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Article (Published Version)

Mukherjee, S, Watson, P and Prance, R J (2011) Microscopic resolution broadband dielectric spectroscopy. *Journal of Physics: Conference Series*, 310 (1). 012003. ISSN 1742-6588

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2011 J. Phys.: Conf. Ser. 310 012003

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Microscopic resolution broadband dielectric spectroscopy

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Abstract. Results are presented for a non-contact measurement system capable of micron level spatial resolution. It utilises the novel electric potential sensor (EPS) technology, invented at Sussex, to image the electric field above a simple composite dielectric material. EP sensors may be regarded as analogous to a magnetometer and require no adjustments or offsets during either setup or use. The sample consists of a standard glass/epoxy FR4 circuit board, with linear defects machined into the surface by a PCB milling machine. The sample is excited with an a.c. signal over a range of frequencies from 10 kHz to 10 MHz, from the reverse side, by placing it on a conducting sheet connected to the source. The single sensor is raster scanned over the surface at a constant working distance, consistent with the spatial resolution, in order to build up an image of the electric field, with respect to the reference potential. The results demonstrate that both the surface defects and the internal dielectric variations within the composite may be imaged in this way, with good contrast being observed between the glass mat and the epoxy resin.

1. Introduction

Electric potential sensors (EPS) are ultra-high input impedance devices which may be configured to measure spatial potential, electric field or surface charge with minimal loading to the electric field [1]. The principle of operation has already been described in detail in the literature by the authors [2]. The sensors have previously been applied to imaging applications and to the characterization of dielectric materials [3,4], but were only capable of operation at a single low audio frequency. The purpose of this paper is to present preliminary results for a broadband version of the sensor capable of operating from <10 kHz to >100 MHz with microscopic spatial resolution. Samples of FR4 printed circuit board have been chosen initially, because it is a well characterized composite dielectric material of considerable interest to the electronics community. Preliminary results are presented in the form of images of the spatial potential, close to the surface of the sample, over a range of excitation frequencies from 10 kHz to 11 MHz. From the microscopy point of view, small linear defects of varying widths have been milled on to the surface of the sample, the minimum width being ~200 μm , and the sense electrode being 50 μm in diameter.

2. Method

The sample of FR4 chosen for these measurements was a single sided copper clad board with two linear defects machined into the top surface of the dielectric using a PCB milling machine. The experimental setup is shown schematically in figure 1. The a.c. excitation signal is connected to the lower copper surface of the sample and the sensor electrode is positioned above the sample. The input impedance of the sensor is represented by the C_{in} and parallel resistance in the figure. Typically the

effective input capacitance is of the order of femtofarads in parallel with terraohms. This extreme input impedance is of importance, because when using a microscopic sense electrode to couple to the

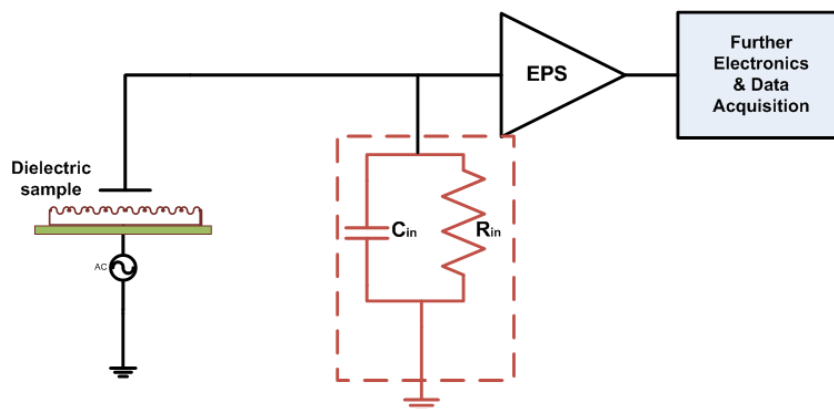


Figure 1. Schematic of electric potential sensor and detail of measurement.

sample the coupling capacitance is usually in the femtofarad range. If the input capacitance of the sensor is considerably larger than this it will act as a capacitive potential divider and attenuate the signal considerably. In addition if the input resistance is insufficient, this forms a high pass filter and will also attenuate the signal. The frequency response for the sensor is shown in figure 2 through a number of well defined coupling capacitors C_c , the smallest being 53 fF.

