A New Dielectric Analyzer for Rapid Measurement of Microwave Substrates up to 6 GHz

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Abstract— **This paper presents a new measurement method based on the parallel plate capacitor concept, which determines complex permittivity of dielectric sheets and films with thicknesses up to about 3 mm. Unlike the conventional devices, this new method uses a greatly simplified calibration procedure and is capable of measuring at frequencies from 10 MHz to 2 GHz, and in some cases up to 6 GHz. It solves the parasitic impedance limitations in conventional capacitor methods by explicitly modeling the fixture with a full-wave computational electromagnetic code. Specifically, a finite difference time domain (FDTD) code was used to not only design the fixture, but to create a database-based inversion algorithm. The inversion algorithm converts measured fixture reflection (S11) into dielectric properties of the specimen under test. This paper provides details of the fixture design and inversion method. Finally, example measurements are shown to demonstrate the utility of the method on typical microwave substrates.**

I.   INTRODUCTION

There is an increasing use of wireless technologies in everyday consumer goods, transportation, communications, and general infrastructure. This increased use drives a demand for better tools to support wireless technology development. To this end, a common technique for characterizing the complex microwave permittivity of radio frequency (RF) substrates is the impedance analysis method.

For dielectric materials, impedance analysis typically uses two parallel electrodes on either side of the specimen, which makes the equivalent of a capacitor. A time-varying field is applied across the electrodes to interact with the material under test. The measured impedance (including resistance and capacitance) can be analytically related to the dielectric permittivity with additional knowledge of the capacitor geometry. The use of this capacitance or impedance technique goes back to research published by Debye, in which he studied the relationship between dielectric response and molecular phenomena in condensed matter [1]. Since then, dielectric spectroscopy has become a well-established method not only for studying electronic properties, but also for providing fundamental understanding of molecular dynamics process in polymers, ceramics, and composites.

The impedance analysis method is often described as a lumped-circuit technique. It typically assumes the effects from parasitic impedances and fringing fields are small enough to be

empirically corrected. Without parasitic effects, the permittivity is a simple function of the area of the electrodes, A, the spacing between them, d, and the measured impedance [2].

In most cases, parasitic effects cannot be ignored and there are various strategies for either minimizing them or correcting for them. For example, the finite size of the electrode can add systematic error to the measured impedance by fringe fields along the electrode perimeter. Designing the electrode spacing to be much smaller than the lateral dimensions reduces the importance of these fringe fields. Another way to reduce parasitic effects incorporates a guard ring into one of the electrodes. However even with a guard electrode, there are still some fringe field effects and it is best to calibrate the electrode area by first measuring the capacitance in air or vacuum (i.e. without the sample). Since the electrodes are placed onto a specimen to set the spacing, measuring the exact same thickness of air is not always practical. When calculating permittivity from unguarded parallel-plate electrode measurements, analytical corrections can be applied to the data. Several of these corrections are described in detail in ASTM D 150 [3].

Even with techniques such as guard electrodes and fringing field corrections, the capacitance method is typically restricted to frequencies below 10 to 100 MHz. Above these frequencies, the parasitic impedances of the fixture begin to dominate the response. In some cases, the frequency range for this method have been extended to up to 1 GHz by careful electrode design that further minimizes parasitic impedance. However, accuracy at the upper frequency of the measurement range is eventually limited as the electrodes and specimen become a sizeable fraction of the operational wavelength and the simple capacitor approximation is no longer valid. Furthermore, high frequency capacitance methods require a complicated calibration process that uses a series of calibration measurements for both the RF analyzer and separately for the capacitance fixturing.

Given the complex calibration procedures and the high-frequency limitations of traditional impedance analysis techniques, there is a need to find improvements for this method. Additionally, the existing fixturing and analyzer equipment for implementing this method is costly, and new method improvements should take advantage of lower hardware costs in emerging analyzer technology. Therefore, the method described in this paper is a new take on the conventional capacitance method. It includes a fixture that resembles a parallel plate capacitor geometry and has the benefits of the conventional

method, including non-destructive and a simple measurement procedure. More importantly, the described method enables higher frequency measurement by 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 i) enable inversion of frequency-dependent dielectric properties within seconds and ii) avoid the need for CEM modeling expertise to be brought into a measurement laboratory.

