Bulk and In-Circuit Dielectric Characterization of LTCC Tape Systems Through Millimeter Wave Frequency Range

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Abstract

Low Temperature Co-fired Ceramic (LTCC) material systems offer a highly versatile microwave and millimeter wave packaging platform. Extremely low microwave loss, excellent control of dielectric constant, uniform dielectric thickness, non-existent water absorption leading to very high hermeticity, ability to support multilayer structure leading to 3-dimensional packaging, ability to embed passive functions within the tape layers, availability of a wide range of metallizations, etc. are some of the key advantages of LTCC for microwave packaging. One of the important parameters which needs to be determined at the very early stages of circuit designs are the dielectric properties - dielectric constant and loss tangent, both of which are functions of frequency. These properties need to be known accurately over the entire frequency range of operation for the circuit. For LTCC based designs, the use of dielectric constant of bulk material can lead to deviations between the performance expected at the design stage and for the fabricated circuit. Such deviations are a significant concern for broadband circuits as well as for circuits with sharp resonant behavior such as filters. One of the significant sources of deviation between bulk LTCC and "in-circuit" dielectric constant is the nature of the thick film metallizations used in LTCC technology. Work described here is a comprehensive characterization of three DuPont™ GreenTape™ LTCC systems 951, 943, and 9K7 - in the frequency range 10 to 70 GHz. Both bulk and "in-circuit" dielectric properties with silver and gold metallizations are studied to quantify the deviations in dielectric properties. A Fabry-Perot open resonator technique is used for the bulk characterization while printed ring resonators are used for the in-circuit characterization. This comprehensive characterization will provide key design data for LTCC designers in the 10 – 70 GHz frequency range.

Keywords: Dielectric constant measurements, LTCC, Millimeter wave material properties

Introduction

Low Temperature Co-Fired Ceramic materials are widely used for microwave and millimeter wave packaging applications due to their excellent properties. LTCC materials support extremely low loss interconnects up to and beyond 100 GHz, have very low water absorption leading to high reliability hermetic packages, are compatible with standard packaging processes such as wirebondng, soldering, and brazing, and have very stable dielectric properties, etc. LTCC systems are a heterogeneous composite of glass, ceramics, and organic binders. All these constituent materials contribute significantly to the dielectric properties of the final material system. From an application point of view it is important to know the dielectric properties of the circuit materials, especially as the frequency of operation increases.

Dielectric Characterization Techniques

There are many techniques available for dielectric characterization of ceramic materials at high frequencies (in the GHz range) reported in literature over the last few decades. Due to the very low loss nature of LTCC materials, cavity perturbation techniques are especially useful for their characterization. While there are a number of useful cavity techniques, NIST has perfected a split cylinder cavity method which is very suitable for LTCC samples [7]. However, as is common with most cavity methods, the split cylinder technique provides dielectric properties only at a particular frequency. For timely design success it is important for the designers to know the dielectric properties of the substrate in the frequency band over which the circuits need to function. A series of separate cavities will be required to handle each frequency of interest if a resonant cavity is used for dielectric characterization. For wide band systems multiple cavities may be required to characterize materials for the same application, which becomes tedious and cumbersome. This poses a significant problem for materials suppliers such as DuPont since our materials are used over a wide frequency range and it becomes practically impossible to provide reliable dielectric data for all customer applications by using resonant cavities. Even if a single cavity can be used for a particular application, the cavity size scales with wavelength and becomes prohibitively small at millimeter wave frequencies.

Another significant limitation of the cavity techniques in general is that they are suitable only for "un-metallized" test samples. In an actual application, the substrates are always metalized since circuit traces are an essential feature of any electronic system. Ceramic materials in general and LTCC materials in particular use thick film metal compositions of gold and silver for circuit traces. These are not pure metals – unlike organic laminates which use pure metallic copper as the metal layers – rather a composite of ceramic, metals, glasses, and organic binders. When these metal "inks" are fired on the surface of LTCC ceramic content of the ink permeates in to the tape thereby changing the local dielectric properties. Even small changes in dielectric properties can adversely affect circuits with sharp resonance behavior such as high-Q filters. Hence, a number of printed resonator techniques have developed over the past several years, with ring resonators and T resonators being the most popular choice for LTCC characterization. The work described in this paper uses ring resonators extensively to provide metalized dielectric data along with the open resonator technique, which is the main focus of the work.

