(\frac{S_{11m}-E_D}{E_{RT}})(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S') - E_L(\frac{S_{21m}-E_X}{E_{TT}})(\frac{S_{12m}-E_X'}{E_{TT}'})}{(1+\frac{S_{11m}-E_D'}{E_{RT}}E_S)(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S') - E_L'E_L(\frac{S_{21m}-E_X}{E_{TT}})(\frac{S_{12m}-E_X'}{E_{TT}'})}$$

$$S_{21a} = \frac{(\frac{S_{21m}-E_X}{E_{TT}})(1+\frac{S_{22m}-E_D'}{E_{RT}'}(E_S'-E_L))}{(1+\frac{S_{11m}-E_D}{E_{RT}}E_S)(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S') - E_L'E_L(\frac{S_{21m}-E_X}{E_{TT}})(\frac{S_{12m}-E_X'}{E_{TT}'})}$$

$$S_{12a} = \frac{(\frac{S_{12m}-E_X'}{E_{TT}'})(1+\frac{S_{11m}-E_D}{E_{RT}}(E_S-E_L'))}{(1+\frac{S_{11m}-E_D}{E_{RT}}E_S)(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S') - E_L'E_L(\frac{S_{21m}-E_X}{E_{TT}})(\frac{S_{12m}-E_X'}{E_{TT}'})}$$

$$S_{22a} = \frac{(\frac{S_{22m}-E_D'}{E_{RT}'})(1+\frac{S_{11m}-E_D}{E_{RT}}E_S) - E_L'(\frac{S_{21m}-E_X}{E_{TT}})(\frac{S_{12m}-E_X'}{E_{TT}'})}{(1+\frac{S_{11m}-E_D}{E_{RT}}E_S)(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S') - E_L'E_L(\frac{S_{21m}-E_X}{E_{TT}})(\frac{S_{12m}-E_X'}{E_{TT}'})}$$

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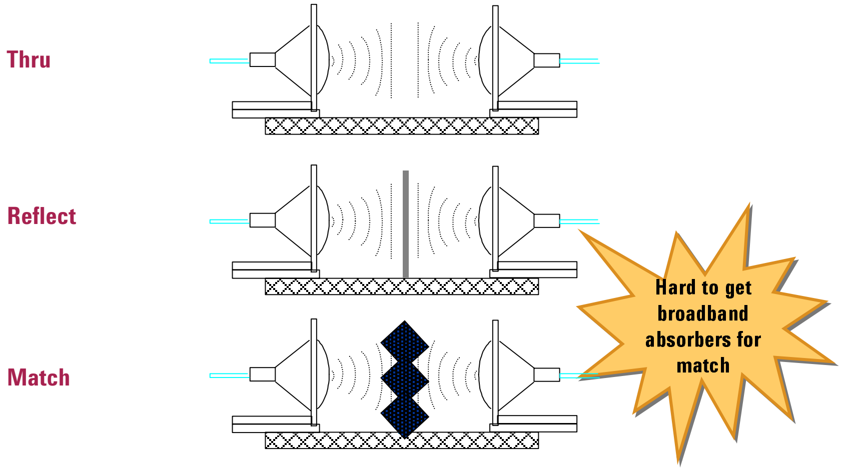
Two-port error correction is the most accurate form of error correction since it accounts for all of the majorsources of systematic error. The error model for a two-port device is shown above. Shown below are the equations to derive the actual device S-parameters from the measured S-parameters, once the systematic error terms have been characterized. Notice that each actual S-parameter is a function of all four measured S-parameters. The network analyzer must make a forward and reverse sweep to update any one S-parameter.

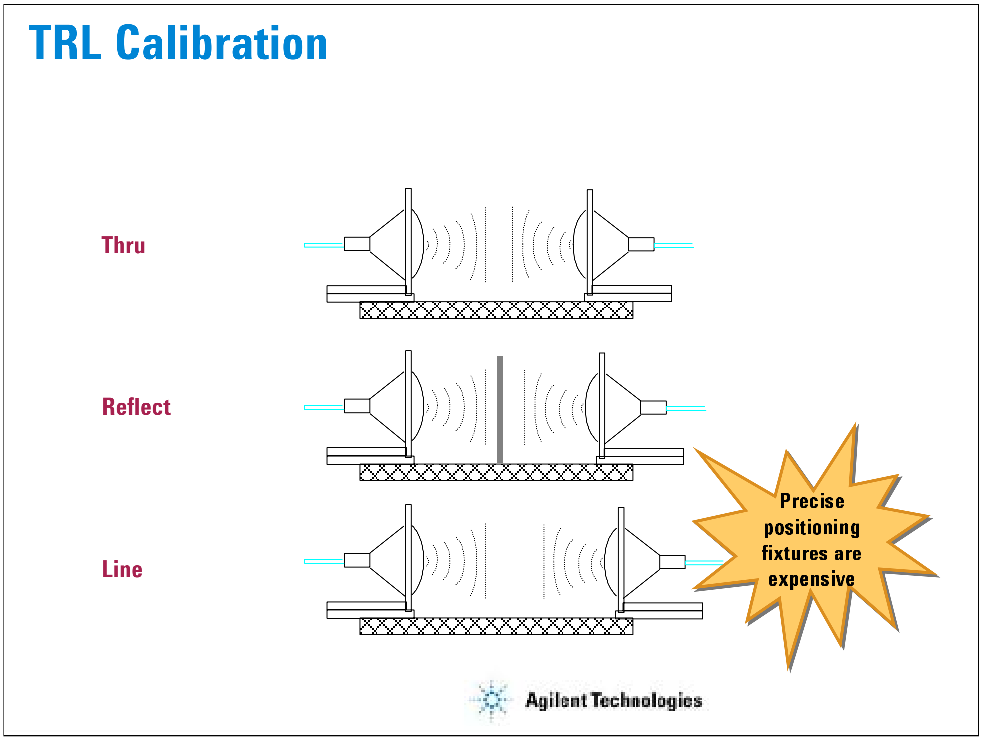
It looks complicated, but with modern network analyzers, it is as easy as connecting calibration standards and pressing a button.

TRM Calibration



Hard to get broadband absorbers for match

One widely use technique has been TRM. This technique uses a thru, reflect standard and matched load standards to calculate the error coefficients. Problem is finding a high broad band absorbing material for the match standard. Imperfections in the match standard cause residual errors after calibration.



TRL Calibration

Thru

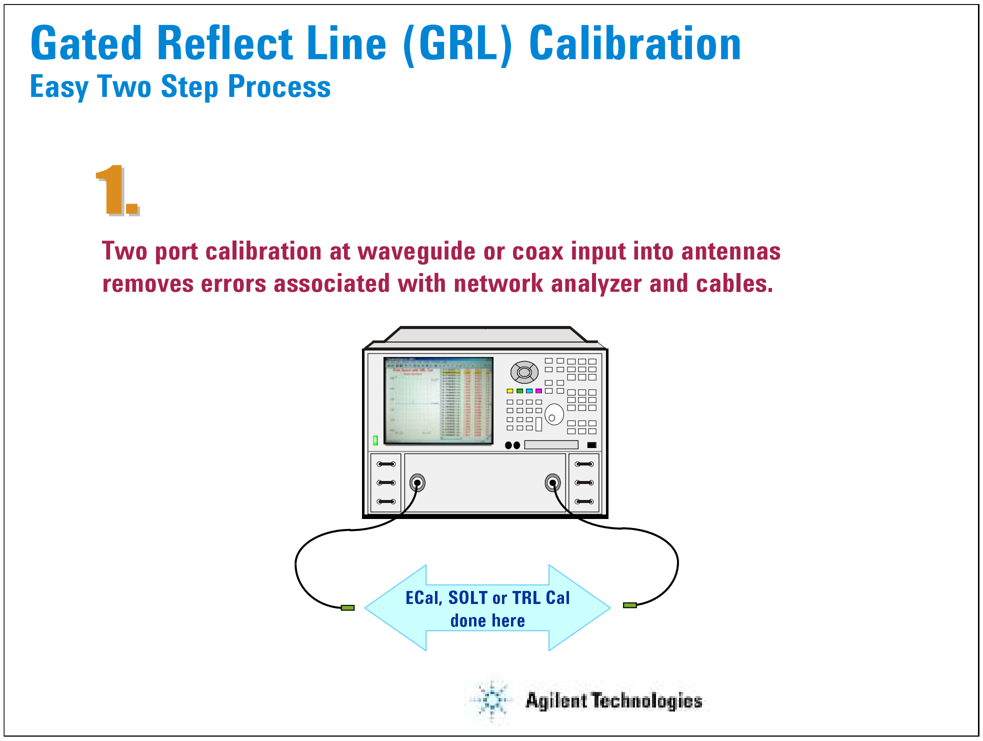
Reflect

Line

Precise positioning fixtures are expensive

Agilent Technologies

A second widely used technique is TRL. TRL uses a thru, reflect and line standard to determine the error coeficients. However, to measure the reflect, the port two antenna must be moved back by the thickness of the metal plate. The line standard is then realized by precisely moving the port two antenna back again. After the calibration the antenna needs to be precisely moved back to its orginal position. In order to do this accurately enough to get a good calibration, expensive positioning fixturing is required.



Gated Reflect Line (GRL) Calibration

Easy Two Step Process

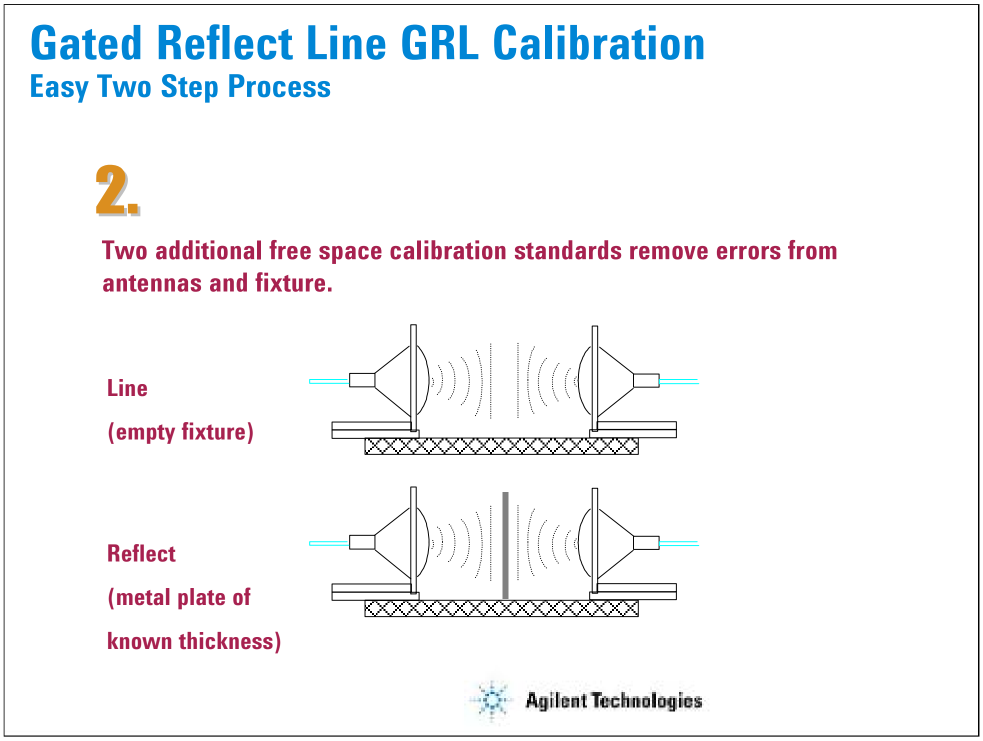
1.

