New Developments in Microwave Materials Measurements

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Fundamental to microwave device design is knowing the electromagnetic performance of materials used in the device. Whether it is a microwave substrate, an antenna radome, or an electromagnetic inference absorber, methods are needed to evaluate materials and determine their intrinsic dielectric and magnetic properties. Designers use these intrinsic parameters (permittivity and permeability) to develop or optimize microwave and RF components. Measuring the performance of microwave materials requires a system that includes i) a measurement fixture and ii) a microwave analyzer. The fixture and the analyzer are usually connected with microwave or radio frequency (RF) cables. Recent technology advances relevant to both parts of the materials measurement system are discussed in this paper.

For RF and microwave frequencies the microwave analyzer can be a vector voltmeter but is most commonly a vector network analyzer (VNA). A couple of decades ago, VNAs were large enough to occupy all of a full-sized equipment rack. Since then, they have steadily reduced in size so that today they occupy a reasonable space on a benchtop or can be mounted as a single component within a rack. Even a bench-top VNA, however, is relatively large and heavy so that it must sit beside a materials measurement fixture, connected by an RF cable. In the last few years a new type of ultra-miniaturized VNA has emerged that has created a new paradigm for materials measurement. These palm-sized VNAs are single port devices, small enough and light enough for direct connection to a materials measurement fixture. Direct connection eliminates the need for an RF cable. For example, a new line of palm-sized VNAs has recently been made commercially available by Copper Mountain Technologies, who were awarded a U.S. Patent related to this cable-less idea[1].

Eliminating the RF cable is important because it has been a persistent source for measurement error. Even accidental 'bumping' of an RF cable can cause enough phase shift in the measured signal for substantial measurement uncertainty. Furthermore, the Teflon materials used in most RF cables exhibit thermal expansion related phase shifts near room temperature. Thus, equipment in a materials measurement laboratory must be calibrated often to account for ambient temperature changes. In some cases, even the cycling of the room air conditioner is enough to induce unwanted measurement errors. Such sensitivity to movement or temperature also makes it difficult to conduct material measurements in a field or factory setting, where the environment is not as controlled as in a laboratory.

The second part of a materials measurement system, the measurement fixture, has also benefitted from recent technology advances. Specifically, improvements in computational electromagnetic (CEM) tools and computer speed have enabled new measurement methods. Traditional measurement fixtures for RF and microwave measurement include capacitive[2] or inductive[3] devices, various waveguides[4], and free space apparatus[5]. These devices have been historically designed so that simplified analytical expressions are used to convert measured reflection or transmission into intrinsic properties.

With new CEM tools, more complicated measurement fixtures can be designed. More importantly, simplified analytical expressions for converting reflection and transmission from a VNA into intrinsic properties are no longer necessary. Computational models of the measurement fixture can be directly used to convert the measured parameters into dielectric permittivity and/or magnetic permeability of the material under test.

This paper discusses the implications of the newly emerged palm-sized VNAs as well as advanced computational fixture design on materials measurement technology. Specifically, it provides two examples of new material measurement systems that have been recently developed around these enabling technologies.

COMPACT MICROWAVE REFLECTOMETER SYSTEM

One of the most important benefits of a compact VNA is the elimination of the RF cable that connects it to a measurement fixture. Along with their associated measurement uncertainties, cables are a costly wear item in measurement systems, especially when motion is necessary. The compact VNA has also created a new material measurement paradigm. Conventional microwave equipment is too unwieldy for use in a factory setting, so 'witness' coupons must be made and brought to the measurement apparatus. With the introduction of miniaturized VNAs, a new possibility of measuring materials and components in-situ is possible, eliminating the need for witness coupons. In other words, miniaturized VNAs bring the materials measurement capability out of the laboratory and onto the more challenging environment of the factory floor. Direct measurement of the materials and components being

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[1] SA Zaostrovnykh, VI Ryzhov, AV Bakurov, IA Ivashchenko, AI Goloschokin, "Measurement module of virtual vector network analyzer," U.S. Patent 9291657B2

[2] JW Schultz, "Anomalous Dispersion in the Dielectric Spectra of Conductive Materials," IEEE Trans. I&M 47.3 (1998): 766-768

[3] JW Schultz, "Computational Analysis of a Permeameter Materials Measurement Fixture," AMTA Proceedings, November 2008

[4] J Baker-Jarvis, et al, "Transmission/Reflection and Short-Circuit Line Methods for Measuring Permittivity and Permeability," NIST Note 1355, (1992)

[5] JW Schultz, <u>Focused Beam Methods, Measuring Microwave Materials in Free Space</u>, ISBN 1480092851, 2012

manufactured increases confidence in the delivered product, lowers risk, and saves cost.

