

High-Frequency Dielectric Measurements

Part 24 in a Series of Tutorials on Instrumentation and Measurement

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Knowledge of the response of materials to electromagnetic (EM) fields in the radio frequency (RF) through terahertz (THz) frequency range is critical to numerous research projects and electronic product development activities. Electromagnetic waves in the high-frequency range can operate in ways that low-frequency signals cannot, such as the ability to travel through guided-wave structures, the ability to launch from antennas as propagating waves, and the ability to carry broadband information over long distances. When applying high-frequency EM fields in scientific exploration and product development, researchers and engineers demand accurate material parameters in order to extract experimental results and to predict their products' behavior [1-3].

In this tutorial, we identify and describe measurement techniques useful for the characterization of dielectric materials. It should aid in the selection of the most

relevant methods for particular applications. The focus is on materials of practical applications, including microelectronics, electronic packaging and interconnection, compact antenna arrays, and capacitors. One area of interest is high-speed and high-frequency electronic circuit development, where knowing the speed and loss of signals propagating on integrated circuits and between

chip packages is vital to system performance.

To provide valuable and practical dielectric characterization, measurement systems must be able to characterize numerous materials with variations in

permittivity and loss, such as glass, quartz, epoxies, insulating

polymers, high-resistivity semiconductors, silicon carbide, alumina, sapphire, lanthanum aluminate, aluminum nitride, various titanates, and novel composite systems including nanocomposite materials. Additionally, dielectric properties of various processed material forms are commonly needed:



three-dimensional bulk solids, printed circuit board (PCB) laminates, low-temperature co-fired ceramics (LTCC), free-standing flexible films, thin solid films, coatings, and liquids. The use of fine-line signal conductors requires characterization of thinner laminates, films, LTCCs, and other substrate materials. As a result of the many applications in which they are used, dielectric material measurements are very difficult to cover inclusively. Instead, this article categorizes existing techniques by material and fixture type and then describes the application of three specific measurement systems of current interest.

Permittivity Characterization

The goal of dielectric measurements is to report the relative permittivity of a specimen under test for a specified orientation of electric field and frequency. The constitutive parameter in dielectrics is permittivity, ϵ . This is a complex-valued parameter that generally depends on frequency and temperature. Permittivity is most often expressed as a relative value ϵ_r : $\epsilon = \epsilon_0 \epsilon_r = \epsilon_0 (\epsilon_r' - j\epsilon_r'')$, where $\epsilon_0 \cong 8.854 \times 10^{-12}$ F/m. Often, engineering applications refer to the real part of the relative permittivity ϵ_r' as the dielectric constant (often D_k), which can be confusing, since it not constant in frequency. The ratio of the imaginary part to real part is called the loss tangent, $\tan\delta = \epsilon_r'' / \epsilon_r'$ (often called the material dissipation factor, D_f).

The concept of expressing charge storage in terms of permittivity dates back to the 18th century and arises from electronic polarization in molecules and atoms when placed under the influence of an electric field. Permittivity is defined by averaging the microscopic Maxwell's equations over many molecules and as such is a mesoscopic or macroscopic quantity. Below the mesoscale length scale, the dipole moment, conductivity, and polarizability are more instructive parameters. In other words, permittivity is an average quantity that is extracted only by "looking" over a sufficient volume of charge dipoles. The values observed will change based on the orientation of an electric field vector relative to the material's dipole orientation. Generally this anisotropy is described with a permittivity tensor, although in most practical applications a specific component of the permittivity tensor is sampled by application of a specific electric-field polarization.

When an electromagnetic field is applied to a material, the atoms, molecules, free charge, and defects readjust positions. The dynamic readjustment of the molecules in response to the field is called relaxation. The response of materials depends strongly on material phase and lattice structure. In many solids, the molecules are not able to appreciably rotate in response to the applied fields, and therefore little relaxation response is observed, and the resulting permittivity can be low. The degree of crystallinity, existence of permanent dipoles, mobility of free charge, and defects all contribute to dielectric response. At high frequencies, the electric response of a material lags behind the applied field and creates loss. In the RF through millimeter range of wavelengths, the permittivity of low-loss materials

