Anritsu envision : ensure

Material Measurements with Vector Network Analyzers

The increasing popularity of mobile communications, wireless data transfers, and instant access technologies is giving rise to the need for faster data rates and more data channels to support an ever-increasing number of users and their devices. To meet these demands, circuits must be made smaller and perform faster than ever before. One way manufacturers accomplish this is by leveraging materials that have good dielectric properties (complex permittivity) in the components and devices used to build these circuits (e.g., FR 4 and RF Duroid among others). Another way is to design these components and devices at higher frequency ranges where more bandwidth is available to transfer data more efficiently. However, while manufacturers are quoting good permittivity of the existing materials at low frequencies, these same solutions may not be adequate for designing high-frequency RF and microwave applications.

This application note will examine the issues component and device manufacturers and their engineers will face when designing their solutions in higher frequencies.

Material Effects on Electromagnetic Waves

When designing components and devices for higher frequency ranges and increased bandwidth requirements, first a simple relationship between a time-domain signal (pulse signal or a 1/0 of digital domain) and the same signal in the frequency domain must be established (for the purpose of this paper, the details of the mathematics will not be detailed). The rise time of a signal in the time domain is inversely proportional to the number of odd harmonic frequency components and how close their amplitude levels are present in the frequency domain (see Figures 1 and 2). Operating at higher frequencies leads to smaller (faster) rise time and fall times, which is why data can be transferred more efficiently. However, if there is something that limits the rise time and fall times of a signal travelling through a medium, then it is important to understand the details of it.

	Fundamental (Rep. Rate) n = 1	3rd Harmonic n = 3	5th Harmonic n = 5	7th Harmonic n = 7	9th Harmonic n = 9
Input Signal 1	83.3 kHz	250 kHz	417 kHz	583 kHz	750 kHz
Input Signal 2	107 kHz	321 kHz	535 kHz	750 kHz	964 kHz
Input Signal 3	150 kHz	450 kHz	750 kHz	1050 kHz	1350 kHz
Input Signal 4	250 kHz	750 kHz	1250 kHz	1750 kHz	2250 kHz
Input Signal 5	750 kHz	2250 kHz	3750 kHz	5250 kHz	6750 kHz

Figure 1: Harmonic components in a signal

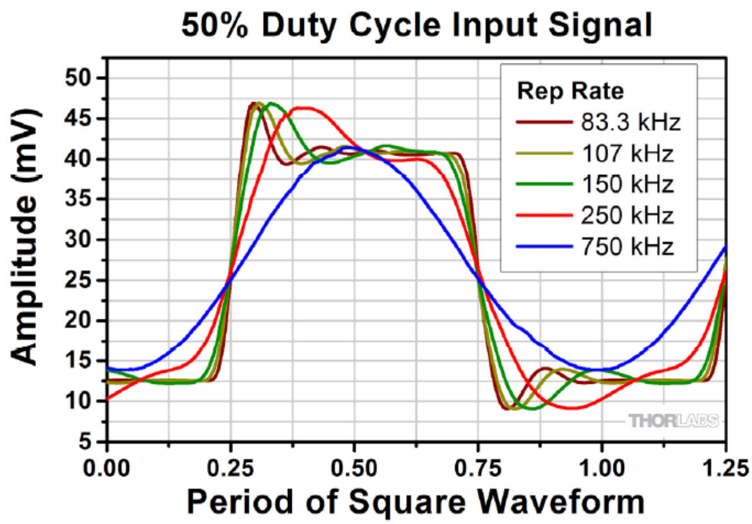


Figure 2: Rise time of a signal with different harmonic content

One example would be where an electromagnetic wave is travelling from one medium (air) to another medium (glass) and finally coming out in air (Figure 3). The moment a higher frequency signal (an electromagnetic wave) enters/exits from one medium to another medium, it goes through a lot of changes at the boundaries (entry and exit points) and also inside the medium. The signal changes in amplitude, frequency, and phase. This is why it is very important to characterize various materials for their effects on electromagnetic waves.

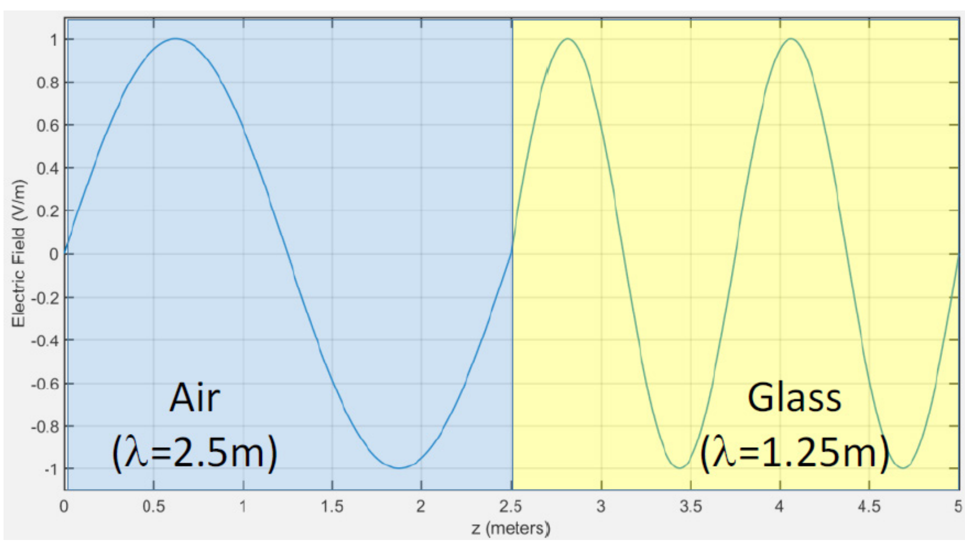


Figure 3: Wave propagation in different media

Propagation of Electromagnetic Waves Through a Medium

There are key parameters, such as complex permittivity, complex permeability, loss tangents, DK/DF, etc., that are widely used for material characterization. These define/characterize materials for their ability to store/dissipate a charge and what changes they can cause when a wave propagates through them. The two parameters that determine the propagation of electromagnetic waves are the electrical permittivity and magnetic permeability of the material. J. C. Maxwell's equations are an integral tool in explaining the dielectric properties of materials. J.C Maxwell presented 4 equations that form the basis of understanding the propagation of electromagnetic waves in a medium.

$$\nabla . E = \frac{\rho}{\epsilon_0} \quad (1) \quad \text{Gauss' law}$$

$$\nabla . B = 0 \quad (2) \quad \text{Magnetic monopoles}$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad (3) \quad \text{Faraday's law}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} \quad (4) \quad \text{Ampere-Maxwell law}$$

Where in these equation:

D (electric displacement field) = εE, (and ε = ε'-jε")

B (magnetic field) = μH (and μ = μ'-jμ")

J (current density) = σE

The equations imply that the interaction between a material and an electromagnetic wave depends on three primary quantities, namely: the permittivity (Ɛ), permeability (μ), and conductivity (σ). These parameters also depict the extent to which the electromagnetic wave can penetrate/propagate through a dielectric medium. Since the focus is mainly on dielectric materials, the discussion will be around permittivity and permeability as dielectrics are not conductive (or σ is extremely low). It is important to understand a little about the different kinds of materials before going in to the details of materials and their characterization.

