Extraction of Material Properties for Low-K and Low-Loss Dielectrics Using Cavity Resonator and Efficient Finite Difference Solver up to 40GHz

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***Abstract*— Liquid crystal polymer (LCP) has been used as an RF substrate material for the packaging. As the technology continues to improve, LCP does not satisfy all of the thickness requirements for mobile applications. Therefore, a new dielectric material (Material-A) has been developed, which can be extremely thin and has a lower processing temperature than LCP. To accurately extract Material-A properties, we present a new extraction method which has a major advantage over the previously published techniques especially for low dielectric and low loss dielectrics. In this paper, the new method has been applied for extracting the frequency-dependent dielectric constant and loss tangent up to 40GHz for Material-A, and a Debye model that satisfies the causality has been developed.**

I. INTRODUCTION

As the operation frequency continues to increase for the next generation of RF applications, fabrication techniques and dielectric materials in RF substrates have to meet very demanding performance requirements. In addition, many of the dielectric materials that are widely used for the microwave circuit design have limitations on the implementation for higher frequency applications. For instance, FR4 becomes dysfunctional because of prohibitively large losses in the high gigahertz range, and low temperature co-fired ceramic (LTCC) has a relatively high cost [1]. One potential material that could overcome these limitations is liquid crystal polymer (LCP). Although LCP has low loss (loss tangent = 0.002-0.004 for $f <$ 105GHz) and low cost (\$5/ft^2 for 2-mil single-clad low-melt LCP) [2], the high processing temperature (290 °C) and compatibility with build-up substrates cause other barriers.

Since advanced technology leads to the miniaturization of the system, a new dielectric material is crucial for accommodating the needs of extremely thin dielectric substrates. Therefore, new low-K and low-loss dielectrics (Material-A) that is capable of 9 μm thickness per layer is being developed.

To accurately estimate the properties of extremely thin low-K and low loss dielectrics, the frequency-dependent dielectric constant and loss tangent have to be extracted. The square cavity resonator has been chosen over microstrip or ring-gap resonators because the cavity resonator is suitable for a thin dielectric material and easy to fabricate [3], [4]. Measurement is done by corner-to-corner plane probing method. This corner-to-corner plane probing method requires only two metals layered plane structure; hence it is simple to fabricate and measure [5]. The extraction method in [5] is based on the rapid solver which has some drawbacks. The rapid solver assumes a constant loss tangent and can only be applied in the low frequency range where the conduction loss is not affected by the surface roughness factor. Therefore, the extraction has been done only up to 10GHz.

In this paper, a new extraction algorithm is presented, which is based on an Efficient Finite Difference Solver (EFDS). EFDS not only can extract the frequency-dependent loss tangent, but it is also suitable for high frequency simulation (beyond 10GHz) because it takes into account the surface roughness factor of the dielectric material. After extracting the dielectric constant and loss tangent, a causal model is developed to represent the complex dielectric constants and loss tangents by using the vector fitting method.

II. TEST VEHICLE DESIGN AND EXTRACTION ALGORITHM

Four square plane resonators (32.5, 12.5, 9.5, and 6.5 mm), which is shown in Fig. 1, are fabricated for the purpose of varying the resonance frequency points from 1GHz to 40GHz.

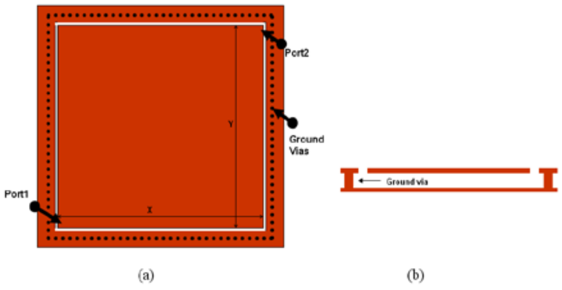


Fig. 1. (a) Top view and (b) cross section of the square planes.

The measurements are taken by using the corner-to-corner plane probing method, which is described in [5]. Typical methodology for extracting material properties is to use an electromagnetic solver to match the simulated result with the measurement over the frequency range of interest. This methodology requires a lot of iterations, and hence takes considerable time.

In comparison to the method presented in [5], EFDS has several advantages: 1) Use of exactly the same sampling frequency points from the measurement for the simulation. 2) Efficient extraction algorithm that simulates only two frequency points including the resonance frequency for finding the minimum value respect to the measurement. 3) Inclusion of the surface roughness factor for high frequency simulation and extraction. 4) Complete automation of the extraction process without human intervention.

