A New Method for VHF/UHF Characterization of Anisotropic Dielectric Materials

John W. Schultz*, James G. Maloney
Compass Technology Group
Roswell, GA USA
John.schultz@compasstech.com

Abstract— **Recent interest in anisotropic metamaterials and devices made from these materials has increased the need for improved RF material characterization. Practical methods for measuring these types of materials at low frequencies has been limited to fully or partially filled VHF waveguides, which are large, expensive, and slow. This paper introduces a new fixture that greatly simplifies the process of obtaining intrinsic properties for inhomogeneous and anisotropic dielectric materials. The fixture combines low frequency capacitance and high frequency coaxial airline concepts to measure cube shaped specimens, and is termed an "RF Capacitor." Furthermore, a new inversion technique is introduced, based on a full-wave, finite difference time domain (FDTD) solver to exactly model the measurement geometry. This FDTD solver is applied in a novel way to enable inversion of frequency-dependent dielectric properties within seconds. This paper presents the fixture design and calibration method along with example measurements of isotropic and anisotropic dielectric materials. In particular, 3" (76 mm) cube specimens are measured and the bulk dielectric properties in the three principal directions are determined by measuring the same specimen in three different orientations within the fixture. Finally, calculations are presented to show the relative accuracy of this method against some probable uncertainty sources.**

I. Introduction

The quest for measurement methods of inhomogeneous and anisotropic materials at VHF and UHF frequencies has long been one of the primary stretch goals of the RF materials measurement community. Recent interest in anisotropic metamaterials and devices made from these materials has also increased the interest in advanced RF material characterization methods. Up until now, the most practical method for these types of materials has been either fully filled or partially filled VHF waveguides, which are large, expensive, and slow. While there are other methods that work at these frequencies, such as coaxial airlines or stripline waveguides, they are poorly suited for materials that are inhomogeneous and anisotropic.

One method that has been successfully used to characterize homogenous dielectric materials is the impedance analyzer, which forms a capacitor out of the specimen under test. This idea of creating a capacitor out of a material specimen has been in use for many decades. It forms the basis of the discipline of dielectric spectroscopy [1], which typically uses thin, flat specimens sandwiched between two parallel electrodes. The key assumption of dielectric spectroscopy is that the capacitor formed by the specimen is small, so that it can be modeled as a lumped circuit element. This assumption works when the specimen is electrically much smaller than a wavelength in its largest dimension and when the specimen is much thinner than it is wide so that it can be made into a parallel plate capacitor with minimal fringing fields. Such dielectric spectroscopy methods have been extended to UHF and even microwave frequencies [2][3], however the specimen size is necessarily small for these methods. Metamaterials, on the other hand, have interior structures with periodicities that are a significant fraction of a wavelength in dimension. Even some traditional materials, such as honeycomb core are inhomogeneous, with length scales that are too large to be accurately represented by conventional dielectric spectroscopy geometries, especially at higher frequencies.

A more recent attempt to address materials such as dielectrically lossy honeycomb core in a capacitor-like fixture was done by C.Y. Choi [4]. Like the method presented in this paper, Choi measured cubed shaped specimens at different orientations to obtain anisotropic material properties. The specimens are large enough, 3" (76 mm) cubes, to encompass the characteristic inhomogeneity length scales of honeycomb core, but this is too thick for measurement with conventional dielectric spectroscopy fixtures.

Nevertheless Choi's method still appears to make assumptions based on the lumped circuit model. Errors induced by this simplified model are dealt with by applying multiple calibration standards. However, the inherent disadvantage of this method is the lack of representative calibration standards with accurately known dielectric loss. Moreover, the 3" cube is large enough to have significant fringe fields and radiation from the specimen, which are attenuated by the use of absorber. This makes it difficult to fully account for the dielectric loss induced by the unknown specimen since not all the power is accounted for during the measurement.

A 3" cube is large enough to encompass many of the material inhomogeneities in a typical honeycomb core material, as well as many metamaterials. However because many of these materials have significant dielectric loss, a new method is needed to more accurately determine the dielectric properties when loss is present. Thus this paper introduces a new fixture that greatly simplifies the process of obtaining intrinsic properties for inhomogeneous and anisotropic dielectric materials with or without significant dielectric loss. The fixture combines the concepts behind low frequency capacitance and high frequency coaxial airline devices to make an "RF Capacitor" fixture that works at VHF and UHF frequencies.