Different Types of Materials

In general, various materials can be categorized as conductors, semiconductors, or insulators (or dielectrics). The difference between them is (illustrated in Figure 4):

- **Insulators (dielectrics):** the energy gap between the valence and conduction band is huge, so no **free electrons are available.**
- **Semiconductors:** the energy band gap is smaller, so some electron movement from the valence band to the conduction band can happen.
- **Conductors:** the conduction and valence bands overlap, so electrons can move freely between the valence and conduction bands.

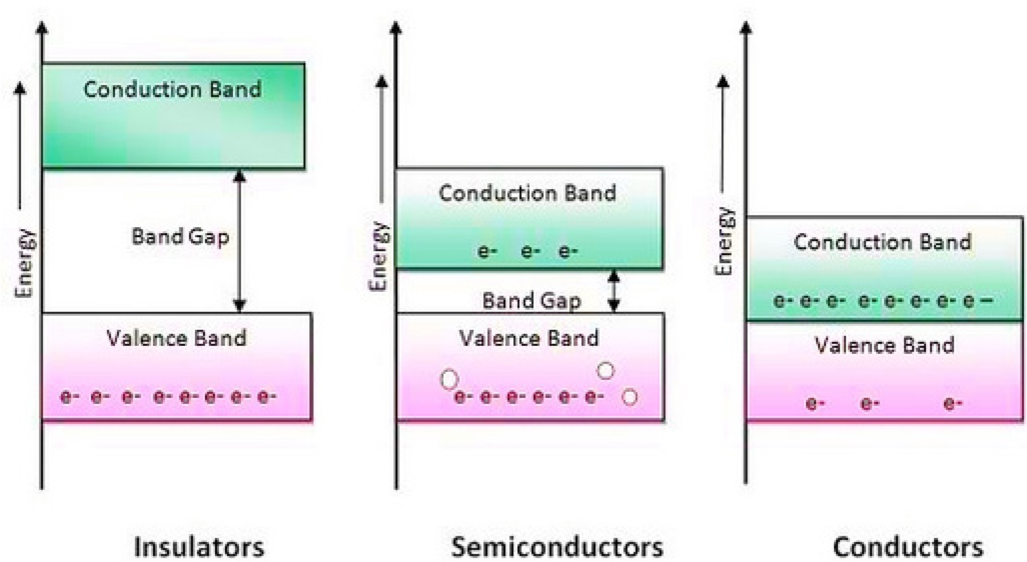


Figure 4: Energy bandgap in various materials

Most of the high-frequency electronic circuits in today's world are built on dielectric materials and their operation depends on the dielectric properties of the material. In order to design these circuits, it is essential to have a vital understanding of the properties of the dielectric materials, especially the dielectric constant and loss tangent at the operating conditions. The most important parameter for a material is the dielectric constant, which is the real part of the complex permittivity given by (illustrated in Figure 5):

Complex/relative permittivity: given by the ε_r which is the absolute permittivity over the permittivity of free space, that is $\varepsilon_r = \varepsilon/\varepsilon_0$ also sometimes denoted by terms K is equal to $\varepsilon_r = \varepsilon' - j\varepsilon''$ where:

- Real part ε' is the dielectric Constant (D_k) and is the measure of the amount of energy stored in the medium when an external electric field is applied.
- Complex part ε'' is the measure of amount of energy lost in the material (sometimes also called as loss factor) when the material is under the influence of an external electrical field.

The ratio of the imaginary part and the real part of the complex permittivity is called the loss tangent, generally termed as $\tan\delta_c = \varepsilon''/\varepsilon'$, and is also called the dissipation factor (D_f). It gives the ratio of the lost portion of energy to the stored portion of energy and it's inverse is called the quality factor $Q = 1/D$.

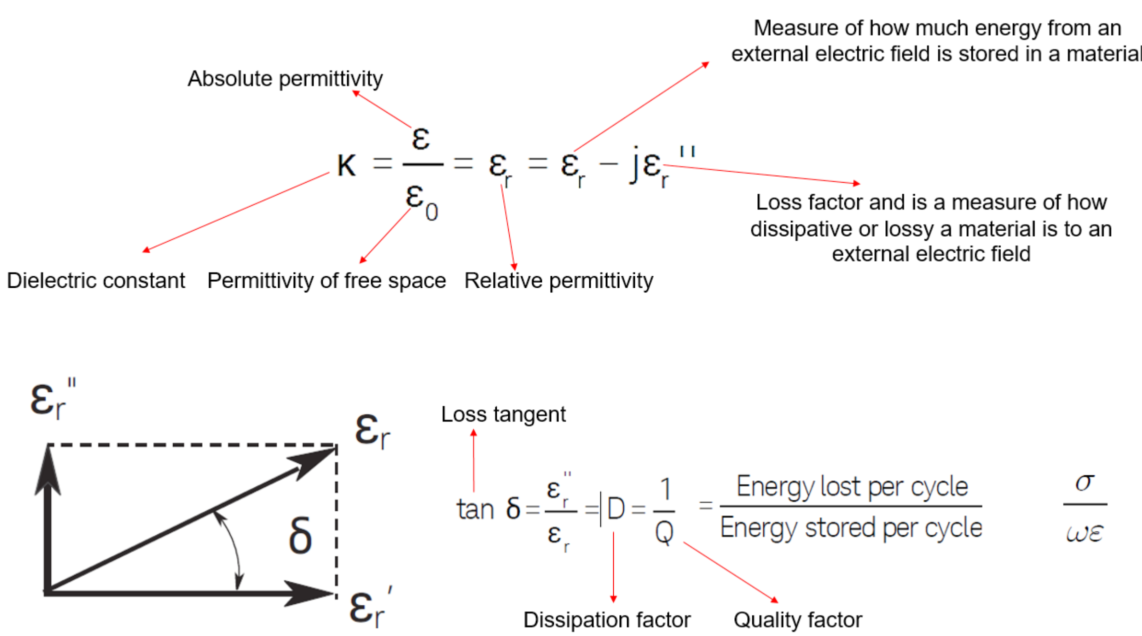


Figure 5: Material measurement – terms and parameters

As mentioned earlier, the real part of the complex permittivity, also known as the dielectric constant, is a measure of the amount of energy from an external electrical field stored in the material. The imaginary part is zero for lossless materials and is also known as loss factor. It is a measure of the amount of energy loss from the material due to an external electric field. The dielectric properties of the material provides valuable information about the storage and dissipation of electric and magnetic fields in materials, and also provides insight into the feasibility of using the material in potential applications. Just like the permittivity of a material, there is also a magnetic response parameter for all dielectric materials called permeability, and is given by $\mu = \mu' - j\mu''$. In this application note, we will not be discussing magnetic permeability in detail.