Two port calibration at waveguide or coax input into antennas removes errors associated with network analyzer and cables.

Recently, Agilent introduced a new free space calibration technique that overcomes the weaknesses of the two previously discussed techniques. It is a simple two step process. The standards are easily obtained and it is completely automated.

Two step Calibration process

1. Two port calibration at the waveguide or coax input into the antennae using ECal, TRL or SOLT calibration processes.



Gated Reflect Line GRL Calibration

Easy Two Step Process

2.

Two additional free space calibration standards remove errors from antennas and fixture.

Line

(empty fixture)

Reflect

(metal plate of known thickness)

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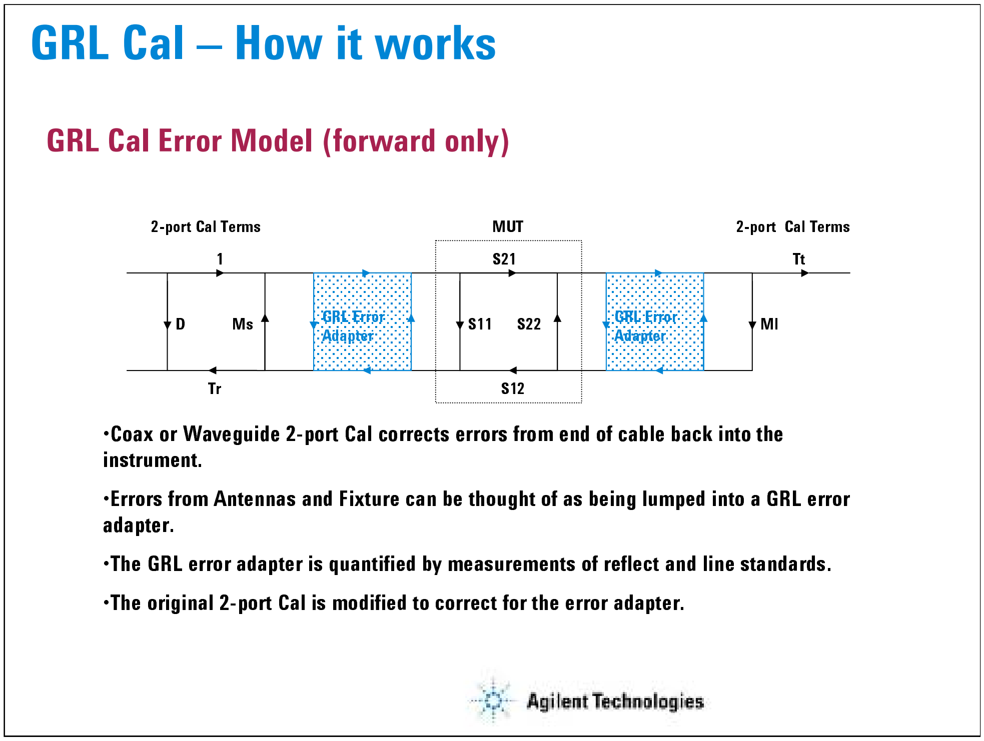
Step 2.

Two simple standards, A thru and a metal plate, complete the calibration by removing the errors associated with the antennas and fixturing.



GRL Cal – How it works

GRL Cal Error Model (forward only)

- Coax or Waveguide 2-port Cal corrects errors from end of cable back into the instrument.
- Errors from Antennas and Fixture can be thought of as being lumped into a GRL error adapter.
- The GRL error adapter is quantified by measurements of reflect and line standards.
- The original 2-port Cal is modified to correct for the error adapter.

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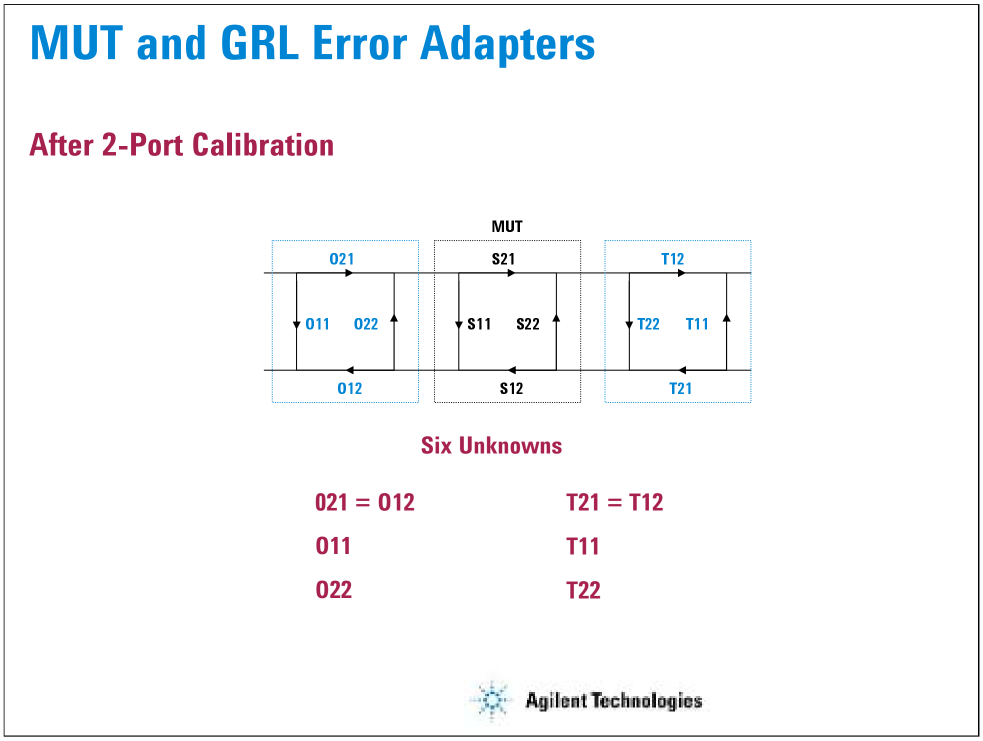
Gated Reflect Line Calibration

Here is how it works. The GRL technique requires that a calibration be performed at the ends of the cables that connect to the antennas. The GRL technique modifies this calibration such that the reference plane is transformed from the end of the cables to the surface of the metal plate used for calibration. When the calibration is complete the empty fixture measures as a slice of air the thickness of the metal plate. Before the modification the fixture can be thought of as two error adapters between the end of the cables and the space that the metal plate occupies.



MUT and GRL Error Adapters

After 2-Port Calibration

Six Unknowns

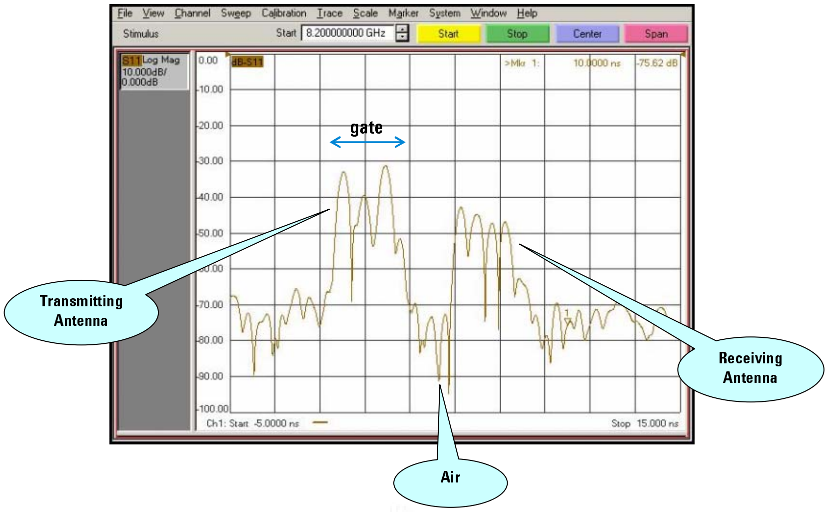
O21 = O12
O11
O22

T21 = T12
T11
T22

Here is a signal flow graph showing just the GRL adapters and a MUT. The Oxx parameters refer to port 1 and the Txx refers to port 2. The goal is to determine all the Oxxs and Txxs and embeding them into the orginal calibration. Each of the error adapters can be modeled by their four s-parameters. Because of the passive nature of these error adapters O21=O12 and T21 = T12. This leaves six unknowns.

GRL Cal – How it works

Time Domain of Empty Free Space Fixture



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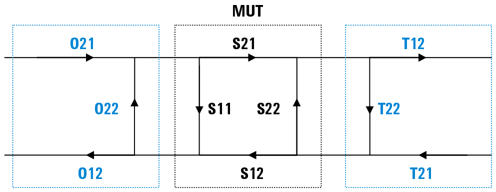
Above is a time domain S11 graph of the measured fixture when the fixture is empty

Note that you can identify the various responses as the reflection associated to the transmitting antenna, followed by the low reflection of air and then the reflection associated with the receiving antenna and its associated supporting structure. The GRL places time domain gates around the responses associated with the transmitting antenna. The frequency domain of this gated measurement is O11 of the port one error adapter. The same approach can be used to determine T11 of the port 2 error adapter.. These terms can be then embedded into the original 2-port calibration.

Using this new calibration set the other terms of the error adapters can be calculated from the s-parameter measurements of the Thru (empty fixture or air) and the Reflect (metal plate) standards.

MUT and GRL Error Adapters

After O11 and T11 are embedded into the original 2-Port calibration.



