Millimeter-Wave Characterization Of Several Substrate Materials For Automotive Applications

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Abstract

Automotive radar systems, such as collision warning, which are under development are driving the advancement of low cost millimeter-wave materials and processes. This is especially true of material properties data. These automotive systems operate in the 30-100 GHz range. However, most vendor specifications for substrates give dielectric constant and loss tangent at a frequency of 10 GHz or lower. Several test methods have been developed over the years to obtain this type of data. These methods are compared, and one is used to evaluate LTCC from Ferro Corporation, commercial grade TMM from Rogers Corporation, and reinforced Teflon from Allied Signal at 95 GHz. The test method is described and test data is presented.

Introduction

Millimeter-wave materials data can be difficult to obtain for dielectric substrates. Most substrate vendors supply dielectric constant and loss tangent at 10GHz or lower frequency. For some millimeter-wave systems, this data is not sufficient. However, several methods have been developed over the years to determine the desired data. The purpose of this paper is to compare the available test methods, and obtain data at 95 GHz for several popular materials using the preferred method. The preferred method requires the least amount of test equipment, minimal sample preparation, and low cost fixturing.

Materials test methods being used today can be roughly divided into three categories. The first is the resonator method. This includes waveguide resonators and microstrip ring resonators printed on the dielectric[1,2]. The ring resonator method may be difficult to use at 95 GHz since the wavelength is so small (~ 0.050" at 95 GHz for $\varepsilon_{reff} = 6.0$). The waveguide resonator method requires the fabrication of waveguide resonators which is expensive. Tolerance requirements also make this method undesirable.

The second method measures the reflected and transmitted energy from a plate of dielectric material which is radiated by an antenna. This method requires the positioning of the sample to be accurate to within 1 µm at 95 GHz to keep the error in ε" below 1% [3]. Furthermore, a rather elaborate and expensive test fixture must be developed to allow for precise positioning of the sample. The benefit of this method is accuracy.

The third method uses dielectric samples inserted into hollow waveguide. By measuring scattering parameters, one is able to determine dielectric constant and loss tangent. The benefits of this method are the ease at which the measurements can be made, moderate sample preparation, and the simplicity of the theory. Strictly speaking this is also a resonator technique. This method is called the Fabry-Perot Method[4] and has been used to test Ferro Corporation A6 ceramic (LTCC) and Allied Signal 603 (reinforced Teflon substrate), and Roger Corporation TMM-4003 (commercial grade TMM).

Test Method

The test method is straight forward. Material samples are obtained with the correct thickness which is equal to the waveguide height.

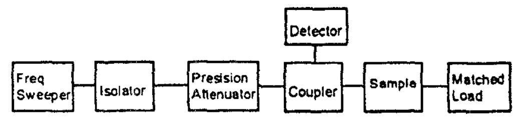

Figure 1. Testing arrangement used.

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The samples are then diamond saw cut into rods which fit into waveguide. At 95 GHz, WR-10 is the standard. It has a width of 100 mil and a height of 50 mil. For low loss measurements, the samples should be several wavelengths long within the guide. The test setup used in the test is shown in Figure 1. A return loss calibration is done between the coupler and matched load. The sample is then inserted into a piece of waveguide connecting the coupler and matched load.

The test data is compared to what is predicted by Equation (1) [4]. Note the βL dependence. This allows one to either vary the length of the samples or the frequency. The tests were conducted by varying the frequency for each sample length. This yields a data point (ε_r and tanδ) for each sample. If the frequency is fixed and the samples lengths are varied, one obtains a single data point for several samples.

$$|S_{11}| = \frac{\dfrac{R[1-\exp(-2\alpha L)]^2}{(1-R)^2\exp(-2\alpha L)} + \dfrac{4R}{(1-R)^2}\sin^2(\beta L)}{\dfrac{[1-\mathrm{Re}xp(-2\alpha L)]^2}{(1-R)^2\exp(-2\alpha L)} + \dfrac{4R}{(1-R)^2}\sin^2(\beta L)} \quad (1)$$

Where:

$$\alpha = \frac{\pi}{\lambda}\tan\delta\frac{\varepsilon_r}{\sqrt{\varepsilon_r - [\lambda/2a]^2}}, \beta = \frac{2\pi}{\lambda}\sqrt{\varepsilon_r - [\lambda/2a]^2}$$

$$R = \frac{\sqrt{\varepsilon_r - [\lambda/2a]^2} - \sqrt{1-[\lambda/2a]^2}}{\sqrt{\varepsilon_r - [\lambda/2a]^2} + \sqrt{1-[\lambda/2a]^2}}$$

λ = free space wavelength

a = waveguide width

ε_r = dielectric constant of substrate sample

L = length of substrate sample

tanδ = loss tangent of substrate sample

Test Results

Before running tests using this method, a possible problem needed to be investigated. The concern in using this method is that the dielectric material may not fully fill the waveguide. That is, since this method assumes that the dielectric fills the waveguide, an air pocket where dielectric should be may result in unacceptable errors. HFSS simulations were run to determine the effect of the dielectric not fully filling the waveguide. Figure 2 illustrates the result. It shows the propagation constant as a function of the material not fully filling the waveguide. Notice that the material can be moved away from the side walls by a total of 20 mil (10 mil on each side) with only a 0.5% change in propagation constant. This result may seem puzzling until the electric field distribution is considered. It has its maximum in the center of the guide and goes to zero at the side walls. Therefore, it makes sense that a pocket of air on the sides of the substrate would have a small effect.