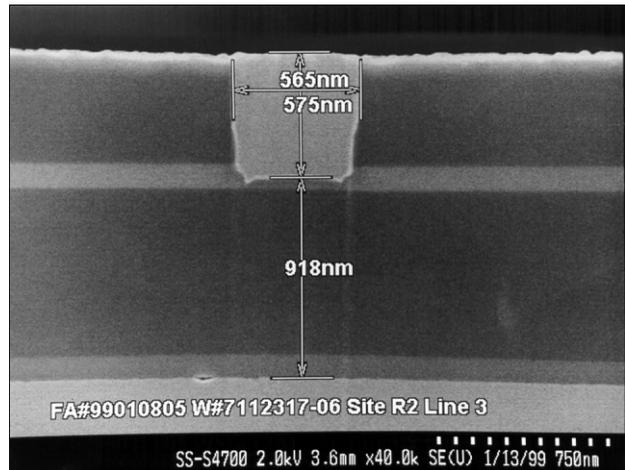


Fig. 1. Example of *Thin* material category: cross-sectional photomicrograph of rectangular metal conductor in thin insulating layers of semiconductor IC.

will generally slowly decrease as frequency increases, and the loss tangent will generally increase as frequency increases, in many cases in a linear fashion. For materials of medium to high loss the permittivity decreases more rapidly and the loss factor has a relaxation peak. Intrinsic dielectric material resonances do not occur over RF to microwave frequencies. Any resonance behavior is associated with geometric resonances of materials or cavities and these do not relate directly to the intrinsic permittivity.

It is important here to differentiate between constitutive material permittivity and effective permittivity. Usually the term effective permittivity indicates that the fundamental definition of permittivity is relaxed to some degree. Effective permittivity may contain effects of the dielectric material permittivity mixed with polarization effects due to metals and other interfaces, multiple components in composite materials, and/or multiple components of the permittivity tensor.

The spatial dimensions and geometry of the material over which a dielectric measurement will be applied serve as important means to categorize the broad range of techniques. The main measurement categories related to material volume are: Bulk, Thin, and Nanoscale. Bulk materials are of macroscopic dimensions. Examples include PCB laminates, integrated circuit substrates, plastic product packaging, building materials, and liquids. Thin materials are on the scale of micrometer or sub-micrometer scale in only one dimension. The Thin category includes thin films encountered in integrated circuit processing (Fig. 1), free-standing polymer sheets, and various coatings. The Nanoscale category includes nanowires, quantum dots, and large molecules.

In this review, we concentrate on the measurement methods for *Bulk* and *Thin* materials, because the definition of permittivity is more clearly defined at the macroscale to mesoscale and more widely accepted for these material categories. There is currently intensive ongoing research in the area of measuring charge polarization in nanoscale materials, and it is not discussed here. A complete tutorial is needed to cover the topic.

Measurement Parameters

Dielectric properties depend on frequency, temperature, surface roughness, and in the case of ferroelectrics, applied bias field. Field orientation is important for measurements of anisotropic materials [1-5]. Common measurement needs include characterization of lossy and low-loss bulk materials and liquids, thin substrates and thin films, micrometer to nanoscale material properties, and nondestructive tests. Measurement instruments in which the electromagnetic fields are tangential to the air-material interfaces, such as in TE_{01} cavities, generally yield more accurate results than fixtures where the fields are normal to the interface. Unfortunately, for many applications it is not always possible or even preferable to measure in-plane field orientations. For example, circuit boards and printed-wiring boards operate with the electric field primarily normal to the plane of the panel, and therefore this component of the permittivity tensor is of paramount interest. However, measurements with the electric field perpendicular to the specimen face may suffer from the effects of air-gap or interface depolarization [1]. In transmission-line measurements, air gaps around the conductors produce a large systematic uncertainty because they introduce a series capacitance that results in a severe bias in the calculated permittivity. In cases such as in coaxial matched-load termination measurements, the effects of air gaps can be reduced by metallization of the specimen surfaces or application of conductive pastes to the sections of the specimen in contact with the electrodes; otherwise they may be corrected by numerical techniques. The characterization of anisotropic materials generally requires two techniques, one for the normal component of permittivity and one for the in-plane component. However, the loss measurement is usually not strongly anisotropic and one accurate measurement usually suffices.