Four Unknowns

O21 = O12	T21 = T12
O22	T22

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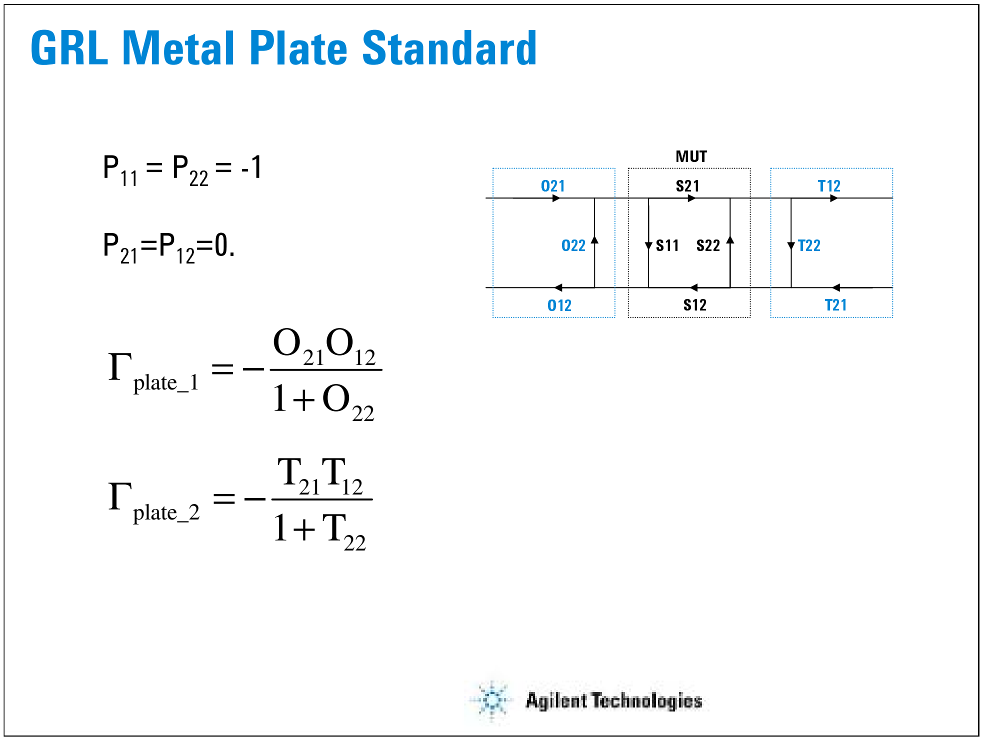
Once O11 and T11 are embedded into the original 2-port calibration, the signal flow graph looks like this, with four remaining terms in the error adapter. They will be removed by measuring two additional standards, the Thru and Reflect.



GRL Metal Plate Standard

$P_{11} = P_{22} = -1$

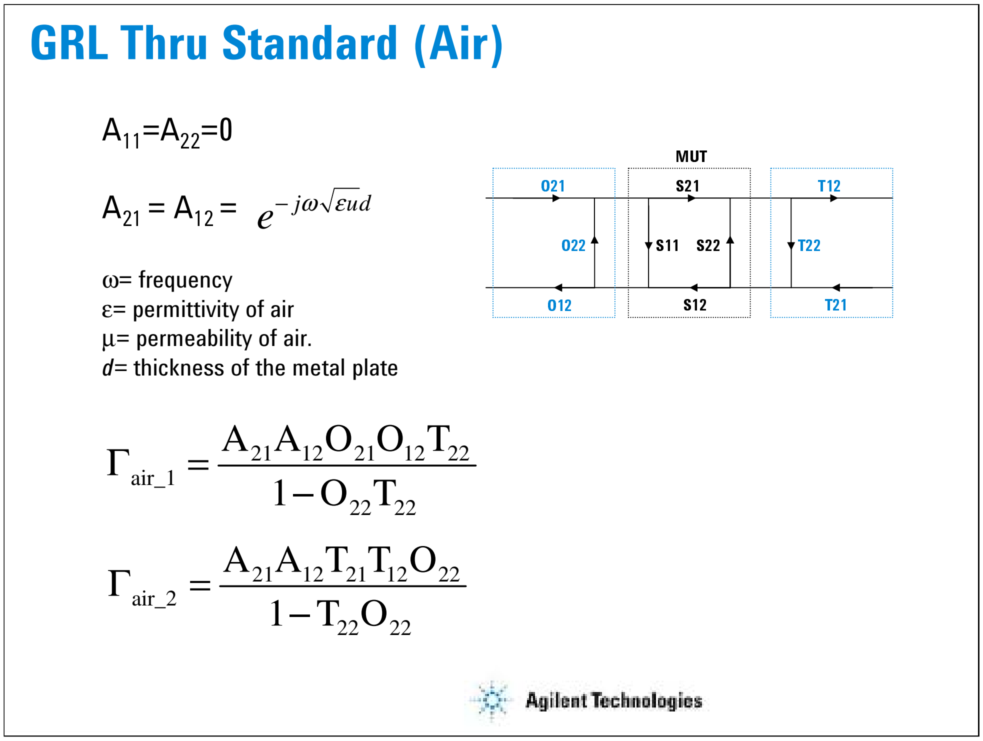
$P_{21}=P_{12}=0.$

$$\Gamma_{\text{plate\_1}} = -\frac{O_{21}O_{12}}{1+O_{22}}$$

$$\Gamma_{\text{plate\_2}} = -\frac{T_{21}T_{12}}{1+T_{22}}$$

The plate standard is the metal plate of know thickness. In a perfect freespace system, the metal plate will reflect all energy back, so P11 and P22 are set to minus one. Since all energy is reflected, no energy passes through, so P12 and P21 are set to zero.

Using Mason's rule, the S-parameters of the port one and two plate standards are established.



GRL Thru Standard (Air)

$A_{11}=A_{22}=0$

$A_{21} = A_{12} = e^{-j\omega\sqrt{\varepsilon u}d}$

ω= frequency
ε= permittivity of air
μ= permeability of air.
d= thickness of the metal plate

$$\Gamma_{\text{air\_1}} = \frac{A_{21}A_{12}O_{21}O_{12}T_{22}}{1-O_{22}T_{22}}$$

$$\Gamma_{\text{air\_2}} = \frac{A_{21}A_{12}T_{21}T_{12}O_{22}}{1-T_{22}O_{22}}$$

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The Thru standard is the empty fixture or air and designated here by A. Since in a perfect free space system, S11 or air, or A11 here, would see no reflection back, A11 and A22 are set to zero.

A21 and A12 are equal to the expression above.

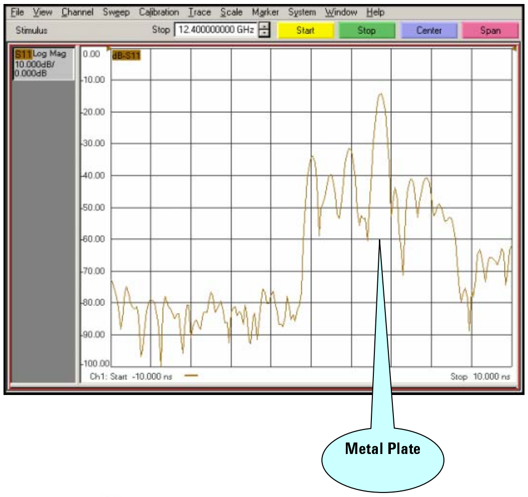
Once again, using Mason's loop rule, we can establish expressions for the S-parameters of the port one and two air standards. With these four equations, the two here and the on the previous slide, the four remaining coefficients of the error adapters can be solved for. These are then embedded into the original calibration. The result is a full two-port calibration with the reference planes at the surface of the metal plate.

The two equations on the previous slide and these equations are used to solve for the remaining coefficients of the error adapters. These terms are then embedded into the original calibration. The result is a full two-port calibration with the reference planes at the surface of the metal plate.

GRL Cal – System Considerations

- •Determine Sample Position
- •Determine Sample Size
- •Choose Metal Plate

Fixture with Metal Plate



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There are several considerations when setting up a system to performing a GRL cal.

Distance to Sample

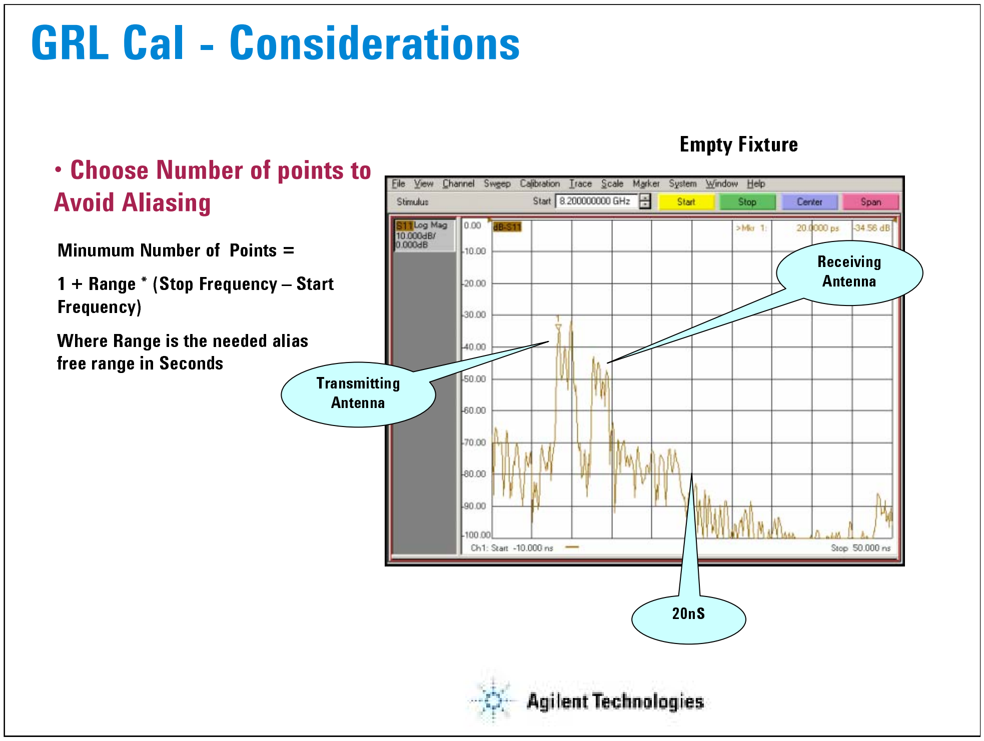
The distance from the antenna to the sample can be determined by looking at the time domain response of the metal plate measurement. There should be a low reflection span of time between the last response of the antenna and the metal plate.

