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Split-Post and Split-Cylinder Resonator Techniques: A Comparison of Complex Permittivity Measurement of Dielectric Substrates

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Abstract—**We provide an overview of two nondestructive techniques, the split-post and split-cylinder resonator, which are under consideration as standard test methods for measuring the relative permittivity and loss tangent of bare low-temperature cofired ceramic (LTCC) substrates over the frequency range of 1-30 GHz. The capabilities and limitations of the split-post and split-cylinder resonator are outlined, and the level of agreement between the two techniques is examined through comparison of the relative permittivity and loss tangent measurements of a fused silica and an LTCC substrate.**

Keywords—**Cavity, dielectric, loss tangent, permittivity, resonator, split-cylinder, split-post, substrate**

Introduction

As the low-temperature cofired ceramic (LTCC) industry moves toward adopting a portfolio of standards, techniques for measuring the frequency-dependent dielectric properties of LTCC substrates remain at the top of the list of electrical test needs. This is not surprising, as the substrate's relative permittivity and loss tangent can affect a signal's propagation speed and attenuation on an interconnect as well as a transmission line's characteristic impedance. As a result, microwave circuit designers need accurate values of the substrate's relative permittivity and loss tangent. Material manufacturers also require accurate test methods so that they can validate that the dielectric properties of their materials have minimal variation from lot to lot.

Unfortunately, selecting a particular method for measuring the dielectric properties is complicated by the fact that there are hundreds of techniques available in the literature, and we must remain cognizant that every method has some inherent limitations. A short list of these limitations include the method's frequency range, sample preparation and geometry, complexity of measurement procedure, difficulty of analytical and/or numerical modeling, cost of microwave test equipment, and the expected level of measurement uncertainty.

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Working in conjunction with the LTCC industry, we have identified specific attributes that a standard test method should possess. First, the method must employ planar samples, as the time and cost of machining the material into other geometries is prohibitive. The technique should operate somewhere in the frequency range of 1-30 GHz, where a majority of LTCC-based devices operate. The measurement procedure must be simple enough that a technician can routinely and quickly perform an accurate measurement. Finally, the typical relative uncertainty for the relative permittivity can be no greater than 1%, while the absolute uncertainty for the loss tangent should be less than 10^{-4}.

After considering various techniques, we identified two measurement methods that meet this list of criteria, namely the split-post and split-cylinder resonator methods. In this paper, we outline the capabilities and limitations of both techniques and overview the measurement procedure for each. To investigate the agreement between measurements performed with the two methods, we present results for the relative permittivity and loss tangent of both a fused silica and an LTCC substrate.

Split-Cylinder Resonator

The split-cylinder resonator is a nondestructive method for measuring the permittivity and loss tangent of low-loss dielectric substrates. Originally proposed by Kent [1], this method employs a circular-cylindrical cavity that is separated into two halves, as shown in Fig. 1. A planar dielectric sample is placed in the gap between the two shorted cylindrical waveguide sections. In order to excite the TE_{0np} family of resonant modes, coupling loops in the cylindrical waveguide sections are connected to the input ports of a network analyzer. From measurements of the resonant frequency f_0 and quality factor Q of the TE_{0np} resonant modes, the relative permittivity and loss tangent of the sample can be calculated.

The advantage of the split-cylinder method is that the sample needs only to be planar and to extend sufficiently far beyond the diameter of the two cylindrical waveguide sections. No other sample machining is necessary, making this method attractive for accurate, nondestructive measurements of low-loss substrates. Unfortunately, having little or no sample preparation comes at the cost of needing a more complicated theoretical model. In order to obtain accurate measurements of

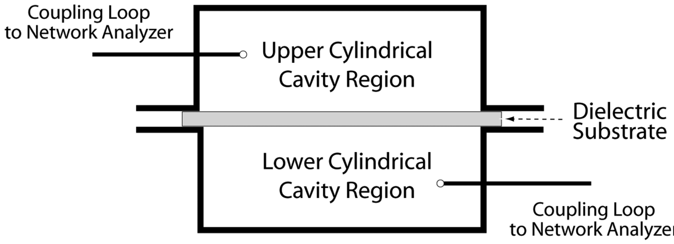

Fig. 1. Schematic for split-cylinder resonator.