Another class of highly accurate and repeatable dielectric characterization technique for low loss materials such as LTCC is the Free Space method, which is also known as "Open Resonator" method since these techniques do not use any enclosed structures to confine the field, rather the entire set up is open. In a general form, this method uses two horn antennas – one in radiating mode and another in receiving mode – to send a collimated beam of microwave radiation through the sample under test. The transmission coefficient is monitored using a Vector Network Analyzer (VNA) as a function of frequency. From the transmission parameters, the dielectric properties of the sample can be calculated.

A variation of this technique uses two concave reflectors in place of the antennas and is known as the Fabry-Perot open resonator. The point source radiator is located at the center of one of the concave reflectors, which will focus the radiating beam rather than collimating it. At the focal point, the mode field diameter will have the minimum value since the radiating beam is Gaussian in nature. The sample under test is located at the focal point of the beam. A series of sharp resonances occur due to multiple reflections of the Fabry-Perot setup, depending upon the separation between the reflectors. From the S-parameters measured through the VNA, the dielectric properties of the sample can be extracted. An open resonator, such as the Fabry-Perot setup, measures dielectric properties at a series of closely spaced frequency points (compared to a standard resonant cavity) yielding both dielectric constant and loss tangent as a function of frequency.

To surpass the limitations imposed by resonant cavities we have investigated the use of open resonators for characterizing DuPont's industry leading GreenTape™ LTCC materials. This report summarizes the techniques, measurements, and data obtained during this investigation. It is important to note that the focus is not on the details of open resonator technique. Our focus rather is on the dielectric properties of LTCC materials in a

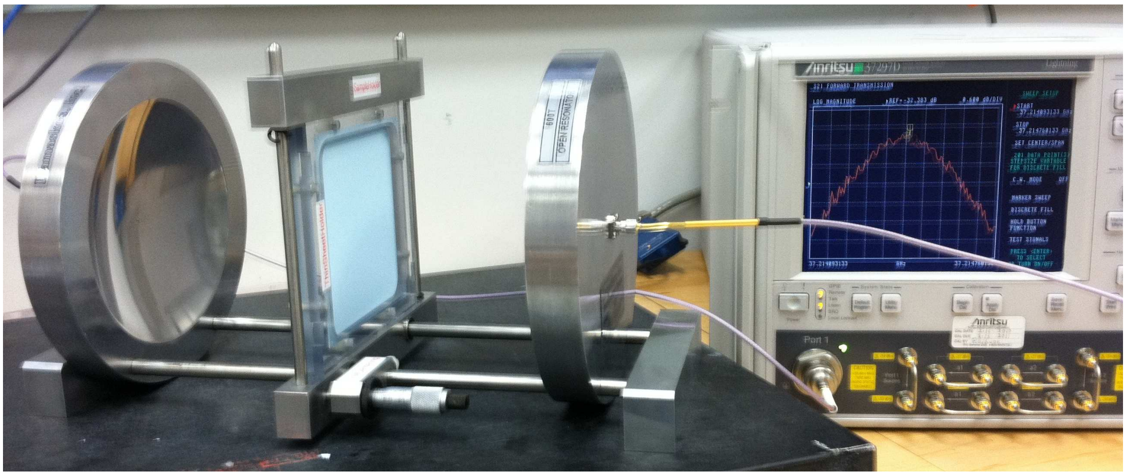

Figure 1: Open resonator test setup with the test sample centered between the concave reflectors.

frequency range of 10 – 70 GHz. For the testing purposes we used a commercially available open resonator from Damaskos, Inc and used their proprietary software for dielectric property extraction.

