Effects of Mechanical Flaws in Open-Ended Coaxial Probes for Dielectric Spectroscopy

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***Abstract*—A detailed study of dielectric properties of breast tissue in the 0.1 to 20 GHz frequency range currently under way uses open-ended teflon coaxial probes as sensors. This letter quantifies the effects of small mechanical imperfections at the probe aperture on the measured reflection coefficient. The mechanical flaws in the probe can lead to significant errors, thus probes for dielectric spectroscopy of breast tissue have to be carefully manufactured.**

***Index Terms*—Dielectric spectroscopy, mechanical flaws, microwave frequencies, open-ended coaxial probes.**

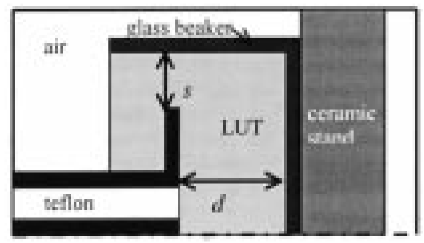

Fig. 1. Generalized simulation space.

I. Introduction

ADVANCES in broadband, confocal microwave breast cancer detection systems [1]–[3] depend on the definite knowledge of dielectric properties of normal and neoplasmic breast tissue in the 0.1 to 20 GHz frequency range [4]. A study is currently under way to extend sparse, existing data [5]–[8] and create an extensive and complete database of breast tissue dielectric parameters. The measurement technique used in the project relies on open-ended coaxial probes [9], due to their broadband response and simplicity, and no need for complex sample preparation. Small aperture probes of 2.2 and 3.6 mm have been selected for the pilot study reported in this paper [10].

Complete characterization of the probe response is critical to the database reliability. In [4], volume sensing characteristics of selected probes were investigated. During the measurements, we have observed that simple probes made of sections of semi-rigid cable yielded, occasionally, reflection coefficients that were significantly different from expectations. Closer analysis of the problem revealed that the discrepancies were typically due to mechanical imperfections in the open end of the teflon filled semirigid probe. The imperfections arise from inferior manufacturing, handling, or different thermal properties of the materials, and are typically undetectable with naked eye.

Some aspects of geometrical imperfections of coaxial probes have already been reported in the literature. In [11], the effects of variations in metal flange and conductor thickness of a 3.6-mm probe were reported, while in [12], the effects of differential thermal expansion of a ceramic probe were examined on a bigger scale.

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Liquids covering a range of dielectric properties were used in this study. FDTD simulations provided a more controlled environment than measurements to quantify and understand the effects of very small structural flaws. Additionally, we have examined variations of measured reflection coefficient with the immersion depth of the probe into the liquid.

II. Methods

A two-dimensional (2-D) body-of-revolution (BOR) FDTD code [11] is used for the simulations. Dispersive materials are handled using a method described in [13] and Debye parameters describing liquids under tests (LUT) at 20 °C are taken from [14], [15]. The schematic presentation of the simulated structure is shown in Fig. 1. The probe is positioned at $s = d = 15$ mm in all tests presented in this study. Both the probe and the imperfections are assumed axially symmetrical.

The following cases have been examined: i) variations in the position of teflon with respect to the metal conductors, ii) effects of inner or outer conductor partially covered with a thin layer of teflon (due, e.g., to polishing of the probe end), and iii) unsealed metal-teflon interface resulting in leakage of the LUT into the probe [Fig. 2(a)–(f)].

Despite the assumed symmetry, some of the observed imperfections were, in fact, not axially symmetrical, and could not be fully simulated with the BOR code. The variations in the reflection coefficients predicted by the simulation should, therefore, be seen as the worst-case scenario.

III. Results

A number of different probes were examined. In general, the bigger the probe, the smaller are the effects of imperfections, as can be expected. Also, the existence and size of the flange has considerably smaller effect on the probe characteristics than the imperfections considered here. As a representative example, the results obtained with a 2.2-mm probe (no flange, teflon semi-rigid cable) are presented in this paper.

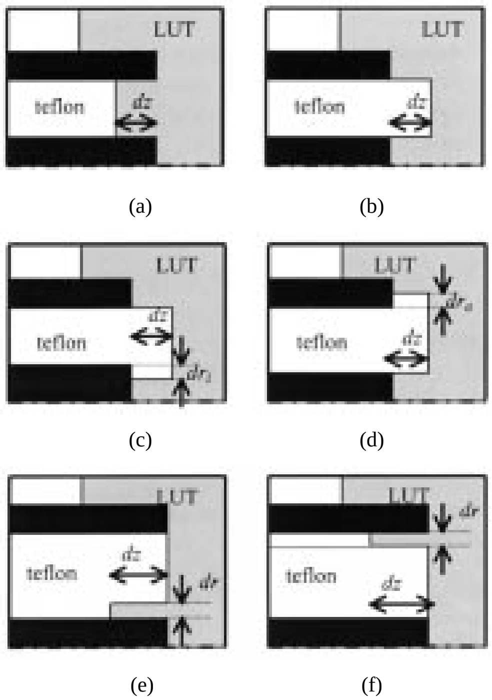

Fig. 2. Geometries of simulated probe structural flaws: (a), (b) changes of teflon position with respect to metal conductors; (c), (d) teflon partially covering metal conductors; and (e), (f) LUT creeping in the space between teflon and metal conductors.