As just described, a significant limitation of past capacitor measurement methods is their reliance on approximate analytical models to invert material properties. These analytical models restrict the available geometries and frequency ranges that a measurement fixture can have. Conversely, the method described in this paper avoids this limitation by also implementing a new inversion technique 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 methods. In addition, this FDTD solver is applied in a novel way to enable inversion of frequency-dependent dielectric properties within seconds.

II. RF Capacitor Description

The design principles underlying the RF capacitor include the idea that a specimen cannot be simply modeled as a lumped circuit element. Instead the material under test is part of a high frequency transmission line. Because of the desire to have cube shaped specimens, this leads to a square coaxial airline as a basis for the fixture. The conceptual design of the RF capacitor is shown in Figure 1. The fixture consists of a square coaxial airline section with both an inner conductor and an outer conductor, that is transitioned to an RF cable on one side, and that is terminated to an electrical short on the other end. The coaxial airline is sized so that the specimen replaces a section of the center conductor of the square coaxial transmission line. A metal plate is positioned adjacent to the material specimen to form the shorted end. Since this fixture is a one-port microwave network, it can be used with one of the many low-cost vector reflectometers that are commercially available, or with any existing laboratory network analyzer.

Because the fixture is a coaxial transmission line, it is straightforward to impedance-match it to a typical 50 ohm RF cable by insuring the cross sectional dimensions of the square coax also correspond to a 50 ohm transmission line. Thus 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 back 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 1. As will be shown later, 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.

In addition, as Figure 1 shows, the center conductor on one side and the short on the other side are in direct contact with the material specimen forming the RF equivalent of a parallel plate capacitor. Air gaps or electrode blocking effects may be of concern in such a geometry [1]. These blocking effects can lead to Debye-like relaxation behavior at low frequencies that are artifacts of the measurement device. To date, no such problems have been observed in testing of the RF capacitor. If such a situation does occur, then it is a simple matter of placing non-conductive dielectric spacers of known thickness on either side of the specimen under test. Because of the computational-based inversion method described below, these dielectric spacers can be easily accounted for by the inversion algorithm.

Figure 2 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.

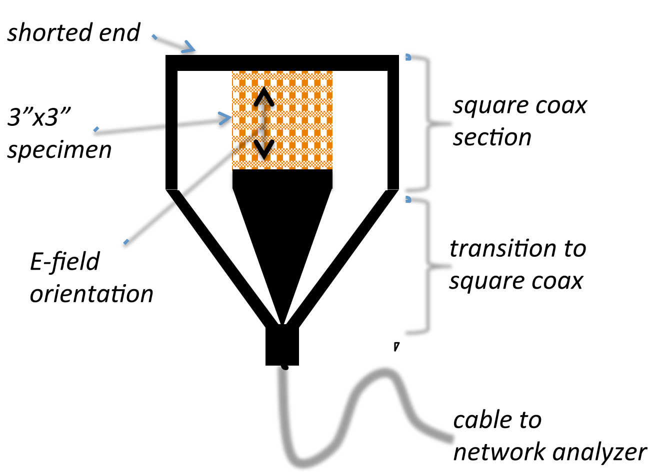

Figure 1 Conceptual design of RF capacitor.

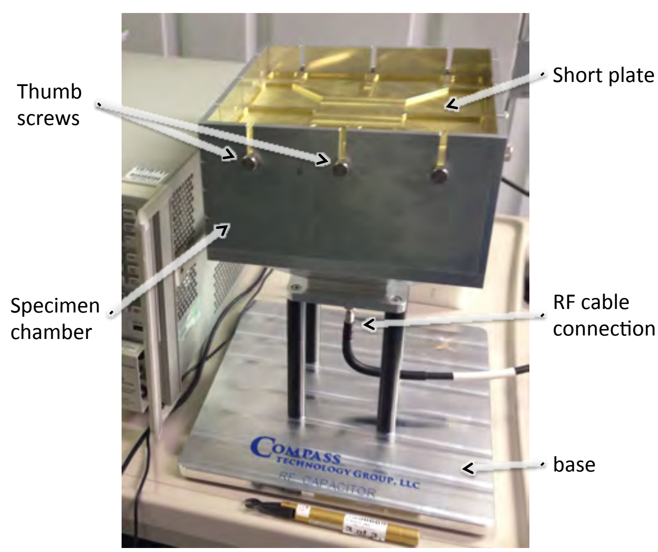

Figure 2 Photograph of RF capacitor.

