Response Characterization of the Precision Open-Ended Coaxial Probe for Dielectric Spectroscopy of Breast Tissue

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I. Introduction

Large-scale dielectric spectroscopy of healthy and diseased breast tissue in the 0.1 to 20 GHz frequency range is currently underway at the Universities of Calgary and Wisconsin-Madison. Open-ended coaxial probes are used as sensors to record the reflection coefficient of the tissue samples. The measured reflection coefficient is converted to the dielectric properties data through a suitable inverse technique. The collected data will aid in further advances of the microwave technology for early breast cancer detection [1-3]. Thus, it is crucial to ensure the highest possible accuracy and reliability of the tissue measurements.

Open-ended coaxial probes of small diameter have been shown to achieve a high degree of accuracy in the measurements of biological tissue [4]. However, the measurement repeatability of existing teflon-filled open-ended coaxial sensors may be compromised by various environmental factors. For example, aperture deterioration due to thermal variations in the probe environment can lead to errors as high as 30% at high frequencies [5]. Additionally, copper conductors do not provide sufficient protection against biological and chemical factors. Thus, precision 3.0 mm stainless steel probes without flanges, filled with thermally matched dielectric, have been specifically designed to alleviate the abovementioned problems.

One of the manufactured probes and the X-ray of the probe tip are shown in Fig. 1. The probes have been built out of several sections of coaxial lines. The final section (at the probe aperture) is a 2.3 mm borosilicate glass line, hermetically sealed to the stainless steel metal conductors. The thermal expansion coefficients of the borosilicate glass and stainless steel are low and matched (3.0×10^{-6} m/°C and 5.0×10^{-6} m/°C, respectively). Due to a more complex geometry of the precision probes, a suitable deembeding technique needs to be developed and incorporated into the calibration procedures.

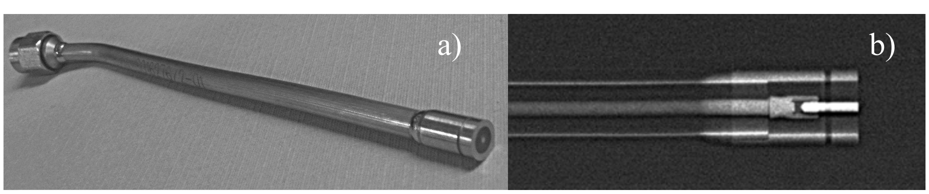

Figure 1. a) Precision probe. b) X-ray of the probe tip showing the air transition.

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II. Methods

The probes are used in a measurement system together with a vector network analyzer (VNA). The calibration procedure is as follows. The VNA is first calibrated at the connector using calibration standards. After the probe is connected, time-gating is used to remove unwanted reflections at the connector. Finally, a numerical model of the probe is used to deembed the measurements at the probe aperture. The precise dimensions of the coaxial line sections comprising the probe can be accurately measured from the X-ray films using a microscope to numerically generate the S-matrix for the probe and deembed the measurements.

The numerical model of the precision probe, depicted in Fig. 2, is built out of five sections of ideal transmission lines, two of which are very short high-impedance lines at the dielectric transitions, and three capacitors at the metal conductors' geometry transitions. The geometry of the air transition is such that the induced parasitic effects should cancel out,. However, due to variations in the manufacturing process and fixed length of the high-impedance lines, this cancellation is not perfect. The theoretical values of the model parameters, based on the ideal transition geometry [6], are C1 = 0.269 fF, C2 = 3.59 fF, C3 = 9.32 fF, $Z_{h,1}$ = 65.57 Ω, and $Z_{h,2}$ = 96.75 Ω. These values are further optimized to model the real geometry of the air section (for example, welding smoothes out the edges of the metal conductors at the transitions, changing the values of capacitance and impedances of the short sections).