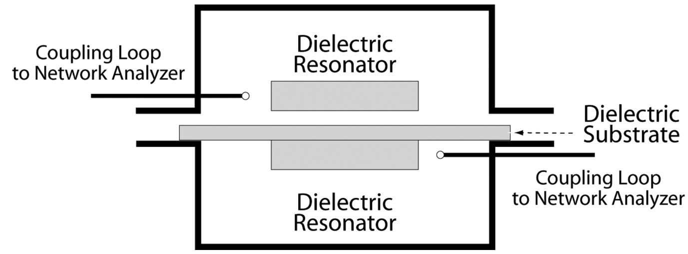

Fig. 2. Schematic of split-post dielectric resonator.

relative permittivity and loss tangent, the derivation of the theoretical model for the split-cylinder resonator must include the effects of the electric and magnetic fields that extend into the sample region beyond the cylindrical waveguide regions.

Previously, we developed [2] a theoretical model employing Hankel transforms that rigorously accounted for these fringing fields and improved the accuracy of the permittivity measurements. From this theoretical model, we derived a resonance condition for the split-cylinder resonator, which allowed us to calculate the sample permittivity. Although accurate, this new model was computationally intensive, so we developed a new theoretical model for the split-cylinder resonator [3], based on the mode-matching method. Using this model, we derived equations for calculating the relative permittivity and loss tangent of a sample.

The ability of the split-cylinder method to measure the relative permittivity and loss tangent of the dielectric substrate at several frequencies is one of this method's advantages over other resonator techniques that operate at only a single frequency. Besides the TE_{011} resonant mode, the theoretical model for the split-cylinder resonator includes higher-order TE_{0np} modes, and from measurements of the resonant frequency and quality factor of these TE_{0np} modes, a dielectric substrate can be characterized over a wider frequency range.

Note that the theoretical model includes only TE_{0np} resonant modes. The orientation of the electric field for these axial-symmetric modes is in the plane of the dielectric substrate. For isotropic samples this poses no problem, but if we wish to measure the various components of relative permittivity of an anisotropic sample, then another measurement method, such as the re-entrant cavity [4], should be selected.

By employing the higher-order TE_{0np} resonant modes, relative permittivity and loss tangent measurements have been performed up to 50 GHz by use of the split-cylinder resonator [5]. There are, however, some difficulties at these higher frequencies. First, other mode families beside the TE_{0np} modes are excited in the split-cylinder resonator. At higher frequencies, identifying the correct mode becomes more difficult, and the chances of resonant modes interfering with one another increases. Also, at millimeter wavelengths, the size of the split-cylinder resonator decreases, and tight geometrical tolerances for the dimensions and alignment of the two halves of the split-cylinder resonator are necessary in order to measure with high accuracy.

Split-Post Resonator

The split-post resonator, shown in Fig. 2, is another well-established nondestructive measurement method for characterizing the relative permittivity and loss tangent of low-loss dielectric substrates [6, 7]. It has geometry similar to that of the split-cylinder resonator, except for the introduction of two circular-cylindrical dielectric resonators, one in each half of the split-post resonator. Two coupling loops connected to a network analyzer excite a TE_{011} resonance whose frequency is a function primarily of the geometry and relative permittivity of the dielectric posts. With the introduction of a sample between the two dielectric resonators, the field structure between the posts is perturbed, resulting in a change in both the resonant frequency and quality factor of the TE_{011} mode. From these changes in the resonant frequency and quality factor, the substrate's relative permittivity and loss tangent can be calculated. For substrates with low thickness uncertainties, we can measure the relative permittivity to within 0.3% and the loss tangent with a resolution of 2×10^{-5} [8].

With dielectric resonators incorporated into the design of the split-post resonator, the geometry is more complicated, and advanced numerical methods, such as the finite-difference, mode-matching, or finite-element methods must be used to correctly model the split-post resonator [7]. Despite this increase in complexity, the addition of the dielectric resonators has several advantages. Most of the electromagnetic fields in a split-post resonator are confined to the dielectric resonators and the region between them. There is little interaction between the fields and the metallic walls that make up the rest of the resonator. Consequently, little power is dissipated in the metal walls. This is in contrast to the split-cylinder resonator, where conductive losses in the waveguide regions reduce the ability to measure loss tangent below 5×10^{-5}. Since the loss tangents of the dielectric resonators are low, the quality factor of the split-post resonator is high, resulting in more sensitivity for measuring the substrate's loss tangent. The dielectric resonators also provide greater control over the resonant frequency of the TE_{011} mode. The frequency shifts as measured when the dielectric sample is introduced are relatively small compared with the frequency shifts seen in the split-cylinder resonator. This is an important point if we wish to characterize substrates of varying thicknesses and relative permittivities at nearly the same frequency.

