

One-sided Measurement of Material Dielectric Properties Using a Liquid Dielectric Immersion Technique

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Abstract

One of the most important factors that limit the accuracy of nondestructive measurements of dielectric and related physical properties of solid electrically insulating materials is the presence of an erratically non-uniform air gap between the sensor head and the material surface due to electrode thickness and surface roughness and deformations. Sensitivity analysis shows that the statistical error of interdigital sensor measurements due to non-ideal contact conditions may be reduced by filling the air gap with a dielectric liquid that has relatively high dielectric permittivity.

A feasibility study with several combinations of liquid and solid dielectrics is presented. Two measurement approaches are explored. In the first case, the capacitance of a reference interdigital single-wavelength sensor immersed in a dielectric liquid is compared to the capacitance of a twin sensor in the same dielectric liquid adjacent to the solid dielectric. Borrowing the methodology from more common parallel-plate methods, one mixes two liquids with different properties until matching of the dielectric constant of the solid and liquid dielectrics is achieved. In the second case, multiple penetration depth measurement options are utilized to measure properties of the solid dielectric. The achieved accuracy and the potential improvements of this approach are discussed.

Introduction

The interdigital frequency-wavenumber dielectrometry methodology is based on excitation of several sets of spatially periodic interdigitated electrodes with a sinusoidal voltage over a wide frequency range [1]. By varying the spatial periodicity of interdigital electrodes, it is possible to vary the depth of penetration of the generated fringing electric fields into the dielectric medium. The review of techniques and methods used in this technology is available in [2-4].

In many cases, the interpretation of the sensor re-

sponse depends on simple calibration procedures, yet in other cases, it requires sophisticated signal processing algorithms and deep understanding of the physics and chemistry of the dynamic processes that are being monitored. Since the changes in the dielectric properties are usually induced by changes in various physical, chemical, or structural properties of materials, the dielectrometry measurements provide effective means for indirect non-destructive evaluation of vital parameters in a variety of industrial and scientific applications.

The accuracy, sensitivity, selectivity, and reliability of interdigital dielectrometry measurements still raises many questions. This paper presents a feasibility study for one of the techniques identified as a possible way of improving accuracy of interdigital dielectrometry. It concerns measurements of properties of solid dielectrics that are in direct contact with the sensor head. Since the ideal contact is usually not achievable, it is important to alleviate and quantify the effects of the non-ideal surface contact.

Three-wavelength Sensor

The top view of the sensor used in this study is shown in Figure 1. It consists of three sets of topologically identical interdigital electrodes etched on a common flexible substrate. The gray shaded area indicates guard backplanes on the reverse side of the substrate. The highly hydrophobic Teflon[®] substrate is 254 μm thick and has a relative dielectric permittivity ϵ_r of 2.1. The transconductance and transcapacitance between electrode fingers are measured by driving one of them with a sinusoidal voltage signal.

In our normal practice, the frequency of this signal varies between 0.005 Hz and 10 kHz. For the simplicity of analysis and presentation, only high frequency data (1 kHz) is analyzed in this paper. The conduction currents are negligibly small in comparison with capacitive currents for all materials used in this study.

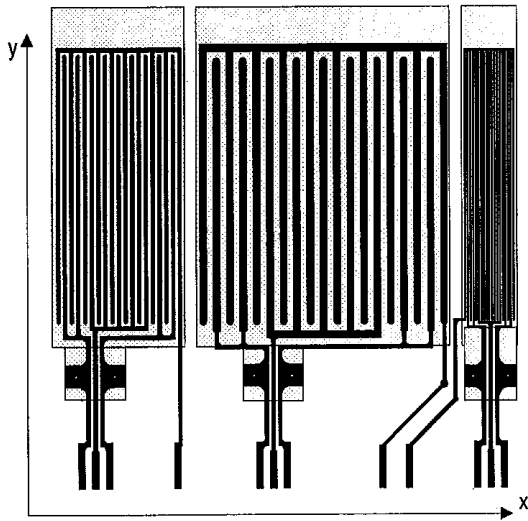


Figure 1: The three-wavelength interdigital sensor with spatial periodicity of 2.5 mm, 5.0 mm, and 1.0 mm.

Matching Fluid Approach

If various secondary effects are neglected, it is possible to estimate the dielectric properties of irregularly shaped solid materials by positioning them between the electrodes of the test cell, which can be, for example, a parallel-plate capacitor or a coaxial cylindrical capacitor. If the dielectric permittivity of the solid material under test is uniform, it can be determined in the following way. Two identical test cells are positioned in the same container filled with some kind of a dielectric liquid. One cell contains only this liquid, and the other cell contains the solid material under test surrounded by the same dielectric liquid. The capacitances between the corresponding pairs of electrodes are equal when the dielectric permittivity of the liquid is equal to the dielectric permittivity of the solid sample. Initially, the capacitances of each cell are different, but by varying the dielectric permittivity of the liquid, one can bring them to be equal. The easiest way to estimate the dielectric permittivity of the solid dielectric is to gradually mix two miscible dielectric liquids with approximately equal specific gravity, as was done in [5] to measure the dielectric permittivity of various grains. For this type of measurement, it is necessary that the relative dielectric permittivity of the solid dielectric be between the dielectric permittivities of the two liquids.