This is not the case for air pockets above (or below) the filling substrate material. Significant errors result from air pockets in this region. Figure 2 shows that the propagation constant changes by 3% when the dielectric is 2 mil smaller than the waveguide (in the y-direction). Again, this makes sense because the

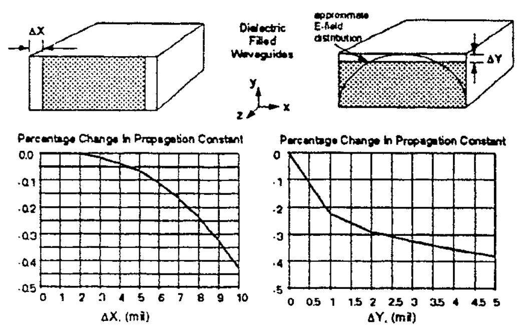

Figure 2. HFSS modeling results

electric field distribution is maximum in the center of the guide. One should note that there is a square root relationship between the propagation constant and the dielectric constant of the material filling the waveguide. The errors in Figure 2 should be increase by the square factor to find the error in the dielectric constant of the material. Using these results, samples were ordered which fit this requirement.

sample #	LTCC Y= 48.5mi	Allied Y=48 mil	Rogers Y=47 mil
1	X=93.0 mil Z=1.4777 in	X=97mil Z=1.5789in	X=96mil Z=0.5007in
2	X=93 mil Z=0.9991in	X=97mil Z=1.2019in	X=97 mil Z=0.9890in
3	X=94 mil Z=0.7268in	X=98mil Z=0.7268in	X=97 mil Z=1.3014in
4	X=94 mil Z=0.4491in	X=98mil Z=0.4491in	-
5	X=99mil Z=0.6693in	X=97mil Z=0.6693in	-
6	X=99mil Z=1.1994	-	-

Table 1. Dimensions of the samples used in the tests

LTCC was measured. Ferro LTCC (A6 ceramic) substrate was ordered with a height of

0.0485" to be used with standard WR-10 waveguide which has a height of 0.050". The substrate was diamond saw cut to the correct width and length. Six different lengths were made. The size of each sample was measured using a precision microscope and positioning table. Table 1 documents the test piece details. In this test, each piece was measured in the 90-95 GHz range. The measured reflection coefficient was compared to the predicted reflection coefficient. The model values for ε_r and tanδ were varied until the predicted value matched the measured value. This technique yields a measured value of ε_r and tanδ for each sample length. Table 2 shows the test results. The average dielectric constant was found to be 5.81 for LTCC at 95 GHz (vendor specification is ε_r = 5.9 at 1.0 MHz).

The same approach was used for the other samples. The average dielectric constant is 2.93 for Allied Signal 603 (vendor specification is ε_r = 2.95 at 1 MHz), and 3.39 for TMM-4003 (vendor specification is ε_r = 3.38 at 10.0 GHz).

sample #	LTCC	Allied	Rogers
1	ε_r = 5.93 Tanδ=0.0007	ε_r = 2.89 Tanδ=0.004	ε_r = 3.44 Tanδ=0.004
2	ε_r = 5.87 Tanδ=0.0007	ε_r = 2.97 Tanδ=0.008	ε_r = 3.38 Tanδ=0.005
3	ε_r = 5.74 Tanδ=0.001	ε_r = 2.91 Tanδ=0.007	ε_r = 3.34 Tanδ=0.003
4	ε_r = 5.88 Tanδ=0.003	ε_r = 2.87 Tanδ=0.007	-
5	ε_r = 5.68 Tanδ=0.002	ε_r = 3.03 Tanδ=0.009	-
6	ε_r = 5.78 Tanδ=0.001	-	-

Table 2. Measured data of the samples used in the tests

Conclusions

The test results showed an error in the test data for ε_r of +/- 2.2% for LTCC, +/- 3.4% for reinforced Teflon and 1.5% for TMM. The loss tangent had greater error. In some applications this error may be acceptable. Due to the limitations of test equipment at 90-95 GHz, and the dimensional variations between samples, it may be difficult to get more accurate results in this instance. Overall, this technique seems to be acceptably accurate, requires a minimum amount of millimeter-wave test equipment, no special fixturing, and moderate sample preparation.

The performance of the material is as expected. LTCC is preferred based upon the low loss tangent and the multi-layer processing capability which exists. The drawback to LTCC and the other materials is the low thermal conductivity, about 2-5 W/mK for LTCC. However, for applications where chips are direct mounted to a metal base through a cutout in the substrate, low thermal conductivity is not a significant concern.

References

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