Another key ingredient for this new, in-situ measurement paradigm is a compact microwave sensor or ‘spot probe’. In the 1970s, Musil, Zacek, et al. proposed the use of spot probes for microwave material measurements. Their probes used dielectric rod filled horn antennas to measure millimeter wave transmission through a material specimen[6]. More recently Diaz et al. designed higher-performance ‘polyrod’ spot probes that worked at microwave frequencies. The polyrod was made of multiple dielectric layers inserted into a horn antenna. Their innovation was to use computational electromagnetic tools to optimize the inserted polymer material for a favorable impedance match of the probe antenna[7].

Since then, a new line of compact and ruggedized spot probes have been developed by the Compass Technology Group (CTG). Like the probes designed by Diaz et al, advanced computational electromagnetic tools were used to optimize the probe performance. However instead of using existing horn antennas, CTG’s probe optimized both the antenna functionality and dielectric rod functionality together into an integrated unit. The outcome is even more performance and greater ruggedization than previous spot probes. As a result, these probes have measurement accuracies similar to larger laboratory measurement systems when measuring materials at normal incidence.[8]

Figure 1 shows an integrated reflectometer that includes a Copper Mountain Technologies’ RP180 combined with Compass Technology’s SP218 spot probe. This system is hand-held and requires cables only for power and communication (USB) with a data acquisition computer. It weighs only about 3 lb (1.4 kg). Use with a battery for power and a tablet PC makes this system especially portable.

Calibration of this device requires only two measurements: a ‘response’ measurement and an ‘isolation’ measurement. The response is a reference standard such as a flat metal plate. The isolation is simply measuring the probe while it is pointed at free space. This isolation measurement allows subtraction of foreground, including the probe response, from the signal of interest. Additionally, time-domain processing is used to further isolate the signal of interest from other unwanted reflections (such as room reflections). Time domain processing transforms the wide-band frequency data into time domain and isolates the reflection of the sample under test from the rest of the detected reflections.

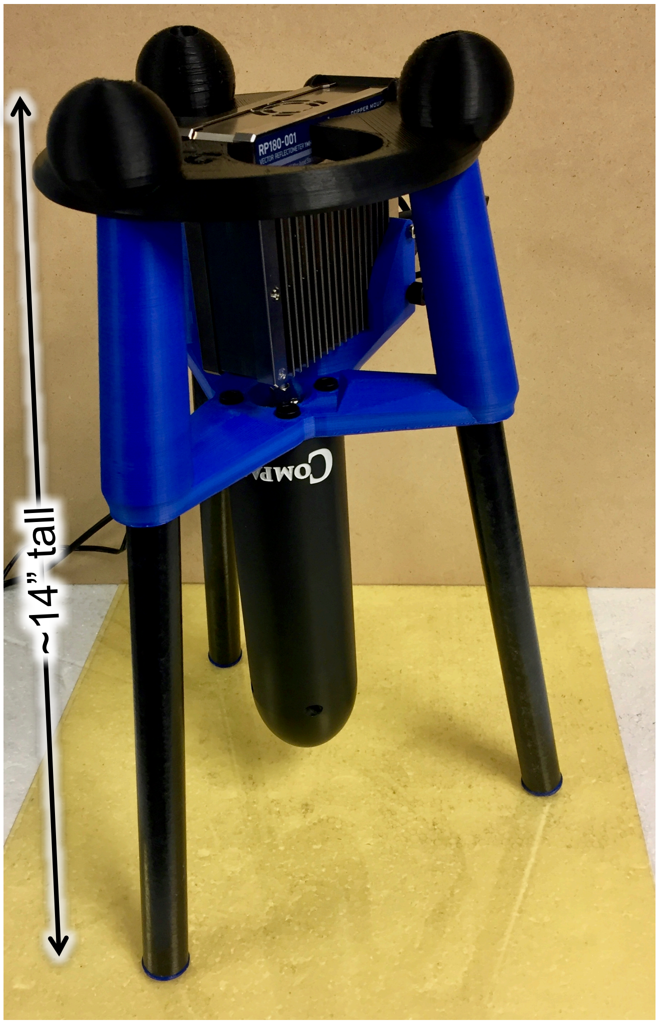

Figure 1 Photograph of an integrated 2-18 GHz reflectometer system including both sensor and a Copper Mountain Technologies RP180 vector analyzer.

