

Characterization of LTCC Material at G-band

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Abstract

New data on the properties of dielectrics normally used in planar circuits, along with a technique for characterizing dielectric materials at high millimetre-wave frequencies, are presented. Comparative data are presented on the dielectric constant (ϵ_r) and loss tangent ($\tan \delta$) for different types of LTCC substrate. A free-space technique was used for the evaluation of dielectrics. The measurement data provided useful information on the permittivity and losses in materials at high mm-wave frequencies.

Key words: Characterization, LTCC, Free Space Measurement, Millimeter wave

1. Introduction

Low temperature co-fired ceramic (LTCC) technology enables the creation of monolithic, three dimensional, cost effective microwave circuits at low cost[1-3]. It combines the benefits of HTCC with those of thick film process to satisfy the demanding electronic market. Thus it is an advanced and valuable solution for miniaturization in electronic packaging. LTCC has been used widely in applications from automotive to military systems. This is due to the high reliability, with excellent electrical performance, offered by the process at low cost.

The particular advantages of LTCC are[4]:

- Potential for parallel processing
- Low loss tangent
- Better control over dielectric properties (ϵ_r , $\tan \delta$ and thickness)
- Easy realisation of VIAs and cavities
- Straightforward integration of active and passive components

All these advantages make it potentially very attractive for use at high frequencies,

especially G-band. However, the lack of published material data at these frequency bands can lead to problems in the precise design of circuits at G-band, and hence it is necessary to establish a proper materials characterization process at these frequencies

A free-space technique was used to characterize the LTCC tapes. This technique was chosen over the normal waveguide-based systems, and over planar techniques, due to the simplicity of the measurement setup. To use the waveguide technique at these frequencies would require very small materials samples to be prepared and precise placement of these small samples into the waveguide [5]. This can be problematic and cause significant measurement error.

Planar measurement techniques at these high frequencies suffer from several uncertainties in the measurement. These are because planar technique, such as resonant ring, measure the total performance of the circuit and rely on computation to separate out the individual properties of the conductor and the dielectric. The reliability of the equations

used for the computation decreases at high frequencies due to the difficulty of precisely defining the surface loss in the conductor, when the skin depth in the conductor is less than the rms surface roughness[6]. Thus an alternative technique for measuring dielectric properties is needed that does not involve the insertion of samples into waveguides and the use of conductor patterns. The free-space method described in this paper provides such a technique, and has been found to yield useful results.

This paper presents the intrinsic data, namely the relative permittivity and loss tangent, of different types of commonly used LTCC material.

The primary contributions of this paper are: (i) the generation of new practical data on LTCC material at frequencies from 145 GHz to 220 GHz; (ii) the establishment of a new free-space measurement technique.

2. Theory

A dielectric may be defined simply as a non-conducting substance. It can be in form of solid, liquid or even gas. The most important properties of dielectrics is the relative complex permittivity, ϵ^* , defined as [7]

$$\epsilon^* = \epsilon' - j\epsilon'' \quad (1)$$

where ϵ' is the real part of the complex permittivity and represents the energy stored in the material, and ϵ'' represents the loss in the material. However, the loss in a dielectric is usually specified in terms of the loss tangent, $\tan \delta$, where

$$\tan \delta = \frac{\epsilon''}{\epsilon'} \quad (2)$$

ϵ' can vary from 1 for air, to greater than 2000 for ferroelectric dielectrics, and $\tan \delta$ can be as low as 3×10^{-5} for crystal to higher than 1 in RAM material. Material with $\tan \delta$ less than 3×10^{-4} is considered as low loss material, suitable for RF applications, and material with $\tan \delta$ higher than 3×10^{-2} is considered to be high loss [8].

The relative permittivity of a dielectric is not a fixed value and is dependent on several factors such as ambient temperature, humidity and frequency, however the focus of this paper is primarily on the frequency

dependence of the permittivity. The properties of the dielectric are critical elements in planar circuit design. The permittivity, thickness and loss of the dielectric influence the characteristic impedance of the line as well as the propagation constant [9].

When a plane wave is incident on a dielectric, there will be reflection, absorption and transmission of the signal. The relative complex characteristics of these quantities will depend on the properties of the dielectric.. This constitutes the basis for the free-space measurement technique.