II. FIXTURE DESIGN

The desire to operate at frequencies at or above 1 GHz requires that the fixture be driven either by an RF voltmeter or a network analyzer. Since both real and imaginary permittivity is desired, the analyzer or voltmeter must measure both amplitude and phase. With an eye to keeping equipment costs low, the present design is based around a 1-port vector network analyzer. In the last few years, low-cost, 1-port analyzers have emerged that exhibit high-fidelity measurement capability in a small form factor. For this fixture, a Copper Mountain Technologies R-60 analyzer was used. It operates from 1 MHz to 6 GHz and has a single N-type connector for measuring reflection amplitude and phase. It is small enough to be directly integrated into the impedance analyzer fixture without the need for RF cables.

Conceptionally the fixture is a parallel plate capacitor that is connected directly to the center conductor of the 50-ohm port on the analyzer. The outer conductor of the port is connected to a base plate that surrounds and shields the bottom electrode. The fixture geometry was optimized via iterative simulations with an FDTD solver to explicitly model the fixture's S11 response for typical material properties. The design optimization balanced fixture sensitivity with smooth, non-resonant, frequency response.

Figure 1 shows a computer design drawing of the fixture geometry. The network analyzer is mounted underneath and the transmission line from the network analyzer port connects to the 13 mm diameter bottom electrode. Once a material specimen is placed over the bottom electrode, the top electrode is then lowered to the top of the specimen to form a capacitive sandwich. The top electrode is designed to be larger than the bottom electrode to reduce positioning errors.

The dark colored structure in Figure 1 that is on top of the fixture that supports the top electrode is simply a non-conductive "yoke" used for positioning the top electrode so that it is centered over the bottom electrode. Unlike conventional capacitive measurement fixtures, the top electrode is electrically floating [4]. In this fixture, minimizing the metal structures above the plane of the bottom electrode improves high frequency performance. In other words, if the yoke structure were metallic it would strongly couple to the fields from the bottom electrode and at higher frequencies, exhibit anomalous resonances and even radiate fields much like an antenna. While a computational EM model does characterize this structure and can in turn account for the coupling to a metal yoke, it is still better to

minimize the strength of the parasitic coupling so it does not overwhelm the desired signal from the specimen filled capacitor.
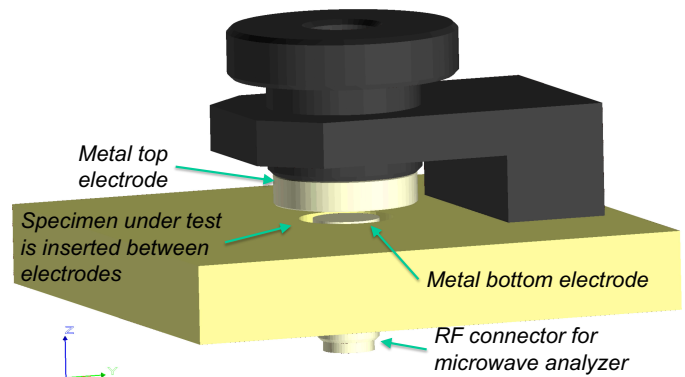