Figure 2 shows an example measurement of a dielectric substrate, poly(etherimide) or PEI. This material is an engineering polymer that is known for its ability to withstand relatively high temperatures. In the data shown, the handheld probe system was used to measure the reflection coefficient of a 0.040-inch sheet of the material. The dielectric properties were inverted using an iterative algorithm with a single layer slab model.

If the dielectric properties are already known, the thickness can be inverted instead. Additionally, multi-layer models of the

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[6] J Musil, F Zacek, A Burger, J Karlovsky, “New Microwave System to Determine the Complex Permittivity of Small Dielectric and Semiconducting Samples,” 4th European Microwave Conference, 66-70, 1974

[7] R Diaz, J Peebles, R Lebaron, Z Zhang, L Lozano-Plata, “Compact Broad-Band Admittance Tunnel Incorporating Gaussian Beam Antennas,” U.S Patent 7889148, 2007

[8] JW Schultz, J Maloney, K Cummings-Maloney, R Schultz, J Calzada, B Foos, “A Comparison of Material Measurement Accuracy of RF Spot Probes to a Lens-Based Focused Beam System,” Proceedings of the 2014 AMTA, Tucson AZ, 2014

material under test can be compared to the measured data for more complex inversions.[9] For example Figure 3 shows the measured reflection coefficient of a fiberglass radome layer with and without a layer of painter's tape applied to one side. In this case, the tape is being used to simulate the effect of painting the radome. The applied tape layer is only 4 mils thick and a two-layer inversion can accurately detect the tape AND measure its thickness. This is especially striking when considering that the tape is a very small fraction of a wavelength.

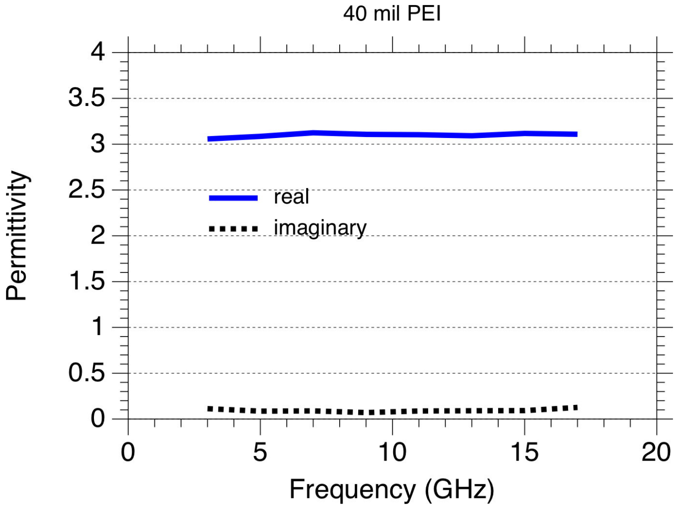

Figure 2 Real and imaginary permittivity of 0.040" PEI specimen measured by reflectometer system

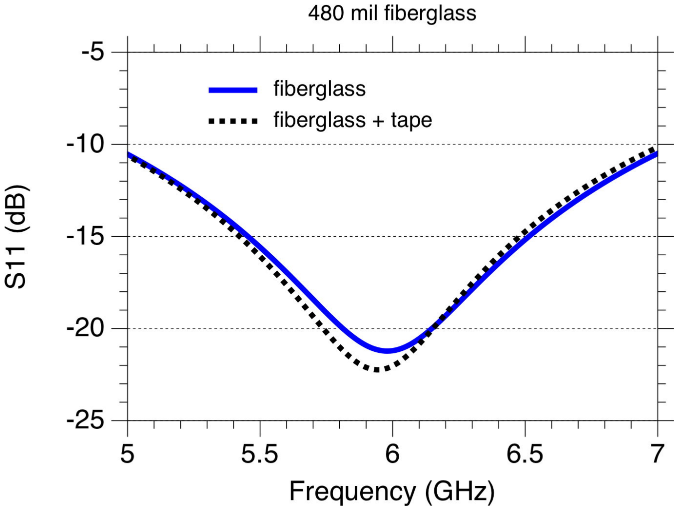

Figure 3 Reflection amplitude (dB) for a 0.480" thick fiberglass with and without simulated paint (0.004" tape)

TABLETOP VHF/UHF MATERIALS MEASUREMENT

The second example measurement system is one that also advances the state-of-the-art in measuring anisotropic and inhomogeneous materials. Anisotropy is the effect in materials where an intrinsic property such as dielectric permittivity has different values when measured in different directions. Inhomogeneity is the idea in composite materials that the dielectric constant is not uniform due to the different constituent regions that make up that composite.