Calibration of this fixture consists of two primary steps. The first step is to calibrate the RF cable connected to the fixture. This is done with a conventional 1-port calibration method, and is similar to what is typically done for existing high-frequency impedance analysis methods. This first step can be done using software that is typically built into commercial microwave analyzers.

The second step connects the RF cable to the RF capacitor and measures the RF capacitor fixture with a low-dielectric foam spacer. This second step is also called the fixture compensation or "response" calibration. When subsequent unknown specimens are measured, the fully calibrated specimen data is then calculated as a simple ratio to the response calibration data:

$$S_{11}^{calibrated} = \frac{S_{11}^{specimen}}{S_{11}^{response}} \quad (1)$$

where S_{11} is the measured or calculated reflection coefficient. 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, which require three calibration standards to properly perform the fixture compensation: short, open, and load. Similarly, Choi's method requires even more calibration standards [4]: short, open, and two loads.

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 determined 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 wide 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 and require multiple measurements of multiple specimens to obtain wide-band data. For the RF capacitor fixture shown in Figure 2, material properties have been successfully obtained from 60 MHz to 800 MHz with a single measurement.

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

In the FDTD method, dielectric materials are most easily modeled by a dielectric constant (i.e. real permittivity) and a bulk conductivity. Therefore a series of calculations were made to create a table with dielectric properties spanning the expected range to be measured with this fixture. 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. With a wideband pulse, the FDTD computational method has the convenient ability of creating broadband data. Therefore each single simulation provided data spanning over a decade of frequencies. 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.

The behavior of reflection coefficient as a function of the dielectric properties of the specimen was found to be 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 were very fast so this pre-computed inversion method only took seconds to convert measured S_{11} data into complex dielectric permittivy.

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.

III. MEASURMENT UNCERTAINTIES

While the geometry of the RF capacitor fixture is exactly modeled for the computational inversion. There are still a few simplifying assumptions made in building the inversion lookup table. In particular, to keep the lookup table tractable, the material under test is modeled as isotropic. This is a reasonable assumption because the E-field within the specimen is predominantly axial, and there is very little cross-component of the E-field interacting with the material. In other words, even though the specimen under test may be anisotropic, the E-field is predominantly only in one direction – parallel to the axis of the square coaxial geometry. Therefore it should not matter what values of dielectric permittivity and conductivity are used in the other two directions, as they should have a negligible effect on the RF capacitor response.

To test this assumption, a set of full anisotropic simulations were made of a material specimen that had a real permittivity of 4, and a microwave conductivity, σ, of 0.3 S/m in the measurement direction. These dielectric parameters are representative of some commercially available absorbing honeycomb core materials. In the two directions orthogonal to the measurement direction, the permittivity and microwave conductivity varied by multiplicative factors of 0.25X, 0.5X, 2X, and 4X relative to the measurement direction. The resulting S_{11} from these simulations were then inverted using the lookup table that was generated from isotropic simulations. The resulting error of this anisotropy is shown in Figure 3 and Figure 4. As these data show, the isotropic assumption induces very low errors for low frequencies. As the frequency increases, the error increases, but is still at manageable levels for most situations.

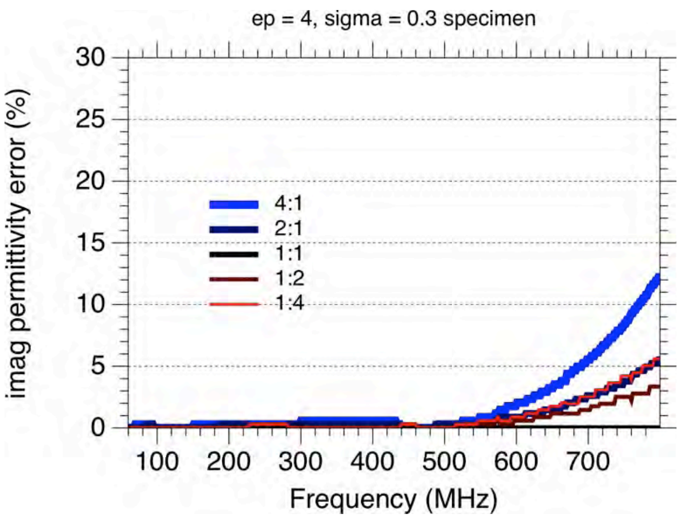

Figure 3 Percent error of imaginary permittivity for different in-plane/out-of-plane permittivity ratios.