Figure 1 Sketch of fixture showing top and bottom electrodes

The response of this fixture with a specimen in place is measured as the reflection coefficient, S11. Both amplitude and phase are measured, with phase being primarily related to the real part of the dielectric permittivity, and amplitude being primarily related to the dielectric loss factor or imaginary permittivity. Example model calculations for a 1 mm thick specimen are shown in Figure 2. These data are the ratio of the relative phase of the fixture to a measurement of the empty fixture. For all three curves the specimen under test is also 1 mm thick. As the data show, the phase response is approximately proportional to the strength of the dielectric permittivity. These data also show that the phase response deviates from a simple dependence versus frequency above a couple of hundred MHz. This non-linear response demonstrates that the simple capacitor formula is no longer valid at high frequencies.
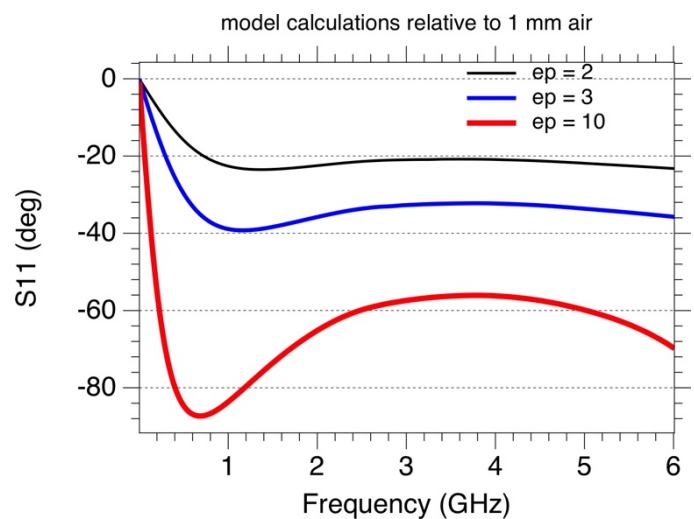

Figure 2 Example model calculations of fixture phase response for different 1 mm thick specimens

Additional model calculations for a 1 mm thick specimen are shown in Figure 3. In this case the specimens are modeled with different amounts of dielectric loss. In FDTD calculations, loss is most easily simulated by varying the material conductivity. The three curves in this figure show the amplitude loss for a specimen with a real permittivity of 3, and with no loss, low loss, and moderate loss (conductivity = 0, 0.001, and 0.01 S/m respectively). Like the case for phase dependence, the trend of the S11 amplitude is a non-trivial function of frequency. Accurately capturing this dependence requires moving beyond the conventional low-frequency capacitor approximation and instead using a full-wave computational electromagnetic (CEM) model.
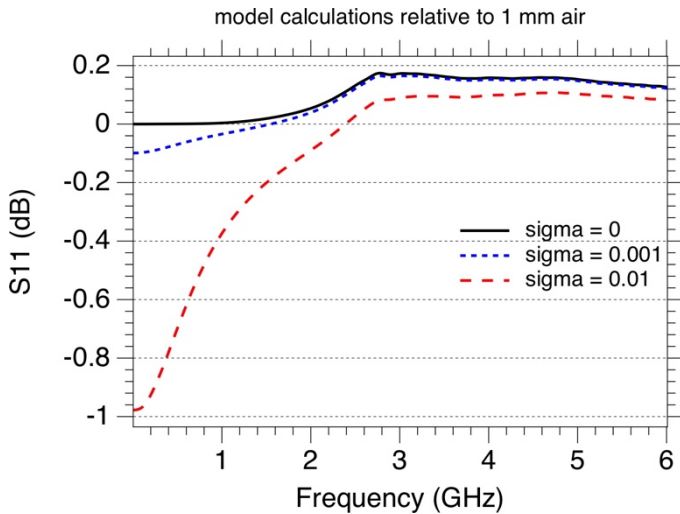

Figure 3 Example model calculations of fixture amplitude response for different 1 mm thick specimens

III.   INVERSION DATABASE

The method described in this paper takes advantage of full-wave CEM modeling not only for the fixture design, but also for inversion of the complex dielectric properties. Traditional material measurement methods consist of a fixture that can be modeled with an analytical approximation. For example, previous capacitive methods use a parallel plate capacitor approximation, $C = \varepsilon A/d$, which relates the capacitance, C, to the dielectric permittivity, ε, the area of the electrodes, A, and the distance between the electrodes, d. Characterizing materials beyond the limitations of conventional methods requires the use of advanced tools such as CEM simulators. In other words, a CEM solver can be used to translate the measured extrinsic parameters, reflection amplitude and phase, into the desired intrinsic properties -- real and imaginary permittivity.

