White Paper

RF and Microwave Material Measurements: Techniques and Applications

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1. Introduction

How can we differentiate cancerous from non-cancerous cell types? What is the propagation time of a signal within a spurline? What is the shielding effectiveness of a component? What is the relative permittivity of a microstrip substrate? What is the performance of a radar absorber? What all these questions have in common is the need to quantitatively characterize material properties at RF and microwave frequencies. Similar questions, coming from different applications, have created a continual demand to accurately measure dielectric and magnetic properties of materials. In this scenario, the vector network analyzer (VNA) represents a tool that allows fast, accurate, and often non-destructive and sometimes even contactless measurements of the material under test (MUT). Over the years, several methods have been developed to characterize the dielectric properties of materials. These techniques include: open-ended coaxial probe methods, free-space techniques, resonators, and transmission line methods. Each technique has its own field of applicability depending on several factors, such as frequency of interest, required measurement accuracy, isotropic and homogeneity properties, form (i.e., powder, liquid, solid), size, requirements in terms of non-destructive or contactless testing, and temperature range. This article presents an overview of the different VNA-based techniques along with some actual examples of novel applications.

2. Dielectric Properties of Materials

At a high-level, materials can be grouped into insulators (i.e., dielectrics), conductors, and semiconductors. Dielectric is also a synonym for electrically insulating, therefore, when a dielectric material is exposed to an external electric field, it will be polarized. The amount of electromagnetic energy that a material stores and dissipates is measured by its dielectric and magnetic properties, namely electrical permittivity and magnetic permeability. Both are complex quantities. The real part of the permittivity is often referred to as dielectric constant. Materials can be divided into dispersive and non-dispersive, depending on whether their permittivity changes as a function of frequency or not, respectively. For dispersive materials, it is necessary to quantify their frequency behavior. Accordingly, the permittivity is typically measured as a function of frequency. The complex relative permittivity, ε_r, is defined as:

$$\varepsilon_r = \varepsilon' - j\varepsilon'' = \varepsilon' - j\frac{\sigma}{\omega}$$

Where $\sigma = \omega\varepsilon''$ is the electrical conductivity (S/m), $j = \sqrt{-1}$ is the imaginary unit, and $\omega = 2\pi f$ is the angular frequency (rad/s). The complex permittivity, ε_r, consists of a real part and an imaginary part. The real part, ε', measures the amount of energy stored in the material, while the imaginary part, ε'', also known as loss factor, measures the amount of energy loss from the material. The ratio of the imaginary part to the real part of the complex permittivity is defined as loss tangent (dissipation factor or loss factor):

$$tan\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\sigma}{\omega\varepsilon}$$

It measures the inherent dissipation of electromagnetic energy by the MUT.

3. VNA-Based Materials Measurements Techniques

As of today, several VNA-based methods exist that allow the measurment of a material's electrical properties, namely electric permittivity, ε, and magnetic permeability, μ, from a few kHz up to THz. For complex S-parameters measurements, both the real and imaginary part of ε and μ can be obtained simultaneously. Four main approaches can be used: open-ended coaxial probe methods, transmission line methods, free-space techniques, and resonators. The dielectric properties of the MUT depend on frequency, anisotropy, homogeneity, temperature, and many other parameters. Accordingly, there is no such thing as the best technique to accurately measure all materials dielectric properties at all frequencies and temperatures. The best method to choose will depend, in fact, on many parameters, such as: frequency band of interest, temperature, loss regime, form of MUT (i.e., powder, solid, liquid, etc.), size (thin film, large panel, sliced sample, etc.), non-destructiveness test needs, or possibility to contact with the MUT or not. What follows is an overview of the four most commonly used methods to probe materials properties at RF and microwave frequencies.

3.1 Open-Ended Coaxial Probe

This approach is widely used to measure lossy materials at high frequencies over a broad frequency range of 0.5 GHz to 110 GHz. The dielectric properties are extracted from the complex reflection coefficient measured by the VNA through a metallic probe pressed against the MUT. A calibration step is used to reference the measured reflected signal at the probe's aperture plane. This can be easily achieved by placing the standards (a short, an open, and a reference liquid) at the open end of the probe. The reference liquid must have known dielectric properties; water, saline, and methanol are commonly used. Flat solid surfaces and liquids are well-suited samples for this technique. For materials with low permittivity, the method introduces some uncertainties and deflections. The method assumes that only the TEM or TE mode is propagating. The main drawback of the open-end coaxial probe approach is that it limits the characterization to 1-port reflection measurements. Moreover, for solid samples, surface preparation must be done very carefully to insure that no air gaps remain between probe and MUT.