The researcher or engineer needs to determine the level of accuracy that is required to satisfy their needs for the task at hand. For example, someone studying building materials might be satisfied with an attenuation measurement, whereas a physics-based study of low-loss ceramics would prefer a permittivity measurement, and an atomic physicist may require the polarizability of a molecule under test. Many applications such as propagation through building materials would require permittivity data known to an accuracy of 10%, whereas for printed wiring boards for resonators we may require an answer to within 1%. Measurements without well-characterized uncertainties are of dubious value. Variations in the repeatability of the measurement are not sufficient to characterize the total uncertainty in the measurement. Estimates for all random and systematic error sources are needed in an accurate uncertainty analysis.

The accurate measurement of low-loss and lossy dielectric materials is challenging because each frequency band and loss range usually requires a different method. Methods may be grouped into either discrete frequency or broadband techniques. Each has strengths and weaknesses. For example, resonant techniques lose sensitivity when applied to lossy

materials. Transmission-line methods are generally strongly influenced by metal losses and lack sufficient sensitivity to measure very low loss but are broadband.

Overview of Permittivity Measurement Methods

In order to meet the measurement needs of bulk and thin dielectric material categories, an abundance of methods has been developed for characterizing material permittivity from DC to millimeter-wave frequencies [1, 2]. Measurement methods include free-space, open-ended coaxial-probe techniques, cavity resonators, dielectric-resonator techniques, transmission-line techniques, and near-field scanning probes. Each method has its niche. For example, split-cylinder cavity resonators are highly accurate for bulk materials of low loss when the E-field is oriented tangential to the sample surface, whereas open-ended coaxial probes are very attractive for non-destructive testing of bulk materials, and scanning resonant probe methods provide permittivity profiles of sub-micrometer thin materials.

To further systematize this large number of measurement methods, we classify them according to fixture type: Discrete Frequency and Broadband. The Discrete Frequency test fixtures include resonant methods that report values at a few resonant electromagnetic modes [1]. Broadband test fixtures do not resonate but pass EM waves through the material in a manner that allows a user to sweep a stimulus frequency

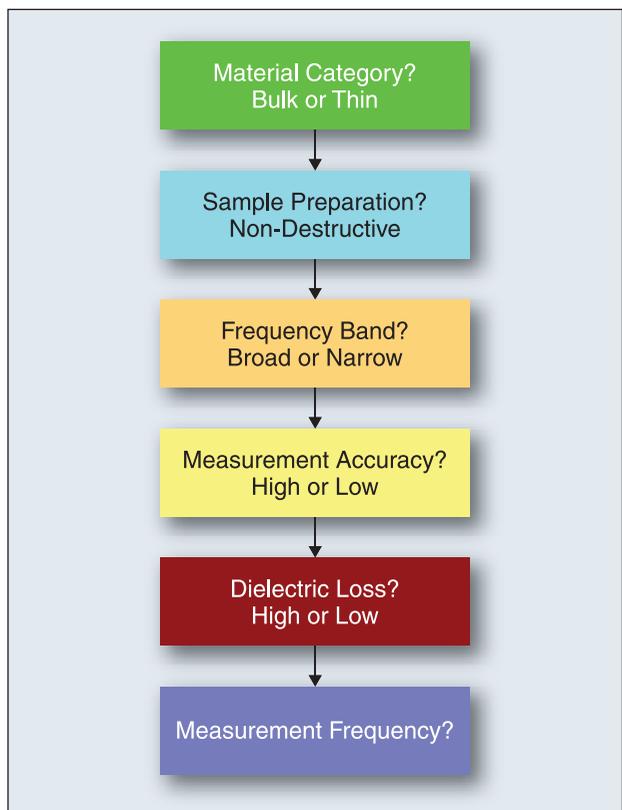


Fig. 2. Flow chart of questions to ask when choosing an appropriate dielectric material measurement system.