Free space dielectric measurement is a non destructive and contactless technique to measure dielectric properties [10-12]. It provides flexibility to do measurements under different conditions, in particular over a wide range of temperature and humidity. It has so far been used to measure dielectric properties up to 100GHz [13].

The measurement setup only requires two antennas to focus the microwave energy, a sample holder to hold the sample in between the two antennas, and a flat conductor with which to calibrate the VNA system. The distance between the horn antennas to the face of the sample must be greater than the near field value to ensure plane wave propagation.

A crucial aspect of the measurement set up is that the main beam from the transmitting horn antenna must be totally within the area of the sample under test. Thus at lower frequencies, where longer distances are required for the sample to be in the far field, a sample with a large cross-sectional area is needed to enclose the beam from the antenna [14]. Therefore at the lower frequencies it is common practice to use lenses to focus the beam onto the sample. At high frequencies the lenses are not needed. Even in the far field of the antenna the area needed to cover the 3dB beamwidth area is still considerably smaller than typical samples size. In this paper, the non-focused beam method was used in the measurement.

In this free space method the permittivity and loss tangent of material may be determined from either transmission or reflection measurements [8]. In the reflection method, a metal plate is placed at the back of the sample and the permittivity and loss tangent is calculated from the reflection coefficient. In this paper, a transmission

method is used to calculate the materials properties. No metal plate is needed for this measurement. The permittivity and loss tangent of material was determined from the transmission coefficient of the sample under test. The effective permittivity and loss tangent can be calculated using the theory given in [13]:

$$S_{21} = \frac{T(1-\Gamma^2)}{1-\Gamma^2T^2} \quad (3)$$

where

$$\Gamma = \frac{Z_n - 1}{Z_n + 1} \quad (4)$$

and

$$T = e^{-kd} \quad (5)$$

Z_n is the normalized impedance and k is the propagation constant of the sample.

where

$$Z_n = \frac{1}{\sqrt{\epsilon_r}} \quad (6)$$

and

$$k_s = k_0 \sqrt{\epsilon^*} \quad (7)$$

with

$$k_0 = \frac{2\pi}{\lambda_0} \quad (8)$$

3. Measurement Technique

Each of the test samples was prepared from several layers of LTCC tape. These were cut, laminated and fired according to the manufacturer's guidelines. It was essential to control the process carefully to ensure perfectly flat sample were produced.

Fig.1 shows the experimental setup for the measurements. The distance between the each antenna to the face of the sample was chosen to ensure the sample was in the far field region. The far field can be calculated by using the equ.9 where D is the widest horn

aperture and λ is the wavelength at the frequency of interest.

$$\text{Far field distance} = \frac{2D^2}{\lambda} \quad (9)$$

Thus the distance between the each antenna to the face of the sample was maintained at 46mm. The WR5 pyramidal horns that were used each had a beamwidth of 20° in the E-plane and H-plane. The horn main beam only illuminated an area of 16.3mm x 16.3mm in the centre of the LTCC tile samples. As all the sample were prepared as either 2 inch square or 4 inch square, the sample tiles are large enough to cover three times the horn main beam. This eliminated one of the main errors in the free-space technique, which is error cause by the diffraction of the beam around the edges of the sample.

The horns were connected to an HP8510 VNA, which had Olsen extenders to cover the frequency range 140 GHz to 220 GHz. For these measurements, the Model 9000 probe station was modified so that the two horns could face each other and the rigid sample holder could be place in the middle. The advantage of using the probe station for this measurement is that the probe station is equipped with micrometer lead screws, which allow accurate movement of the antenna to ensure that precise measurements can be taken.