A limitation of the split-post resonator is that it is a single-frequency technique. To make measurements over a broad frequency range requires several split-post resonator fixtures of various sizes. Also, the method requires the electric field to couple between the two dielectric resonators. Consequently, there is an upper bound on the size of the fixed gap separating the two dielectric resonators before decoupling occurs and the TE_{011} mode is no longer excited. As we approach higher frequencies, the allowed gap size decreases and restricts how

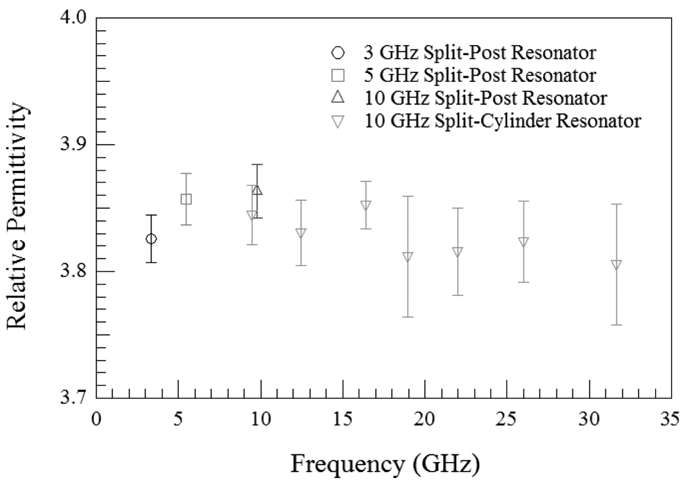

Fig. 3. Relative permittivity of a fused silica substrate.

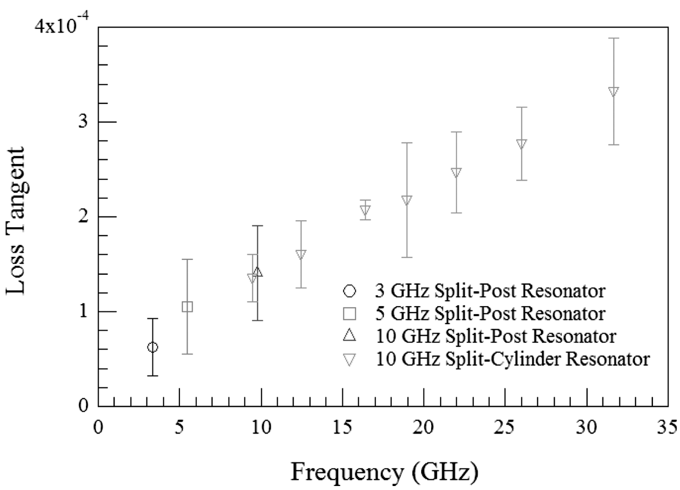

Fig. 4. Loss tangent of a fused silica substrate.

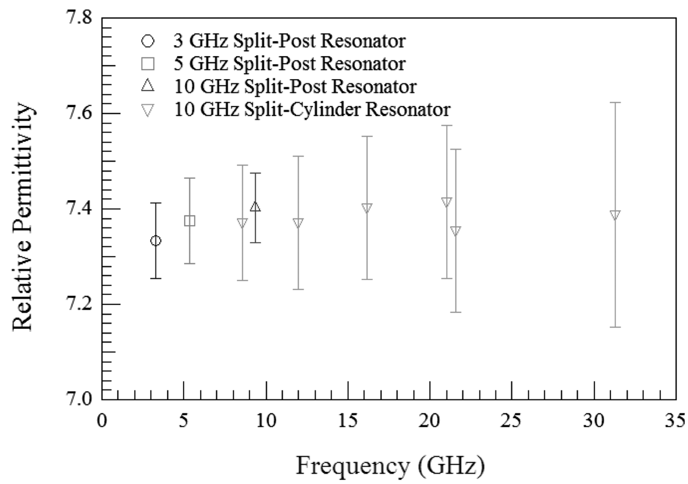

Fig. 5. Relative permittivity of a low-temperature cofired ceramic substrate.