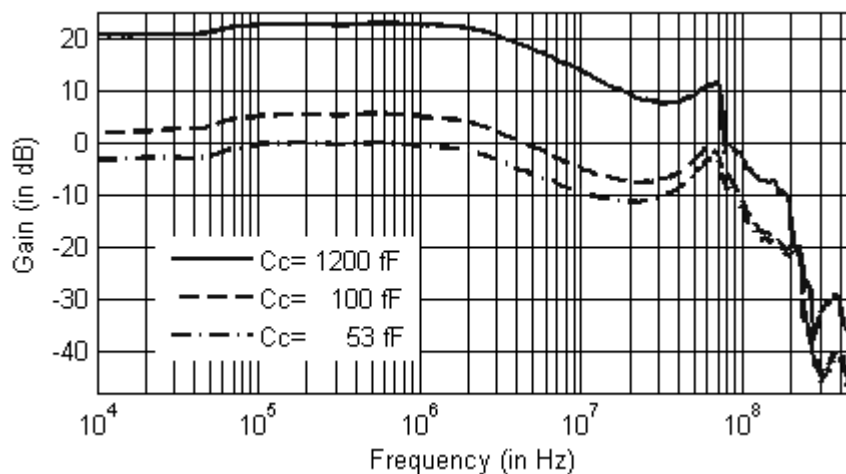


Figure 2. Frequency response of electric potential sensor as a function of coupling capacitance.

The sensor is raster scanned over the surface of the sample with a step size of $63 \mu\text{m}$, at constant height comparable with the diameter as the sense electrode, in this case $50 \mu\text{m}$. The spatial resolution of the image is comparable with these dimensions. Data is collected as a function of position to build up an image of the potential, using the same LabVIEW virtual instrument which controls the raster scanning. A simple algorithm is used to subtract background curvature from the data sets presented.

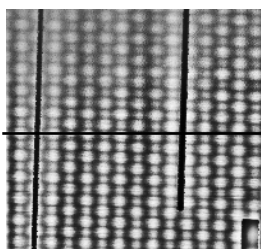
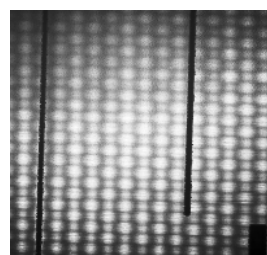
3. Results

Figure 3 shows a 3-D image of the potential $\sim 50 \mu\text{m}$ above the surface of the sample at an excitation frequency of 10 kHz. Two things are immediately apparent from this result, first that the three machined linear defects are clearly visible as black lines and second that the internal structure of the material may be seen. This is manifest as the contrast seen between the resin ($\epsilon_r \sim 3.4$) and the glass mat ($\epsilon_r \sim 6.0$). The average dielectric constant for this composite material depends on a number of factors including the ratio of glass to resin and the frequency of the measurement. The average value has been measured and shown to decrease with increasing frequency [5], from $\epsilon_r = 4.65$ at 10 kHz, to $\epsilon_r = 4.25$ at 10 MHz. The defects milled on the sample surface in this case have a minimum width of $\sim 200 \mu\text{m}$, which as seen in the result, are clearly detectable.

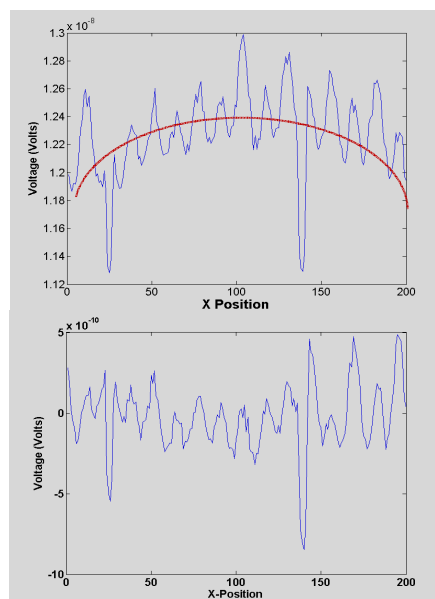


Figure 3. 3-D rendering of surface potential with an excitation signal of 100 kHz. Two linear surface defects may be seen in addition to the internal structure of the material.