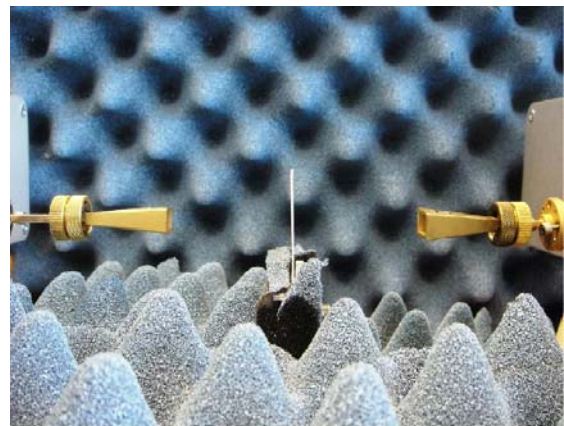


Fig.1. Free space measurement setup

It is extremely important to calibrate the system well in order to produce accurate measurement data. Calibrating the network analyzer at these frequencies is very challenging as there are no available

standards. The *thru*, *line*, *reflect* (i.e. full two port TRL) calibration technique together with time-domain gating was used to calibrate the system [14].

The measurement system was calibrated for S-parameter measurements using:

- *Reflect*: A copper plate in place of the dielectric sample. Antenna at port two was moved by the same distance as the thickness of the copper plate.
- *Line*: The copper plate was removed. The distance between the two antennas was unchanged.
- *Thru*: Supporting alumina tile was left at the same place. The antenna at port 2 was moved back to original position.

After calibration, the reference planes of the measurement were shifted to the face of the sample.

The time domain gating should be used on top of the TRL calibration to increase the accuracy of the measurement [15]. It allows the user to select the specific signal of interest, in this case the main reflection, and gate it. Gate functions act as filters in the time domain to remove the unwanted signal from measurement. These time domain gating functions eliminate another significant source of error in free space measurement, namely that due to multiple reflections and impedance mismatch.

To further minimize errors in measurement, the sample holder should not be moved at anytime during the measurement. It is a good practice to keep the copper plate used as the calibration reflector, and the sample, clean at all times. Contamination on these surfaces can cause the material under test to exhibit higher loss.

Finally, in our measurement procedure we assumed the material to be non-magnetic ($\mu_r=1+j0$), flat, homogeneous and isotropic.

4. Result and Discussion

The measurement was done on five of the most commonly used LTCC materials. Table 1 shows the dielectric samples used, together with respective thickness. Each sample was

fabricated using the normal LTCC fabrication process.

MATERIAL	THICKNESS (MM)
Sample 1	0.830
Sample 2	0.720
Sample 3	0.775
Sample 4	0.785
Sample 5	0.490

Table.1. List of LTCC material used and their respective thickness

To make sure that the system is well calibrated and produced practical result for the range of frequencies concerned, the system was first tested by measuring RT Duroid. RT Duroid is a material which has no dipolar mechanisms hence it has exceptionally stable permittivity across the frequency range. The measurements obtained for the permittivity of Duroid were around $\epsilon_r = 2.327055$ as shown in fig.2. The manufacture suggests that the permittivity is $\epsilon_r = 2.33$ at 10 GHz. These result shows that the system is calibrated well and will produce useful results

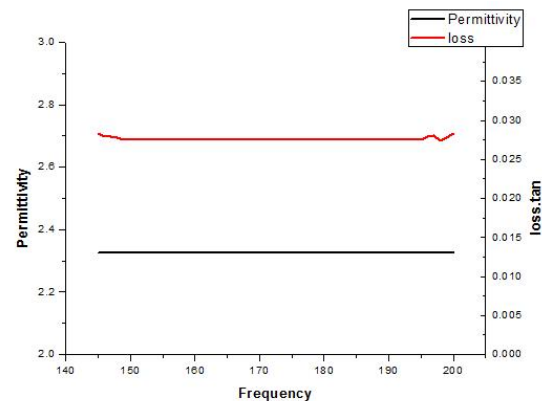


Fig.2. Permittivity and loss tangent of RT Duroid

Sample 1 is one of the most widely used LTCC tapes. It is available in multiple thicknesses and is known for its reliability and stability during fabrication process. From the measurement, the average permittivity across the frequencies of interest was $\epsilon_r = 7.1$, with a $\tan\delta = 0.0212$. The result of the measurement is shown in fig.3.