Sample Size

The size of the sample and the distance the sample needs to be from the antenna can be determined by analyzing your fixture using time domain. The antennas used determine the minimum sample size. First locate the position of the metal plate in time. When the plate is removed, the difference in the response should be large. You should not be able to see the fixture's supporting structure. At least 50 dB. The greater the better. The sample height and width should be large enough that the beam fits inside. This can be easily checked by sliding the metal plate in from the side and seeing when it starts to show in time domain.

Metal Plate

Another consideration is the selection of the metal plate. Ideally the metal plate should approximately the same thickness as the sample to be measured. This puts the measurement reference planes at the surface of the sample. While this is ideal, any thickness differences are accounted mathematically by the sample holder description entries of the 85071E.



GRL Cal - Considerations

- **Choose Number of points to Avoid Aliasing**

Minumum Number of Points =

1 + Range * (Stop Frequency – Start Frequency)

Where Range is the needed alias free range in Seconds

Empty Fixture

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Number of measurement points.

Time domain is used to isolate the reflections off each of the two antennas. Because of this, aliasing must be considered. The alias-free range can be calculated as shown.

Range= (number of points-1)/ (stop frequency - start frequency)

It is important that the alias-free range be greater than the length of the freespace fixture. This includes all paths until the signal is attenuated to an insignificant level. Below is a plot of S11 of the empty fixture with a calibration coaxial/waveguide calibration turned on.

In the plot above, the first series of reflections, after t=0, is the reflections associated with the antenna. Next we see the reflections off the receiving antenna and the supporting structure. The response then reduces to approximately zero at about 20 nsec. Since the measurement was made over x-band (8.2-12.4 GHz) the minimum number of points can be calculated as:

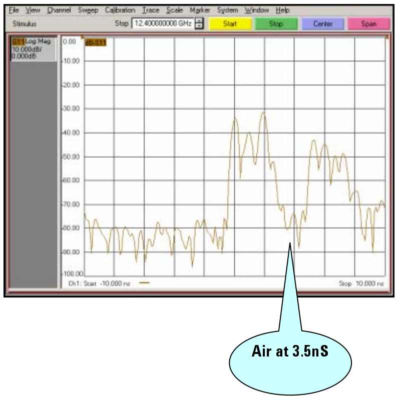
Number of points= 1 + Range*(stop frequency - start frequency)=1 + 20e-9*(12.4 e9 - 8.2 e9) = 85

Based on the required range the minimum number of points requires is 85. In general the more points the better to insure that as little aliasing occurs as possible. The same analysis should be performed on S21.

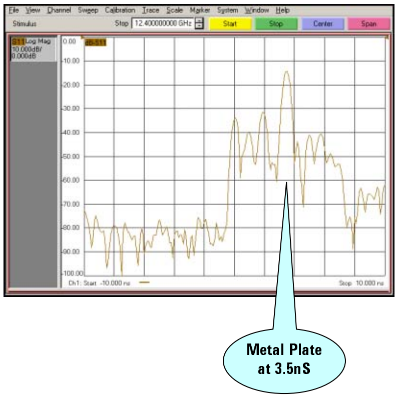
GRL Cal - Considerations

- Choose Time Domain Parameters

Empty Fixture



Fixture with Metal Plate



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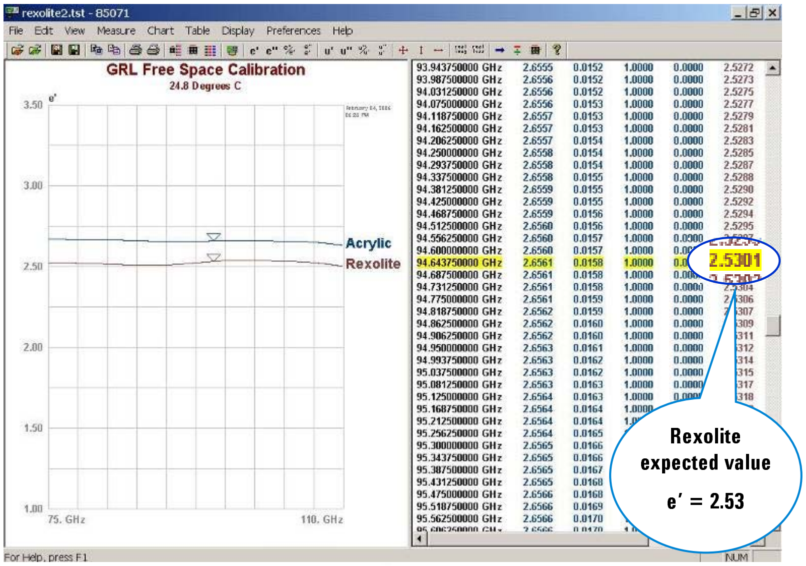
Time domain parameters.

After the initial 2-port calibration is performed, the location of the metal plate in time must be determined. Above is a plot of the empty fixture and a plot of the fixture with the metal plate.

By comparing the two plots, the time position of the plate fall between 2 and 6 nsec. The exact position is not important as long as you specify times where no other reflection has a larger amplitude than the reflection off the plate. This can occur when the reflection off the antenna is larger than the plate.

The final parameters to set are the gate shape and the gate span. These parameters are used during the gated response isolation portion of the calibration. This calibration is separate from the GRL cal and is used to reduce any residual errors. The GRL corrected measurements of the empty fixture and the fixture with the metal plate are gated and used as a separate response /isolation calibration. These terms are applied in the software. The gate span should be set wide enough to include the entire response of the reflection off the plate or the transmission of the empty fixture but narrow enough to minimize the unwanted responses.

mm-Wave Free Space Results



93.943750000 GHz	2.6555	0.0152	1.0000	0.0000	2.5272
93.987500000 GHz	2.6556	0.0152	1.0000	0.0000	2.5273
94.031250000 GHz	2.6556	0.0152	1.0000	0.0000	2.5275
94.075000000 GHz	2.6556	0.0153	1.0000	0.0000	2.5277
94.118750000 GHz	2.6557	0.0153	1.0000	0.0000	2.5279
94.162500000 GHz	2.6557	0.0153	1.0000	0.0000	2.5281
94.206250000 GHz	2.6557	0.0154	1.0000	0.0000	2.5283
94.250000000 GHz	2.6558	0.0154	1.0000	0.0000	2.5285
94.293750000 GHz	2.6558	0.0154	1.0000	0.0000	2.5287
94.337500000 GHz	2.6558	0.0155	1.0000	0.0000	2.5288
94.381250000 GHz	2.6559	0.0155	1.0000	0.0000	2.5290
94.425000000 GHz	2.6559	0.0155	1.0000	0.0000	2.5292
94.468750000 GHz	2.6559	0.0156	1.0000	0.0000	2.5294
94.512500000 GHz	2.6560	0.0156	1.0000	0.0000	2.5295
94.556250000 GHz	2.6560	0.0157	1.0000	0.0000	[illegible]
94.600000000 GHz	2.6560	0.0157	1.0000	[illegible]	[illegible]
94.643750000 GHz	2.6561	0.0158	1.0000	[illegible]	2.5301
94.687500000 GHz	2.6561	0.0158	1.0000	[illegible]	[illegible]
94.731250000 GHz	2.6561	0.0158	1.0000	0.0000	[illegible]
94.775000000 GHz	2.6561	0.0159	1.0000	0.0000	[illegible]
94.818750000 GHz	2.6562	0.0159	1.0000	0.0000	[illegible]
94.862500000 GHz	2.6562	0.0160	1.0000	0.0000	[illegible]
94.906250000 GHz	2.6562	0.0160	1.0000	0.0000	[illegible]
94.950000000 GHz	2.6563	0.0161	1.0000	0.0000	[illegible]
94.993750000 GHz	2.6563	0.0162	1.0000	0.0000	[illegible]
95.037500000 GHz	2.6563	0.0162	1.0000	0.0000	[illegible]
95.081250000 GHz	2.6563	0.0163	1.0000	[illegible]	[illegible]
95.125000000 GHz	2.6564	0.0163	1.0000	[illegible]	[illegible]
95.168750000 GHz	2.6564	0.0164	1.0000	[illegible]	[illegible]
95.212500000 GHz	2.6564	0.0164	[illegible]	[illegible]	[illegible]
95.256250000 GHz	2.6564	0.0165	[illegible]	[illegible]	[illegible]
95.300000000 GHz	2.6565	0.0166	[illegible]	[illegible]	[illegible]
95.343750000 GHz	2.6565	0.0166	[illegible]	[illegible]	[illegible]
95.387500000 GHz	2.6565	0.0167	[illegible]	[illegible]	[illegible]
95.431250000 GHz	2.6565	0.0168	[illegible]	[illegible]	[illegible]
95.475000000 GHz	2.6566	0.0168	[illegible]	[illegible]	[illegible]
95.518750000 GHz	2.6566	0.0169	[illegible]	[illegible]	[illegible]
95.562500000 GHz	2.6566	0.0170	[illegible]	[illegible]	[illegible]

Rexolite
expected value

e′ = 2.53

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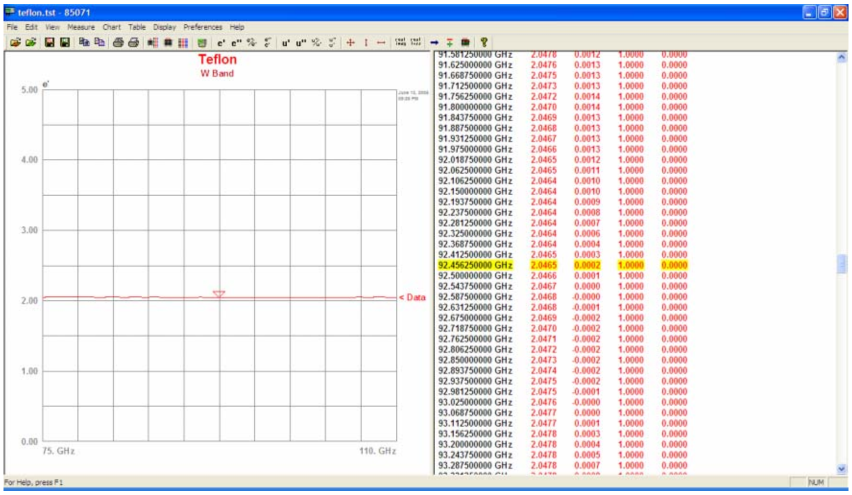
Here is some measurement results using the simple W-band system you saw earlier.

A rexolite sample is used as a verification standard because it has well known dielectric properties into the hundreds of GHz. Published value for rexolite epsilon prime is 2..53. You can see the marked frequency point is almost exact. Results over the 75-110Ghz range were within 1 percent.