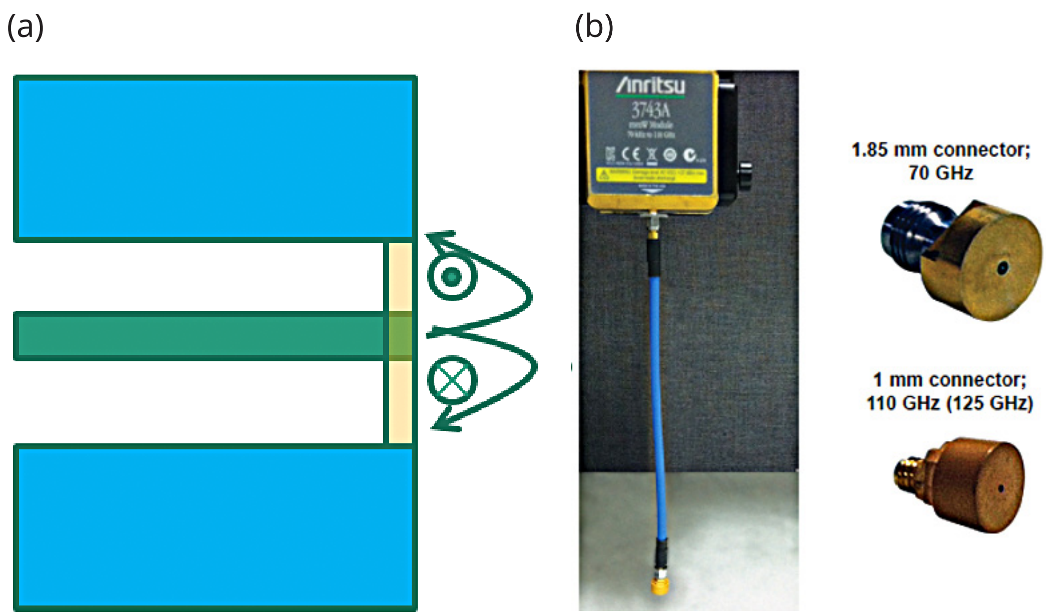


Figure 1. Open-end coaxial probe method. (a) Sketch of the probe with E-field lines at the probe/MUT interface. (b) Application of the method at millimeter-wave (mmWave) frequencies using Anritsu's 3743A mmWave modules and with a coaxial cable and zoom of 1.85 mm (70 GHz) and 1 mm (125 GHz) connectors.

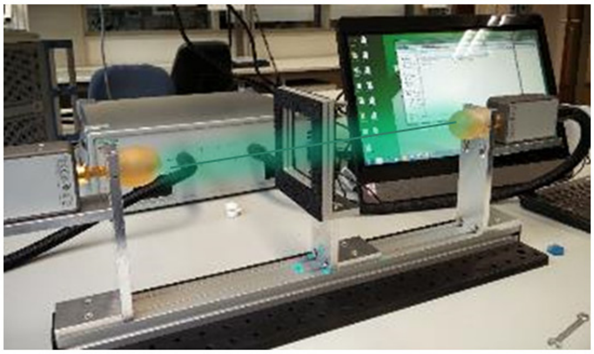
3.2 Transmission Line Method

This is a widely used broadband technique whereby the MUT is placed inside a transmission line, which can either be a piece of waveguide or coaxial cable. Permittivity and permeability are characterized from the measured transmission and reflection S-parameters. The method can be used for both solids and fluids, and has higher accuracy and more sensitivity than the open-ended coaxial probe technique. On the other hand, the frequency range is relatively narrower than in coax. The transmission line method assumes that only the fundamental waveguide mode (i.e. TE mode in waveguides and TEM mode in coaxial lines) propagates. The sample needs to fill the fixture cross-section with no air gaps at the walls. Thus, a key point of this method is the ability to fabricate MUT samples having flat faces, perpendicular to the long axis, and with known thickness > 20 – 360 λ. At higher frequencies, such as in mmWave applications, it can be quite demanding and more time consuming fabricating a sample that precisely covers the entire cross-section area of a line, in slab, or annular geometry form. General error rates of the transmission line method are <5% for the permittivity and permeability, and < 10% for the loss tangent. Another aspect to take into account is attenuation due to conduction or radiation loss occurring at the transmission line fixture. Common values for the resolution of the loss tangent are ±0.01; accordingly, materials having $\tan\delta < 0.01$ are not characterizable.