Figure 6 qualitatively shows the typical behavior of permittivity (ε') and (ε") as a function of increasing frequency. The permittivity of a material is related to a variety of physical phenomena. Various effects like dipolar relaxation, electronic polarization, atomic polarization, and ionic conduction contribute to the permittivity of a dielectric material. In the lower frequency range, the loss factor (Df) is dominated by the influence of ion conductivity. The variation of permittivity in the microwave range is mainly caused by dipolar relaxation; and the absorption peaks in the infrared region and above is mainly due to atomic and electronic polarizations. Note that specifically for the 1 to 10GHz and 10 to 100GHz ranges, both the ε' and ε" start behaving very differently. This is why it is important to measure the dielectric properties of the PCBs and other materials that are used in domains like communication, research and development, as well as aerospace and defense so as to measure the effects of electromagnetic waves carrying information/energy through these media.

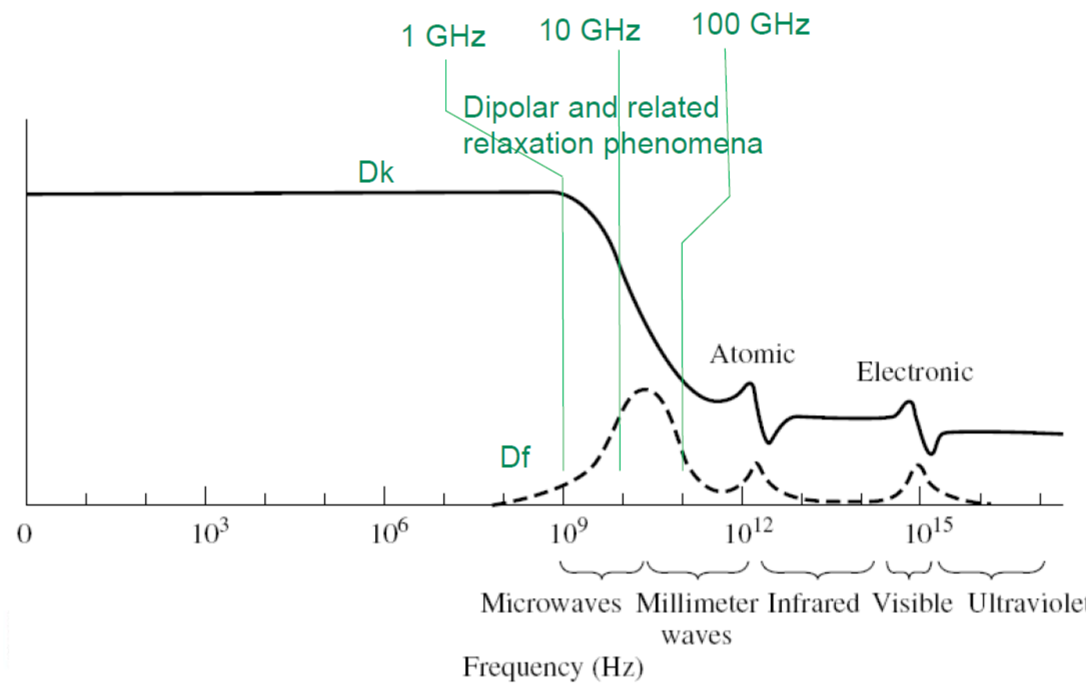


Figure 6: Dk and Df behavior for RF/microwave/mmWave frequency ranges

Polarization

Polarization is an ordering in space of an electrically charged unit under the influence of an external electric field. The charges become polarized to compensate for the electric field such that the opposite charges move in opposite directions (Figure 7). The external field causes the formation of an electric moment in the entire volume of the dielectric material in each polarizing unit (namely an atom, ion, or molecule). Linear dielectrics show a direct proportionality between the induced electric dipole moment p acquired by the polarizable unit during the process of polarization and the intensity E of the field acting on it as given by $p = \alpha E$, where α is the polarizability, which reflects the properties of individual polarizable units. Polarizability is independent of the dielectric volume and this parameter is very important to define the electrical properties of a dielectric material. As a result of polarization, the charges that are displaceable will accumulate at physical barriers (like the grain boundary) and hence interfacial polarization or space charge polarization occurs.

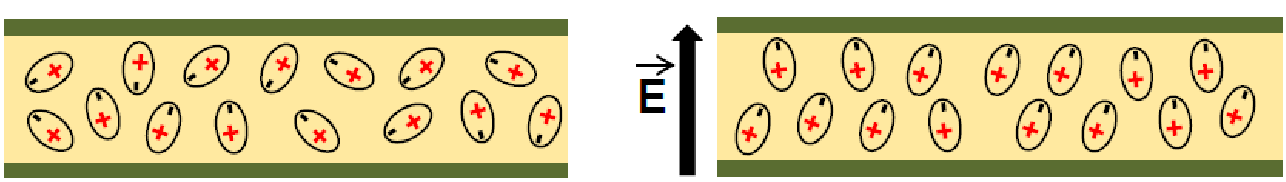


Figure 7: Polarization effect

The mechanism of polarization, which gives the dielectric constant, is different at different frequency regions. For example, dipole orientation and ionic conduction interact strongly at microwave frequencies (such as the dipole of water molecules, which rotate to follow an alternating electric field). This is the basic principle behind microwave ovens used for the warming of food. Atomic and electronic mechanisms are relatively weak. As frequency increases, the slow mechanisms lose effect and leave the faster ones to contribute to ε'. Based on the dipolar effect, the dielectric constant changes significantly at certain frequencies or will remain stable. Figure 8 depicts the different frequency regions and different polarization mechanisms.