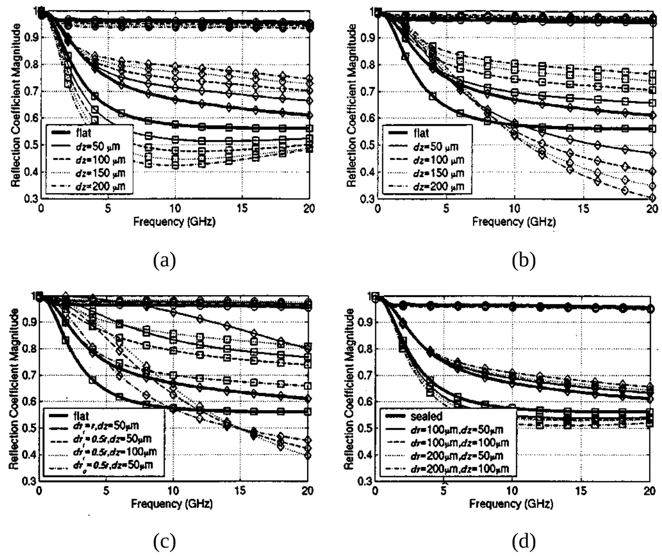

Fig. 3. Effects of mechanical flaws on reflection coefficient values on water (◇), methanol (□), and butanol (○): (a) teflon retracting into the probe, (b) teflon bulging out into LUT, (c) teflon partially covering inner and outer conductors (r = radius of inner conductor; t = thickness of outer conductor), and (d) LUT filling the space between teflon and inner conductor.

Teflon retracting into the probe [Fig. 2(a)] was one of more common imperfections observed under a microscope. This mechanical flaw can be a result of improper manufacturing, and/or an effect of differential thermal expansion. It can be seen [Fig. 3(a)] that even small inaccuracies of the order of 0.1 mm can lead to dramatically changed behavior of the probe, as the error, particularly at higher frequencies, can be as high as 25%. Limiting case for teflon retracting in is the simple case of reflection in a coaxial line partially filled with LUT. Not surprisingly, the effects are smallest for butanol (low dielectric constant and high relaxation time), as its parameters are closest to teflon across most of the frequency range.

Equally strong effects can be observed for the case when the probe dielectric material is protruding into the LUT [Fig. 2(b)]. The plot in Fig. 3(b) clearly indicates that small geometrical changes in the probe aperture region have profound effects on the observed reflection coefficient. A 0.1-mm layer of teflon can change the reflection coefficient by 30%. Again, the magnitude of the effect is related to the difference between the dielectric parameters of LUT and material filling the probe. Accordingly, the effects for the butanol are considerably smaller.

Close examination of some of our probes revealed that polishing of probe end could stretch and pull teflon. That, in turn, can cause metal conductors of the probe aperture to be covered in teflon and thus partially isolated [Fig. 2(c)–(d)], resulting in a surprisingly high error, as shown in Fig. 3(c). It can be observed that in case of water and methanol, the magnitude of the reflection coefficient can easily be different by as much as 30% compared with ideal aperture.

Finally, simple semi-rigid coax cable based probes are not sealed, allowing for the liquid to leak into the space between metal walls and dielectric material. Liquid can leak between the dielectric and inner conductor [Fig. 2(e)] or dielectric and outer conductor of the probe [Fig. 2(f)]. Simulation proved that the inner conductor problem is a more severe one. Although the effects are not as dramatic as in the previous cases, even a small layer of liquid [$dr = 100$ μm and $dz = 50$ μm, Fig. 3(d)] can induce errors of 7% for the 2.2 mm probes.

As an additional test, we have examined how the reflection coefficient is affected by the immersion depth of the probe into LUT. As expected, the effect turned out negligible for flanged probes (below 0.1%). For nonflanged probes, the magnitude of the effect corresponded to the frequency, difference in dielectric constant and the size of the aperture. Accordingly, the maximum difference in reflection coefficient (simulated and measured) between probes at 0 and 10 mm depth was observed for water and methanol at 20 GHz, and was 2.4% and 4.8% for 2.2 mm and 3.6 probes, respectively.

In summary, the results indicate that the biggest source of error affecting the reflection coefficient comes from the probe dielectric not being perfectly aligned with the metal conductors at the probe aperture. Care must be therefore taken in the design and manufacturing of probes for dielectric spectroscopy. If aggressive liquid materials are to be measured, probes must be sealed.

IV. Conclusion

Imperfection in the probe aperture can lead to surprisingly high errors in the reflection coefficient, particularly at higher frequency (20 GHz) and for materials with dielectric constant significantly different from that of a probe. The probe for spectroscopy of breast tissue has to be carefully designed and manufactured and hermetically sealed.

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