The quest for measurement methods of inhomogeneous and anisotropic materials at VHF and UHF frequencies has long been a stretch goal of the materials measurement community. Until now, the most practical method for these types of materials has been VHF waveguides, which are large and expensive. While there are other methods that work at these frequencies, such as coaxial or stripline waveguides, they are poorly suited for inhomogeneous and anisotropic materials.

For homogenous dielectric materials, a conventional method at VHF frequencies and below is the impedance analyzer, which forms a capacitor from the specimen under test. This method is the basis of the discipline of dielectric spectroscopy,[10] which typically uses thin, flat specimens sandwiched between parallel electrodes. The key assumption of dielectric spectroscopy is that the capacitor formed by the specimen is small, so that it can be modeled with a simple circuit model.

Inhomogeneous materials such as engineered metamaterials have interior structures with periodicities that are a significant fraction of a wavelength in dimension. Other engineered materials, such as honeycomb, are **in**homogeneous with length scales too large to be accurately represented by conventional dielectric spectroscopy, especially at higher frequencies. Thus, the measurement system describe here has some similarities to older impedance analysis methods in that it resembles a capacitor. However, it differs in that it also accounts for radio frequency (RF) and higher effects that occur when making a fixture for larger specimens. For this reason, it is termed an 'RF Capacitor' material measurement system.

Like the reflectometer system described above, the tabletop VHF/UHF measurement system leverages the new palm-sized 1-port VNA's to eliminate cables and have a small footprint. The fixture design also used a CEM code to optimize performance for the materials of interest. Additionally, this new measurement device has one more distinguishing feature in that it uses the results from CEM calculations to do the material property inversion. This contrasts with conventional measurement algorithms which are constrained by analytical approximations. As a result, the measurement accuracy and over-all capability of this system has not been available before in conventional methods.

The measurement system described here accounts for high frequency effects by implementing a new inversion technique

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[9] JW Schultz et al, "Non-Contact Determination of Coating Thickness," Patent Pending 20150285621

[10] JW Schultz, "Dielectric Spectroscopy of Polymers," in Encyclopedia of Analytical Chemistry, pp. 7543-7562, (R.A. Meyers, Ed.), Wiley, (2000).

based on a full-wave, finite difference time domain (FDTD) solver. The FDTD solver is used to exactly model the measurement geometry accounting for all fringe fields as well as parasitic capacitances and inductances that plague conventional impedance analysis. In addition, this FDTD solver is applied in a novel way to enable inversion of frequency-dependent dielectric properties within seconds.

The conceptual design of the RF capacitor is shown in Figure 4. The fixture consists of a square coaxial airline section with both an inner conductor and an outer conductor, that is transitioned to N-type connector on one side, and terminated to an electrical short on the other end. The square coaxial airline section is sized so that the specimen replaces a section of the center conductor of the transmission line. A metal plate is positioned adjacent to the material specimen to form the shorted end. This fixture's single port integrates with the miniaturized 1-port VNAs, such as those manufactured by Copper Mountain Technologies.

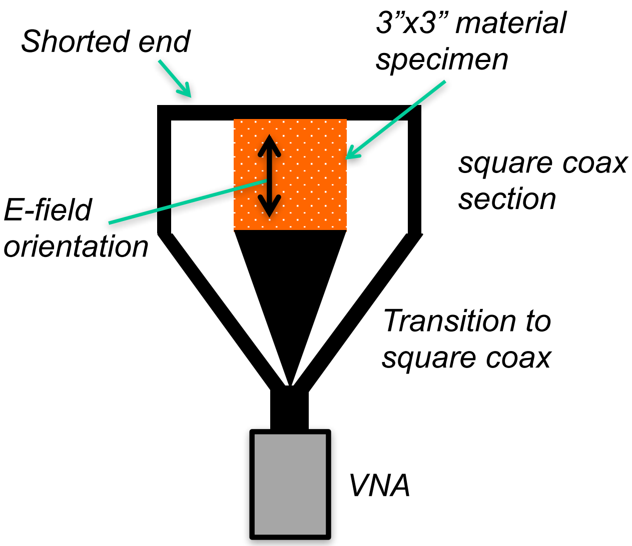

Figure 4 Conceptual design of RF capacitor

Because the fixture is a coaxial transmission line, it is impedance-matched to the 50-ohm output impedance of the VNA by insuring the cross sectional dimensions of the square coax also correspond to a 50 ohm transmission line. The measurement of a specimen consists of measuring the reflection coefficient of the fixture with the specimen inserted.