This brings up a practical point: proper execution of CEM calculations requires advanced training that is significantly different than what is typically required by personnel working in traditional materials measurement laboratories. Furthermore, CEM solvers are not instantaneous, and running a series of simulations may take hours or days to accomplish, particularly if it has to iterate many times to match the measured data. When the measurement time takes minutes while the inversion takes

hours or days, the method becomes inconvenient if not impractical. In laboratories where a large series of specimens are characterized, this time to invert each specimen makes CEM inversion unviable.

The present method overcomes this difficulty by conducting the CEM simulation work before the measurement. Specifically, a series of simulations of the measurement fixture are made for a range of potential material intrinsic properties. In this case dielectric permittivity and loss. In addition, a range of different specimen thicknesses are also possible, so a third variable of thickness is part of the simulation matrix. The pre-calculated simulations are then incorporated into a database that can then be accessed by the measurement software to do a simple look-up algorithm for translating measured reflection (S11 amplitude and phase) into complex permittivity.

An example snapshot of this inversion database in shown in Figure 4. This figure is an image, where each pixel represents a different FDTD run corresponding to a specimen's real permittivity and loss or conductivity. The pixel color corresponds to S11 phase at 1 GHz. A Gaussian shaped time-domain pulse is used in these simulations so each FDTD run provides data over a wide range of frequencies. Similarly, the database also contains amplitude data which is more related to dielectric loss. The snapshot in Figure 4 is for a 1 mm thick specimen. The database also includes simulations for a range of thicknesses from 0.2 mm to 3.5 mm. Thus the inputs to the inversion are measured S11 amplitude and phase, along with specimen thickness.
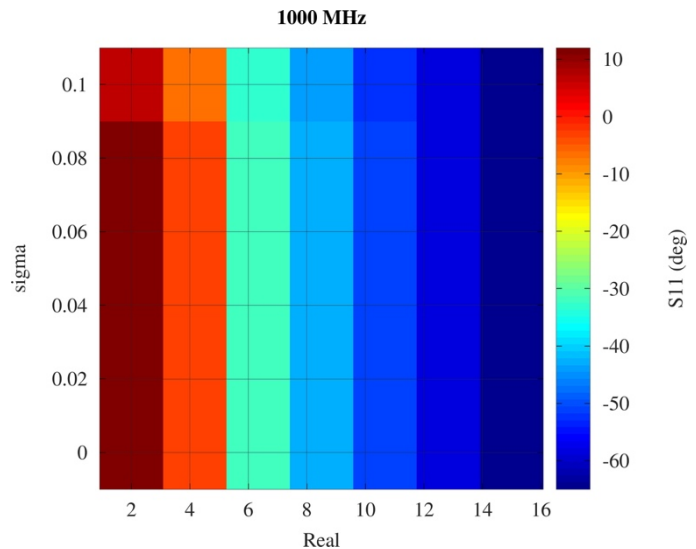

Figure 4 Snapshot of CEM calculated inversion database showing S11 phase in degrees as a function of real permittivity and conductivity

A computer cluster is used to conduct the series of CEM simulations for creating this inversion database. Depending on the size of the cluster, the database can take several weeks or more of computing time to complete. In this case, the FDTD model is constructed with 0.1 mm size cells and must be run for enough time steps to capture data down to below 10 MHz. Given

enough time, the database can become arbitrarily dense. However, it is sufficient to use interpolation between data points to obtain precise inversions in a sparser database. This interpolation represents an approximation; however, the key to accuracy is making sure the database is dense enough so that non-linearities in the fixture response are accounted for, and that systematic errors from the interpolation are no greater than other measurement uncertainties in the hardware. With this inversion method, measured results can be instantaneously converted into the desired intrinsic properties. Finally, this inversion, while relying on CEM hardware and software, is done ahead of time so that the personnel operating the measurement fixture need no additional training or expertise.