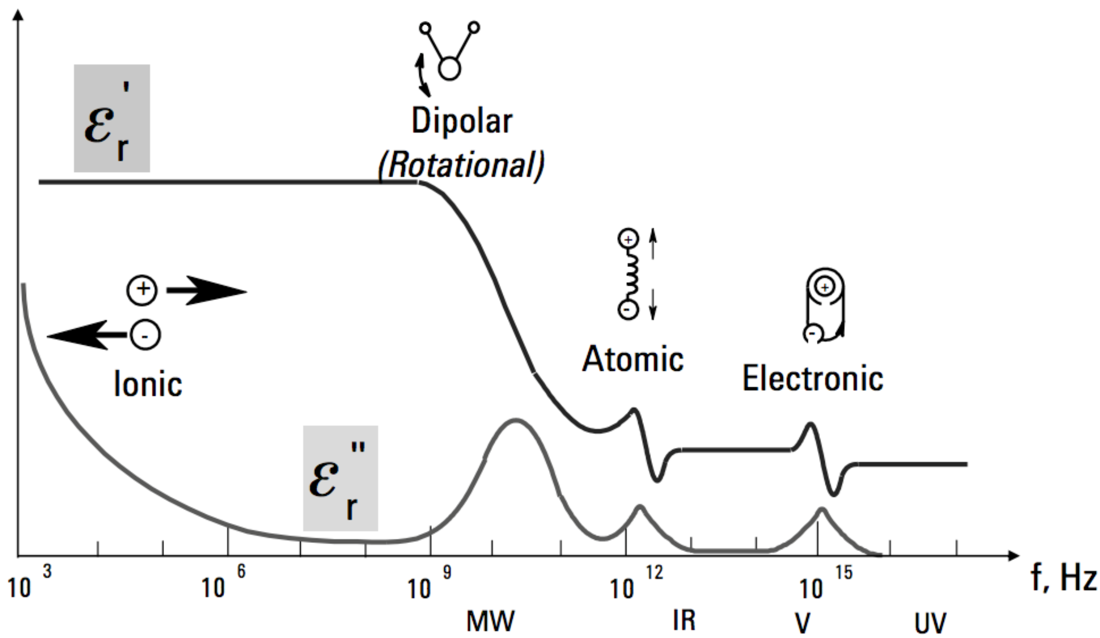


Figure 8: Various polarization phenomenon at different frequency ranges

Material Measurement Methods and Techniques

Dielectric measurement is an important tool to understand material behavior, especially at high frequencies. This can provide the electrical or magnetic characteristics of the materials, which is a critical parameter required when implementing the material in applications. A number of methods have been developed to measure the complex permittivity/permeability of materials in the time/frequency domain based on reflection and reflection-transmission measurements.

For the dielectric measurement, one cannot rely on a single technique to characterize all the materials over a wide range of frequencies. The techniques and methods for measuring a lossy versus a low loss material can be totally different as will the accuracy of their results (there is always uncertainty in dielectric measurements while characterizing various materials; some significant factors that affect the accuracy of the measurements are frequency range, temperature, material nature, thickness, and size). Broadly speaking, material measurement methods can be divided into two categories: resonant and non-resonant.

- Resonant methods: limited by measurements on single/discrete frequency points, but very accurate.
- Non-resonant methods: measurements can be performed over a wide range of frequency, but normally used to observe the behavior of the EM waves.

Resonant Methods

As already mentioned, resonant methods are more accurate and precise in comparison to the non-resonant methods. Resonant methods generally include the **resonator** and the **perturbation** method.

1. **The resonator method** is based on the fact that the resonant frequency and quality factor of a dielectric resonator with given dimensions are determined by its permittivity and permeability. This method is often used to measure low loss dielectrics whose permeability is $\mu 0$.
2. **The perturbation method** is based on the resonant perturbation theory. For a resonator with given electromagnetic boundaries, when part of the electromagnetic boundary condition is changed by introducing a sample, its resonant frequency and quality factor will also be changed. From the changes of the resonant frequency and Q, the properties of the sample can be derived. This method is suitable for lower and moderate loss samples. There are further classifications of fixtures in the resonant perturbation method but those are out of the scope of this application note.

Resonant method includes five main families of resonant techniques:

1.) Micro strip type (Figure 9)

2.) Cavity resonator type (Figures 10 and 11)