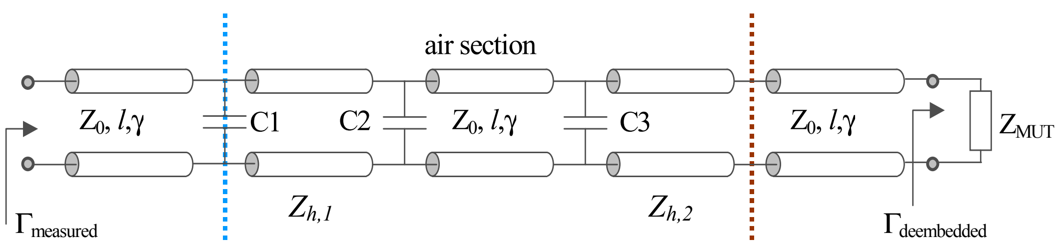

Figure 2. Numerical model of the precision probe to account for its propagation characteristics. Z_{MUT} is the equivalent impedance of the reference liquid.

To evaluate the effectiveness of the deembeding procedure, the measurement results are compared to the FDTD simulations of the reflection coefficient of an ideal, geometrically homogeneous borosilicate line. Reference liquids covering a range of permittivities are used for testing. Desirably, the measurements and the FDTD simulations should agree within 1% and 1° in the magnitude and phase of the reflection coefficient to keep the errors in the permittivity bound to 10% [7]. To achieve this, the model parameter values are optimized using the MATLAB's built-in least squares optimization function.

III. Results

The deembedding procedure yielded measurement results that are within 2% in the magnitude and 5° in phase of the theoretical results obtained from FDTD simulations across the full frequency range of interest. Fig. 3 shows the comparison of the deembedded and simulated reflection coefficient in water. The optimized numerical model is used in the deembeding process. Table 1 summarizes the optimized capacitance and impedance values, as well as the optimized values for the lengths of the high-impedance lines.

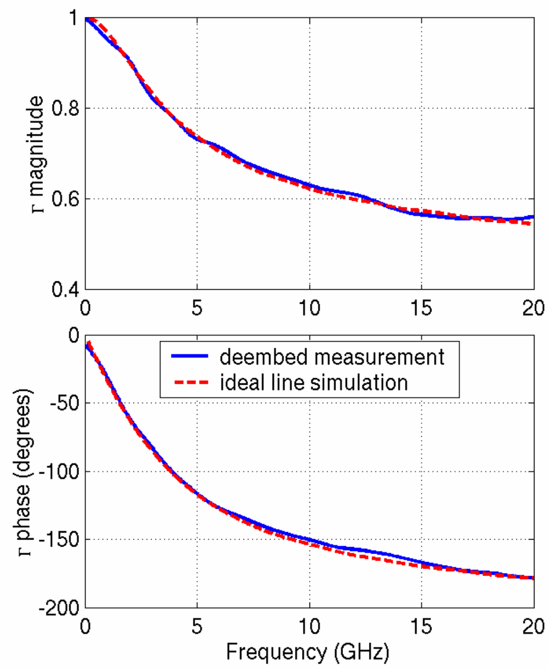

Figure 3. Comparison of the deembedded and simulated reflection coefficient in water in the frequency range of interest.

C1 (fF)	C2 (fF)	C3 (fF)	$Z_{h,1}$ (Ω)	$l_{h,1}$ (mm)	$Z_{h,2}$ (Ω)	$l_{h,2}$ (mm)
0.218	6.516	7.529	67.98	0.228	100.0	0.166

Table 1. Optimized model parameter values for the precision probe.

The above results show that the above numerical model is partially successful when used to deembed the measurements at the probe aperture. One of the reasons for this is the fact that the same values for the optimized model parameters are used across the 0.1 to 20 GHz frequency range. To get closer to the desired fit , optimization of the model parameters in several smaller frequency bands, as well as addition of more model elements, are being investigated and show some improvement over the above results. Another approach is to use the theoretical values for the model parameters and optimize for the residual reflection [8].

IV. Conclusions

The results show that the new precision probe is capable of achieving accurate, repeatable results for the reflection coefficient measurements of tissue samples. Furthermore, the measurement results showed consistency over time, indicating the probe's robustness to the environmental factors and increased measurement reliability.

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