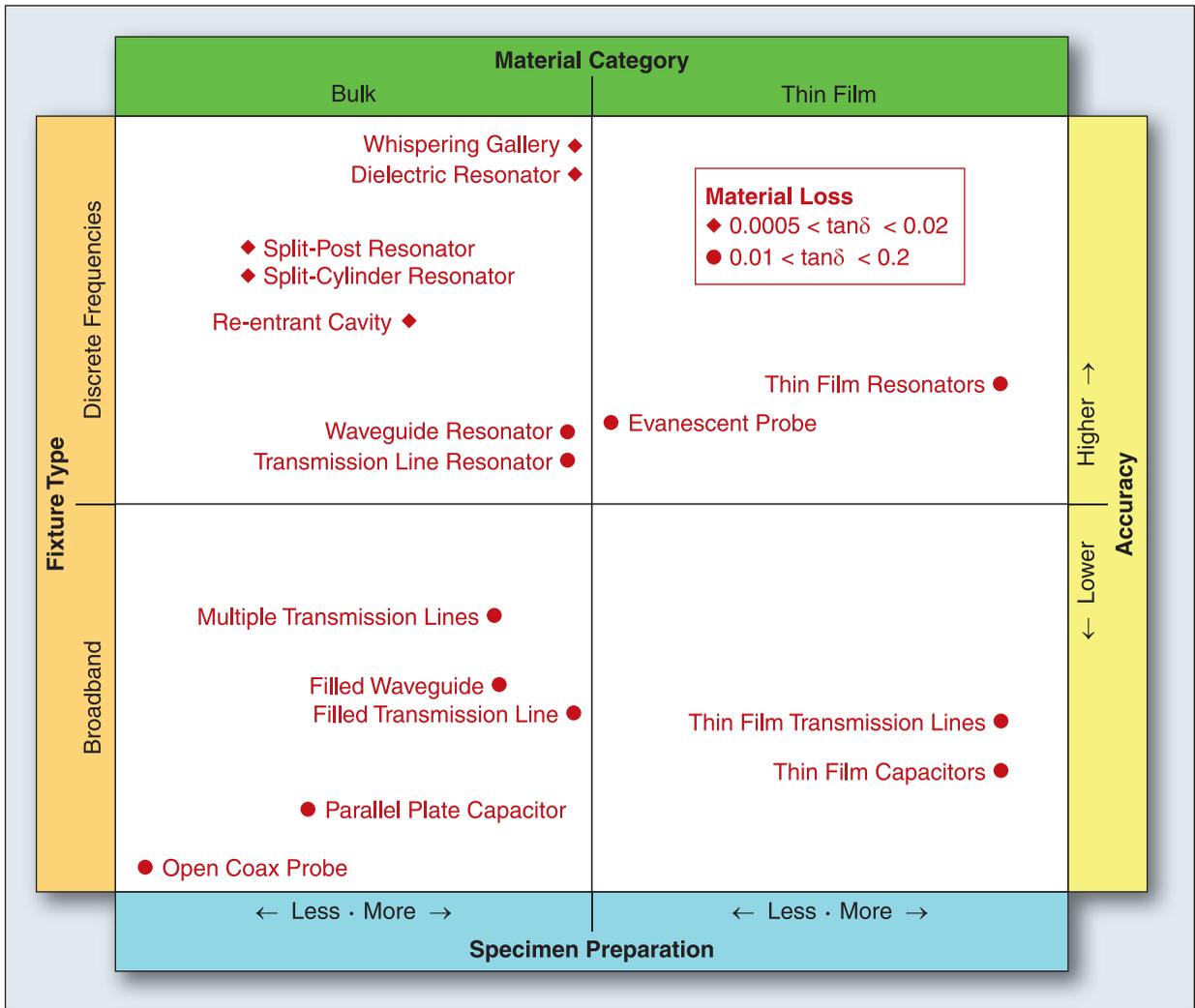


Fig. 3. Matrix of dielectric measurement methods grouped and organized according to material category / sample preparation and frequency band / relative accuracy. The matrix also identifies valid material loss ranges.