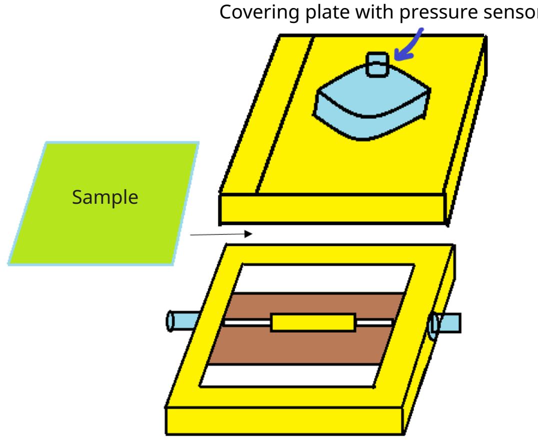


Figure 9: Diagram of a micro strip type

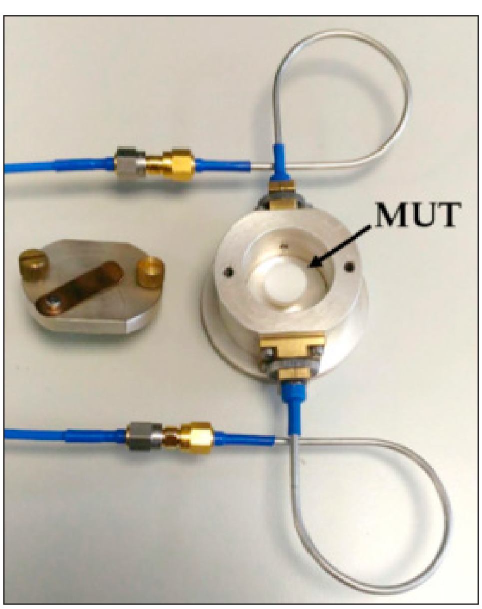


Figure 10: TE01δ mode cavity resonator

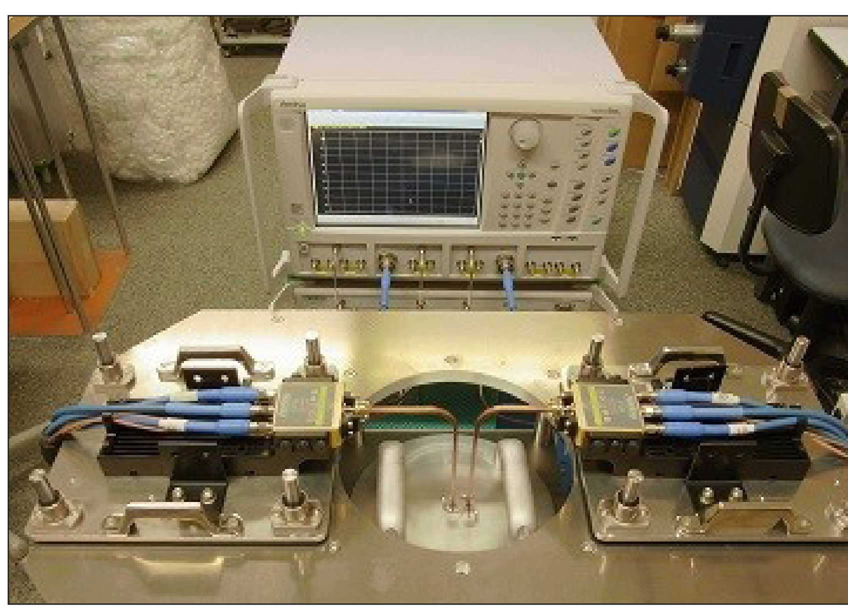


Figure 11: Open resonator method

3.) Dielectric resonators (Figure 12; note that the advantage of these methods lies in accessing the material from the resonator, as it is much simpler than in other devices; meaning the material is less likely to become damaged via insertion or removal)

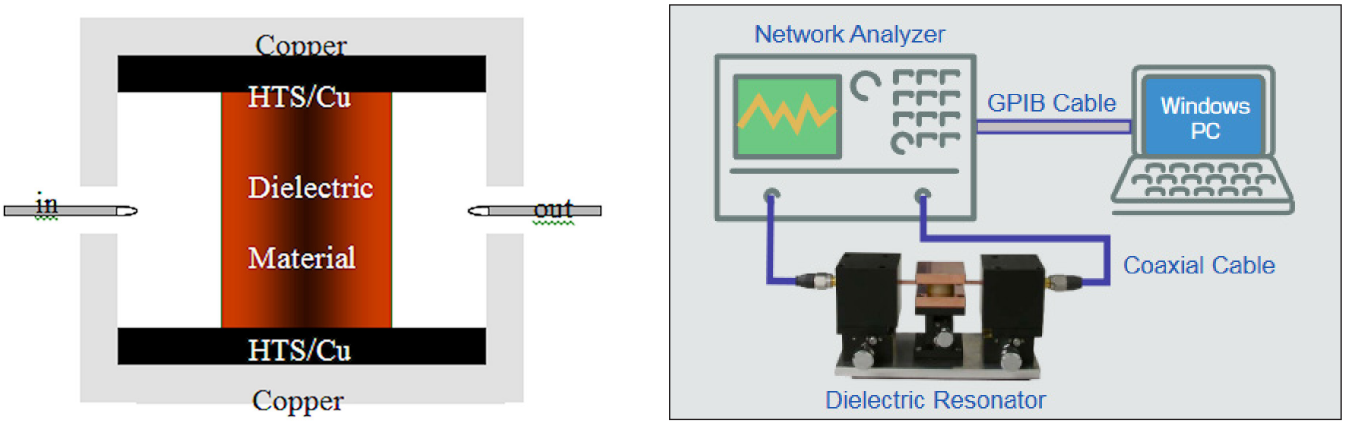
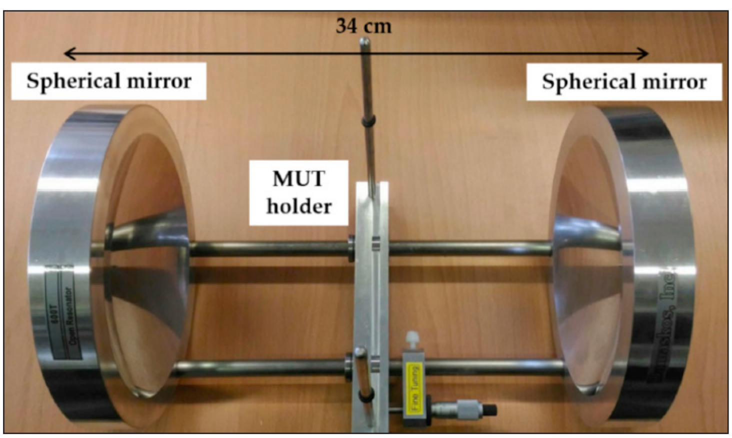


Figure 12: 2 different setups for dielectric resonators

4.) Open resonators, which also includes the Fabry-Perot resonator (Figure 13)



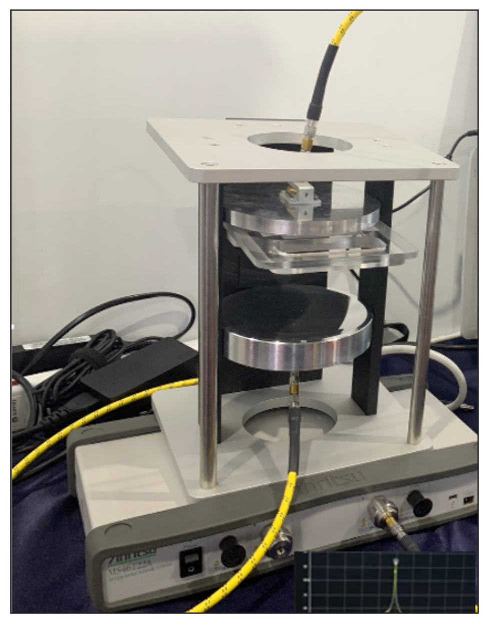


Figure 13: 2 different types of open resonators

5.) Split post resonators (SPDR) are a very accurate measurement that can be performed as a function of temperature, however, as it is a resonant technique it can only be measured at one frequency (Figure 14)

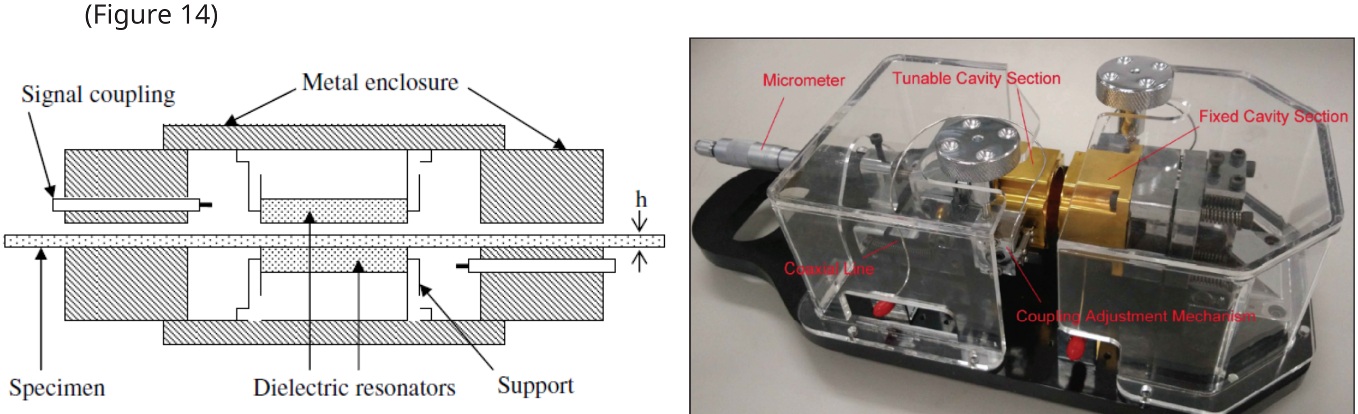


Figure 14: 2 different types of split post resonators

How are Permittivity and Permeability Calculated?