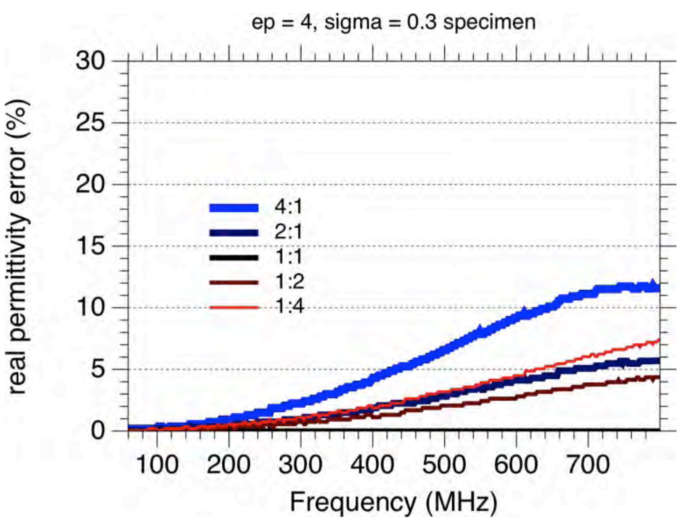

Figure 4 Percent error of real permittivity for different in-plane/out-of-plane permittivity ratios.

Another potential source of error for this RF capacitor fixture is due to the interface between the specimen and the metal short and square coaxial center-conductor. Because the short is actually a metal plate that slides, gravity will always ensure that i) it is in intimate contact with the specimen and ii) the specimen is in intimate contact with the coaxial center-conductor on its other side. However, when a material such as honeycomb core is machined into a cube specimen, there may be damage to the surface of that specimen that slightly alters the material properties near the cut. In other words, while there will never be a full air gap between the specimen and the metal, there may be a "partial" air gap due to this cutting damage. Additionally, contact with the metal may be incomplete if the specimen surface is not perfectly flat.

Figure 5 shows the computed errors in the inverted real permittivity (solid lines) and imaginary permittivity (dotted lines) of a lossy dielectric specimen (real permittivity of 4 and microwave conductivity of 0.4 S/m). These errors are for a damaged surface region of 1 mm thickness, and the damage was simulated by assuming that the dielectric properties of that 1 mm surface region were some percentage of the bulk specimen properties. In this Figure, 0 percent corresponds to air and 100 percent corresponds to an undamaged, perfectly flat surface. These data show that even if the surface region has properties that are only 50 percent of that in the bulk of the material, the resulting uncertainties are only a few percent or less.

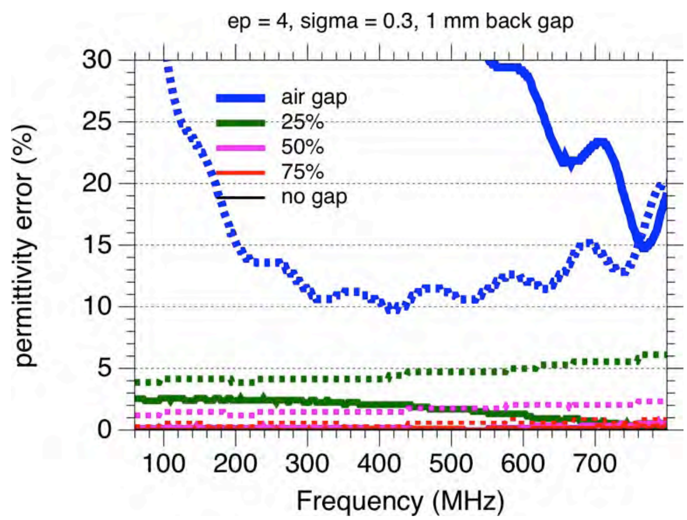

Figure 5 Percent error of real (solid) and imaginary (dotted) permittivity for different 1-mm "gaps."

IV. Example Measurements

To test the ability of the RF capacitor to determine dielectric properties, a number of 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 very near 2.6 across all microwave frequencies. It is also known to have a dielectric loss factor very close to zero [5]. Delrin® is the trade name for polyoxymethylene (POM), and is known as 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. In particular as shown in Figure 2, 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.