Once the system was measured, the MUT or in this case Acrylic sheet was measured. Actual value of this sample was unknown, but expected results are somewhere between 2.4 to 2.8.

mm-Wave Free Space Results



91.581250000 GHz	2.0478	0.0012	1.0000	0.0000
91.625000000 GHz	2.0476	0.0013	1.0000	0.0000
91.668750000 GHz	2.0475	0.0013	1.0000	0.0000
91.712500000 GHz	2.0473	0.0013	1.0000	0.0000
91.756250000 GHz	2.0472	0.0014	1.0000	0.0000
91.800000000 GHz	2.0470	0.0014	1.0000	0.0000
91.843750000 GHz	2.0469	0.0013	1.0000	0.0000
91.887500000 GHz	2.0468	0.0013	1.0000	0.0000
91.931250000 GHz	2.0467	0.0013	1.0000	0.0000
91.975000000 GHz	2.0466	0.0013	1.0000	0.0000
92.018750000 GHz	2.0465	0.0012	1.0000	0.0000
92.062500000 GHz	2.0465	0.0011	1.0000	0.0000
92.106250000 GHz	2.0464	0.0010	1.0000	0.0000
92.150000000 GHz	2.0464	0.0010	1.0000	0.0000
92.193750000 GHz	2.0464	0.0009	1.0000	0.0000
92.237500000 GHz	2.0464	0.0008	1.0000	0.0000
92.281250000 GHz	2.0464	0.0007	1.0000	0.0000
92.325000000 GHz	2.0464	0.0006	1.0000	0.0000
92.368750000 GHz	2.0464	0.0004	1.0000	0.0000
92.412500000 GHz	2.0465	0.0003	1.0000	0.0000
92.456250000 GHz	2.0465	0.0002	1.0000	0.0000
92.500000000 GHz	2.0466	0.0001	1.0000	0.0000
92.543750000 GHz	2.0467	0.0000	1.0000	0.0000
92.587500000 GHz	2.0468	-0.0000	1.0000	0.0000
92.631250000 GHz	2.0468	-0.0001	1.0000	0.0000
92.675000000 GHz	2.0469	-0.0002	1.0000	0.0000
92.718750000 GHz	2.0470	-0.0002	1.0000	0.0000
92.762500000 GHz	2.0471	-0.0002	1.0000	0.0000
92.806250000 GHz	2.0472	-0.0002	1.0000	0.0000
92.850000000 GHz	2.0473	-0.0002	1.0000	0.0000
92.893750000 GHz	2.0474	-0.0002	1.0000	0.0000
92.937500000 GHz	2.0475	-0.0002	1.0000	0.0000
92.981250000 GHz	2.0475	-0.0001	1.0000	0.0000
93.025000000 GHz	2.0476	-0.0000	1.0000	0.0000
93.068750000 GHz	2.0477	0.0000	1.0000	0.0000
93.112500000 GHz	2.0477	0.0001	1.0000	0.0000
93.156250000 GHz	2.0478	0.0003	1.0000	0.0000
93.200000000 GHz	2.0478	0.0004	1.0000	0.0000
93.243750000 GHz	2.0478	0.0005	1.0000	0.0000
93.287500000 GHz	2.0478	0.0007	1.0000	0.0000

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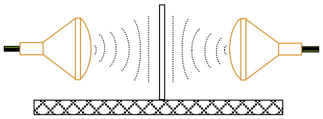
Seminar Outline

- Electromagnetic Properties of materials
- Summary of Measurement Techniques
- Free-space Measurement Calibration
- ➢ Free-space Measurement Models
- Additional Free-space Measurements



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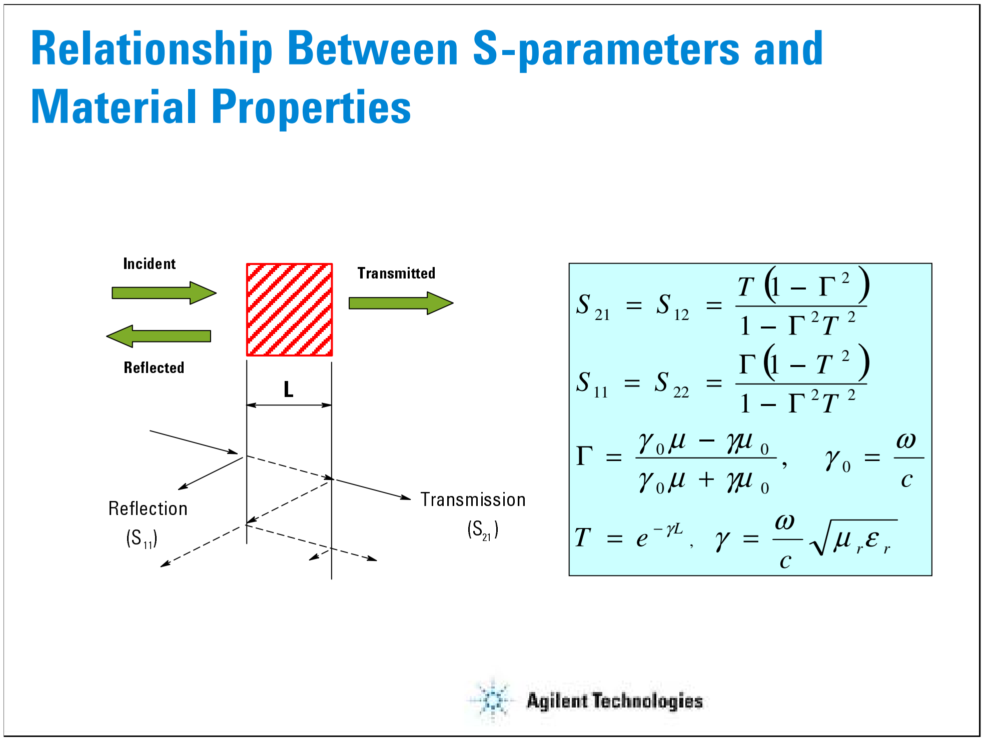

Relationship Between S-parameters and Material Properties

$$S_{21} = S_{12} = \frac{T\left(1 - \Gamma^2\right)}{1 - \Gamma^2 T^2}$$

$$S_{11} = S_{22} = \frac{\Gamma\left(1 - T^2\right)}{1 - \Gamma^2 T^2}$$

$$\Gamma = \frac{\gamma_0 \mu - \gamma \mu_0}{\gamma_0 \mu + \gamma \mu_0}, \quad \gamma_0 = \frac{\omega}{c}$$

$$T = e^{-\gamma L}, \quad \gamma = \frac{\omega}{c}\sqrt{\mu_r \varepsilon_r}$$

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These equations illustrate the relationship between the measured free-space s-parameters and the sample thickness, measurement frequency, permittivity and permeability. TEM propagation is assumed.

Free-space Measurement Models

- Nicolson-Ross Model
- NIST Model
- Transmission Model

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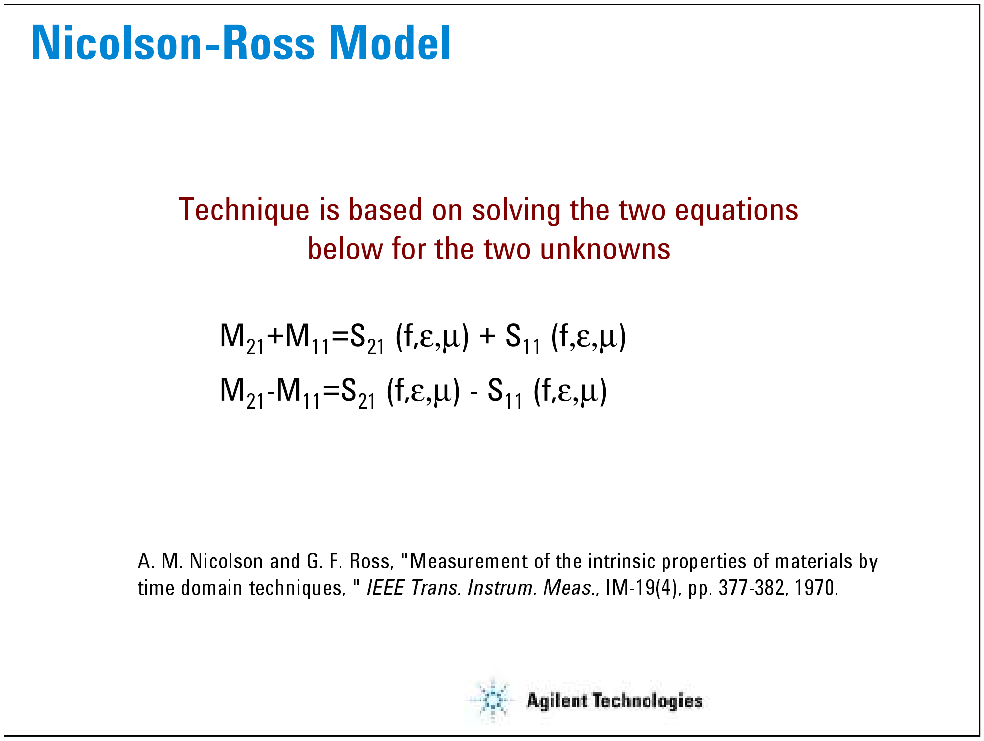
There are three algorithms that are commonly used to calculate permittivity and permeability. We refer to these algorithms as models. Each are based on the equations given on the previous slide. We will now discuss how each differs and why you might want to choose one over another.



Nicolson-Ross Model

Technique is based on solving the two equations
below for the two unknowns

$$M_{21}+M_{11}=S_{21}\ (f,\varepsilon,\mu) + S_{11}\ (f,\varepsilon,\mu)$$
$$M_{21}-M_{11}=S_{21}\ (f,\varepsilon,\mu) - S_{11}\ (f,\varepsilon,\mu)$$

A. M. Nicolson and G. F. Ross, "Measurement of the intrinsic properties of materials by time domain techniques, " *IEEE Trans. Instrum. Meas.*, IM-19(4), pp. 377-382, 1970.

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The Nicolson-Ross model solves for both permittivity and permeability by making transmission and reflection coefficient measurements on a single sample of the material. The M_{xx} in the equations above refers to the measured values of the s-parameters while S_{xx} refers to the values calculated from the previously mentioned equations. Nicolson and Ross showed by taking the sum and difference of transmission and reflection coefficients the values for u and e can be determined.

Problems with N-R Model

- This set of equations become unstable when M11 is equal to zero. One equation, two unknowns.
- The derivation involves taking the log of a complex number. The log of a complex number is not a single valued function.