IV. MEASUREMENT APPARATUS & CALIBRATION

A photograph of the prototype apparatus is shown in Figure 5. This photo shows a specimen of G10 fiberglass inserted in the fixture with the top electrode resting on top of the specimen. The top electrode diameter is 28 mm. Underneath, a compact 1-port vector network analyzer is attached via an N-type connector to the bottom electrode. The analyzer steps through a number of frequency points ranging from below 10 MHz up to as high as 6 GHz. The collected data is reflection or S11 amplitude and phase.

In conventional capacitive measurement fixtures, an extensive calibration procedure is required to obtain accurate data. For example, the calibration procedure may require a traditional 1-port calibration of the network analyzer, and then a second "fixture compensation" that includes an open, a short and a known specimen as a load. In contrast, the CEM inversion methodology used in the present device enables the calibration to be greatly simplified. This is because the computational model captures many of the systematic errors in the fixture (i.e. parasitic inductances and capacitances) that are not captured by a physics-based analytical approximation.

In the present method, the calibration procedure consists of a single step. That step is measurement of a known specimen of known thickness. For the data shown here, a 1 mm thick Teflon specimen was measured ($\varepsilon = 2.0$). The calibration measurement is then used as a reference for a simple response calibration. Similarly, the CEM calculated database is the ratio of each simulated permittivity and loss combination to that of a 1 mm thick Teflon simulation. The Teflon is assumed to have no imaginary permittivity or loss because the accuracy of this method for determining low levels of loss is no better than the typical loss factor of Teflon.

This calibration method is effective for specimen measurements where the unknown specimen is not too different from the calibration specimen. However during initial testing of the prototype fixture, high frequency deviations (above 1 GHz) were apparent that were not calibrated out by this method. Further investigation noted that the airline feed between the network analyzer and the measurement fixture includes a bead for stabilizing the center conductor. The CEM model assumes an ideal coaxial feed. At low frequencies, the bead is nearly invisible, and the assumption of an ideal feed is valid.

Unfortunately, as wavelength decreases, the effect of the bead becomes more notable and cannot be ignored.
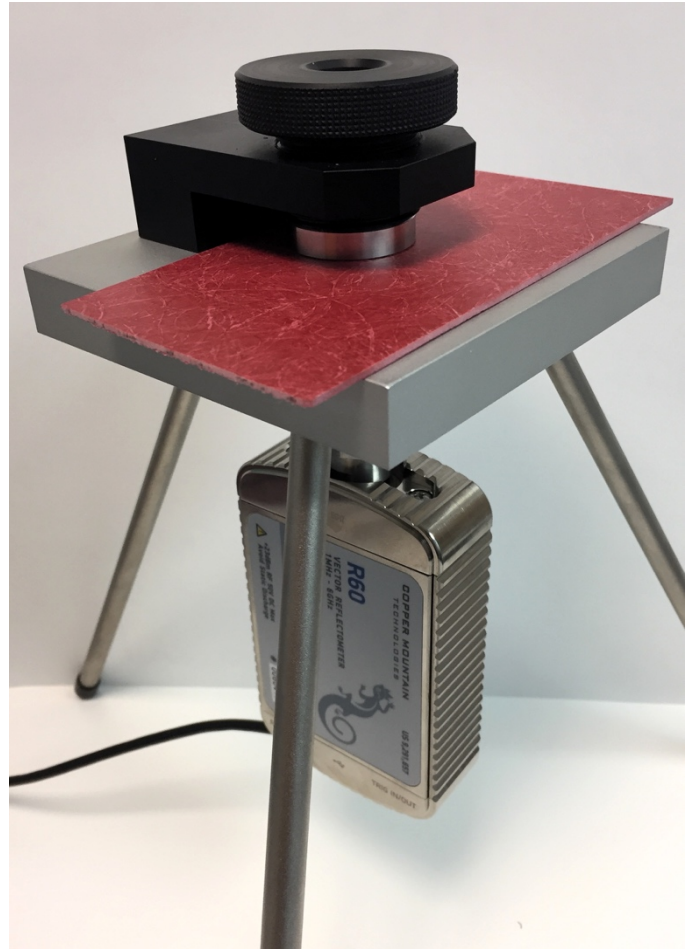