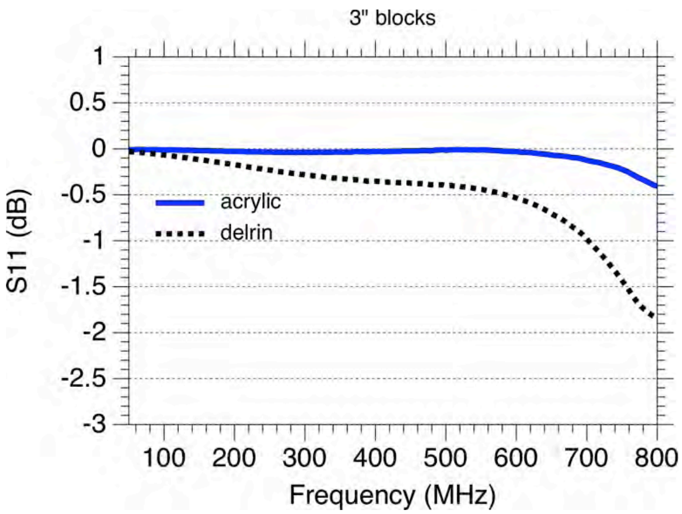

Figure 6 Calibrated S_{11} amplitude from Acrylic and POM specimens.

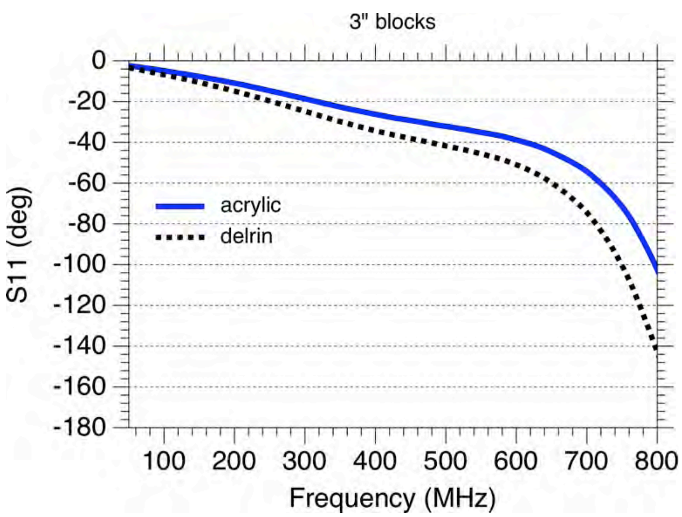

Figure 7 Measured S_{11} phase from Acrylic and POM specimens.

Based on the calibrated reflection loss 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 [6]. As this Figure shows, the literature properties closely correspond to the inverted POM properties from the RF capacitor.