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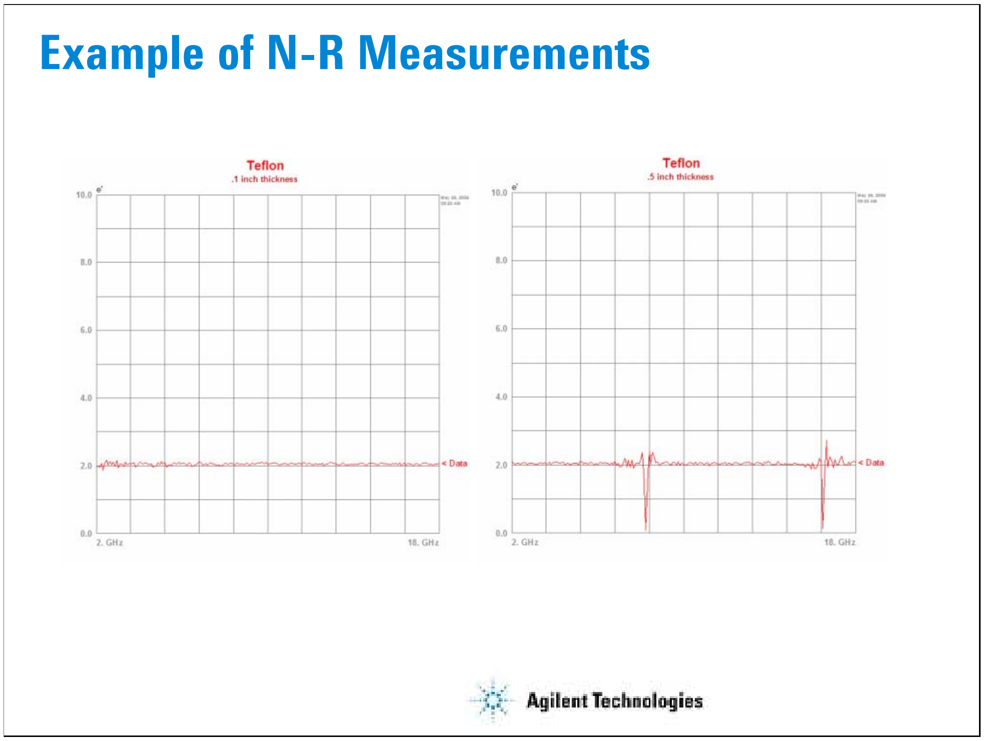
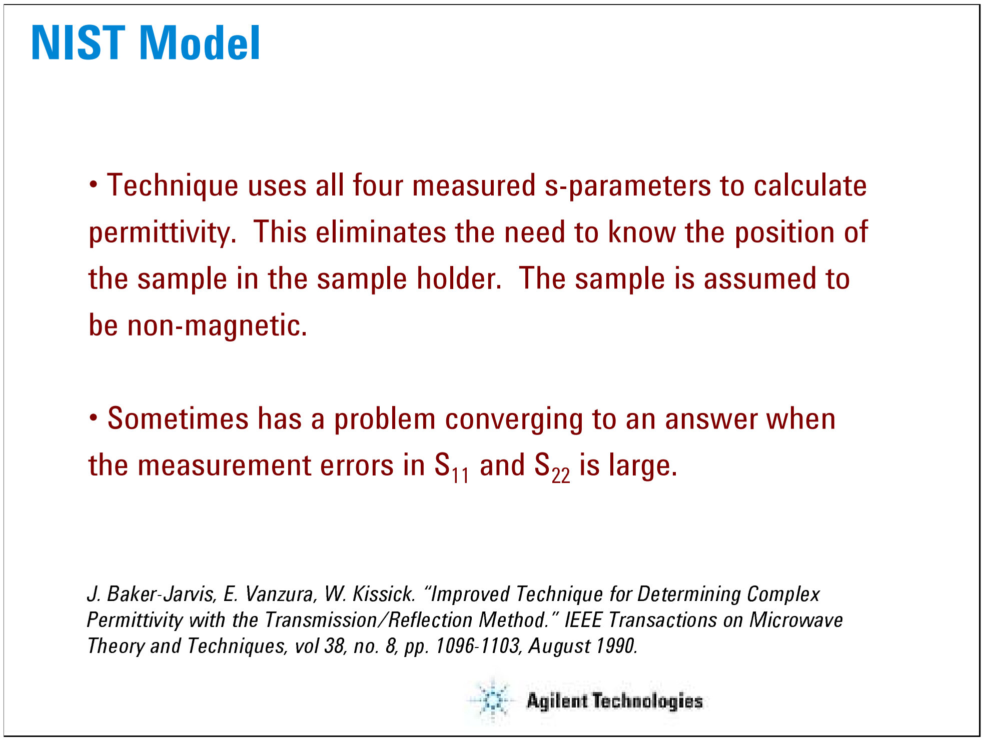
The major flaw in this technique is when the value of S_{11} is equal to zero (or the uncertainty in the measurement is as large as the measurement value) When this happens we have only one independent equation and two unknowns. One way this can happen is when the reflection off the back surface of the material cancels out the reflection off the front surface. Fortunately this seldom happens with magnetic materials. This is because these materials are usually lossey. Non-magnetic materials can be better analyzed by using other models. These models will be discussed later.

Another problem occurs because the derivation proposed by Nicolson and Ross involves taking the log of a complex quantity. The log of a complex number is not a single valued function. This can usually be accounted for by knowing how many 360 degree phase transitions S_{21} makes. You need to know if the -30 degree phase of S21 is really -30 degrees or -30 -360=-390 degrees. This is easy to do if the phase shift at the first frequency point is less than -360 degrees. If not an estimate of u and e is needed. These estimates only need to be accurate enough to correctly predict the number of -360 degree phase shifts. Another possibility is to estimate the number of phase shifts by calculating the group delay.



Example of N-R Measurements

These two plots show measurements made on a sample of Teflon. In the first case the measured value of S_{11} never approaches zero. In the second case, because of the longer length of the sample, the measured value of S11 approaches zero at several frequencies. Since the equations used to solve for u and e are ill-conditioned the computed results are in error.



NIST Model

- Technique uses all four measured s-parameters to calculate permittivity. This eliminates the need to know the position of the sample in the sample holder. The sample is assumed to be non-magnetic.

- Sometimes has a problem converging to an answer when the measurement errors in S_{11} and S_{22} is large.

J. Baker-Jarvis, E. Vanzura, W. Kissick. "Improved Technique for Determining Complex Permittivity with the Transmission/Reflection Method." IEEE Transactions on Microwave Theory and Techniques, vol 38, no. 8, pp. 1096-1103, August 1990.

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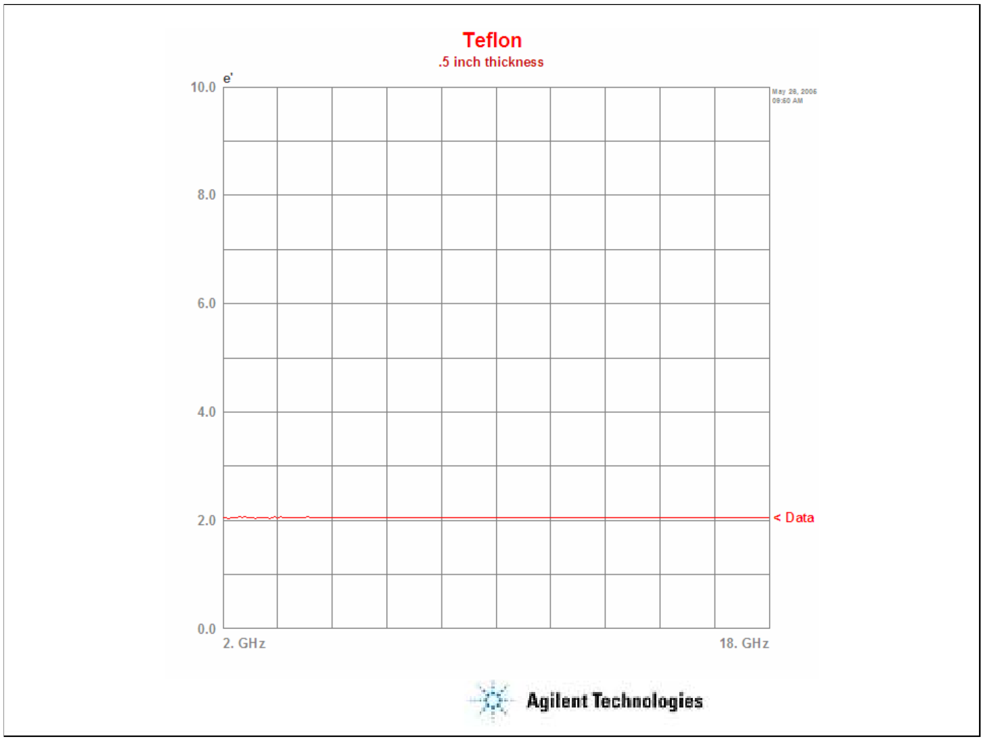
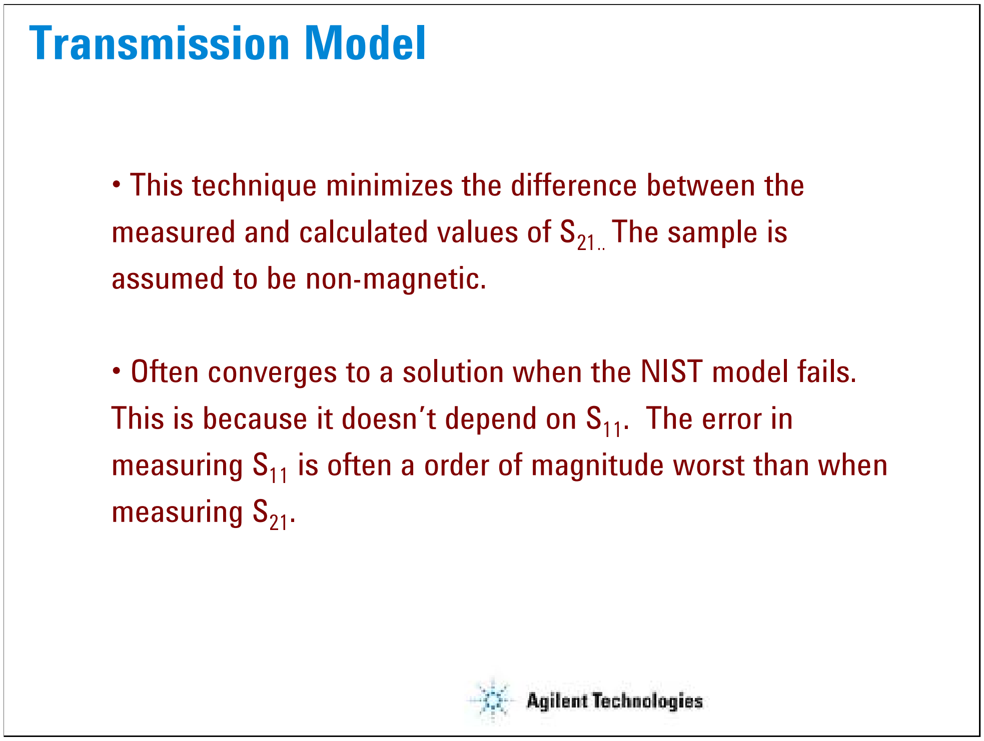
The NIST model was developed by Jim Baker-Jarvis of NIST (and others). It uses all four measured s-parameters to determine permittivity. The material is assumed to be non-magnetic. It is an iterative approach and sometimes has problems converging when the measurement errors in S_{11} and S_{22} are large.