Using the same sampling frequency points from the measurement enables the simulation result to be as close as possible to the measurement. Fig. 2 illustrates variations of the simulation results, which are performed by applying the different types of frequency sampling points for the same permittivity and loss tangent at 2-3GHz.

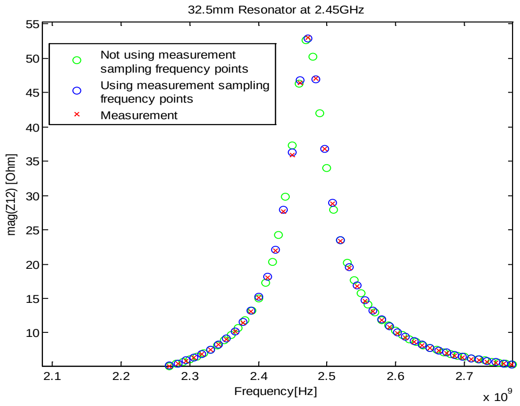


Fig. 2. Simulation results by varying types of the frequency sampling points.

The cross marks in Fig. 2 represents the measurement, and the circles are the simulation result. The simulation result (not using the measurement sampling points) shows the simulated points are not close to the measurement points. However, the cross and circle marks are almost on top of each others for the exact same sampling frequency points simulation; hence, the accuracy of the simulation result with respect to the measurement has been increased.

The key idea of EFDS is that it simulates only two frequency points including the resonance frequency during the extraction process. In conventional simulation technique, the resonance frequency points are defined by human. Then, the extraction process uses a wide frequency range near the resonance frequency so that the simulation is continued to fit the simulation graph to measurement. Since the simulation time is directly proportional to the frequency range of interest, the computational cost of the general simulation technique is very high. On the other hand, the frequency points for EFDS simulation are obtained by extracting the measurement frequency sampling points from measurement files while EFDS defines all of the resonance frequencies without human intervention. As a result, EFDS can easily take a very narrow frequency range near the resonance. Thus, accuracy and simulation time are significantly improved by using the measurement frequency sampling points and very narrow frequency range of interest.

By using very narrow frequency range, EFDS can be used as an automatic extraction. EFDS uses the finite difference method (FDM) [6]. The equations (include conductor and substrate losses and skin effect) for the impedances and admittances of the unit cell in FDM are defined as

$$Y = j\omega C_{uc} + \omega C_{uc} \tan\delta \tag{1}$$

$$Z = j\omega L_{uc} + 2\sqrt{\frac{j\omega\mu}{\sigma}} + \frac{2}{\sigma t} \tag{2}$$

where $\tan\delta$ is the loss tangent, σ is conductivity, t is the thickness of the conductor, and C_{uc} and L_{uc} are expressed as

$$C_{uc} = \varepsilon \frac{w^2}{d},\ L_{uc} = \mu d \tag{3}$$

where ε is the permittivity, w is the width of the unit cell, and d is the thickness of the dielectric. Because EFDS takes at least one of parameters in FDM equation and varies the parameters until the difference between the simulation and the measurement is minimized, EFDS can extract any material properties, which are in FDM equation. Therefore, once the resonance frequency points from the measurement are defined, EFDS continues to find the material parameters of interest for each of resonance frequencies until the least sum square errors between the measurement and simulation result are minimized.

III. SENSITIVITY OF UNIT CELL SIZE AND SURFACE ROUGHNESS FACTOR

A. *Choosing Ideal Unit Cell Size*

The number of unit cells in EFDS is very important because the unit cell size is directly proportional to the simulation time; the final solution form of EFDS involves a matrix inversion. In the ideal case, it will be best to use as small as possible unit cell size in order to have the most accurate simulation result. However, the number of unit cell size has to be optimized to have accurate and efficient simulation results at the same time.

Theoretically, it is recommended that the size of unit cell should be less than a tenth of the wavelength in the dielectric material. By using a tenth of the wavelength for the size of unit cell, the simulation results can in general be matched with measurements. However, the theoretical size of the unit cell can not be used in the extraction process since the simulation results are not accurate enough to extract the material parameters of interest. Fig. 3 demonstrates how the simulation results change as the size of unit cell decreases.