In the cavity perturbation method, the sample under study is introduced into an antinode of the electric field or magnetic field, depending on whether permittivity or permeability is being measured.

If the sample under study is introduced at a junction with maximum electric field and minimum magnetic field, the electric properties (i.e. permittivity of the sample) can be characterized; if the sample is inserted into a place with maximum magnetic field and minimum electric field, the magnetic properties (permeability) of the sample can be characterized.

Non-Resonant Methods

In non-resonant methods, the material properties are derived by the impedance and the wave velocities in the material. When a wave travels from one medium to another, both its impedance and velocity changes. Useful information can be deduced from the reflections and reflection transmission of the wave in the medium. Both permittivity and permeability can be calculated using this procedure.

Non-resonant methods mainly include reflection methods and transmission/reflection methods. In the reflection method, the material properties are calculated on the basis of the reflection from the sample. In the transmission/reflection method, the material properties are calculated on the basis of the reflection from the sample and the transmission through the sample.

- **Reflection method:** Electromagnetic waves are directed to a sample under study and the properties of the material sample are deduced from the reflection coefficient. Usually a reflection method can only measure one parameter, either permittivity or permeability. Two types of reflections are often used in materials property characterization, open- and short-circuit reflections, and the corresponding methods are called open-reflection method and shorted reflection method. As coaxial lines can cover broad frequency bands, coaxial lines are often used in developing measurement fixtures for reflection methods.

   1. **Open-reflection method:** Figure 15 shows the basic measurement configuration of an open-reflection method. In actual applications, the outer conductor at the open end is usually made into a flange to provide suitable capacitance and ensure the repeatability of sample loading. The measurement fixture is called a coaxial dielectric probe. This method assumes that materials under measurement are non-magnetic and that interactions of the electromagnetic field with the non-contacting boundaries of the sample are not sensed by the probe.

      It also assumes that the thickness of the sample should be much larger than the diameter of the aperture of the open-ended coaxial line, and, meanwhile, the material should have enough loss.

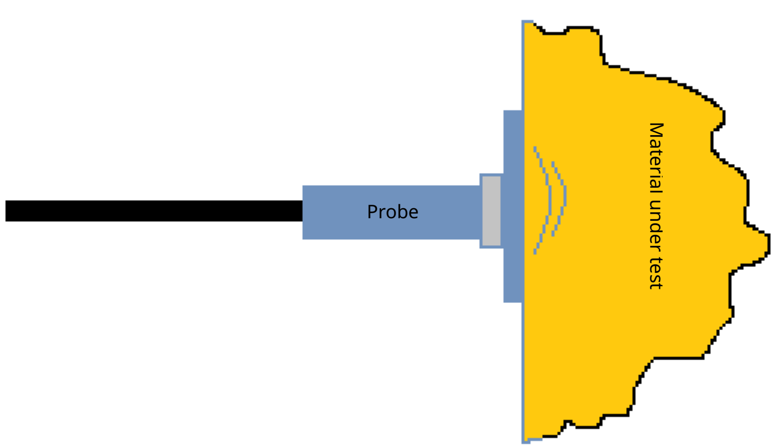
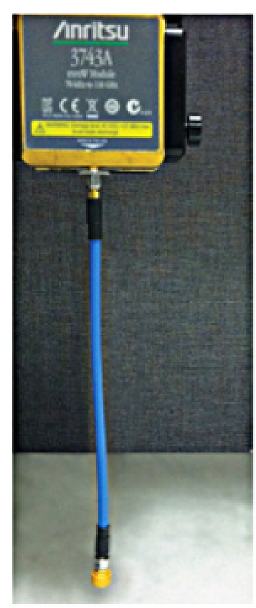


Figure 15: Basic measurement configuration of an open-reflection method



2. **Shorted reflection method:** the sample under study is usually electrically short, and this method is often used to measure magnetic permeability. In this method, the permittivity of the sample is not sensitive to the measurement results, and in the calculation of permeability, the permittivity is often assumed to be ε0

- **Transmission/Reflection Method:** With this method, the material under test (MUT) is inserted in to a piece of transmission line/waveguide, and the properties of the material are deduced on the basis of the reflection from the material and the transmission through the MUT (Figure 16). This method is widely used in the measurement of the permittivity and permeability of low conductivity materials. The principle behind this measurement is the fact that the characteristic impedance of the piece of transmission line loaded with the sample is different from that of the transmission line without the sample. Therefore, such difference results in special transmission and reflection properties at the interfaces. The permittivity and permeability of the sample are derived from the reflection and transmission coefficients of the sample-loaded cell.

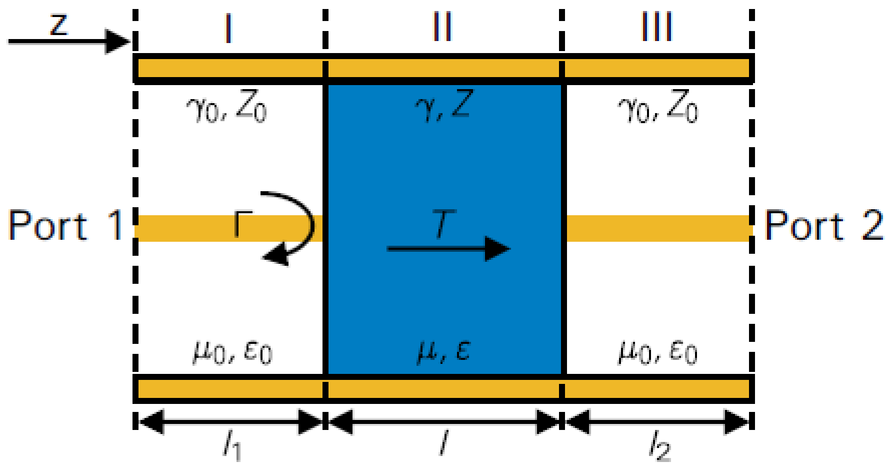


Figure 16: Depiction of a coaxial transmission line for understanding transmission-reflection method mechanism. Zones I and III are filled with air adjacent to MUT in Zone II.