An important feature of this fixture is that it is a closed system. In other words, the outer conductor prevents radiation from the specimen so that all energy is accounted for – either absorbed by the material specimen or reflected to the microwave analyzer. Another feature is that this geometry creates an electric field within the specimen that is oriented predominantly in one direction as shown by Figure 4. There is very little E-field in the other directions so that the dielectric properties in a given tensor direction are determined by only a single measurement.

Figure 5 shows a photograph of the exterior of the RF capacitor fixture. As shown, the shorted end of the fixture consists of a removable plate that can slide in and out of the fixture. When a specimen is inserted into the fixture, the metal plate sits on top of the specimen. The plate is weighted so that intimate contact is ensured with no air gaps. However, the plate is not so heavy as to distort the specimen under test.

Calibration of this fixture consists of a 'response' calibration method. The fixture has a low-dielectric foam standard inserted and the reflection coefficient (S_{11}) is measured. Subsequent material measurements are simply ratioed to the foam measurement response. With this calibration method, no extra signal processing or time-domain gating is necessary. This calibration is considerably simpler than conventional high frequency impedance analysis methods or waveguide methods, which require three or more calibration standards to properly perform the fixture compensation: e.g. short, open, and load. This simplified calibration is possible since the computational model includes the transition explicitly.

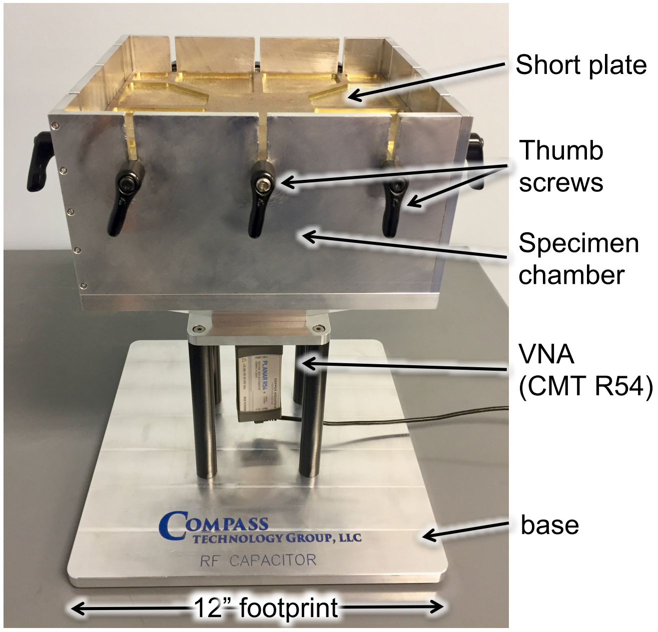

Figure 5 Photograph of RF capacitor measurement system

Once the calibration is complete, the specimens are inserted and measured. The complex dielectric permittivity is inverted from the calibrated reflection coefficient. Both the amplitude and phase of the reflection loss are collected as a function of frequency, so the real and imaginary permittivity can be determined on a frequency-by-frequency basis. Because coaxial airlines are broadband, a broad range of frequency dependent data can be obtained from a single measurement. This is in contrast to the waveguide techniques usually used for measuring these types of inhomogeneous materials, and which are band-limited, requiring multiple measurements of multiple specimens to obtain wide-band data. For the RF capacitor fixture shown in

Figure 5, material properties can be obtained from 60 MHz to 800 MHz with a single measurement.

Inversion of the complex permittivity is done by a table-lookup algorithm where the measured reflection coefficient is compared to pre-computed reflection coefficients from a variety of virtual specimens. The exact geometry of the RF capacitor was modeled with the full-wave FDTD solver, and the results were used to build a table that correlates dielectric properties to calibrated S_{11}.

In the FDTD method, dielectric materials are most efficiently modeled by a dielectric constant (i.e. real permittivity) and a bulk conductivity, which is related to the imaginary permittivity. A series of calculations were made to span the expected range of permittivities to be measured. In the data shown below, the data table consisted of a 25 by 30 element matrix of values for each frequency: 25 different real permittivities, and 30 different bulk conductivities. Thus, a total of 750 different FDTD simulations were run to create this data table. For the inversion table used here, these simulations took less than a day to run on a modest computer cluster. Once a data table is constructed for a given specimen shape (3-inch cube in this case), there is no need to run these simulations again. Additionally, data tables can be generated for other specimen shapes (e.g. different size cubes as well as rectangular or thin sheet specimens).

