THE BEHAVIOUR AND CHARACTERIZATION OF CIRCUIT MATERIALS AT HIGH MILLIMETER-WAVE FREQUENCIES

Nurul Osman, Charles Free
Advanced Technology Institute, University of Surrey, Guildford, UK

Introduction

Recent developments in circuit fabrication technologies have provided the microwave circuit designer with new design opportunities. For example, photoimageable thick-film and LTCC (low temperature co-fired ceramic) provide opportunities to generate high resolution and multilayer circuit structures. However, it is crucial for efficient design that the properties of the materials are well understood, particularly when they are being used in the millimetre-wave frequency range. Dielectrics are often the critical elements in circuit structures for use at high frequencies. The properties of the dielectric determine the circuit dimensions, and provide the medium through which the electromagnetic energy travels.

From the viewpoint of the RF circuit designer, the most important parameters for circuit substrates are the relative permittivity and the loss tangent. The values of these two parameters are not fixed value, but dependent on several factors such as ambient temperature, humidity and frequency [1-2]. It is the frequency dependence that is of most concern for microwave design. Manufactures of dielectric materials often supply frequency dependant data with their material; however these data are usually measured at lower end of the frequency spectrum (~2 *GHz*). With the trend towards the use of higher frequencies into the millimetre-wave region, there is a need for accurate characterization at frequencies higher than those specified by the manufacturer.

In this paper, data on the performance of a selection of common dielectrics at frequencies between 145 GHz to 200 GHz will be presented, along with details of the measurement techniques that were used. The choice of the technique used will also be discussed and justified.

Measurement Technique

There are various methods that can be used to characterize dielectric materials. However, not all these technique are suitable for use at high frequencies. Waveguide measurement systems are not appropriate for high mm-wave frequencies due to the limitation of small internal waveguide dimensions [3]. The waveguide dimension at these high frequencies is too small to allow easy insertion of the dielectric samples under test, and moreover would require very small materials samples to be prepared. This is not only challenging, but makes the measurement procedure prone to error.

Planar techniques such as the resonant ring, or the use of meander lines, are still suitable for use at very at high frequencies. However, since these techniques involve depositing conductor lines on a substrate they rely on computation to separate the properties of the conductor and the dielectric. The equations used for the computation become questionable at high frequencies where the skin depth in the conductor is less than the *rms* surface roughness [4]. Under these circumstances it is difficult to precisely define the surface loss in the conductor, and consequently it is difficult to extract precise information about the dielectric substrate

In the current work, a free-space measurement technique was used to measure the properties of dielectric directly, with no deposited conductors [5-6]. This technique was chosen due to the simplicity of the measurement setup and proved to be advantageous at higher frequencies [7]. It is a non destructive and contactless technique that required minimum sample preparation [8]. Figure (1) shows the essential setup of the measurement. The measurement only requires two antennas to direct the microwave energy, a sample holder to precisely locate the specimen, and a suitable VNA .