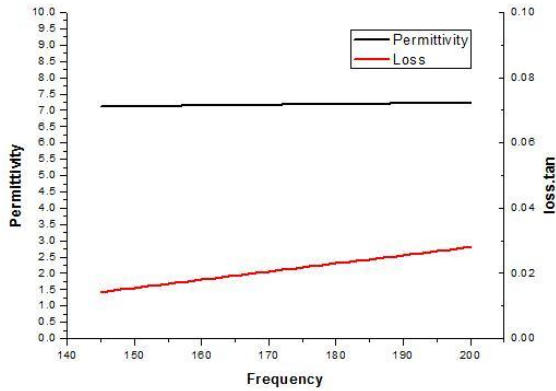


Fig.3. Permittivity and loss tangent of sample 1

Sample 2 is the LTCC tape which has a unique self-constraining properties with nearly zero shrinkage in X and Y axis. Fig.4 shows the measurement result. The average permittivity is $\epsilon_r = 6.78$ and average loss tangent of $\tan\delta = 0.01122$.

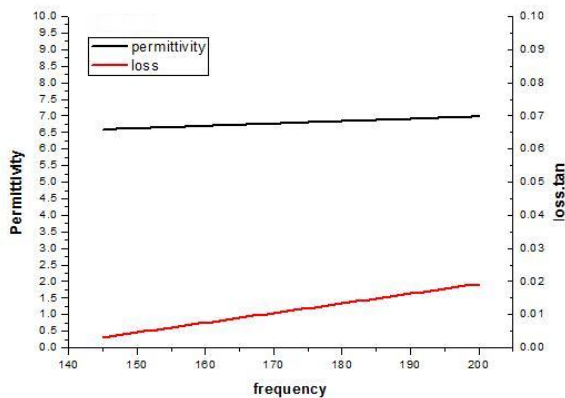


Fig.4. Measured permittivity and loss of sample 2.

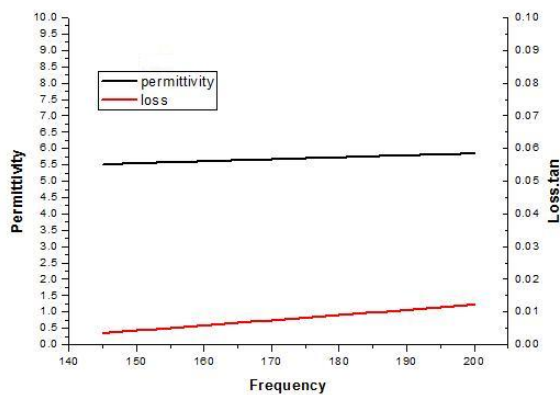


Fig.5. Permittivity and loss tangent of sample 3

Fig.5 and fig.6 shows the permittivity and loss tangent of sample 3 and sample 4 respectively. Both tapes are designed for wireless frequency application between 2.45GHz to 100 GHz. The measurement produce average permittivity of sample 3 to be $\epsilon_r = 5.677$ while sample 4 has permittivity is $\epsilon_r = 5.77$. Average loss tangent for sample 3 and sample 4 is $\tan\delta = 0.078$ and $\tan\delta = 0.048$ respectively.

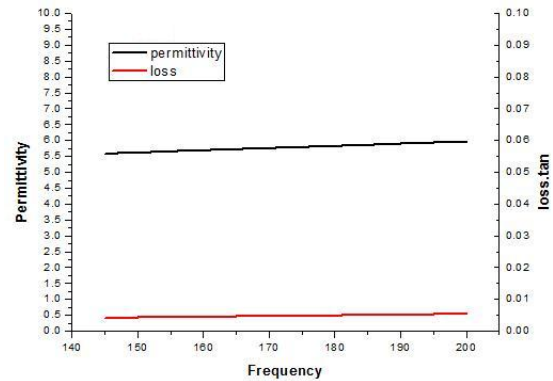


Fig.6. Permittivity and loss tangent of sample 4 LTCC

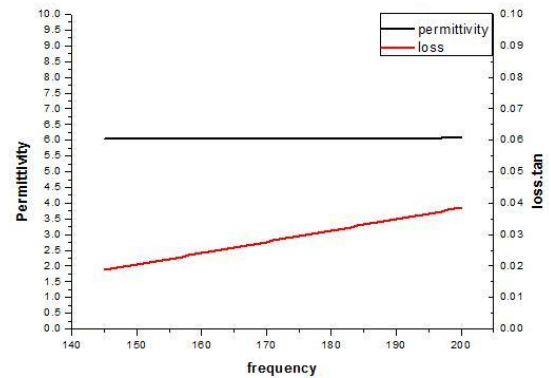


Fig.7. Sample 5 Permittivity and loss tangent

The sample 5 LTCC tape produced permittivity of $\epsilon_r = 6.058$ and loss tangent of $\tan\delta = 0.028608$.