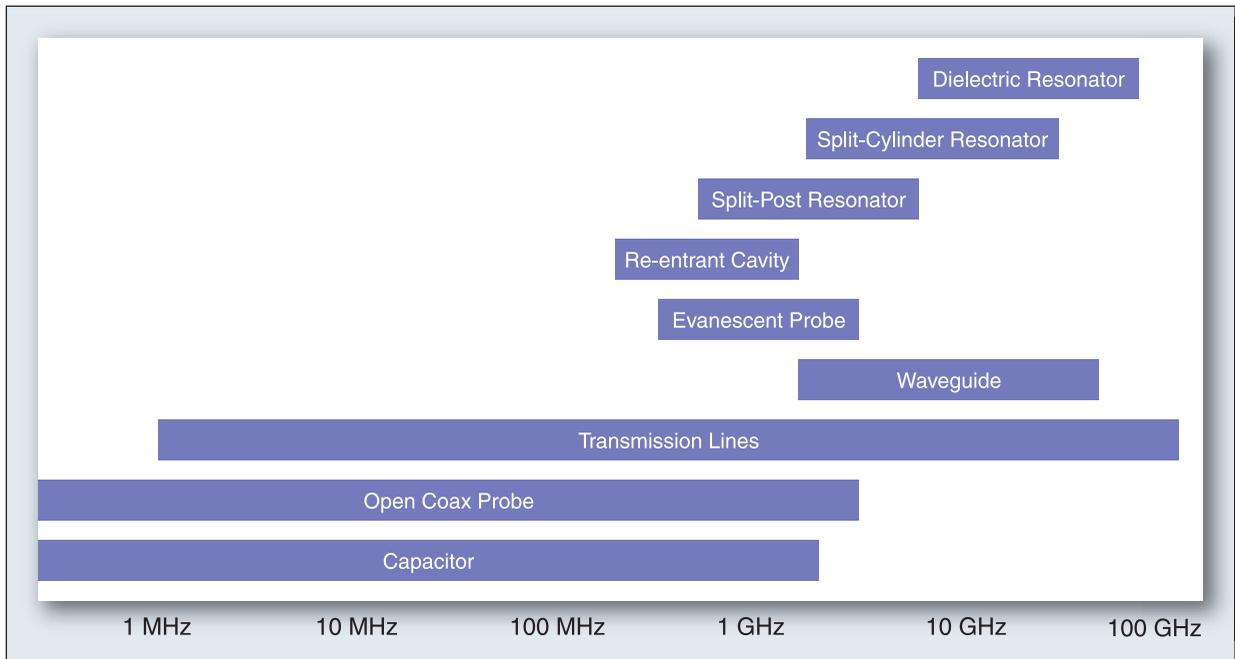


Fig. 4. Frequency range of various dielectric test fixture categories. Each category may include both discrete frequency resonators and broadband structures. In some cases, the fixture is a metal pattern deposited on the specimen.

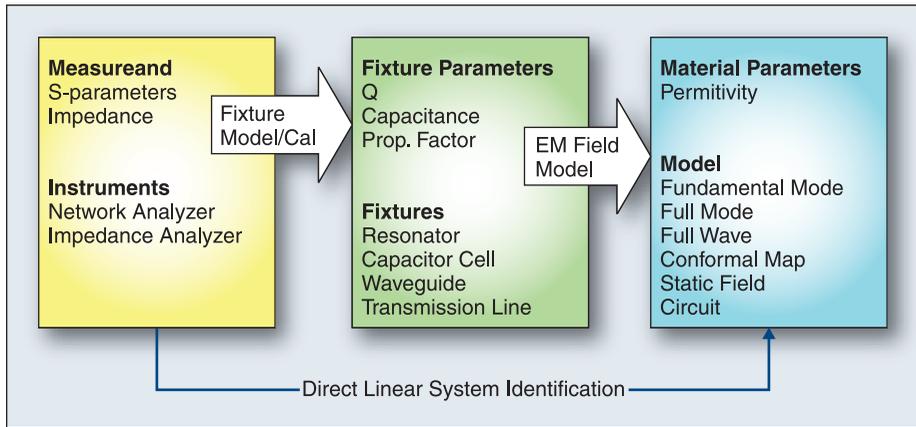


Fig. 5. The general flow of the permittivity measurement process showing instruments measuring response of fixture with material under test and the field models required to go from fixture response to material parameters.

continuously over the band. Figures 2, 3, and 4 show a generic classification system of measurement methods that are best suited to a given material category by combining fixture type with material category.