Open Resonator Test Setup

An open resonator technique described by multiple sources was used [1-3]. Dielectric constant and loss tangent measurements in the frequency range of 10-65 GHz were performed using an open resonator manufactured by Damaskos, Inc. (Model 600) [2]. The open resonator was connected to a vector network analyzer (VNA), as shown in Figure 1 This specific open resonator was selected for its ability to adjust the distance between the reflecting mirrors and its capability to measure a dielectric's in-plane complex permittivity at frequencies up to and beyond 65 GHz.

A calibration was performed to measure the resonance frequency and quality factor of the $TEM_{0,0,q}$ mode of the unloaded cavity, where q is the order of the mode along the axis between the probes. During calibration, the software will also calculate the distance between the reflecting mirrors at each resonance with a very fine resolution. Test samples were then placed in a sample holder and centered between the reflecting mirrors using the provided micrometer. To ensure a high accuracy in the measurements, care must be taken to adjust the sample to the exact center between the reflecting mirrors. The introduction of the dielectric in the center of the open resonator will change the measured resonant frequency, from which, the real part ε' of the complex permittivity can be calculated. The change in quality factor of the resonance is used to determine both the imaginary part ε'' of the complex permittivity as well as the loss tangent ($\tan \delta_{\varepsilon}$). Proprietary software from Damaskos Inc. was used to perform the calibration, the measurements of the samples, and the complex permittivity calculations.

Two separate measurements were performed on each test sample. A longitudinal distance of 6.5" was used for measurements over the range of 10-37 GHz, while a distance of either 9.5" or 11.3" was used for the range of 37-65 GHz. The measurements for each thickness group of each of the three GreenTape™ systems were compiled into comprehensive reports. These measurements were also compared to historical data from prior characterizations of these LTCC systems using a split cavity resonator and metalized ring resonators.

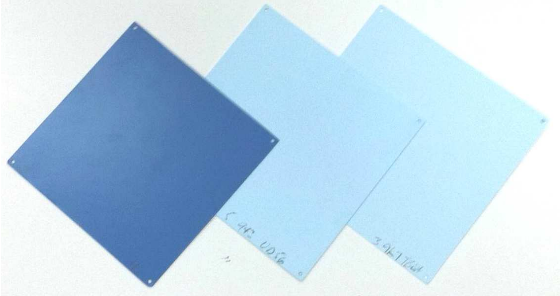

Figure 2: 951, 943, and 9K7 test samples

Sample Preparation

Thin, low-loss, planar samples are required for accurate measurements in the open resonator setup. However, a slight increase in a sample's thickness helps to increase sensitivity and to reduce calculation errors due to thickness uncertainty [1]. In order to determine whether these benefits can be realized without experiencing the interference between modes that can occur with thicker samples, samples of varying thicknesses were fabricated for use in this experiment.

Test samples, shown in Figure 2, were constructed of varying layers of PX (10 mil) tape to create 5.0" square samples with a green thickness measuring 20, 30, 40, 50, or 60 mils. Samples were laminated at 3000psi then fired at a maximum temperature of 850°C. 9K7 samples and 943 samples were box fired with a 26.5-hr profile, while the 951 samples were belt fired using a 3.5-hr profile. The 5.0" green squares were chosen because the sample holder had an exposed square area with sides measuring 4.3"; during firing, the test samples experienced a typical X-Y shrinkage, resulting in the test samples measuring approximately 4.4" square, thus filling the entire sample holder. Five samples for each of the five different thicknesses were fabricated for all three LTCC systems. Thickness of each individual fired sample was measured using a micrometer with 0.5μm resolution using a standard 4 point thickness measurement.

Other Dielectric Measurement Techniques

The dielectric properties calculated using the open resonator will be compared to similar calculations using data collected from ring resonators and a split cavity resonator.