Similar to the liquid displacement approach described in [6], the two-fluid method provides a potentially higher accuracy of measurements, especially with

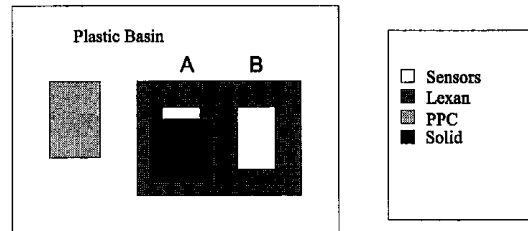


Figure 2: Schematic of the measurement setup for two fluids measurement. A parallel plate capacitor (PPC) on the left is used to measure the dielectric permittivity of the liquid mixture.

irregularly shaped material surfaces. This project evaluated the applicability of two-fluid methods to determine ϵ_r with a greater accuracy than could be achieved otherwise. Two nearly identical 2.5 mm wavelength sensors (identical in terms of metallization and capacitance) were submerged in a liquid composed of 2000 ml transformer oil ($\epsilon_r = 2.2$) and castor oil ($\epsilon_r = 4.5$) (as shown in Figure 2). A solid sample was placed on one of the two single wavelength sensors. The sensors were placed on a piece of Lexan ($\epsilon_r = 3.0$) to ensure good contact with the solid sample since the bottom of the basin was flexible and not flat. Additionally, a parallel plate capacitor was used to give another measure of the permittivity of the liquid. The castor oil was mixed into the transformer oil until both sensors measured the same capacitance (adjusted for the small difference in metallization) and permittivity. At this point, a value for the permittivity of the solid sample could be obtained. Although the only necessary stopping criterion is that the measured dielectric permittivity be the same, the equality of the capacitance provided an additional check.

Figure 3 shows the change of apparent relative dielectric permittivity computed from measurements under the assumption that the sensor head is in contact with a homogeneous dielectric medium. The two lines intersect at the correct value of the Lexan relative dielectric permittivity $\epsilon_r = 3.0$ when the amount of added castor oil is equal to 1000 ml.

The estimation of the relative dielectric permittivity plotted in Figure 3 requires either calibration of interdigital sensors or a model-based inverse problem algorithm. It is also possible to bypass modeling by adding the measurement data from the parallel-plate capacitor to the analysis. The ratio of capacitances of the two interdigital sensors is plotted in Figure 4 against the relative dielectric permittivity measured by the parallel-plate capacitor. The intersection of the measured capacitance

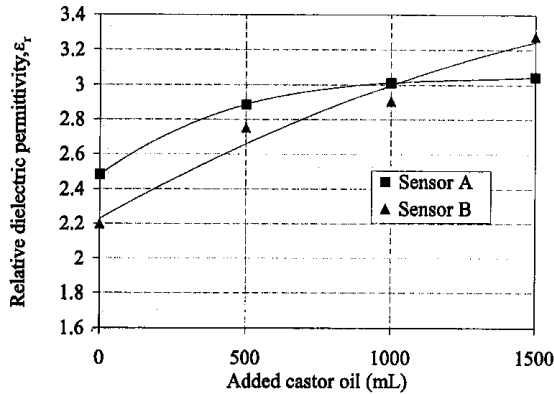


Figure 3: Apparent relative dielectric permittivity measured by two nearly identical 2.5 mm wavelength interdigital sensors as a function of added castor oil volume. The transformer oil volume is 2000 ml. Both sensors are immersed in the oil mixture with Sensor A also pressed against the Lexan sample. Solid lines are a third order polynomial fit to the experimental data.

ratio curve with the equal capacitance curve gives the estimate of the relative dielectric permittivity of material under test ($\epsilon_r = 2.95$). The equal capacitance curve comes from the measurement of the capacitance of each interdigital sensor in air; the values are not exactly 1.0 because the sensors are not completely identical due to inherent manufacturing imprecision of flexible circuits.

Multiple Wavelength Measurement Sensitivity

The major interest that drives multiple wavelength measurement technique development stands from the ability to determine several material properties with a single device. Such an approach also implies a possibility to increase measurement accuracy of properties of interest by reducing the effect of measurement perturbations. The following example shows that filling the gap between the sensor head and the solid material under test may improve selectivity of the measurement. The gap is modeled here as an ideally flat one. This representation is adequate for purely capacitive cases with no significant conduction currents. Figure 5 shows lines of equal capacitance computed with finite element simulation for a specific point in a two-variable (ϵ_r and h) solution space. The values of relative dielectric permittivity ϵ_r and equivalent air gap h can be found from two measurements with different spatial wavelengths, different ambient media, or both. The angle between the iso-capacitance lines should be as close as possible to 90 degrees in order to provide the best selectivity with

