Measurement of Dielectric Property Distributions Using Interdigital Dielectrometry Sensors

Alexander Mamishev Yanqing Du Markus Zahn
Department of Electrical Engineering and Computer Science
Massachusetts Institute of Technology
Cambridge, MA 02139, USA

Abstract

Estimation of physical properties of insulating materials may effectively be done by using non-destructive ω-*k* (frequency-wavelength) dielectrometry technology. Essential to this technology are pairs of interdigitated electrodes, which respond to the change in resistive and capacitive properties of the surrounding media. This paper presents both experimental and theoretical data, which helps to investigate the ability of the sensor to characterize multi-layered insulating and semi-insulating materials. Issues of precision and reliability of the measurements are discussed.

Introduction

Interdigital electrode structures are currently used in microwave integrated circuits as capacitors, in surface acoustic wave modulators as emitting electrodes [1], as capacitive electrodes in various detectors, and for other applications. The first works in using interdigital electrodes for characterization of properties of multi-layered materials had been conducted in the early eighties [2]. Due to the small size of the sensors, the thickness of each layer of studied materials was on the order of microns. A promising technological step, application of this technology to monitoring of moisture dynamics in the transformer pressboard, requires penetration depth of the sensor (and, consequently, its spatial wavelength of interdigitation) to be on the order of millimeters [3].

Although the idealized model of the interdigital structure exists [2], various geometric factors introduce distortions which become significant when relative thickness of the electrodes, and the ratio of the finger length to the meander length becomes small [4]. The discrepancy between the idealized theoretical model and the actual structure complicates development of parameter estimation algorithms. The study presented in this paper helps to validate the theoretical model and to estimate the errors of the parameter estimation.

Description of the Sensor

The structure of the three-wavelength interdigital sensor used in this investigation is shown in Figure 1. The flexible sensor consists of three sets of electrodes deposited on a common flexible polyimide substrate (Kapton). The sensing electrodes are shielded by guard electrodes driven by the buffer stage in the interface circuit, and the guard electrodes are shielded by ground electrodes [5].

The idealized model for which the closed form expression for the electrodes' electric field exists requires the electrodes be an infinitely long and wide array of infinitely thin microstrips placed on the surface of the insulating substrate. The thickness of the electrodes (35 μm in our case), the finite length and finite number of the fingers, the capacitance of the leads of the electrodes to the ground and to each other, and the metallization ratio (described as ratio of the area covered with copper to the total area of the sensor) are the most important contributors to the discrepancies between the theoretical model and the real measurement data.

Theoretical Background

The sensor is connected to a microprocessor-controlled voltage source through an electronic interface circuit. Altogether with the interface, it creates a resistive-capacitive divider, the output of which is recorded and analyzed.

When the lumped parameter representation of the sensor structure is used, the test response is equivalent to voltage gain G and phase Φ of a RC circuit. The voltage measured in the sensing electrodes V_S can be expressed in terms of the driven voltage V_D as:

$$\frac{V_S}{V_D} = Ge^{j\Phi} = \frac{Y_{12}}{Y_{12} + Y_{11} + Y_L}, \qquad (1)$$

where Y_{12} is the admittance between driven and sensing electrodes which reflects the dielectric property of the test materials, Y_{11} is the admittance between the sensing electrode and the ground, and Y_L is the load admittance of the electronic interface.

From the electroquasistatic field point of view, the potential of the field excited by the driven electrodes is a solution to Laplace's equation. At any constant z position, the field is periodic in the y direction and uniform in the x direction. It can be written as an infinite series of sinusoidal Fourier modes of fundamental spatial wavelength λ and decays away in the z direction [5]:

$$\Phi = \sum_{n}^{\infty} \Phi_n \text{hyp}(k_n z) \cdot \text{trig}(k_n y), \qquad (2)$$

where $\text{hyp}(k_n z)$ stands for any hyperbolic function, the $\text{trig}(k_n y)$ stands for any trigonometric function, and $k_n = 2\pi n/\lambda$ is the wavenumber of each mode.