The behavior of reflection coefficient as a function of the dielectric properties of the specimen is monotonic over most of the frequency range of interest. So, simple interpolation was used to obtain arbitrarily fine resolution of the inverted properties. At higher frequencies, multiple solutions were occasionally possible, but this is easily dealt with by limiting the lookup table search to be within the neighborhood of solutions obtained at the lower frequencies, where only single solutions are possible. Table lookups and interpolations are very fast so this pre-computed inversion method only takes seconds to convert measured S_{11} data into complex dielectric permittivity.

Finally, once an inversion table is constructed no special computational electromagnetics expertise or high-power computers are needed to use it. This makes this new inversion method especially appropriate for use in either a traditional laboratory or in an automated manufacturing setting.

To demonstrate the ability of this method to determine dielectric properties, several 3” cube specimens were constructed and measured. The first two specimens were simple isotropic materials: Acrylic and Delrin®. Acrylic is the trade name for poly(methyl methacrylate) and is well known to have a relative dielectric constant near 2.6 across all microwave frequencies. It is also known to have a dielectric loss factor very close to zero. Delrin® is the trade name for polyoxymethylene (POM), and is one of the few polymers that has significant dielectric loss at microwave frequencies. POM also has a slightly higher real permittivity than Acrylic. The measured amplitude and phase of specimens of these simple polymer specimens are shown in Figure 6 and Figure 7 respectively.

As Figure 6 shows the reflection loss amplitude for Acrylic is close to 0 dB except at the highest frequencies. Since the amplitude is mostly related to the energy absorbed by the specimen and because Acrylic has a very low dielectric loss factor, it is expected to be close to zero for Acrylic. On the other hand, POM exhibits an insertion loss of a few tenths of a dB because its dielectric loss factor is not zero at these frequencies. Note that the insertion loss amplitude even for Acrylic is not negligible at frequencies above 700 MHz, and this is an artifact of the measurement device. As shown in Figure 5, thumbscrews are used to electrically connect the short plate to the outer conductor of the RF capacitor. At a small enough wavelength (i.e. above 700 MHz in frequency), RF energy may leak out of the fixture between these thumb screws.

The phase of the reflection coefficient represents the delay in the energy propagating through the specimen, corresponding to the speed of light within the material and therefore its real dielectric permittivity. As shown in Figure 7, POM shows a slightly increased phase delay compared to the Acrylic material, indicating a higher real dielectric permittivity.