Advantages of transmission/reflection line method:

- Coaxial lines and waveguides are commonly used to measure samples with medium to high loss.
- It can be used to determine both the permittivity and permeability of the material under test.

Disadvantages of transmission/reflection line method:

- Measurement accuracy is limited by the air-gap effects.
- It is limited to low accuracy when the sample length is the multiple of one-half wavelength in the material.

Figure 17: Example of a corrugated waveguide measurement

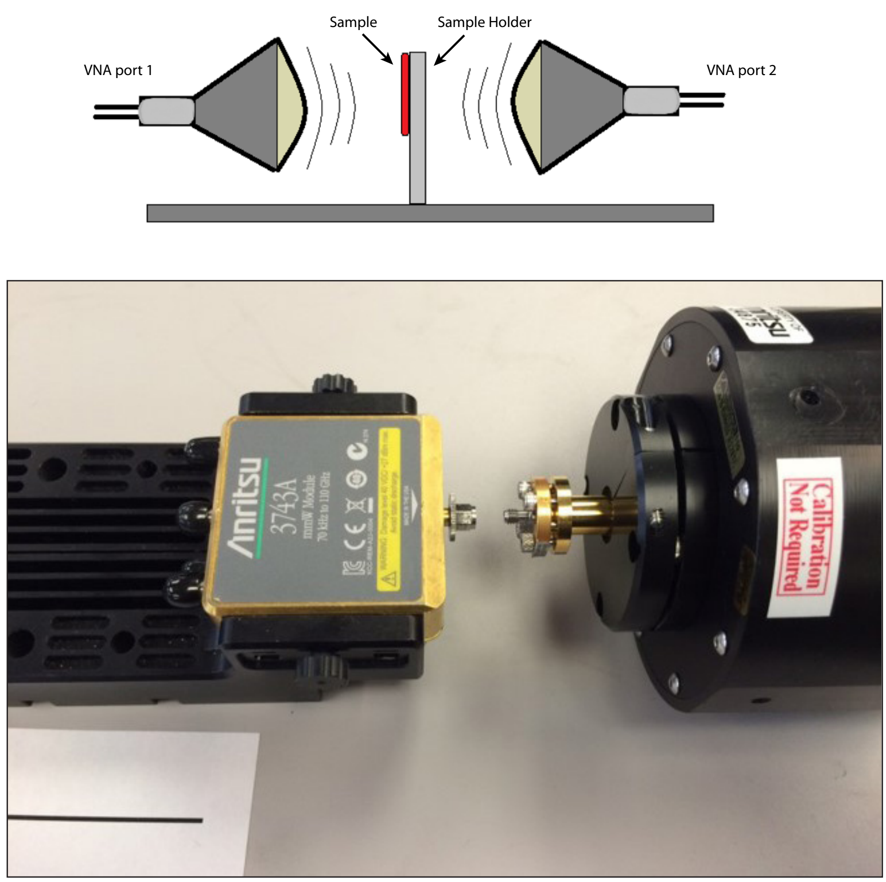
Free Space Material Measurement Technique

Free space material measurements are used for characterizing materials that remain in an unchanged state. There are many advantages associated with the free space material measurement technique since the MUT can be placed under a variety of conditions (i.e., temperature, pressure, and tensile variations as well as others) and the response can be monitored using the same setup for a broad range of frequencies. Two conditions that must be met by the MUT is that it must be large and flat.

Free space material measurements usually utilizes two antennas (could be simple horn antennas or in many cases focus beam antennas) placed facing each other and connected to a vector network analyzer's (VNA) ports 1 and 2 respectively (Figure 18). Since the VNA itself has a lot of components and uncertainties associated with it, therefore it should be calibrated before making these measurements.

There are a number of calibration methods that can be used for free space material measurements since the reference plane has to be in the middle of the setup (i.e. midpoint of the two antennas). The most common calibration techniques are the through-reflect-line (TRL), through-reflect-match (T/LRM), and the line-reflect-line (LRL). The LRL calibration method, having the highest calibration quality, is often chosen. Interested readers can refer to the Anritsu measurement and calibration guide for more info on the LRL calibration method. Once the system is calibrated, the S-parameter of an empty sample holder is measured by placing the sample holder midway between the two antennas. The MUT is then placed on the sample holder between the antennas and the S-parameter measurement is performed again. Using the de-embedding function of the VNA, the influence of the sample holder can be cancelled out and only the S-parameter of the MUT can be determined. The S-parameter for both the reflection and transmission coefficients can be determined.

It is important to state the importance of time domain gating here as it ensures that the multiple reflections from the DUT and edges of the antennas are not counted by the VNA in the final measurement calculations. The dielectric properties are then determined by post-processing the measured reflection and transmission coefficient using a program. Use of focal/lens antennas in the free space material measurement further enhances the accuracy of the system as it takes care of the diffraction from the edges of the samples.



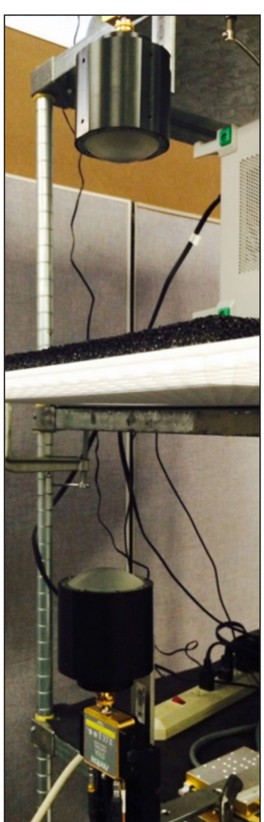


Figure 18: Anritsu VectorStar VNA 110 GHz based setup and its components for free space material measurements