Figure 5 Photograph of measurement fixture with specimen inserted and 1-Port network analyzer attached

To mitigate the effects of the bead, a transmission-line model was added to the total fixture model. While doing a full-wave CEM model of the bead was considered, it would add additional time to constructing the inversions database. Additionally, adding an experimentally fitted transmission line model accounts for any other non-ideal behavior of the network analyzer along with the beaded transmission line. Thus a two-shunt transmission line model was added to the CEM calculated fixture response. One shunt accounts for the bead, while the second shunt accounts for imperfections in the network analyzer response. Each of the two shunt impedances are modeled as a parallel resistor-capacitor plus series inductor. An optimization routine was used to fit the six parameters to a measurement of the known Teflon specimen. This was done before conducting the Teflon response calibration so that the frequency dependence of the impedance line model could be properly established.

Implementing this additional transmission line model significantly improves the accuracy of the measurement fixture. Materials, such as polymers and composites that have permittivity within a factor of seven or eight of the Teflon

calibration material see reasonable inverted data at frequencies all the way up to 6 GHz. Higher dielectric materials however, still suffer from increasing spurious responses at the highest end of the frequency range (2 GHz and up). Thus, future improvements to the transmission line model are still needed to increase the accuracy of data above 2 GHz for high-dielectric specimens. Alternately, a high dielectric known calibration standard, such as alumina (ep ~ 10) could be used to get better accuracy for high-dielectric materials.

V. MEASUREMENT RESULTS

Measured and inverted permittivity and loss for several dielectric specimens are shown in Figure 6. The top plot in this figure contains the real permittivity while the bottom plot has imaginary permittivity data. Data from 5 MHz up to 6 GHz are plotted for these specimens. As discussed above, a single measurement of a 1 mm thick Teflon specimen was used as the calibration standard.

The thicker black curves in these two plots are for a 1.56 mm thick unfilled Ultem specimen (polyetherimide or PEI). Ultem is an engineering thermoplastic used for a variety of purposes ranging from aerospace to medical applications. Literature data for Ultem claim a dielectric permittivity of 3.15 with low loss at 1 KHz. The data plotted in Figure 6, are consistent with this number since dielectric permittivity of low loss polymers is known to very slowly decrease (relax) as frequency increases.

The thin red curves in these plots are for a 0.8 mm thick specimen of Delrin. Unlike the Ultem, the Delrin shows a significant change of the real permittivity at UHF frequencies, along with a corresponding peak in the imaginary permittivity. This is the classic 'Debye relaxation' observed in many materials, and Delrin is known to exhibit this behavior at UHF frequencies. The measured Delrin properties are consistent with data found in the literature [5] as well as previous measurements of Delrin measured in another fixture by the author [6]. Close inspection of the loss factor for the Delrin specimen shows an anomalous spike at close to 3 GHz. Modeling and experimentation with this specimen indicate that this spike is related to manufacturing tolerances of the prototype fixture. Specifically, the top conductor is offset from its assumed position by about 1 mm. Future versions of the measurement fixture will be built to higher tolerances and are expected to reduce or eliminate this anomaly.