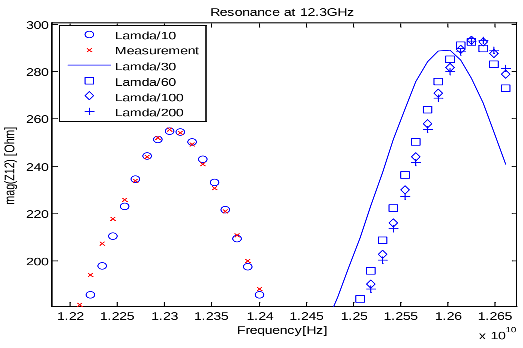


Fig. 3. Simulation result for the sensitivity of unit cell size.

The extracted parameters obtained from the use of the theoretical unit cell size are applied to the same resonance frequency by decreasing the size of the unit cell. Consequently, the simulation graph continues to shift to the right as the sizes of the unit cell are decreased. By comparing squares and diamonds in Fig. 3, it can be drawn that the simulation graph is not shifted much after the unit cell becomes smaller than a sixtieth of the wavelength. Eventually, the simulation result has converged when the unit cell is smaller than two-hundredth of the wavelength.

To find the ideal unit cell size in terms of the simulation speed and the convergence of the result, the extracted dielectric constants for one thirtieth, one sixtieth, and one two-hundredth are compared. The difference between one sixtieth and one two-hundredth was about 0.01%, and the difference between one thirtieth and one sixtieth was about 0.08%. Moreover, the variations from extracted loss tangents were negligible. Therefore, it can be concluded that a thirtieth of the wavelength is the ideal unit cell size because the simulation speed for a thirtieth of the wavelength is 8 times faster than one sixtieth of the wavelength, and the difference between them is negligible.

B. *Surface Roughness for High Frequency Simulation*

When the skin depth of the conductor approaches the surface roughness factor as the frequency increases, the constant conductivity that was valid for the low frequency simulation is no longer valid because the surface roughness factor significantly increases the conduction loss at the frequency where the skin depth becomes smaller than the surface roughness factor. To accurately model high frequency conduction loss, the frequency-dependent conductivity is required. By using equations in [7], the frequency-dependent conductivity of the conductor can be expressed as

$$\sigma_c = \frac{\sigma}{K_w^2} \tag{4}$$

where σ corresponds to the material's original conductivity, and K_w is defined as

$$K_w = 1 + \exp(-\frac{s}{2h})^{1.6} \tag{5}$$

where h is the surface roughness factor, and s is the skin depth. Because the skin depth is a function of the frequency, the frequency-dependent conductivity can be modelled by using (4). Fig. 4 shows the skin depth of the conductor (copper) and frequency-dependent conductivity of copper from 1GHz to 40GHz.

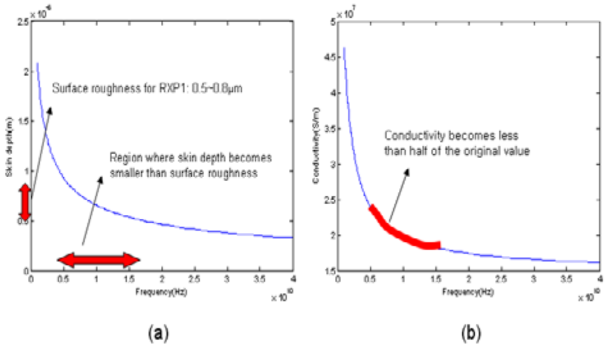


Fig. 4. (a) Skin depth and (b) conductivity of the copper for 1-40GHz.

The surface roughness for the fabricated resonator was measured as 0.5-0.8μm, which approximately falls in the frequency range of 5-15GHz where the skin depth becomes smaller than the surface roughness. In that frequency range (5-15GHz), the frequency-dependent conductivity becomes less than half of the original conductivity, which is shown in Fig. 4 (b). Since the conductivity is inversely proportional to the conductor loss, this frequency-dependent conductivity has to be included in the high frequency simulation to model the high frequency conduction loss.

IV. CHARACTERIZATION OF MATERIAL-A

For estimating property of Material-A and verifying EFDS, the frequency-dependent dielectric constant (3.48 at 1GHz) and loss tangent (0.0038 at 1GHz) of Material-A were extracted up to 40GHz. All of fabricated square resonators are characterized by using EFDS. High frequency simulation results by using the extracted dielectric constants and loss tangents verify the accuracy of EFDS; Fig. 5 shows the simulation result for one of the high resonance frequency, which is well matched with the measurement.