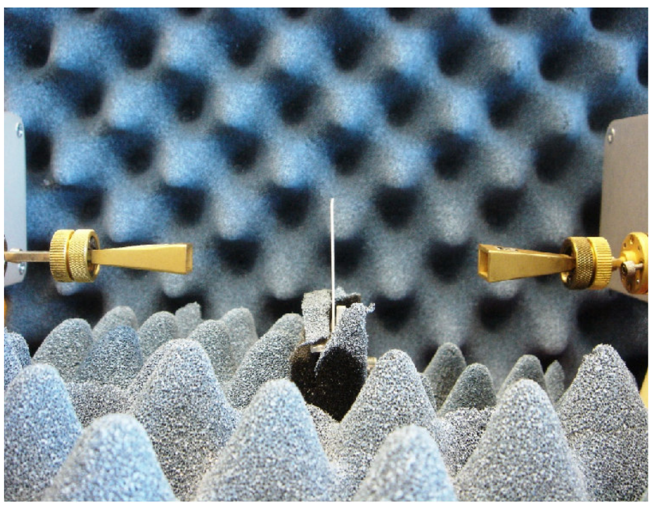


Figure 1: The setup for the free-space measurement

For measurement, the sample must be flat and placed at the distance from the antenna that is greater than the near field value. This is to ensure plane wave incidence on the sample. The area of the sample under test also must be big enough to cover the 3 *dB* beam width of the antenna. As frequencies become higher the near field distances become short and contribute to smaller beam width, hence the area needed to cover the 3 *dB* beamwidth area at these frequencies is smaller than typical samples size needed at lower frequencies. Figure (2) shows the difference in samples size needed for measurement at different frequencies. At frequencies between 145 *GHZ* and 220 *GHz* a reasonably small sample area is needed, and hence there is no need to employ lenses to reduce the area of the sample illuminated by the beam.

For 8Ghz-18GHz horn antenna

E	H	Beamwidth (E)	Beamwidth (H)
67mm	85mm	23°	22°

Far field:

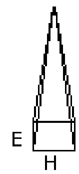
=2HH / lambda

=(2 X 85m)/ (c / 18G)

=867mm

Hence the 3dB beam width area:

=352.78mm X 377mm



For 145Ghz- 220GHz horn antenna

E	H	Beamwidth (E)	Beamwidth (H)
4.9mm	6.8mm	20°	20°

Far field:

=2HH / lambda

=(2 X 6.8m)/ (c / 150G)

=46.24mm

Hence the 3dB beam width area:

=16.33mm X 16.33mm

Figure 2: Comparison on the sample size needed at different frequencies

Result and Discussion

Measurements were made to measure the permittivity and loss tangent of several different dielectric samples at frequencies from 145 *GHz* to 200 *GHz*. Each sample was measured several times to check for consistency in the measurement procedure. The system was calibrated using the two horns without the sample as the S21 reference through path, and a metal plate in the plane of the sample to provide the S11 and S22 reference data [9 - 11]. Each sample was made to be 5 *cm* x 5 *cm*, this was enough to ensure the beam was totally enclosed within the sample area over the frequency range of interest.

Figure (3) shows the measurement results for the RT-Duroid material. Using RT-Duroid is a good way to check for the system performance. As RT-Duroid is a material which has no dipolar mechanisms, it has exceptionally stable permittivity across the frequency range. The measurements obtained for the permittivity of Duroid were around ε_r = 2.327055. The manufacturer suggests that the permittivity is ε_r = 2.33 at 10 *GHz*. These results indicate that the system is reasonably well calibrated.

Alumina is one of the most useful substrate materials for RF and microwave electronic systems. It is a very durable material with very good thermal properties. Figure (4) shows the measured permittivity and the loss tangent of the samples that were uses. The manufacturer's data for this material are only available at 1 *MHz* with permittivity of ε_r =9.8 and loss tangent of $\tan\delta$=0.0001. From the measurement the average permittivity across the measured frequencies is ε_r= 9.09 and loss tangent is $\tan\delta$= 0.05.