Finally, the third set of blue data curves in Figure 6 are for the specimen of epoxy/fiberglass composite pictured in Figure 5. It also exhibits a dielectric relaxation as indicated by the decreasing real permittivity combined with the non-zero imaginary permittivity. Its relaxation behavior is not as strong as the Delrin material but is not surprising since it is a marine-grade fiberglass composite and not intended for low-loss electromagnetic uses. Dielectric properties of similar glass-fiber composites, such as FR-4 are typically in the range of 4.5. The measured data here are slightly lower, but this is expected since this measurement fixture characterizes the out-of-plane permittivity rather than in-plane permittivity. In other words, the E-field for this device is oriented perpendicular to the plane of the specimen. The glass fibers are mostly oriented in-plane.

Since the glass has a higher permittivity than the epoxy, the in-plane permittivity should be higher than the out-of-plane permittivity, consistent with the lower average value of approximately 4 observed for these measured data.
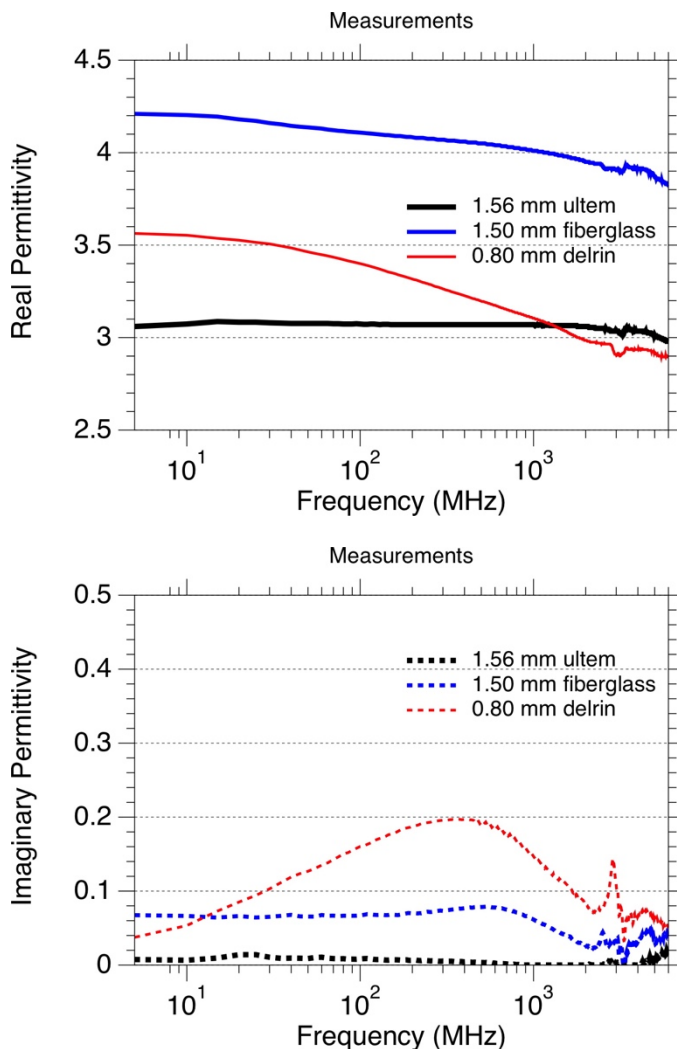

Figure 6 Example inverted real (top) and imaginary (bottom) permittivity for various polymer substrate specimens

VI. CONCLUSION

A new dielectric measurement method was presented. This method is a significant improvement on the conventional impedance analysis technique, which makes a parallel plate capacitor out of the specimen under test. Unlike conventional impedance analysis, the present device uses CEM model-based inversion to obtain intrinsic permittivity, rather than the conventional use of physics approximations. As a result this method can obtain dielectric data at higher frequencies than previous impedance analysis methods. Additionally, the CEM based inversion is implemented in a novel way, as a pre-computed database that is used along with interpolation to

quickly obtain intrinsic material properties. From a hardware standpoint, the present method is also novel in that it integrates a 1-port network analyzer directly into the fixture. This eliminates errors associated with RF cables and simplifies the measurement hardware. Measurement examples show that this new method is reasonably accurate and can obtain dielectric properties up to 6 GHz in some cases.

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