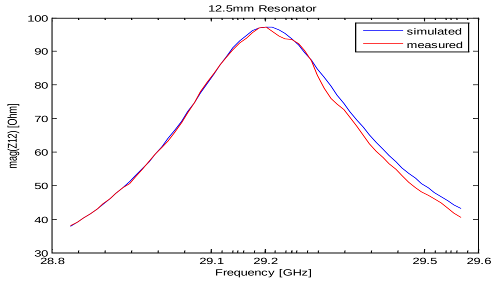
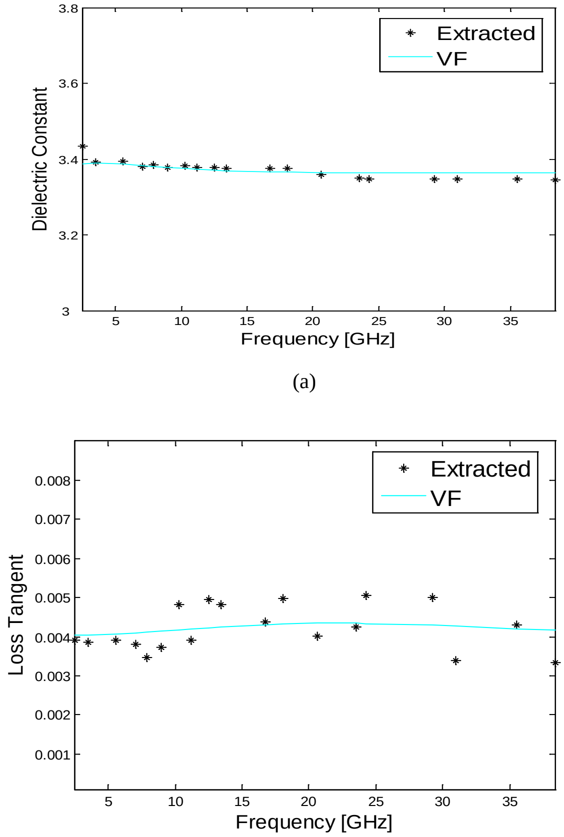


Fig. 5. Simulation result comparison with the measurement at one of the high resonance frequency (29.2GHz).

All of extracted dielectric constants and loss tangents as a function of the frequency are shown in Fig. 6.



(a)

(b)

Fig. 6. Comparison of the Debye model and extracted (a) dielectric constant and (b) loss tangent.

As expected, the extracted dielectric constants monotonically decrease as the frequency increases. An important aspect of the extracted parameters is that the extracted parameters assume there are no imaginary parts of the parameters. However, this assumption does not guarantee the system satisfies the Kramers-Kronig relationship; hence can violate the causality. Therefore, the complex dielectric constant that satisfies the causality has to be developed as well. A model that satisfies this condition is the Debye model.

The Debye model can be constructed by using the vector fitting method [8]. Based on the extracted parameters and frequency sampling points, vector fitting method creates the state space representations, which can be expressed as the Debye model

$$\varepsilon(\omega) = \varepsilon_\infty + \sum \frac{c_i}{s - a_i} \qquad (6)$$

where a_i represents a pole and c_i represents a residue. Fig. 6 also contains the results of the Debye model for the dielectric constant and loss tangent.

The causal model result at 40GHz was 3.36 that is about 3% difference from $\varepsilon_r = 3.48$ at 1GHz and 0.004 that is about 5% difference from $\tan\delta = 0.0038$ at 1GHz.

V. CONCLUSION

The dielectric properties of Material-A have been characterized from 1GHz to 40GHz using corner-to-corner plane probing. EFDS has successfully been used to extract the material properties without the need for human intervention. This paper also presented an implementation of the surface roughness factor into the finite difference method equation so that the accuracy of the high frequency simulation can be improved. EFDS will be very useful for the extraction of material properties of any dielectric material over a high frequency range as well.

The results show $\varepsilon_r = 3.42 \pm 0.06$ up to 40GHz and $\tan\delta < 0.0041$ up to 40GHz. In addition, the extracted material properties were fitted with the Debye model to ensure the causality by using the vector fitting method. Material-A is shown to have very attractive qualities as a packaging material for RF applications and as a high-performance ultra thin substrate.

ACKNOWLEDGMENT

The authors would like to thank V. Sundaram, F. Liu, H. Chan, G. Krishnan, and D. Athreya from PRC members for supporting the fabrication process, and S. Kennedy, D. Baars, and J. Dobrick for providing the substrate material in time. The authors are also grateful to K. Han from EPSILON group for discussion of the extraction algorithm.

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