Other classification bins could be included; however, they are not readily generalized. The typical E-field orientation relative to the broad surface of the sample for each method and frequency ranges are summarized in published test method standards. A more complete table of permittivity methods is found in [1].

Generally, high-frequency techniques involve the connection of an impedance or vector network analyzer to the material under test through a test fixture such as a cavity, probe, or transmission line. In dielectric measurements, the instrument reports values of its intrinsic measurand, impedance or scattering parameters. Then an EM field model of the test fixture transforms test fixture parameters to material permittivity, as Figure 5 shows. While a full linear system identification of the entire system would allow a direct mapping of permittivity to actual measured values, this is not as common because there is a desire to connect a given test fixture to a wide variety of instruments.

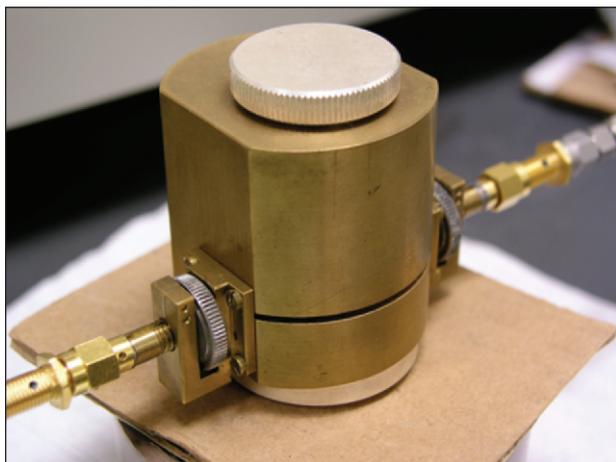


Fig. 6. A Split-Cylinder Resonator.

The Description of Three Dielectric Measurement Methods

We give overviews of three different dielectric material characterization techniques: a split cylinder resonator, multiple transmission lines, and a near-field probe method.

The Split-Cylinder Resonator

Dielectric substrates commonly need to be characterized over microwave to millimeter-wave frequencies [5]. Resonant methods have the lowest uncertainties, usually less than 1% for the real part of the permittivity. For resonant measurements, the permittivity is determined from measurements of the resonance frequency and quality factor (Q). The quality factor is usually calculated from $Q = f_0 / \Delta f$, where f_0 is the resonance frequency and Δf is the frequency difference between 3 dB points. A circle fit routine yields more accurate values [1]. The split-cylinder (Fig. 6) and split-post resonators are particularly useful for these measurements because they are nondestructive and can measure substrates of varying thicknesses.

The procedure for a resonant system measurement such as a measurement made with a split-cylinder resonator is:

- ▶ Measure empty cavity resonance frequency and Q
- ▶ Determine the best estimate for the specimen thickness across substrate
- ▶ Insert the material and measure the loaded resonance frequency and Q
- ▶ Re-insert the material and measure again at various sample rotations
- ▶ Run software developed from theoretical Q to compute permittivity from Q and f_0

Note that the resonance frequency is determined by the permittivity of the sample under test, because the load of the sample decreases the resonance frequency. A detailed model of this type of system is in [5].

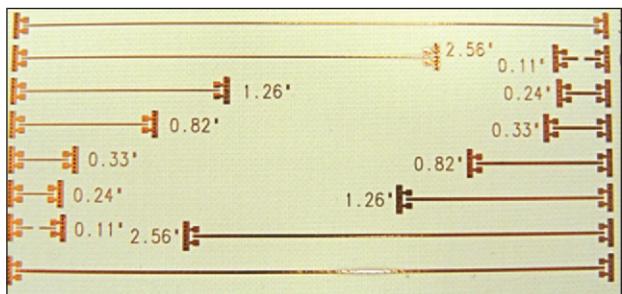


Fig. 7. A Printed Circuit Board with Microstrip Multiline Test Structures.