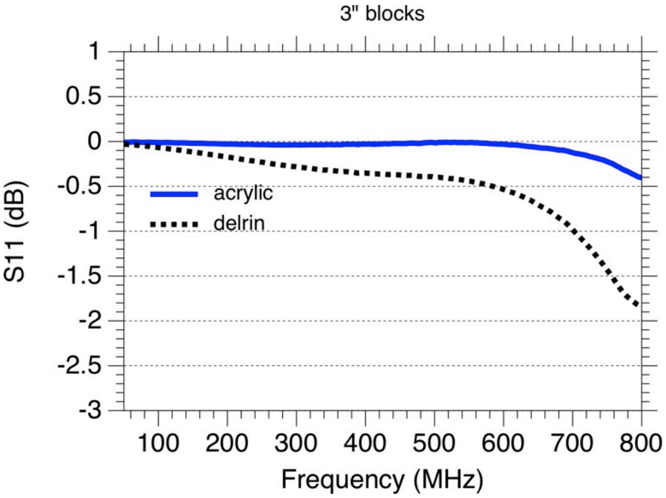

Figure 6 Calibrated S_{11} amplitude from Acrylic and POM specimens

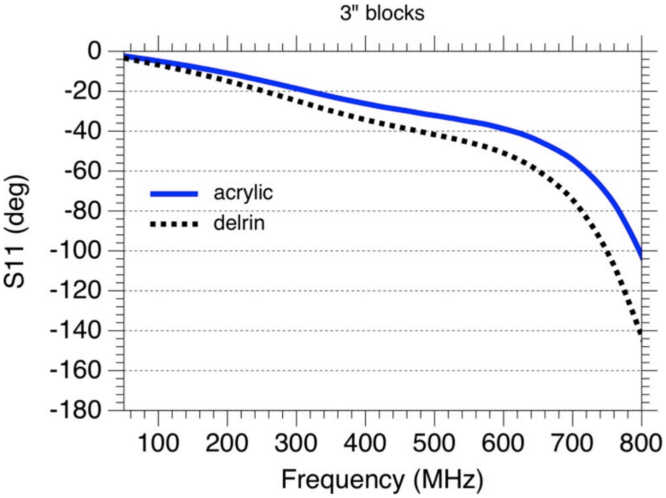

Figure 7 Measured S_{11} phase from Acrylic and POM specimens

From the calibrated reflection data of Figure 6 and Figure 7, the inverted real dielectric permittivity (solid lines) and imaginary permittivity (dotted lines) are shown in Figure 8 for Acrylic and in Figure 9 for POM. In addition to the inverted specimen data, Figure 8 also includes the known dielectric properties of Acrylic ($\varepsilon \sim 2.6 - 0i$), which overlays with the RF capacitor measured results. Figure 9 also includes measured properties of low-moisture POM from the literature using a conventional impedance analyzer method[11]. As this Figure shows, the literature properties closely correspond to the inverted POM properties from the RF capacitor measurement system.

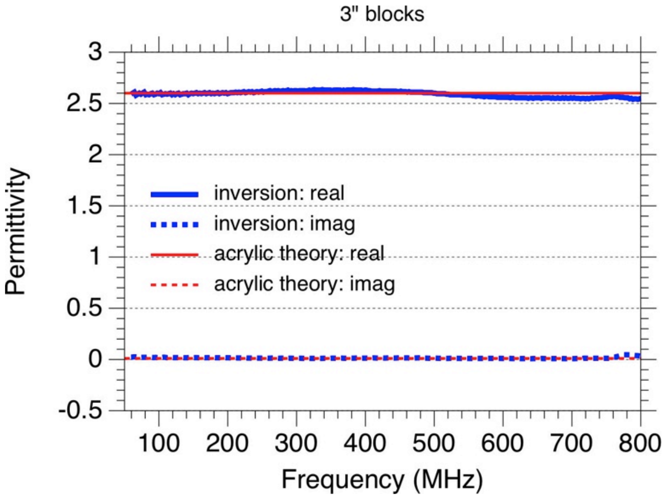

Figure 8 Inverted real (solid) and imaginary (dotted) permittivity of Acrylic

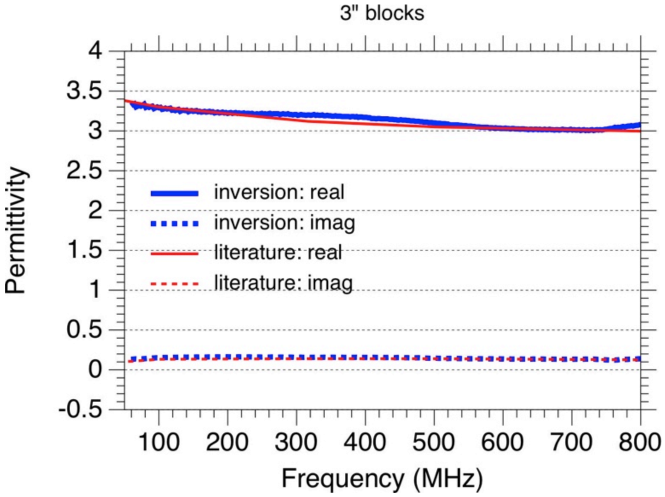

Figure 9 Inverted real (solid) and imaginary (dotted) permittivity of POM

Finally, an anisotropic artificial dielectric material was constructed by interspacing 6 thin layers of conductive carbon-loaded foam between layers of low-dielectric foam. The carbon foam layers were 0.125" (3.175 mm) thick while the low-dielectric layers were 0.25" (6.35 mm) thick. Such a layered material will have high loss in the directions parallel to the plane of the layers and low loss in the direction perpendicular to the layers. This is because the parallel direction has fully connected carbon foam in which current can flow, while the perpendicular direction has low-loss dielectric layers interrupting current flow. This anisotropy in the dielectric properties is shown in the inverted permittivity data of Figure 10. These data show that the RF capacitor is very capable of measuring and inverting properties of anisotropic materials.