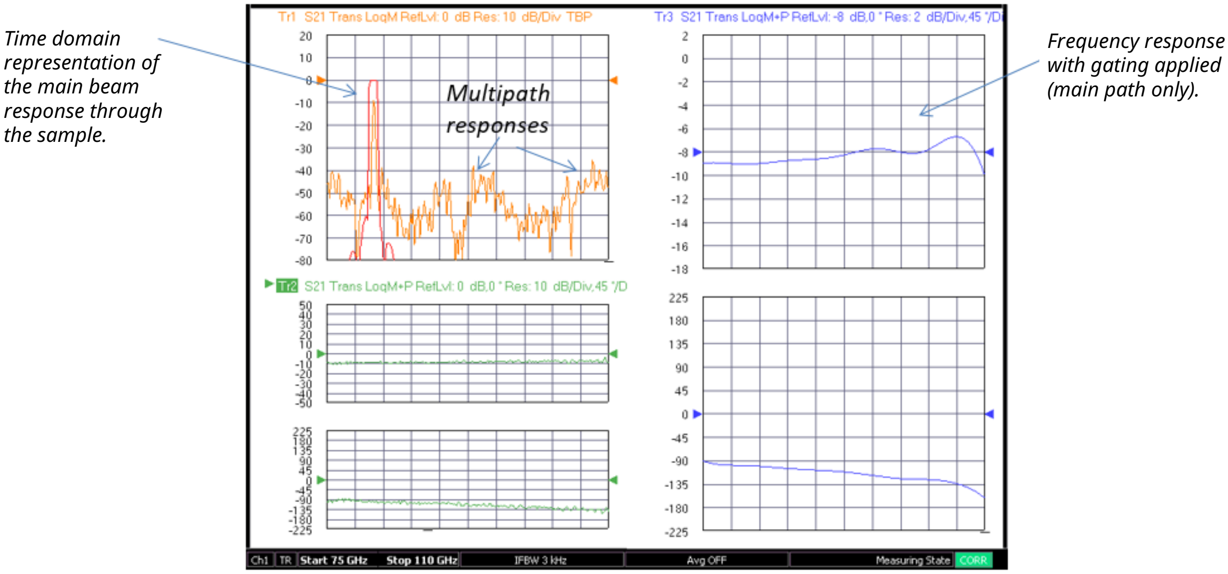


Figure 19: Time domain gating significance

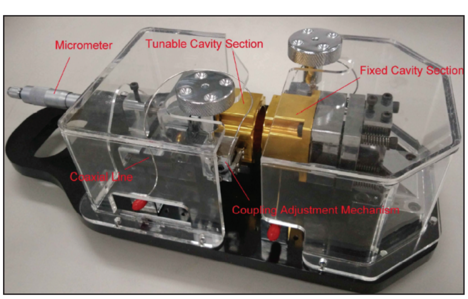
Measurement Setup for all Material Characterization

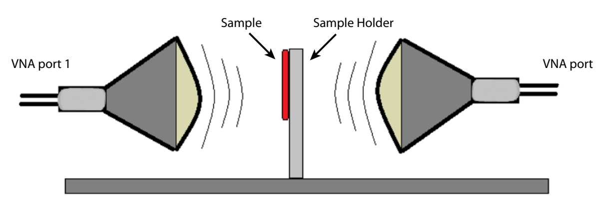
1.) A high performance vector network analyzer with cables and calibration kit
2.) MUT
3.) Material holder/fixtures based on the measurement techniques as per requirements
4.) Software to run either on the VNA or on a standalone PC

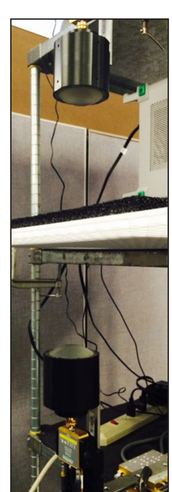
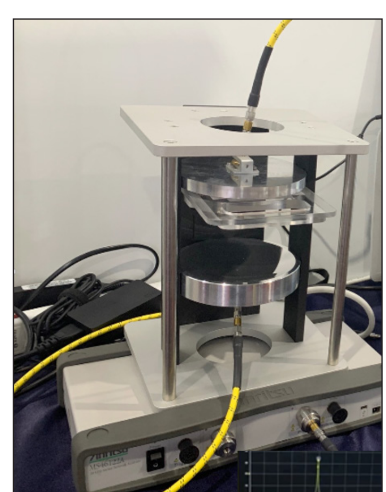
VNA



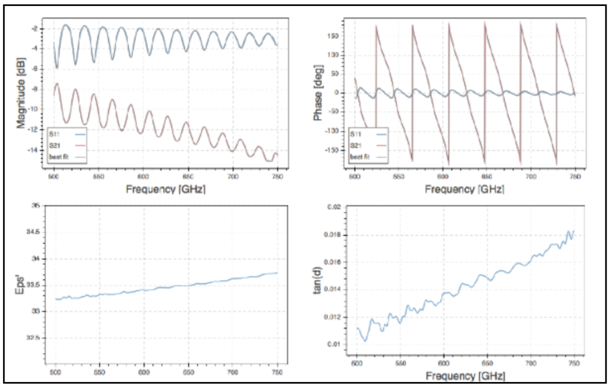

Material Measurement Fixtures

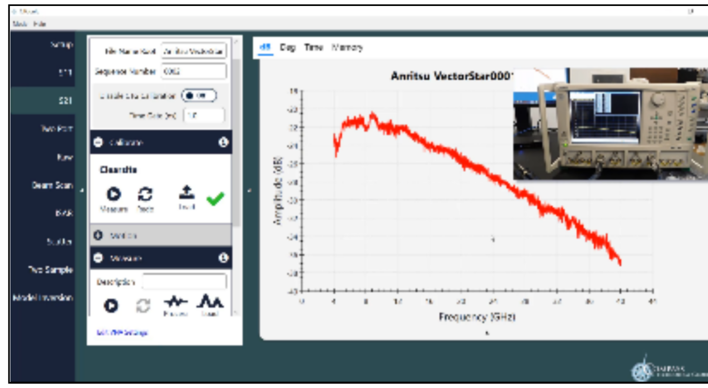




Software





In collaboration with third party solution providers, Anritsu can help customers with a complete solution for material characterization.

S. No.	Material Measurement Method	Frequency Range	Permittivity and Tan Delta	Permeability
1	Free Space material measurement	Up to 110 GHz	Yes	Yes
2	Various Resonant cavity (multiple solutions available)	Up to 110 GHz	yes	Yes
3	Transmission line Method (supports co-axial and waveguide)	Up to 110 GHz	Yes	Yes
4	Co-axial probe method	Up to 110 GHz	Yes	
5	Parallel plate capacitor	Up to 1 GHz	Yes	
6	Magnetic material characterization	Up to 30 GHz		Yes
7	Corrugated waveguide measurements	Up to 1.1 THz	Yes	

Summary

There are various methods of testing and characterizing a material under test. Concepts like polarization, permittivity, dielectric constant, and other key parameters were defined. Also discussed were specific procedures/fixtures for various materials and, depending upon their size/structure and type, the characterization can be done with varying levels of accuracy.

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ISO 9001 Registered

11410-01190, Rev. A Printed in United States 2020-05