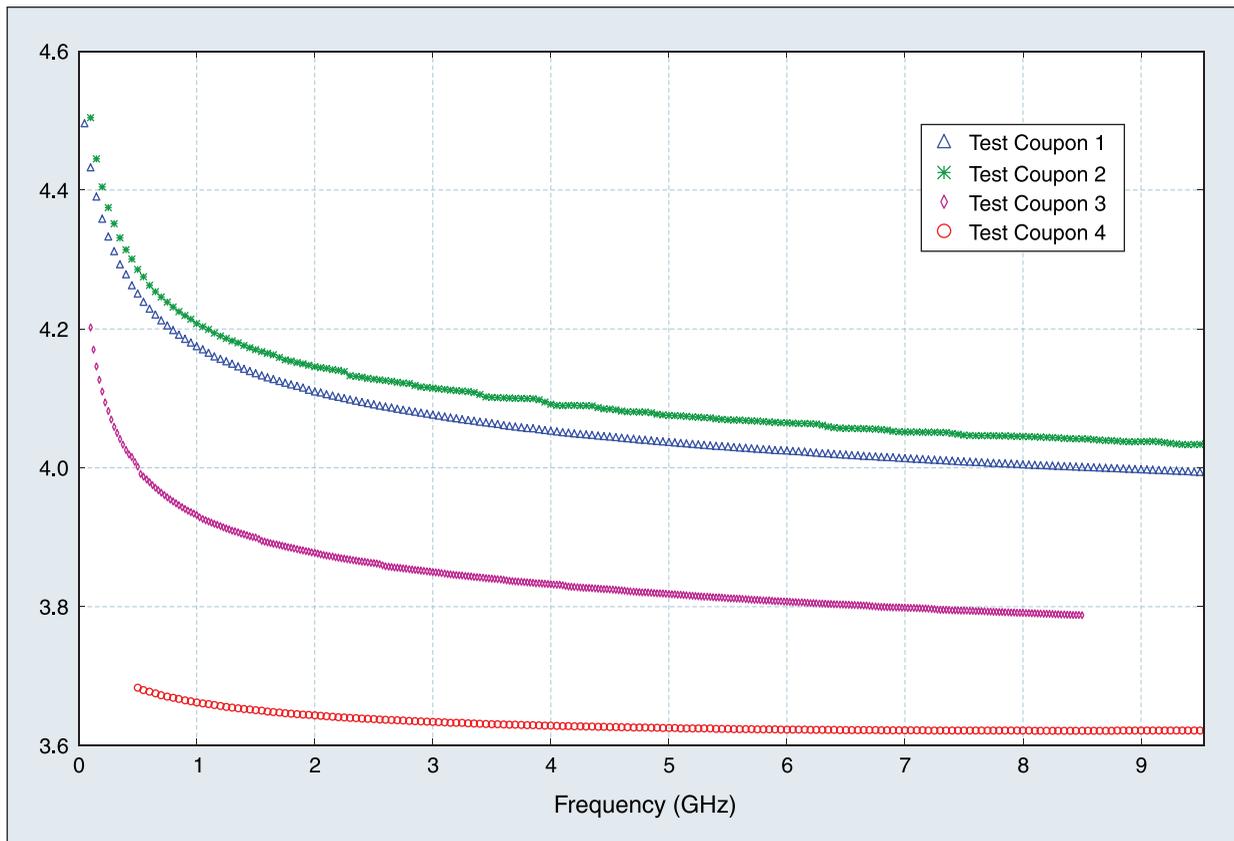


Fig. 8. Broadband permittivity ϵ_r' for circuit board materials acquired using the multiple transmission line method.

Multiple Transmission Lines

The material permittivity of circuit-board substrates, polycrystalline, single crystal substrates, and thin films can be measured through the application of the Multiline Method [4]. Here, electrical transmission lines are patterned in metal layers that are on one or both sides of a substrate or in a stack of multiple layers of dielectric materials (Fig. 7). Coplanar waveguide (CPW), microstrip, and stripline structures are used. The process involves acquiring scattering parameters with a vector network analyzer (VNA); using the Multiline algorithm to compute the fixture parameters, in this case the transmission line propagation constant; and then using a cross-sectional field model or full-wave analysis to solve for the material parameters.