Figure 2. Transmission line setup for broadband materials measurements. The setup is composed of an Anritsu VectorStar™ ME7838E VNA with 70 kHz to 110 GHz (1 mm coaxial output) full sweep capability and a set of waveguide components covering the wideband range. At the bottom, a zoom of a WR-19 waveguide transmission line is shown, with the MUT located at the central junction.

3.3 Free-space setups

When an electromagnetic wave propagates from free-space into the MUT, both the wave's path impedance and velocity are changed. As a result of the path impedance change, there is a partial reflection of the incident wave at the point of change, namely at the interface between air and the MUT. Characterization of both the reflected and transmitted portions of the wave provide the information from which the dielectric properties of the MUT can be extracted. As long as the wave-fronts are nearly planar throughout the sample, free-space techniques share the same de-embedding algorithms as transmission line methods. The main difference for free-space setups is that the S-parameters are calculated between two antennas, where the sample is placed in the line of sight and the free-space acts as a transmitting channel. A typical free-space setup includes a horn pair corrected by dielectric lenses placed over their apertures, thus configuring a common focal point at the MUT's surface. In this way, via the lens, the transmitting horn radiates a collimated Gaussian beam, thus limiting diffraction contributions from the MUT edges. In general, common sources of error in free-space setups are transmitting probe and sample misalignments as well as diffraction effects. Another critical aspect is that precise manufacturing and alignment of the lenses is required to limit wave-front aberrations and multiple reflections. This makes the cost of the free-space setups quite expensive, especially for broadband applications.



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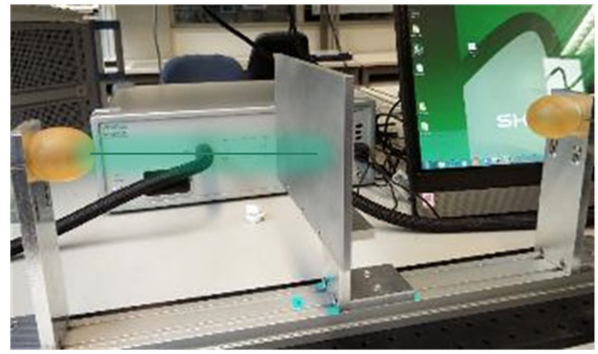

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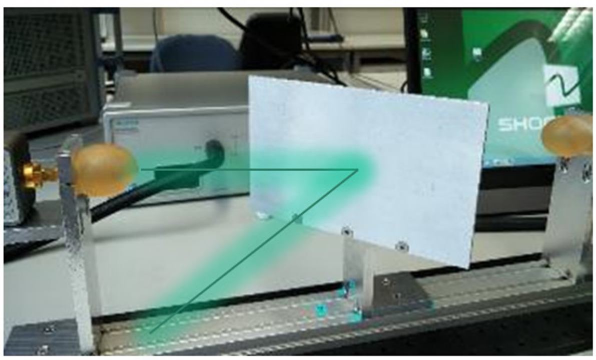

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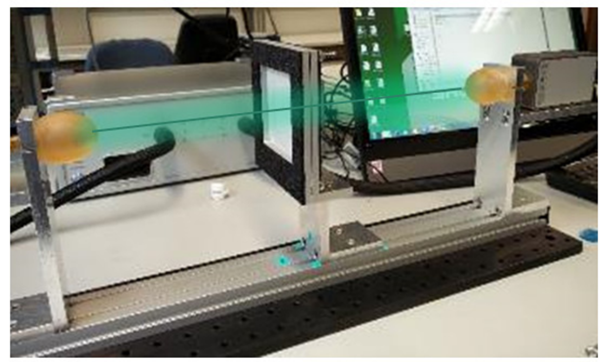

MUT Standard

Figure 3. Free-space setup for material measurements from a joint project involving Fraunhofer FHR, RWTH Aachen IHF, and Anritsu (more info here: https://www.anritsu.com/en-US/test-measurement/video-gallery/e-band-dielectric-measurement). The setup is composed of an Anritsu Shockline™ MS46522B-082 VNA with small tethered source/receiver modules and a base chassis. The modules are attached to the chassis through one-meter cables that are permanently attached to the unit. The remote modules have native WR-12 waveguide interface, and are interfaced to horn antennas and a custom designed lens system. The three steps of a TRM calibration are shown, together with the actual measurement of the MUT.