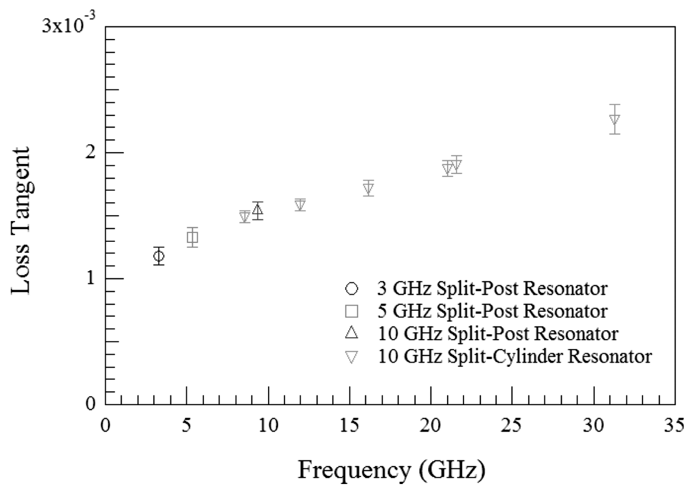

Fig. 6. Loss tangent of a low-temperature cofired ceramic substrate.

thick a dielectric sample can be. As was the case of the split-cylinder resonator, the electric field of the TE_{011} resonant mode is oriented in the plane of the dielectric sample, so measurement of all the relative permittivity components of an anisotropic sample is not possible. Finally, the fabrication of the dielectric resonators is difficult at millimeter-wave frequencies because of the small geometric tolerances necessary to keep the measurement uncertainties to a reasonable level. For this reason, we normally restrict split-post resonator measurement to below 10 GHz.

Measurement Intercomparison

In order to examine the level of agreement between the split-post and split-cylinder resonator techniques, we measured relative permittivity and loss tangent of both a fused silica and an LTCC substrate. The fused silica sample was 55 mm square and 0.81 mm thick, and the LTCC substrate was 55 mm square and 0.91 mm thick. For this study, we employed three split-post resonators that operate at 3, 5, and 10 GHz, and a single split-cylinder resonator that has the capability of performing measurements at multiple frequencies above 10 GHz by using the higher-order resonant modes.

We selected these four fixtures not only because they covered the desired frequency range, but also because each fixture could accommodate a 55 mm square dielectric substrate that was also less than 1 mm thick. We could have also performed measurements at 1.4 and 2 GHz with additional split-post resonators, but this would require an additional 100 mm square dielectric substrate. With our study limited to the three split-post and one split-cylinder resonator, we measured the same 0.55 mm square dielectric substrate in all four resonators, thereby eliminating any issues related to the use of multiple samples that might exhibit slight variations in permittivity and loss tangent.

In Figs. 3 and 4, we show results for relative permittivity and loss tangent for the fused silica substrate. As expected, the relative permittivity slowly decreases with frequency, while the loss tangent exhibits a linear increase as the frequency increases. For each measurement, we also report the combined standard uncertainty. In most cases, the measurement uncertainties will increase with frequency, because the uncertainties are more sensitive to variations in substrate thickness and cavity dimensions at higher frequencies. In addition to dimensional uncertainties, the resonant curve may become slightly asymmetric due to the presence of interfering higher-order resonant modes as well as undesired coupling between the loops used to excite the resonators. This is especially true at higher frequencies and will lead to a higher uncertainty for the measured quality factor, resulting in a larger uncertainty for the loss tangent.

In Figs. 5 and 6 we show results for relative permittivity and loss tangent for the LTCC substrate. Again, we note the good agreement between the split-post and split-cylinder resonator, even in this case, where the loss tangent is an order of magnitude higher than that of the fused silica.

Conclusions

We have demonstrated that both the split-post and split-cylinder resonator can be used to accurately measure the relative permittivity and loss tangent of dielectric substrates over the frequency range of 3-30 GHz. For both low-loss dielectric substrates, such as fused silica, and medium-loss material, such as LTCC substrates, the split-post and split-cylinder resonator show good agreement for both relative permittivity and loss tangent. Over the frequency range of 1-10 GHz, we recommend the use of split-post resonators for high-accuracy relative permittivity and loss tangent measurements. In addition, the split-cylinder resonator requires large substrates at lower frequencies, making it impractical at frequencies below 5 GHz. For the frequency range of 10-30 GHz, we recommend the use of the split-cylinder resonator method, not only because the construction of split-post resonators is problematic at these frequencies, but also because the split-cylinder resonator can perform both relative permittivity and loss tangent measurements at multiple frequencies, thereby reducing the number of measurement fixtures.

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