The transmission line propagation factor is a function of the geometry and four parameters: the conductor resistance, R , and inductance, L , per unit length, the structure's capacitance, C , and the conductance, G , per unit length. Solving for the permittivity requires a model for R and L in order to de-embed the C and G parameters from the propagation factor. Once C and G are available, a field map is used to estimate the permittivity and loss tangent.

The method follows these general steps:

- ▶ Fabricate test structures with transmission lines that differ only in length
- ▶ Use a probe station or precision connectors and connect the lines to a VNA

- ▶ Measure all four S-parameters for each line
- ▶ Compute the propagation factor by use of the Multiline algorithm
- ▶ Model conductor R and L behavior by use of a low-frequency impedance analyzer to guide the model values.
- ▶ Estimate C and G by de-embedding R and L from the propagation factor.
- ▶ Compute the permittivity using a field model and the C and G values as Fig. 8 shows.

In transmission-line methods, the majority of the signal passes through the material without reflection. In resonant systems, the fields pass through the materials many times which enhances accuracy. However, transmission-line methods provide acceptable accuracy for many applications and are one of the best methods for acquiring permittivity over very broad frequency bands, for example 10 MHz to over 100 GHz.

Near-field Microwave Probe

In order to measure the local properties of thin materials, it is necessary to focus the fields. This is most easily done by using the near field, because the resolution can be much smaller than $\lambda/2$. A near-field probe can be used to scan thin films or measure submicron materials [1]. The near-field microwave probe (Figure 9) usually consists of a resonator connected to a probe on the bottom, so that as the probe approaches a material, it shifts the cavity resonance. The technical challenge for using

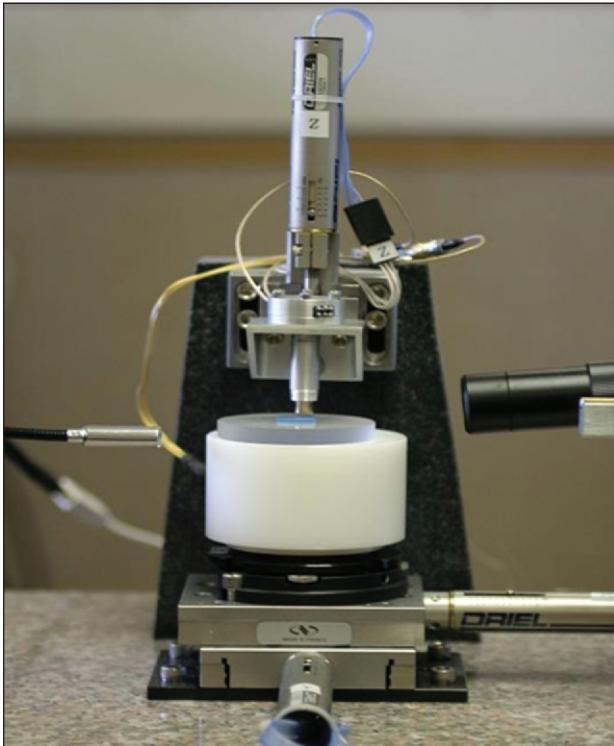


Fig. 9. Near-field Microwave Scanning Probe

this method is the development of a theoretical and numerical model that relates shifts in the system's cavity resonator to the material under test.

The procedure is summarized as:

- ▶ Measure resonance frequency and Q without specimen.
- ▶ Lower probe close to specimen and measure the loaded resonance and Q_L .
- ▶ Run software developed from theoretical model to compute permittivity from Q and f_0 .

Discussion and Conclusions

The demands on dielectric material measurements have increased over the years as electrical components have been miniaturized and device frequency bands have increased. Well-characterized dielectric measurements on thin materials are needed for circuit design, minimization of crosstalk, and characterization of signal-propagation speed. Bulk material applications have also increased. For accurate dielectric measurements, each measurement band and material geometry requires specific fixtures. Engineers and researchers must carefully match their material system and uncertainty requirements to the best available measurement system. Broadband measurements require transmission-line methods, and accurate measurements on low-loss materials are performed in resonators. The development of the most accurate methods for each application requires accurate fixture selection in terms of field geometry, accurate field models, and precise measurement apparatus.

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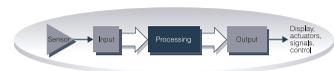
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