Complex permittivity can be measured using any of a variety of ring resonators. The dielectric constant of a standard stripline ring resonator can be calculated using the following equation [9] :

$$\varepsilon_{eff} = \left(\frac{n * c}{2\pi * r * f} \right)^2 ,$$

where n is the mode, c is the speed of light in free space, r is the mean radius of the ring, and f is the measured frequency of the nth resonant mode. The data from ring resonators has been collected from previously published data for each tape system [4-6].

The split cavity resonator is an accurate method to measure the complex permittivity of ceramic substrates [7-8]. The method places a ceramic substrate between two halves of a hollow cylinder of equal dimensions. With a known radius and depth of the identical half-cylinders, the complex permittivity of the sample can be calculated from the resonant frequency and quality factor of the TE_{011} mode.

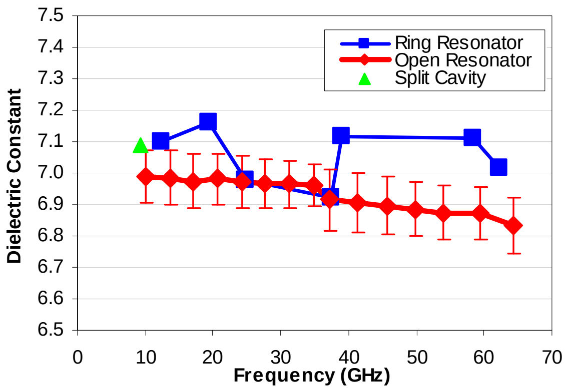

Figure 3: A comparison of the dielectric constant of 9K7 GreenTape™ calculated from measurements from an open resonator, a split cavity resonator, and metalized ring resonators.

GreenTape™ 9K7

Each of the 5 thickness groups measured by the open resonator had relatively similar values at each respective frequency for both dielectric constant and loss tangent measurements. The group containing the 40 mils green test samples was determined to be the best representative of the overall data. This was the case over the entire experiment, as the 40 mils green test samples also were the best representative of both the 951 and 943 test groups. For the group, the average dielectric constant over frequency is shown in Figure 3. This figure also

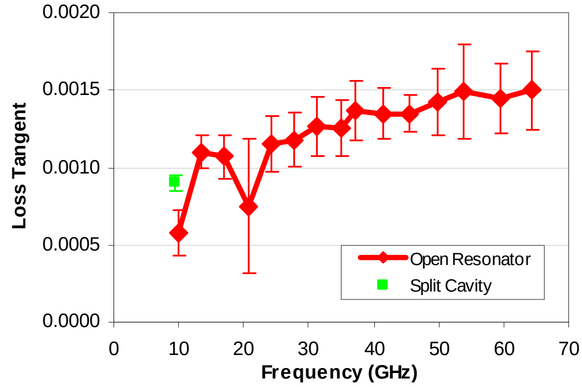

Figure 4: Loss Tangent of 9K7 GreenTape™ calculated from measurements taken using an open resonator and a split cavity resonator.

Results

includes data generated from two different 9K7 stripline ring resonators [4] and the average dielectric constant for 9K7 as measured using the split cavity resonator. The split cavity resonator is used to qualify every production lot of 9K7 and yielded an average of 7.09 (with a standard deviation of 0.01, which is not shown on the graph). The graph of loss tangent over the same frequency range is shown in Figure 4 for measurements using the open resonator and the split cavity resonator.

The data from the open resonator compares favorably to the ring resonator data. The open resonator yielded a more consistent and predictable curve for the dielectric constant over frequency than did the ring resonator. When attempting to characterize a dielectric using metalized resonant structures, errors originating from resistive loss, radiation loss, and manufacturing quality may be present. These various factors often lead to dielectric constant and loss tangent measurements that vary significantly over the test frequency range. Loss tangent measurements from metalized samples especially suffer from these factors and are often unreliable, which is why no metalized loss tangent data is reported here. Printed microstrip resonators yield only the effective dielectric constant – not the actual dielectric constant – from the fundamental resonance equation. The material dielectric constant is calculated using empirical equations with limited validity. Moreover, the effective dielectric constant is dependent on the specific circuit geometry such as the ring radius and width and is a function of frequency. Hence, the frequency dependence of dielectric constant obtained from such resonators will be somewhat exaggerated which explains some of the variation we are seeing as well. It must be noted that the strip line printed resonators do not suffer from this limitation to the same extent as the microstrip resonators since stripline structures are fully enclosed within the substrate by definition. While resonant structures provide valuable information about the in-circuit performance of the dielectric, they do not provide the bulk characterization of the dielectric that an open resonator can provide.