3.4 Resonators

Resonant methods enable the measurement of the dielectric properties at a single frequency or at a set of discrete frequencies. This allows reaching higher accuracy – such as four digits in the permittivity and loss tangent – and sensitivity with respect to the previously described non-resonant methods. Here, the MUT is placed inside a resonant cavity having known resonant frequency and quality factor. The change in the latter quantities introduced by the MUT is thus measured, and the permittivity and permeability are determined. Different types of resonators exist, such as coaxial, cylindrical cavity, and split resonators. Typical errors associated with resonator-based methods are less than 1% for the permittivity and 0.3% for the loss tangent. However, such high-accuracy fails for high-loss materials, such as the resonant peak, broadens as the loss increases.

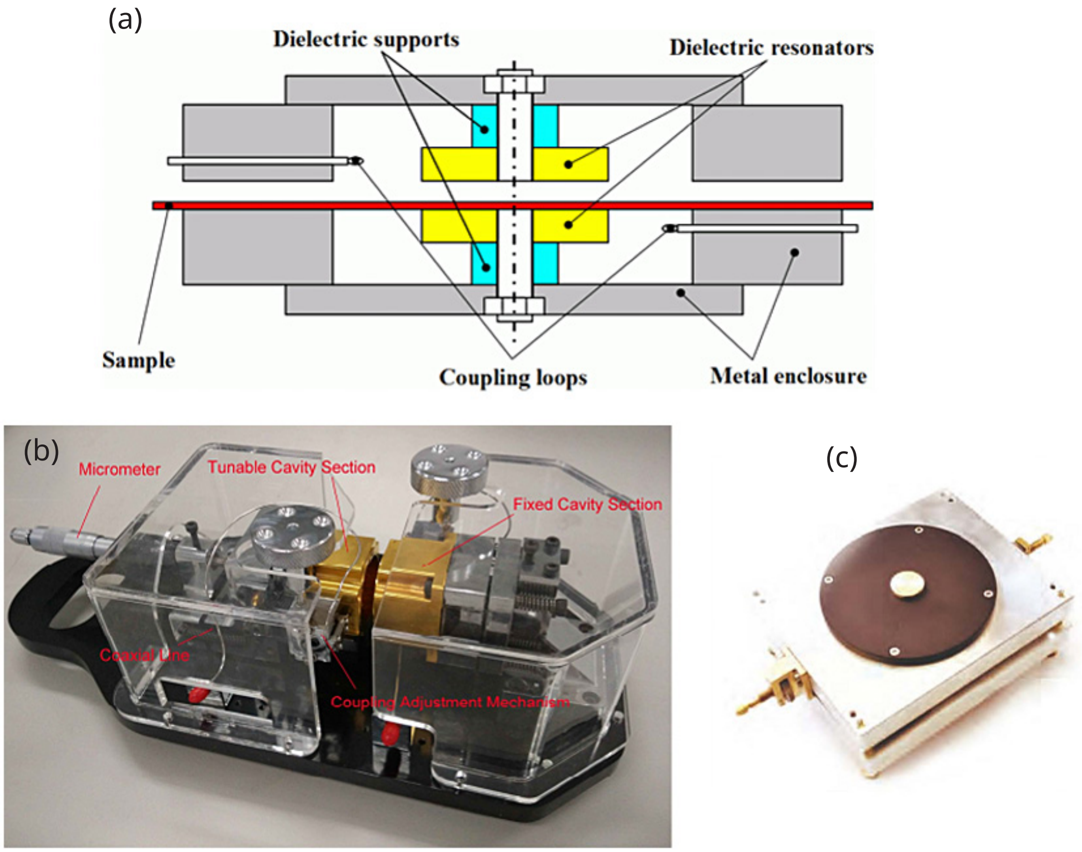

Figure 4. Cavity resonator setup for materials measurements. (a) Sketch of the sample holder stage showing the dielectric supports and resonators, the sample plane (red), and the coupling loops. (b) and (c) show actual cavity resonators.