Here is an example of using the NIST model to calculate the value of permittivity for a Teflon sample.



Transmission Model

- This technique minimizes the difference between the measured and calculated values of $S_{21..}$ The sample is assumed to be non-magnetic.

- Often converges to a solution when the NIST model fails. This is because it doesn’t depend on S_{11}. The error in measuring S_{11} is often a order of magnitude worst than when measuring S_{21}.

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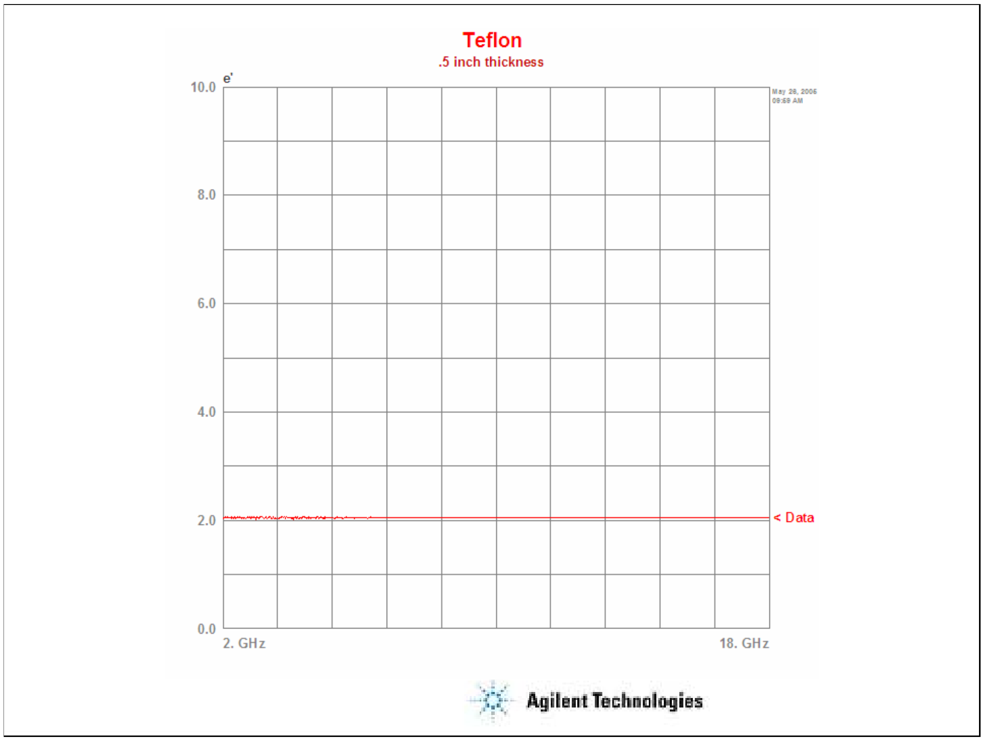
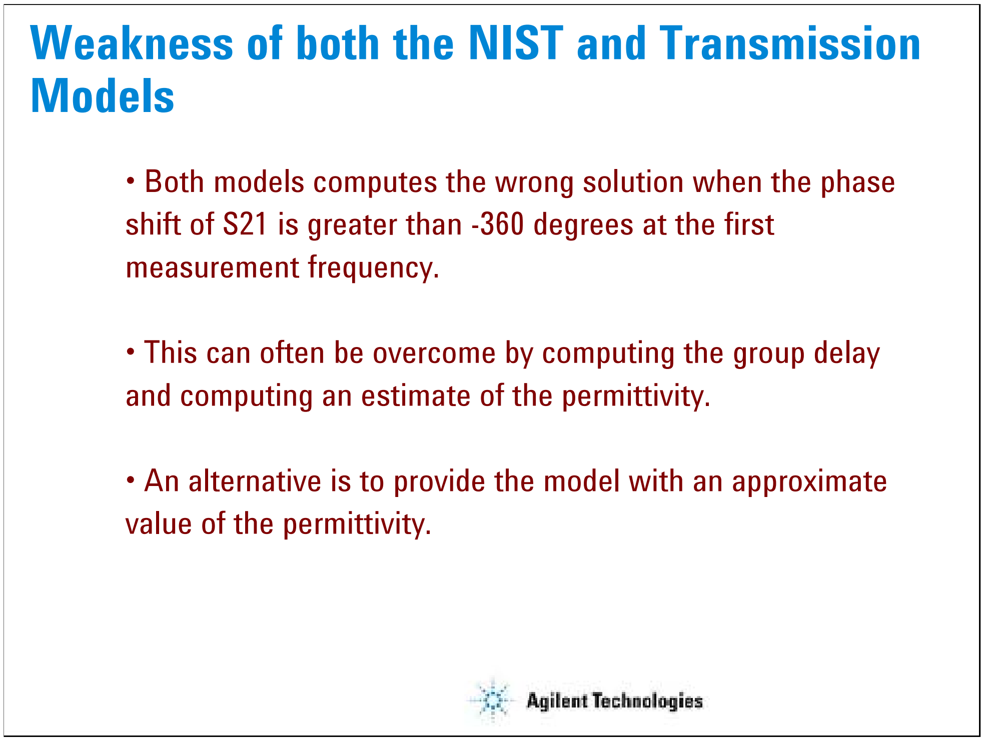
The transmission model is based on minimizing the difference between the measured value of the transmission coefficient and the computed value. It assumes that the material is non-magnetic. It is an iterative method that starts with an initial guess for permittivity (usually 1+j0) and improves the guess until the difference is near zero.



Here is the computed value of permittivity for a Teflon sample. It is virtually identical to the values computed by the NIST model.



Weakness of both the NIST and Transmission Models

- Both models computes the wrong solution when the phase shift of S21 is greater than -360 degrees at the first measurement frequency.

- This can often be overcome by computing the group delay and computing an estimate of the permittivity.

- An alternative is to provide the model with an approximate value of the permittivity.

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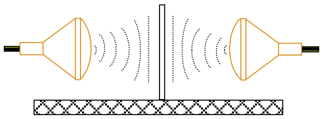
Both models can become “confused” when the length of the sample is long compared to the wavelength of the measurement frequency. There are several values of permittivity that satisfies the measurements. This problem can be overcome by either making a shorter sample, lowering the first measurement frequency or providing additional information such as group delay or an initial guess of permittivity.

Seminar Outline

- Electromagnetic Properties of materials
- Summary of Measurement Techniques
- Free-space Measurement Calibration
- Free-space Measurement Models
- Additional Free-space Measurements



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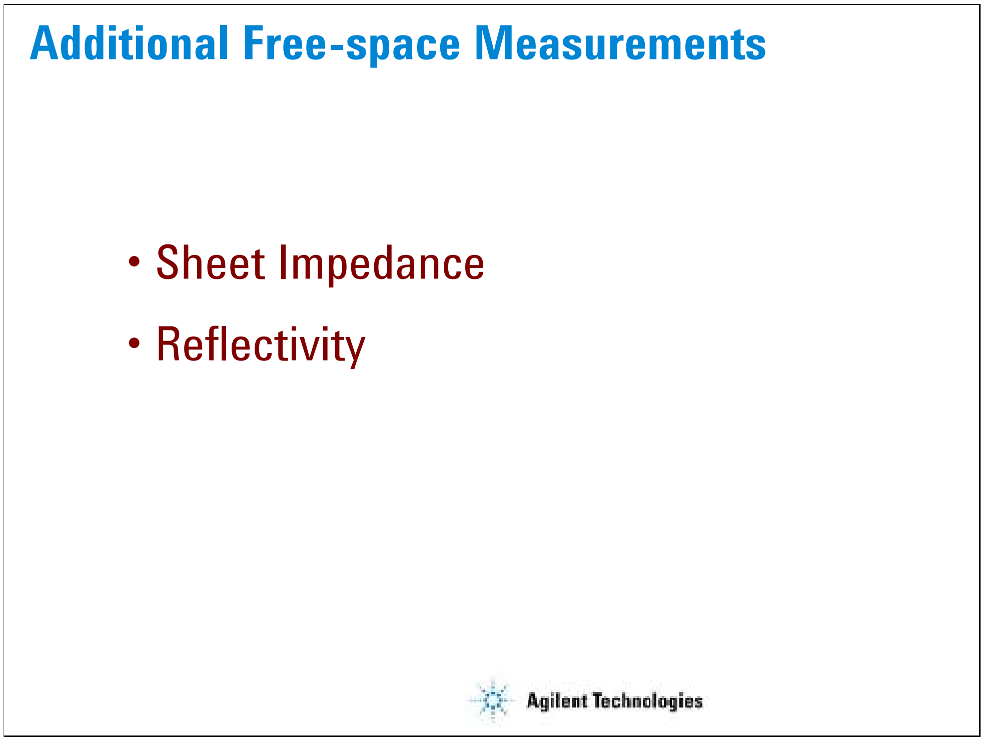