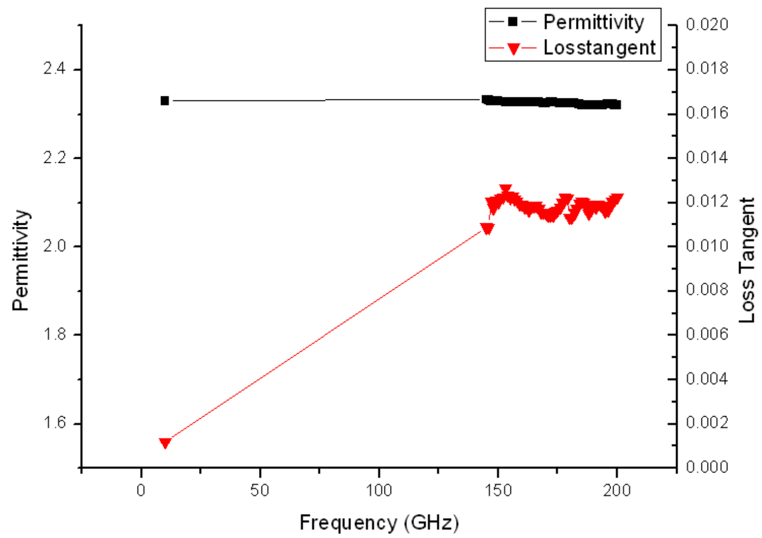


Figure 3: Permittivity and loss tangent of RT-Duroid

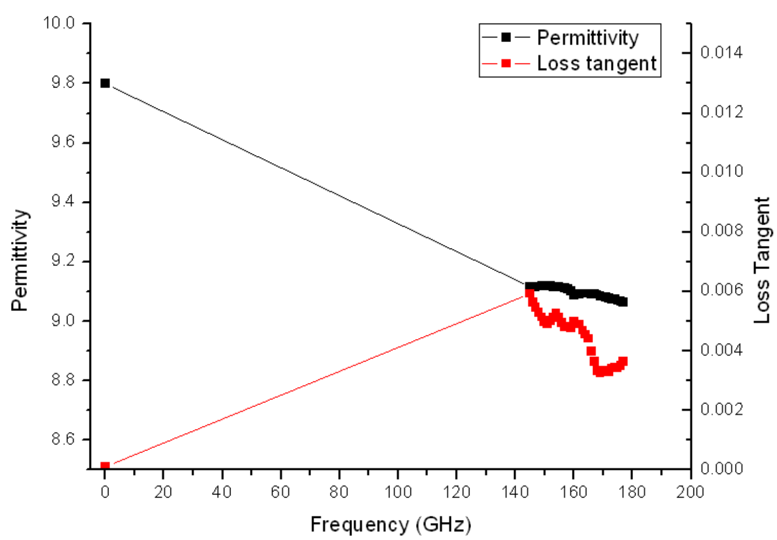


Figure 4: Permittivity and loss tangent of 99% alumina sample

The next material investigated was LTCC. This material has proved to have many advantages in term of fabrication processes and material properties. It also permits the inclusion 3-D microwave structures. Figure (5) and figure (6) shows the results for two of the LTCC samples measured. Even though the manufacturer's of LTCC boast about the performance of LTCC at higher frequencies, from the two figures it is clear that LTCC have higher loss tangent than alumina samples measured at the same frequencies. DP951 has a loss tangent higher than $tan\delta$=0.01 while HL2000 have loss tangent of nearly $tan\delta$=0.01. This might limit the usability of this material at higher frequencies. Although it should be pointed out that at mm-wave frequencies the devices are physically rather small, and therefore the loss tangent may have less significance than at lower frequencies.

Barium Strontium Titonate is a ferro-electric material. This type of material has a very high permittivity that can be tuned when a DC electric field is applies. At lower frequencies BST has been used as a tuning element; however the use at higher frequencies has been limited due to concerns that the material may be too lossy. Figure (7) shows the measured results for thick-film BST samples. The permittivity of the material was measured to be around ε_r=228 and loss tangent of *tanδ*=0.021. This loss tangent is in fact high for a dielectric material, however it was found to be comparable the LTCC material. As only a small amount of BST will be used as part of tuning element, the advantage of not having to use any active components should overcome disadvantage of the high loss.