3.5 Comparison of different methods

Each methodology has its own field of applicability and, as described, the best choice often depends on: frequency range of interest, required measurement accuracy, isotropic and homogeneity properties, form (i.e., powder, liquid, solid), size, requirements in terms of non-destructive or contactless testing, and temperature range. The table below summarizes the advantages, fields of applicability, and limitations of each technique.

Measurement Techniques	Materials	S-Parameters	Dielectric Properties	Benefits
Open-end coaxial probe	• Liquids • Biological samples • High-loss	S_{11}	ε_r	• Broadband • 1-port only • Low accuracy
Transmissin line	• Machineable	S_{11}, S_{21}	ε_r, μ_r	• Broadband • Machineable solids
Free-space	• High-temparature • Large flat solids • Gas • Hot liquids	S_{11}, S_{21}	ε_r, μ_r	• Broadband • Contactless • Alignment issues • Multiple reflections
Resonant method (Cavity)	• Rod-shaped solids • Liquids	Resonance frequency, Q-Factor	ε_r, μ_r	• High accuracy • Single frequency • Low-loss or thin samples

4. From S-parameters to dielectric properties

Different techniques have been proposed to extract dielectric properties from S-parameters. A popular and pioneering method is the Nicholson-Ross-Weir (NRW) method, which can be applied both on reflection and transmission line measurements. The technique involves four steps: a first step in which three S-parameters are measured (S11 and S21 with the sample, and S21 without the sample); then, three unknowns are calculated (reflection coefficient, and wave propagation constant with and without MUT); from the three unknowns, the refractive index and the impedance can be calculated in a third step; finally, the MUT's permittivity and permeability are obtained from the latter two quantities. The NRW method is fast and non-iterative, but its accuracy drops significantly when the MUT size is integer multiples of the incident beam's half-wavelength. This, especially when broadband measurements need to be performed, often cannot be avoided. A second technique, proposed by Baker-Jarvis of NIST in 1990, uses the NRW solution as the starting point and applies an iteration method to solve for the dielectric parameters. The NIST algorithm, although more complex than the NRW, helps overcome the issues concerning the sample dimensions, and is suitable for long samples and for characterizing low-loss materials.

5. Applications

The variety of available VNA-based techniques for measuring materials properties gives users extreme flexibility in choosing the best method for a specific application. As such, VNA-based techniques have spread out to different fields, each having different requirements. For example, the open-end coaxial cable method has been successfully applied in shielding effectiveness research studies [1]. The transmission line method has been used to study the electromagnetic absorption properties of carbon nanotube nanocomposite foam filling honeycomb waveguide structures [2], the dielectric properties of soil [3], and to study the activity of neurological cell solutions [4]. Also, a novel multimodal transmission line method for broadband characterization of dielectric materials properties has been proposed not long ago [5]. Recently, an innovative method to simplify the calibration steps in free-space setups has been proposed [6]. An eye-catching and useful study based on free-space measurements have been shown [7], whereby measurements of EM building wall attenuation have been carried out in the city of Rome, Italy, in different buildings topologies: historical buildings from the Roman Empire up to middle 19th-century and modern reinforced concrete buildings. The resonator approach has been successfully applied to develop a new mmWave sensor for identification and dielectric characterization of non-ionic surfactants [8]. Other use cases of the resonator method include the dielectric characterization of nematic liquid crystals at mmWave frequencies using a patch resonator approach [9], and the development of a simple and low cost technique to estimate relative permittivity and tangent loss of dielectric sheets used in printed circuit boards [10].

6. Conclusions

This paper has discussed the use of VNAs as a flexible and versatile tool to accurately and quantitatively characterize materials properties, such as electrical permittivity and magnetic permeability, ranging from a few kHz up to the THz range. Additionally, different methods have been presented to extract permittivity and permeability of the MUT from either 1- or 2-port S-parameter measurements. The type of MUT that can be characterized using a VNA ranges from biological matter and liquids to solids and powders. The available algorithms that allow converting the measured S-parameters into relevant materials properties have been discussed. An overview of recently published real case studies employing different VNA-based techniques have been presented, showcasing the broad applicability of the VNA as a tool to characterize materials properties at high frequencies.

7. References

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