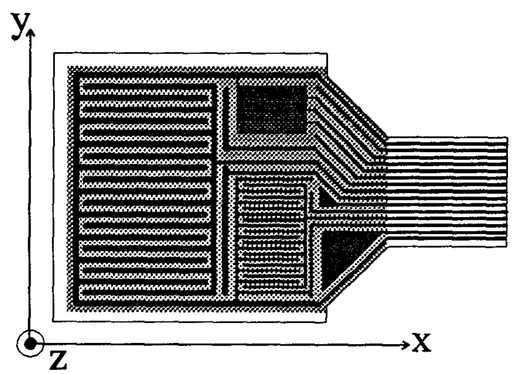

Figure 1. The three-wavelength interdigital sensor.

Experimental Arrangement

The goal of the series of experiments presented in this paper is to test the dependence of the sensor response on the thickness of the material above the sensor. Figure 2 depicts the cross-section of the experimental setup. Two materials with known properties form a two-layer medium. When the thickness of the lower material is reduced, the interlayer boundary moves down, and the influence of the upper material increases. The upper material is thick enough to be considered infinitely thick.

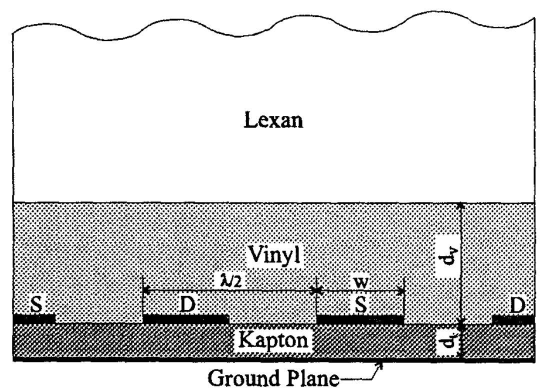

Figure 2. The cross-section of the interdigital sensor with two layers of materials above it.

Two commercially available insulating polymers, monolithic pieces of Lexan (GE polycarbonate brand name) and thin-filmed vinyl, had been used. The thin film enables us to control the thickness of the test sample by changing the number of sheets of vinyl. In order to press the whole structure together and provide a good contact between the materials, a heavy slab of lead had been positioned on top of the test cell. In general, highly conductive metal would strongly affect the distribution of the electric field in the studied region, unless it was sufficiently far from the strong field region. It can be seen from (2) that the electric field excited by the sensor dies away exponentially in the vertical position with the penetration depth of $\lambda/2\pi$. Let us denote the distance at which the electric field potential reduces by one order of magnitude as an effective penetration depth of our sensor. The total thickness of Lexan was 17 mm, which is about 10 times the effective penetration depth of the largest wavelength.

The schematic view of the experimental setup in Figure 2 shows one and a half periods of the interdigitated electrodes. The character D refers to the driven electrode and S refers to the sensing electrode. A one volt peak sinusoidal voltage was applied to the driven electrode. The voltage magnitude and phase of the sensing electrode was measured and recorded. As the distance d_v becomes smaller the influence of dielectric properties of the Lexan becomes stronger which is illustrated in the following sections.

Results of Measurements

The dielectric permittivity of the materials had been predetermined using a parallel-plate capacitor of known geometrical dimensions with (3):

$$\varepsilon_a = \frac{\pi \cdot C}{L + W + W\ln\left(\frac{\pi L}{d}\right) + L\ln\left(\frac{\pi W}{d}\right) + \frac{\pi LW}{d}}, \quad (3)$$

where L and W are the length and width of the parallel-plate capacitor, d is the distance between the plates, and C is its capacitance. Equation (3) takes into account the fringing fields of a parallel-plate capacitor and is derived using a Schwarz-Christoffel transformation.

The dielectric permittivity of the polycarbonate Lexan sheet has been estimated to be equal to 2.6, and that of vinyl film is equal to 3.8. The conductivity of Lexan is on the order of 10^{-17} Sm/cm and in our frequency range its effect is negligible. The conductivity of vinyl is on the order of 10^{-11} Sm/cm, and the vinyl appears to be a dispersive material. Only qualitative discussion of conductivity effects is given in this paper. Precise measurements of all quantities with interdigital sensors will be performed in the near future.