Figure 4a shows results obtained at a higher excitation frequency of 1 MHz where we observe a lower contrast between the glass mat and the resin than was seen at 100 kHz. The data is represented as 2-D images in this case with raw data at the top of the figure and processed data at the bottom. Figure 4b illustrates the image processing which has been applied to this data, a single line of raw data across the centre of the sample is shown at the top and the same line signal processed at the bottom. A simple fitting algorithm has been used to subtract the background curvature from the data set. This effect is caused by the surface curvature of the sample not being sufficiently well controlled at the $50 \mu\text{m}$ level. Variations in the sample to sensor spacing change the coupling capacitance and hence the effective gain, as may be clearly seen from figure 2.



(a)



(b)

Figure 4. (a) 2-D plots of potential at 1 MHz, (b) line plots of potential showing background curvature and detail of glass mat. Raw data (top) and data with background subtracted (bottom).

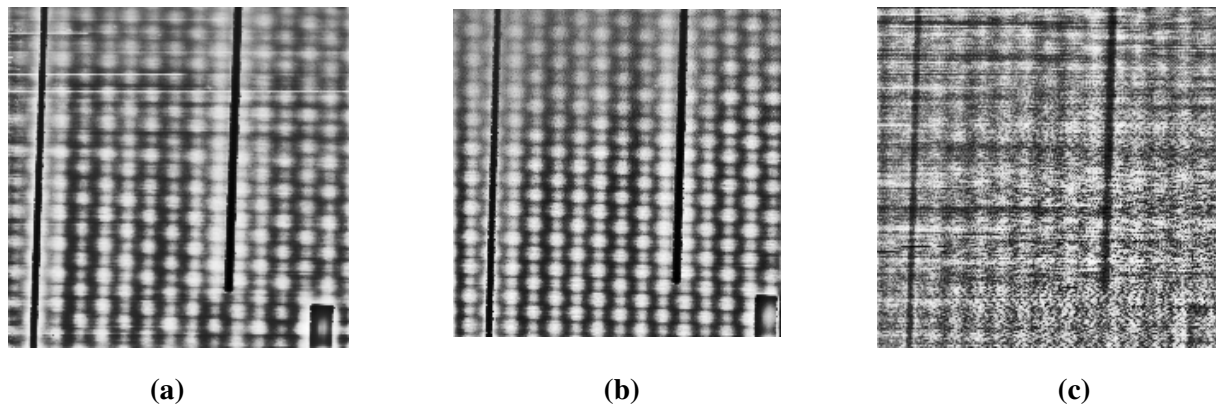


Figure 5. 2-D plots of surface potential at frequencies of: (a) 10 kHz, (b) 1 MHz and (c) 11 MHz.

In figure 5 data is presented as 2-D plots for three excitation frequencies, of 10 kHz, 1 MHz and 11 MHz. In all three cases the two machined linear surface defects are clearly visible, but there is a marked difference in the detail of the highest frequency image where the signal obtained from the sensor is relatively more attenuated resulting in poor dielectric contrast. However, the two machined defects and some internal structure are still discernable. This has resulted due to two reasons. It is worth noting that it has been reported that the loss factor for FR4 is a maximum in the 1-10 MHz region [5].

4. Conclusions

Preliminary results have been described for an imaging system based on the electric potential sensor and capable of producing images of the potential close to the surface of a dielectric material. The sample was excited via a copper backplane using an a.c. source. These images contain information about both the surface features and also about the local variations in dielectric properties in the material. A sample of FR4 circuit board was chosen for demonstration purposes as an example of a well characterised composite dielectric material. Results were obtained over a range of frequencies from 10 kHz to 11 MHz, with a spatial resolution of the order of 50 μm . In other applications we have already demonstrated the capability of achieving 1 μm resolution which also sets the limit for detection resolution of surface defects in dielectric materials [4], microscopic surface charge imaging [6] and the use of arrays of sensors to speed up the acquisition of images [7]. Clearly, the detection resolution is essentially proportional to the spatial resolution and scales down with it making it possible to detect the sample defects of widths comparable to the dimension of the sense electrode.

Acknowledgements

The authors would like to thank the Engineering and Physical Sciences Research Council for supporting this work under Grant No. EP/E042864/1.

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