A small step is noticed between 34.9 GHz and 37.2 GHz. This can be attributed to the change in test setup, as the frequency range from 10 – 37 GHz was measured with a longitudinal distance of 6.5" between the reflecting mirrors, while the frequency range from 37-65 GHz was measured at a distance of 11.3". The data points are easily within the standard deviation of the opposite point.

GreenTape™ 951

DuPont's 951 GreenTape™ is designed for LTCC applications which mainly operate below 30 GHz. Thus, the dielectric properties of 951 were characterized up to 37 GHz using the open resonator technique.

The average dielectric constant vs. frequency is reported in Figure 5. The measurements

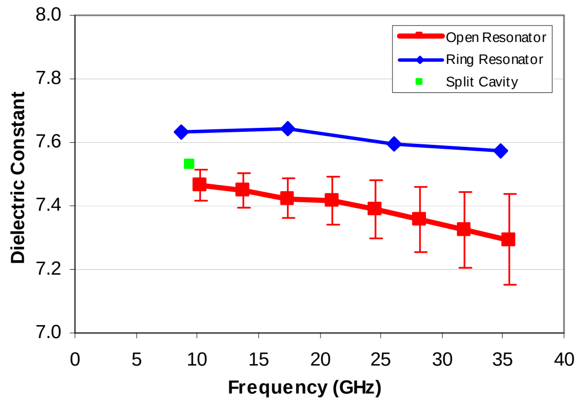

Figure 5: A comparison of the dielectric constant of 951 GreenTape™ calculated from measurements from an open resonator, a split cavity resonator, and metalized ring resonators.

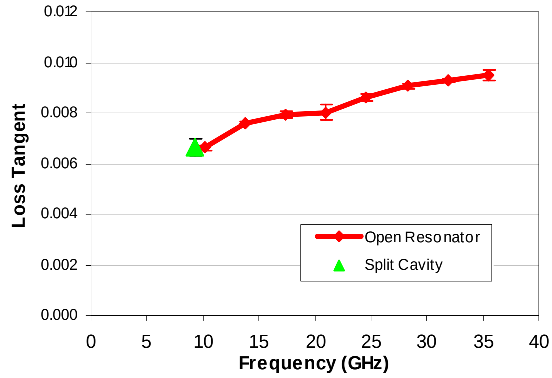

Figure 6: Loss Tangent of 951 GreenTape™ calculated from measurements taken using an open resonator and a split cavity resonator.

of a 4mm ring resonator fabricated in 951 up to 37GHz is shown as a comparison (data was reported through 65 GHz, but is only shown through 37 GHz here) [6]. Notice that the dielectric constant calculated from the metalized ring resonator is between 0.2 and 0.3 greater than the dielectric constant as measured by the open resonator. Figure 5 also shows the average dielectric constant of 951 as measured by a split cavity resonator. The split cavity measurements reported are a single frequency measurement at approximately 9.4 GHz (the error bars depicting the standard deviation of 0.021 are not shown), where the average dielectric constant was measured to be 7.53. Loss tangent measurements from both the open resonator and split cavity resonator are reported in Figure 6. The dielectric properties of the 951 samples as measured by the open resonator at 10.2 GHz closely resemble the measurements of the split cavity measurements at 9.4 GHz. The similarity in these results is expected from two measurement techniques that utilize non-metallized dielectrics.