As discussed above, according to the idealized model, the effective penetration depth of an interdigital sensor must be about one-third of the sensor's spatial wavelength λ. In our case, the metallization ratio is close to 0.5 for 5 mm and 2.5 mm wavelengths, and it is about 0.36 for the 1 mm wavelength. The results of a high frequency scan (1 kHz) are shown in Figure 3 for all three wavelengths. A good correspondence with the theory can be observed. The smallest structure does not respond to the changes of the thickness because in almost all cases it exceeds one-third of 1 mm. The response of the 2.5 mm structure flattens off at about 0.7 mm, and for 5 mm at about 1.2 mm. It should be noted, however, that since the distinction must be made between levels of attenuation which differ only by 1 or 2 dB, the sensitivity to the error in such measurements is relatively high. Of course, if the difference between the values of the dielectric permittivity of the two materials was larger, the effect of the movement of the interlayer boundary would have been more observable.

As seen from Figure 3, given the geometrical dimensions of this setup, the measurements with the 5 mm wavelength are the most descriptive in terms of sensitivity of the sensor to the position of the interlayer boundary. The results of the frequency scans of setups with varying thickness are shown in Figures 4 and 5.

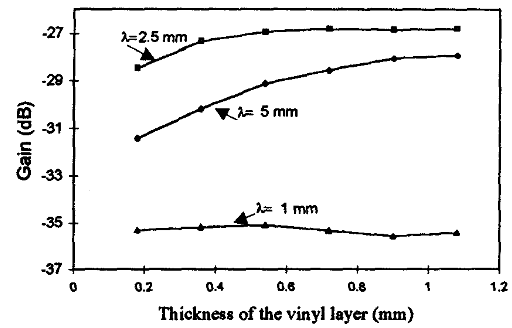

Figure 3. Experimental estimation of the effective penetration depth of a three-wavelength sensor.

At high frequencies,. the gain is approximately equal to the ratio of the capacitances in (1). Since the dielectric permittivity of vinyl is higher than that of Lexan, the equivalent capacitance measured by the sensor becomes smaller as the distance d_v decreases. Thus, the gain shifts towards the flat gain of the non-conductive Lexan-insulated interdigital capacitor. As the frequency is lowered, the slightly conductive vinyl makes the test cell behave like a first order system with one pole and one zero in the transfer function. It has a minimum in the phase-frequency curve whose position is determined by the location of the pole and zero (see Figure 5). It should be noted that depending on the ratio of interelectrode capacitances and conductances, and the load capacitance, the phase minima may shift either to the left or to the right, since the conductivity of Lexan is lower, and the dielectric permittivity is lower than that of vinyl.

In the curves shown in Figure 3, the small negative phase-shift is not considered, primarily because it does not affect the overall estimation of the effective penetration depth. In the graphs shown in Figure 6, the gain, measured at the frequency of 10 kHz (the right-most data points in Figure 4, curve 1), is compared with the gain calculated with a finite-element electric and magnetic field calculation package Ansoft (curve 2). The irregularity of the shape of the experimental curve 1 is mostly due to the A/D conversion limitations at 10-kHz. The highest frequency of the sweep had been used to reduce effects of the conductivity on the output data.

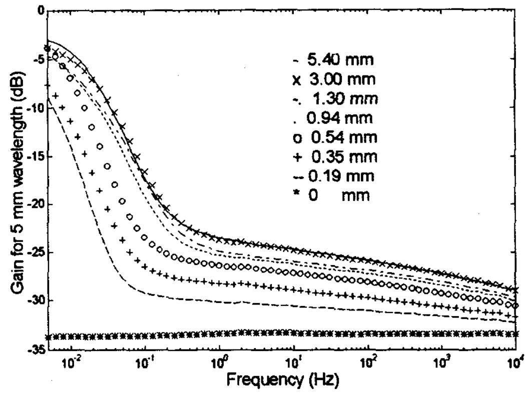

Figure 4. Response of the sensor's gain to the movement of the interlayer boundary, d_v.