Table 2 and table 3 show the measured values of permittivity and loss tangent compared to the manufacture value.

MATERIAL	MANUFACTURE PERMITTIVITY	MEASURED PERMITTIVITY (AVERAGE)
Sample 1	7.8 @ 3GHz	7.1
Sample 2	7.3 @ 2.5 GHz	6.78
Sample 3	5.9 @ 100 GHz	5.677
Sample 4	5.9 @ 100 GHz	5.77
Sample 5	6 @ 1MHz	6.058

Table.2. Comparison between measured permittivity value and manufacture data sheet.

As shown in table 2, the measured result is less than the manufacture's given value. However this is not a fair comparison as only sample 3 and sample 4 material has so far been characterised by the manufacturer at frequencies of up to 100 GHz. For both of these materials the results produced by the measurement were acceptable as the permittivity of dielectric material will slowly decreased as frequency increased [16].

MATERIAL	MANUFACTURE LOSS.TAN	MEASURED LOSS.TAN (AVERAGE)
Sample 1	0.006 @ 3 GHz	0.021155
Sample 2	0.0026 @ 2.5 GHz	0.01122
Sample 3	0.020 @ 100 GHz	0.007806
Sample 4	0.020 @ 100 GHz	0.004754
Sample 5	0.003 @ 1MHz	0.028608

Table.3. Loss tangent from the measurement compared with manufacture value

On the other hand, the loss tangent from the measurements produces interesting results. The loss tangent measured is much higher than the manufacture value.

5. Uncertainty Measurement

After the system was properly calibrated, the measurement obtain from the setup was assumed to be error free. However there is a possibility that the sample holder moved during process of changing the dielectric sample. These errors are usually human error in handling the measurement.

The sample holder used in the setup can hold the sample firmly in vertical direction but not in horizontal direction. As the sample holder was screwed to the metal base there was the possibility of it being twisted out of alignment during the measurement, thus causing the reference plane to be shifted. This would in turn cause an error in the angle of incidence of the wave on the sample, and change the area of the sample illuminated by the beam. At bigger angle some of the wave might not incident on the sample at all. This is demonstrated in fig.8.

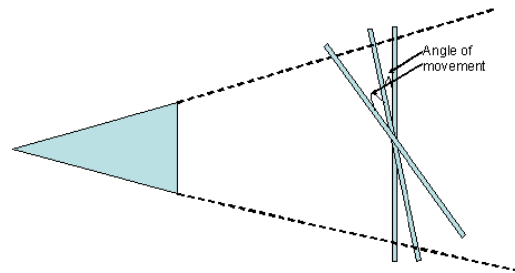


Fig.8. Effect of twisted sample holder (top view)

Fig.9 shows the measurement results from the alumina sample. In this case the sample holder was purposely twisted to some desired angles during the measurement to see the effect. A circular protractor is used to determine the angle.

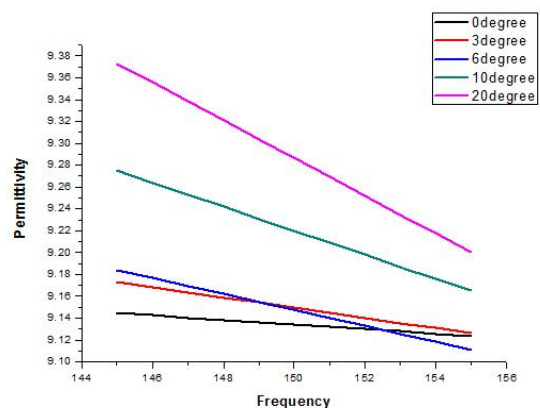


Fig.9. Measured permittivity of alumina with introduce error.