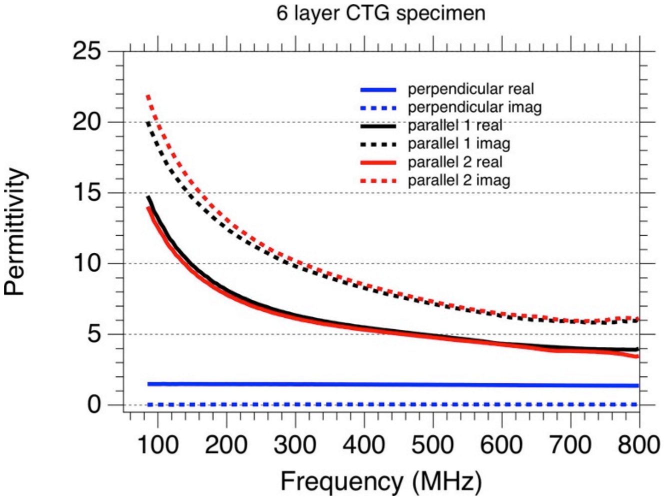

Figure 10 Inverted real (solid) and imaginary (dotted) permittivity of an artificial dielectric made of carbon foam and low-loss foam layers

As further verification of the RF capacitor data, Figure 11 compares the RF capacitor measured data for the artificial dielectric specimen to high frequency, free-space measurements. A probe-based free-space method was used to measure both the carbon foam and low dielectric foam constituents of the artificial dielectric, and then a simple parallel-circuit effective medium model was used to calculate the composite dielectric properties plotted in Figure 11. The data shown are averaged over both parallel directions. As these data show, the RF capacitor results are consistent with the high frequency properties of the specimen.

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[11] DA Wasylyshyn, "Effects of Moisture on the Dielectric Properties of Polyoxymethylene (POM)," IEEE Trans. Dielectrics & Elec. Insulation, 12(1), 183-193, February 2005

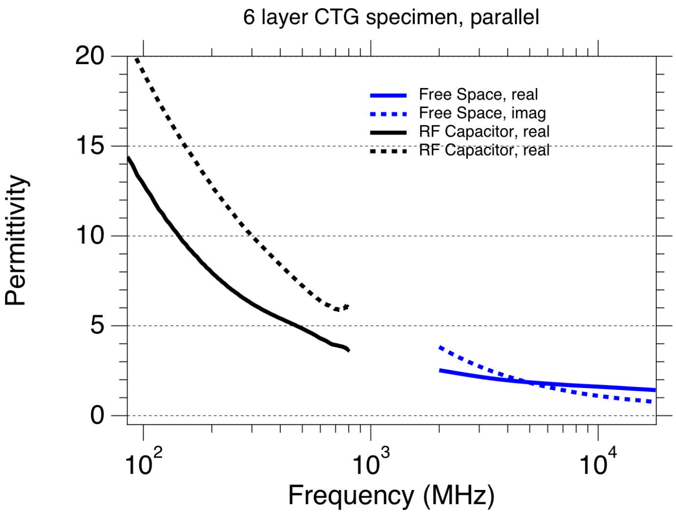

Figure 11 Comparison of RF capacitor to free space measurement of artificial dielectric material.

CONCLUSION

Traditionally, RF measurements of materials have been dominated by the paradigm of taking witness samples into the laboratory. This is because of the historically large size of both the microwave analyzer equipment and the fixturing. Recent technology developments in both compact spot probes and compact microwave analyzers are now enabling a dramatic shift in this paradigm. This article discussed the concept of a hand-held reflectometer system for measurement of microwave relevant materials. The technology described here integrates the microwave analyzer and sensor, thereby eliminating the need for RF cables.

A second recent technology improvement that has also advanced the design of new materials measurement fixtures is advanced computational electromagnetic simulation. High accuracy modeling techniques combined with ever faster computers allow new measurement fixture designs. In the past, fixtures were designed so that they could be modeled with simplified analytical equations. Now fixtures can be designed without this constraint. Additionally, numerical simulations can be used to convert measured parameters directly into the desired intrinsic material properties. This article showed an example of such a system, which uses a computed look-up table to do this material property inversion at VHF and UHF frequencies. Because of this, newer engineered composites such as meta-materials can be characterized. In general, the described system provides a new capability for measuring effective dielectric properties on materials that are both anisotropic and inhomogeneous.

From these measurement system examples, it is evident that the advances of i) miniaturized VNAs and ii) CEM based design and inversion provide critical enabling technologies for the creation of new materials measurement systems. From this, the microwave industry can expect to see new measurement devices and methods, with capabilities that were not previously attainable with conventional techniques.