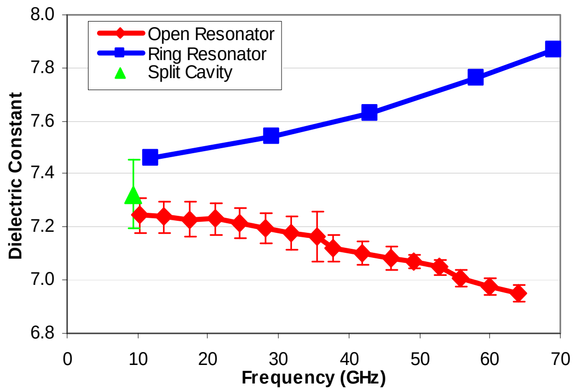

Figure 7: A comparison of the dielectric constant of 943 GreenTape™ calculated from

measurements from an open resonator, a split cavity resonator, and metalized ring resonators.

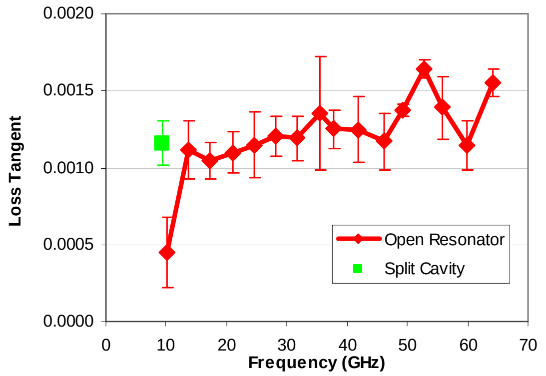

Figure 8: Loss Tangent of 943 GreenTape™ calculated from measurements taken using an Open Resonator and a split cavity resonator.

GreenTape™ 943

A compilation of dielectric constant measurements using the open resonator, the split cavity resonator, and metalized ring resonators is shown in Figure 7. There is a perceptible difference between the dielectric constant calculated from ring resonator measurements [5] and those values calculated from the open resonator measurements. The reason for this difference is the presence of thick film metallizations for the ring resonator as explained above. The split cavity measurements align well with the open resonator's calculated dielectric constant values which is expected since both the split cavity and open resonator are related techniques and use unmetallized samples. Loss tangent measurements from both the open resonator and split cavity resonator are shown in Figure 8.

Conclusion

An open resonator was used to measure the dielectric properties of thin, non-metallized samples of DuPont™ GreenTape™ LTCC systems 951, 943, and 9K7 over the frequency range of 10-70 GHz. The measurement data are compared to other techniques such as printed ring resonators as well as split cylindrical cavity resonator methods. Good agreement between these techniques observed. Characterization using the open resonator enables broadband measurements without some of the drawbacks of alternate methods, such as uncertainties in metalized resonant structures.

Previous work with the characterization of non-metallized LTCC substrates has been limited to a single point measurement using a split cavity method. While the split cavity test is accurate and reliable, its measurements are restricted to only the frequency, of the TE_{011} mode (which for these tapes typically measures in the range of 9.0 – 9.5 GHz). Alternatively, the characterization of LTCC dielectrics using metallization samples with various resonant structures introduces several sources of error and uncertainty such as printing defects, resistive losses, and radiation losses. Resonant microstrip structures require long calculations to extract the effective dielectric constant from the measured dielectric constant, which can produce a large uncertainty range. These techniques create problems for microwave design engineers, who typically are interested in the dielectric properties at a specific frequency or over a certain frequency band. The open resonator enables the broadband measurement of the dielectric properties, giving design engineers valuable information about the dielectric properties at their frequencies of interest.

Future work may include the measurement of 9K7, 951, and 943 up to 110 GHz. Future plans also include using the open resonator to measure the dielectric properties of the newest DuPont™ GreenTape™ LTCC system, 9K5.

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Disclaimer: *The tables, graphs, and data presented in this paper show anticipated physical and electrical properties for DuPont™ GreenTape™ materials based on specific controlled experiments in our research labs and are not intended to represent the product specifications, details of which are available upon request.*

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