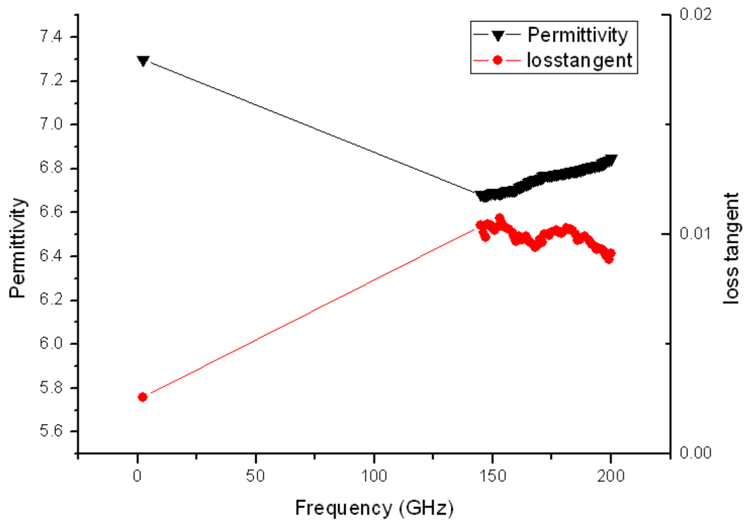


Figure 5: Material data of HL2000 LTCC samples

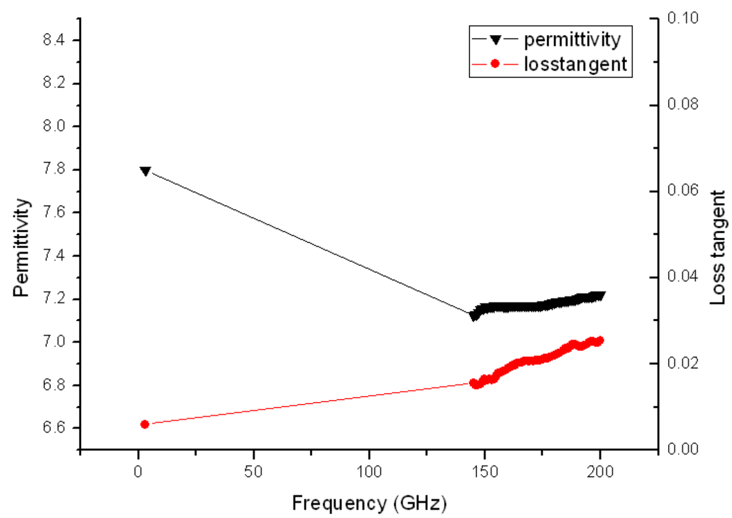


Figure 6: Material data of DP951 LTCC samples

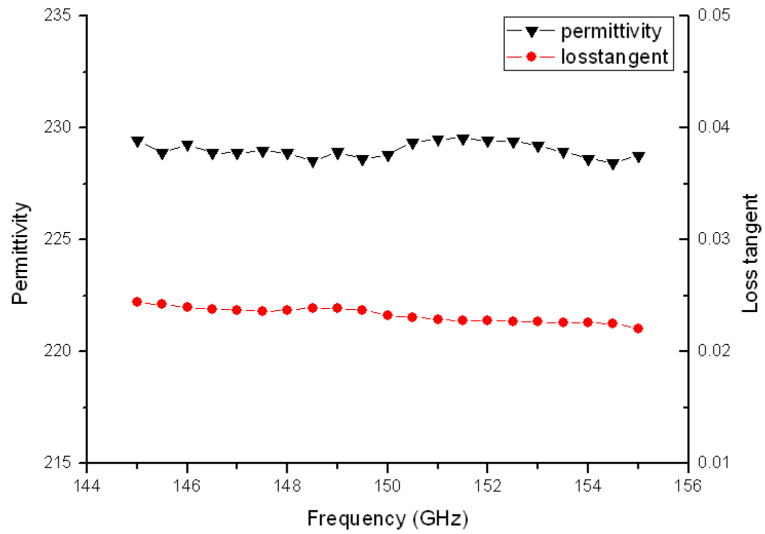


Figure 7: Loss tangent and permittivity of thick film BST sample

Conclusion

In general the measured data showed that the performance of commonly used substrate materials was such as to make them suitable for use at very high frequencies. Although the loss of some of the materials tested was rather high, the significance of this is offset by the fact that the size of components can be very small at these high mm-wave frequencies.

The results for BST were interesting in that they showed that the losses in the material were of an acceptably low level for use in miniature tuning components.

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