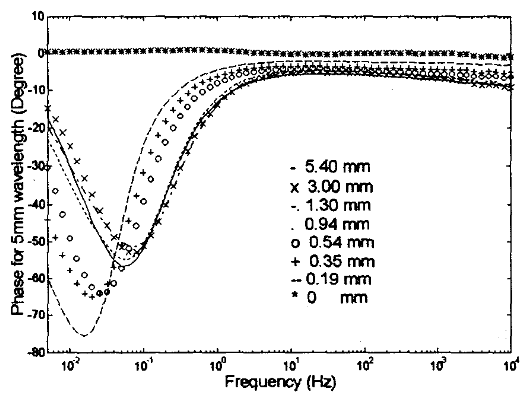

Figure 5. Response of the sensor's phase to the movement of the interlayer boundary, d_v.

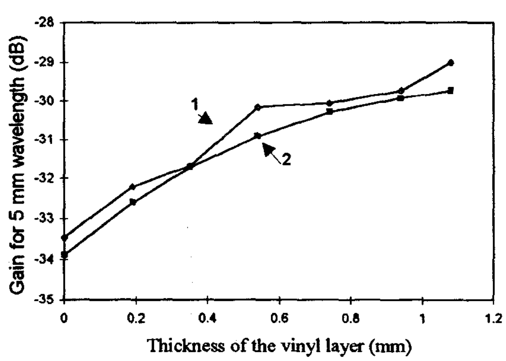

Figure 6. Comparison of measured (1) and theoretical (2) response of an interdigital sensor (λ=5 mm).

Conclusions

Monitoring of changing physical properties of the two-layered structure had been performed using interdigital frequency-wavelength dielectrometry technology. The theoretical values of the penetration depth of the three-wavelength interdigital sensor had been confirmed with experimental data.

In general, both conductive and capacitive properties of the media can be used for the characterization of the materials with spatially varying properties. However, additional work is needed for reliable solution of the inverse problem of parameter estimation.

Acknowledgments

The authors would like to acknowledge continuing support of Electric Power Research Institute, Palo Alto, CA, under WO 3334-1, managed by Mr. S. Lindgren. We also thank Ansoft, Corp., for providing the finite-element software, and Mr. Darrell Schlicker, MIT, for valuable discussions and assistance with the experiments.

References

[1] R.T. Kollipara, A.S. Mohammed, T.K. Plant, and V.K. Tripathi, "Modeling and Design of Interdigital Structures," *IEEE Transactions on Electron Devices*, vol. 38, no. 11, November 1991, pp. 2575-77.

[2] M.C. Zaretsky, L. Mouayad, and J.R. Melcher, "Continuum Properties from Interdigital Electrode Dielectrometry," *IEEE Transactions on Electrical Insulation*, vol. 23, no. 6, Dec. 1988, pp. 897-917.

[3] Y.K. Sheiretov, M. Zahn, "Dielectrometry Measurements of Moisture Dynamics in Oil-Impregnated Pressboard," *1994 IEEE International Conference on Properties and Applications of Dielectric Materials*, University of Queensland, Brisbane, Australia, July 1994.

[4] E. Pettenpaul, H. Kapusta, A. Weisgerber, H. Mampe, J. Luginsland, and I. Wolff, "CAD Models of Lumped Elements on GaAs up to 18 Ghz," *IEEE Transactions on Microwave Theory and Techniques*, vol. 36, no. 2, February 1988, pp. 294-304

[5] Y.K. Sheiretov, M. Zahn, "Dielectrometry Measurements of Moisture Dynamics in Oil-Impregnated Pressboard," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 2, June 1995, pp. 329-351.

[6] A.K. Jonscher, *Dielectric Relaxation in Solids*, Chelsea Dielectric Press, London, 1983.