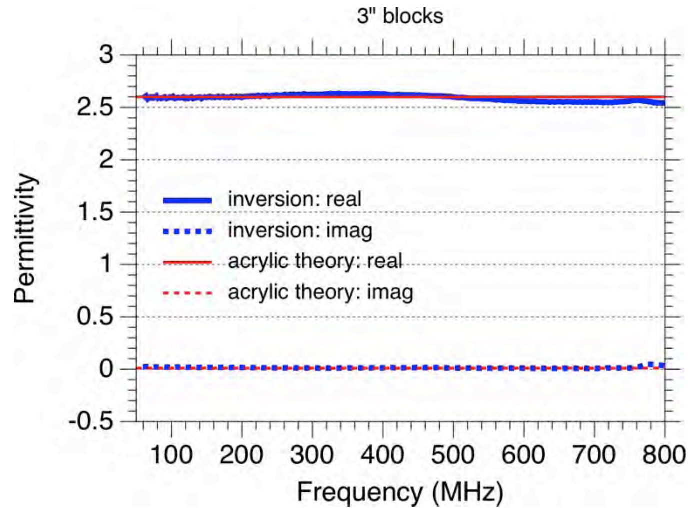

Figure 8 Inverted real (solid) and imaginary (dotted) permittivity of Acrylic

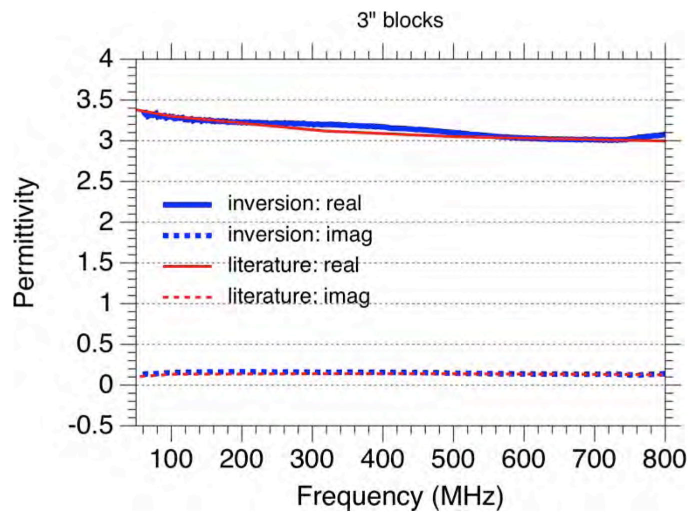

Figure 9 Inverted real (solid) and imaginary (dotted) permittivity of POM.

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 curent can flow, while the perpendicular direction has low-loss dielectric layers interrupting current flow. This anisotropy in the dielectric properties is shown in the measured and inverted permittivity data of Figure 10. These data show that the RF capacitor is very capable of measuring and inverting properties of anisotropic materials.

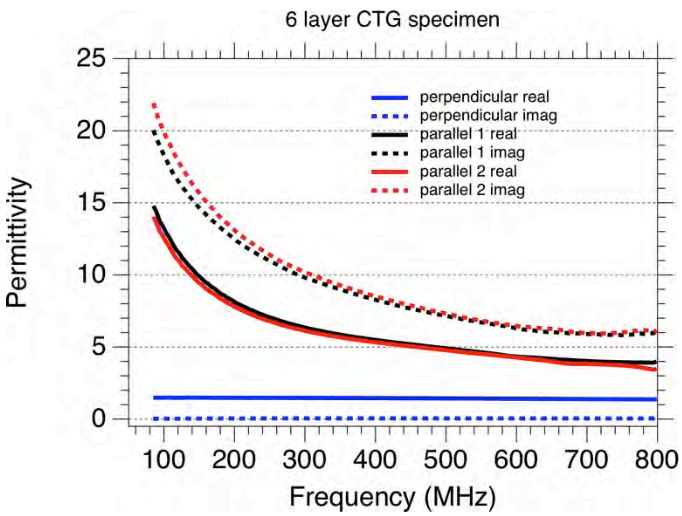

Figure 10 Inverted real (solid) and imaginary (dotted) permittivity of an artificial dielectric made of carbon foam and low-loss foam layers.

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 [7], 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.

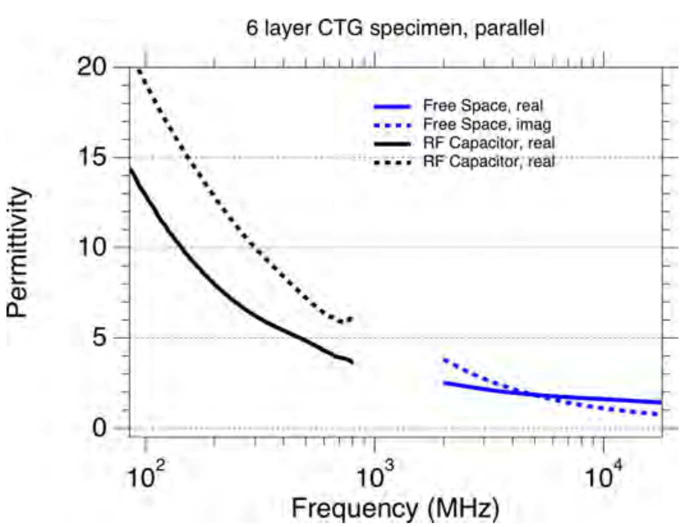

Figure 11 Comparison of RF capacitor to free space measurement of artificial dielectric material.

V. Conclusions

This paper introduces a new dielectric measurement fixture that can measure anisotropic and inhomogeneous materials at VHF and UHF frequencies with a single specimen. The fixture combines microwave concepts with traditional impedance analysis or capacitance methods and is called an RF capacitor. It also uses a novel computational-based inversion algorithm that pre-computes a lookup table, making property inversion very fast.

Initial uncertainty analyses show that the measurement errors are relatively small. Additionally, measurements of known simple dielectric materials show excellent agreement with their known properties. Finally, measurement of an anisotropic artificial dielectric material is compared to high frequency measurements, and shows good agreement.

Acknowledgement

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