As shown in fig.9 the permittivity of the sample under test increased significantly when the sample holder is at an angle. The small angle is the main concern here as angle more than 5 degree is visible by naked eyes and

can be corrected. Angle smaller than 5 degree is hard to notice hence usually left uncorrected.

The permittivity is affected by ± 0.02 at small angle and ± 0.1 at bigger angle. From these results, it shows that the change in permittivity at small rotation angle is negligible. Nevertheless users should try not to move the sample holder by any means to minimize any post-calibration error. It also a good practice to recalibrate the system after few measurements to minimize post-calibration error.

6. Conclusion

The characterization of LTCC at higher frequencies extending into G-band was to address the needs of developing wireless applications.

In this paper, LTCC has been characterized from 145 GHz to 200 GHz using free space technique. The outcome demonstrated that free space measurement technique could be used to yield reasonable result at G-band. Furthermore measurement on different types of LTCC material shows that permittivity and loss tangent of these material make it feasible to be used for high frequencies applications.

The measurement technique that has been reported can easily be applied in industrial situations, due to the simplicity, and acceptable accuracy, of the procedure.

7. References

- [1] A.fathy, F.McGinty, et all "Low Temperature Co-fired Ceramic on Metal(LTCC-M) Packaging Technology", Journal of Materials, Vol. 2, No. 3, pp. 22-33, November, 1992.
- [2] Jia Sheng Hong, M,J,Lancaster "Microstrip Filters for RF/Microwave Applications" John Wiley & Sons, chapter 7, pp 224-227. 2001.
- [3] H.Liang, A.Sutono, J.Lasker, W.R.Smith, "Material Parameter Characterization of Multilayer LTCC and Implementation of High Q Resonator" IEEE MTT-S Digest, pp 1901-1904, 1999.
- [4] A.Bailey, W.Foley, M.Hageman, et all "Miniature LTCC filters for digital Receivers" IEEE MTT-S Digest, pp 999-1002. 1997.
- [5] Max Sucher, "Handbook of Microwave Measurements", The Polytechnic Institute of Brookly, third edition, Chapter 9, pp. 501-5033, 1993.
- [6] R. Hopkins, "Dielectric Material Characterisation above 100GHz using the Microstrip Ring Resonator", Proceedings of IMAPS 2006, San Jose, 2006.
- [7] P.J. Harrop, "Dielectrics", The Butterworth Group, first edition, London, Chapter 1, pp. 3-7. 1972.
- [8] Richard Collier, Doug Skinner, "Microwave measurements", IET Electrical Measurement Series 12, third edition, UK, Chapter 2, 2007.
- [9] Terry Edwards, "Foundation for Microstrip Circuit Design", John Wiley & Sons Publishers, second edition, UK, 1992.
- [10] D.K.Ghogdgaonkar, V.V.Vardan, V.K.Vardan 'Free Space Measurement of Complex Permittivity and Complex Permeability of Magnetic Materials at Microwave Frequencies' IEEE Trans Instrum Meas 39, pp. 387-389,1990.
- [11] D.blackham. 'Free Space Characterization of Materials'Hewlett Packard application note.
- [12] Alabaster, C. 'Permittivity Measurement on Human Skin in The Millimeter Wave Band' Electronics Lett., Voll.39, pp. 1521-1522, 2003.
- [13] R.D.Hollinger, K.A.Jose, A.Tellakula, V.V.Varadan 'Microwave Characterization of Dielectric Material From 8 to 110 GHz Using A Free-Space Setup'. Microwave and optic technology letters, Vol.26, 2000.
- [14] Danial Bourreau, Alain Peden, Sandrick Le Maguer, "A Quasi Optical Free Space Measurement Setup without Time Domain Gating for Material Characterization in the W-band", IEEE Trans. On Instrumentation and Measurement, Vol.55, No.6, 2006.

[15] L.F.Chen C.K.Ong, C.P.Neo, V.V.Varadan and V.K.Varadan, "Microwave Electronic Measurement and Material Characterization" John Wiley & Sons Ltd, first edition,2004.

[16] William D.Callister, "Material Science and Engineering an Introduction", John Wiley & Sons Publishers, seventh edition, Chapter 18, pp. 709-710, 2007.

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