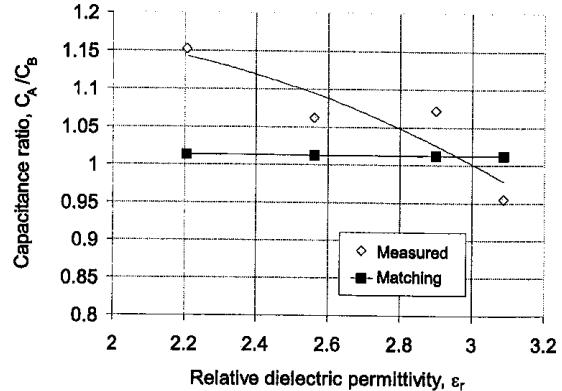


Figure 4: Relative dielectric permittivity of material under test determined through the capacitance ratio. The "Matching" line represents the calibration-based simulated data for two slightly different sensors immersed in a homogeneous dielectric. All points on this line would be at the capacitance ratio of 1.0 for identical sensors.

| | 1 mm | 2.5 mm | 5 mm |
|------------|------|--------|------|
| Air | 6.07 | 4.72 | 4 |
| Castor oil | 10.5 | 6.7 | 4.4 |

Table 1: Calculated capacitance in pF for different wavelengths and filler materials for the operating point ($\epsilon_r = 3.0$, $h = 30 \mu\text{m}$) shown in Figure 5.

respect to both variables, ϵ_r and h .

One of the ambient media in this simulation is castor oil, marked with the letter C in Figure 5, and the other one is air, marked with the letter A. Since the dielectric permittivity of air is smaller than that of Lexan, all three iso-capacitance lines given in Table 1 lie in the first and third quadrants (if the origin is placed at the operation point, where all lines intersect). Similarly, since the dielectric permittivity of castor oil is larger than that of Lexan, all three iso-capacitance lines for castor oil lie in the second and fourth quadrants. Therefore, it is theoretically impossible to obtain a 90 degree angle between iso-capacitance lines for the same media. Also, since the absolute value of the derivative grows with spatial wavelength, it is reasonable to expect that the accuracy of measurement is better for a combination of more distant spatial wavelengths.

Table 2 shows the results of measurements with selected pairs of spatial wavelengths for the same case. The measurements confirm the general trend of improved accuracy when the angle between the iso-capacitance lines approaches 90 degrees.

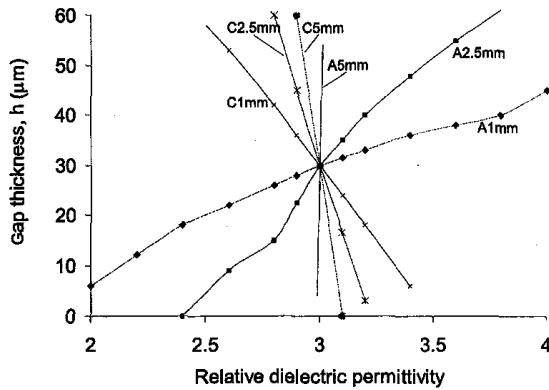


Figure 5: Calculated lines of equal capacitance for different levels of perturbation from the operating point ($\epsilon_r = 3.0$, $h = 30 \mu\text{m}$) for each of the three wavelengths shown in Figure 1 with air (A) and castor oil (C) filling the gap. The values for each iso-capacitance line are shown in Table 1.

Conclusions

Two conceptually similar techniques for improvement of potential accuracy of interdigital dielectrometry measurements with solid dielectrics have been evaluated. Both techniques require immersion of the sensor and the solid material under test into a liquid dielectric. The liquid fills the gap formed due to a non-ideal contact between the sensor and the material surface. The difference between dielectric constants of the liquid dielectric and air provides additional measurement information about the gap and can be used to reduce the effect of the gap measurement perturbations on estimated values of properties for materials of interest. This

| Combination | Permittivity | Relative error (%) |
|-------------|--------------|--------------------|
| A1-A2.5 | 2.6 | -13.33 |
| A1-A5 | 2.9 | -3.33 |
| A2.5-A5 | 2.8 | -6.67 |
| A1-C5 | 2.95 | -1.67 |
| A2.5-C2.5 | 3.0 | 0.00 |
| A2.5-C1 | 3.1 | 3.33 |
| C1-C2.5 | 2.75 | -8.33 |
| C1-C5 | 3.05 | 1.67 |
| C2.5-C5 | 3.2 | 6.67 |

Table 2: Measured dielectric permittivity of Lexan ($\epsilon_r = 3.0$) using different pairs of spatial wavelengths and gap-filling fluid. The accuracy of measurement generally improves with the increasing angle between the iso-capacitance lines shown in Figure 5.

approach is useful for rough surfaces and non-contact measurements as well as for very accurate measurements of material properties. Future work that builds on this feasibility study should include a more rigorous and statistically extensive analysis of measurement sensitivity for different conditions and practical cases of industrial and scientific applications.

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