Additional Free-space Measurements

- Sheet Impedance
- Reflectivity

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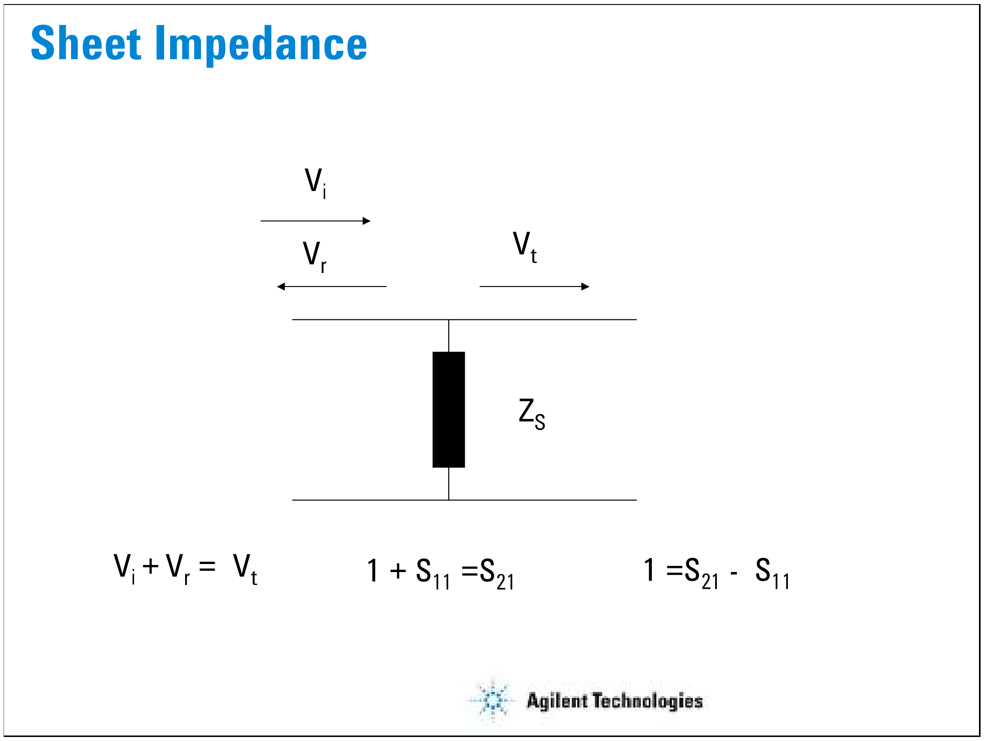
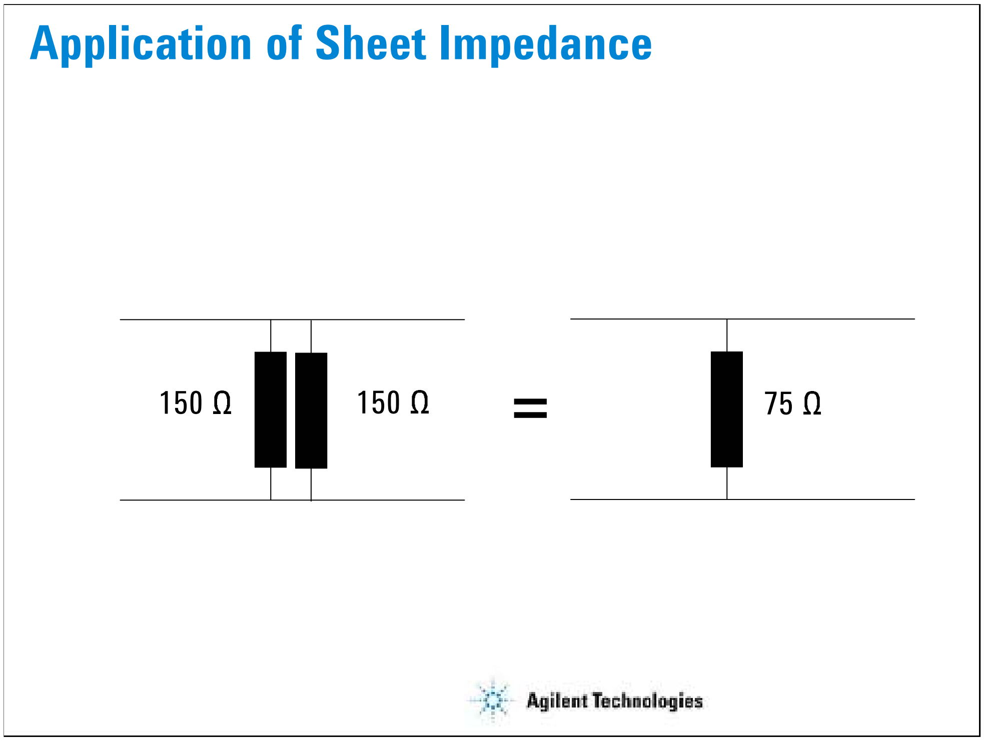
It is often desired to know the sheet impedance of the material or the reflectivity of a material sample.



Sheet Impedance

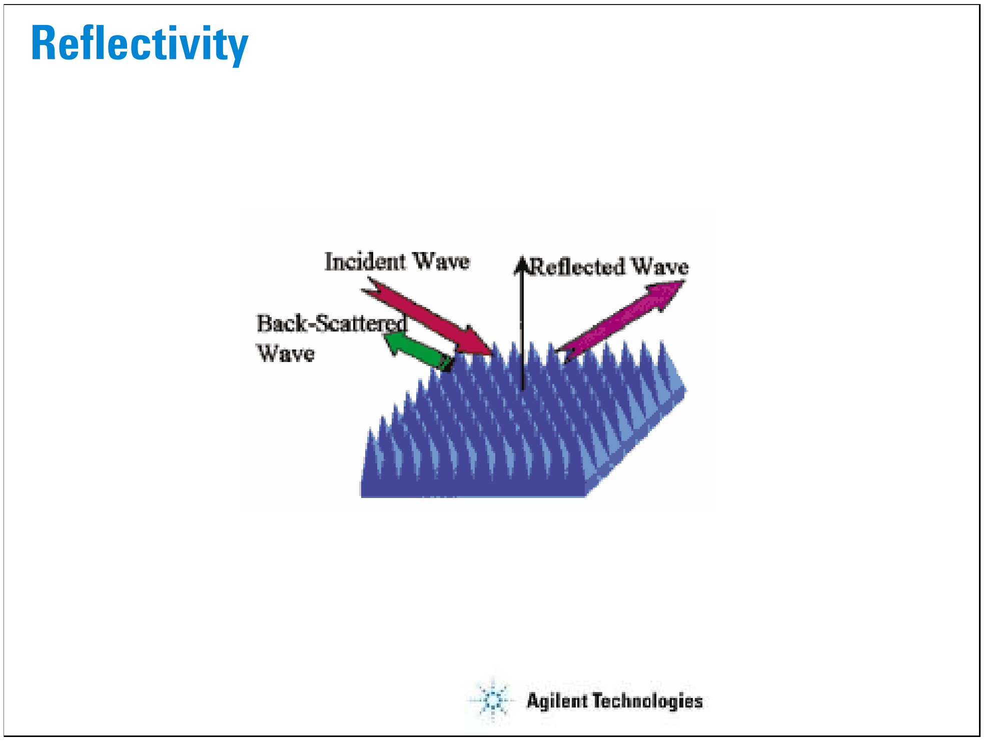
$V_i + V_r = V_t$ $1 + S_{11} = S_{21}$ $1 = S_{21} - S_{11}$

Sheet impedance, measured in ohms or ohms/square, assumes that a sample of material is sufficiently thin so it can be considered a lumped element. Based on this the voltages slightly to the left of Zs is equal to the voltage slightly to the right. Because of this the voltage relationship shown holds. If we divide both sides of this relationship by the incident voltage, Vi, we get the $1 + S_{11} = S_{21}$. Rearranging tis expression we can obtain that $1 = S_{21} - S_{11}$. This expression is useful in determining if a material meets the lumped element assumption. They also allow us to calculate the value of Zs from either a measured value of S_{11} or S_{21}. Usually S_{21} is used because the error associated with its measurement is almost always less that that associated with S_{11}.



Application of Sheet Impedance

This slide illustrate an important application of the sheet impedance concept. We can layer two materials and determine the sheet impedance of the combination by using lumped-element circuit theory.



Reflectivity

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Another free-space measurement of interest is reflectivity. It is often desired to know the reflectivity at a given angle. The material of interest may be an absorber as illustrated of a material intended to be applied to a metal surface.

NRL Arch

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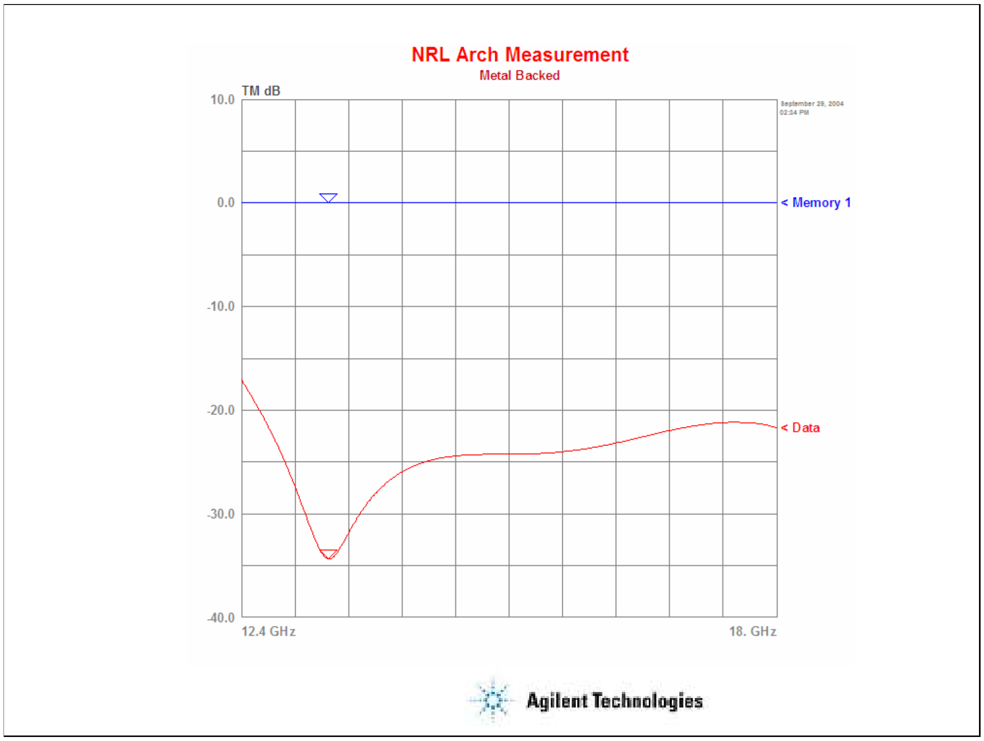
Reflectivity measurements are often measured us a NRL (Naval Research Laboratory) Arch. The arch allows the user to adjust the angle of the antennas being used while maintaining a constant distance to the sample. The material being measured is placed on the table. Prior to making a measurement the system is calibrated. The most commonly used calibration is an isolation-response cal. Time-domain gates are often employed to eliminate unwanted transmission paths.



NRL Arch Measurement

Metal Backed

Here is an example measurement.

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