MODELING-ASSISTED PERTURBATION TECHNIQUE FOR MEASUREMENT OF COMPLEX PERMITTIVITY

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Abstract – Basic assumption and accuracy of complex permittivity measurement by perturbation technique are proposed to be verified by FDTD simulation of experimental cavity with *QuickWave-3D*. Determination of dielectric constant and loss factor of a piece of wet movie-film in rectangular resonator is shown to be very sensitive to film position and approved to be valid for low contents of water.

INTRODUCTION

For microwave heating engineers, measurement of complex permittivity $\varepsilon = \varepsilon' - i\varepsilon''$ has been of utmost importance for many years, so many applied techniques for determination of dielectric constant ε' and the loss factor $\tan\delta = \varepsilon''/\varepsilon'$ have been developed [1, 2]. Despite all the progress, data on permittivity of numerous practically important materials at 915 and 2,450 MHz are still not available, and known techniques have different limitations, so further progress in this field is required.

Since permittivity cannot be measured directly, it is usually calculated via other measurable parameters such as transmission/reflection coefficients [3], propagation constant [4], etc. Measurement of these entities requires very precise and accurate handling, and each experimental approach is usually associated with a specific calculation rule. In the meantime, it appears that many problematic issues in determination of ε' and $\tan\delta$ could be clarified and the whole process simplified if the experimental work is assisted (or its certain part replaced) by appropriate electromagnetic (EM) modeling of the system involved in the measurement. Similar concept in the form of the idea of retro-modeling for determination of material permittivity has been presented in [5] along with an example referring to a degenerate mode cavity. With the use of an EM simulator, an accuracy of measurement of ε' and $\tan\delta$ has been improved in [6].

PROBLEM DEFINITION

The Industrial Microwave Modeling Group at Worcester Polytechnic Institute has recently started a project in developing various techniques of modeling-assisted determination of complex permittivity of materials.

The present paper describes the measures, which could be taken to improve a particular method based on the known *perturbation technique* well described in literature (see, for example [7, 8]). All versions of this technique principally emerge from the assumption of a *small* perturbation, i.e., the supposition that a dielectric sample inserted into the cavity doesn't cause a remarkable change in the electromagnetic field. Hence the method is known to be far from universal, and its accuracy is very sensitive to many factors such as the value of the loss factor, the position of the sample in the cavity, their configurations, etc. On the other hand, the perturbation technique is simple, needs standard and inexpensive equipment, and is able to provide estimations of ε' and $\tan\delta$ acceptable for a number of applications.

In order to facilitate an experimental procedure built on the perturbation technique and to improve its accuracy, we suggest accompanying the measurements by advanced numerical simulation of the electromagnetic processes in the cavity with and without the sample. It is worth emphasizing that while experiments are typically used to *validate* the results of computation, the goal of the present study is rather opposite: *we apply an accurate and reliable computational tool to check the adequacy of an experimental procedure and to evaluate its correctness*. To this end, we work with the FDTD EM simulator *QuickWave-3D* (*QW3D*) (www.qwed.com.pl).

Based on the 3D conformal FDTD method supported by a number of unique innovative options, the software has proven to be efficient and resourceful instrument for high frequency electromagnetic analysis [9, 10], and the results generated by the program have received many experimental confirmations in both communication and non-communication applications [11, 12]. At the same time, the perturbation technique is principally not very accurate, and its correctness depends not only on precision of handling, but also on some electromagnetic characteristics of the experimental setup, which the experimenter may not know about. It appears that using *QW3D* it is possible to clarify various circumstances of perturbation measurement and either approve its practical arrangements, or suggest appropriate corrections for them.

EXPERIMENTAL SETUP

To illustrate the benefits which the perturbation technique could get from advanced simulation, we have analyzed the experimental setup based on a rectangular resonator and used to measure ε' and $\tan\delta$ of a rectangular piece of a wet movie film in the range of its water content [13]. The film (a_1 x b_1 x l_1 = 68 x 22 x 0.4 mm) is placed in the rectangular resonator (a x b x L = 90 x 45 x 182 mm) being securely positioned inside the rectangular Teflon cassette (a_1 x b_1 x $2l$ =

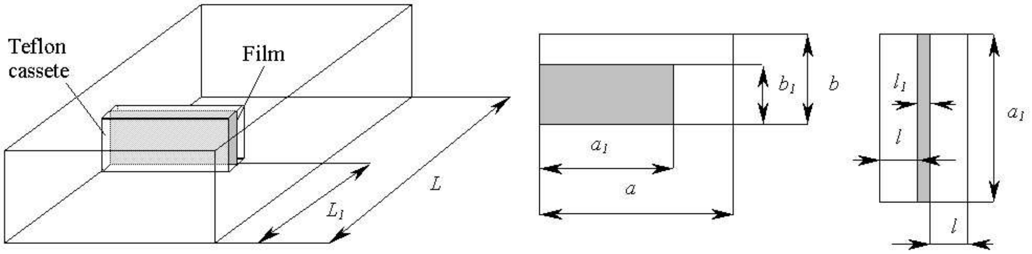

Fig. 1. Geometry of the rectangular resonator with the Teflon cassette and the measured film.

68 x 22 x 5 mm) as shown in Fig. 1. The cassette is placed into the resonator through the one of its removable narrow wall. The measurement is performed in accordance with the layout presented in Fig. 2. The generator is tuned at the resonant frequency of the empty resonator f_0, and the Q-factor of the empty system Q_0 is measured by the wavemeter. Then the resonant frequency and the quality factor of the system with the inserted cassette (f_1 and Q_1) are determined. Complex permittivity is then calculated from the shift of the resonant frequency and the change of the quality factor.

DETERMINATION OF PERMITTIVITY

The dielectric constant ε' and the loss factor $\tan\delta$ are computed with the use of the following expressions:

$$\varepsilon' = 1 + N\frac{\Delta f}{f_0}, \quad \tan\delta = \frac{N}{2\varepsilon'}\left(\frac{1}{Q_1} - \frac{1}{Q_0}\right) \tag{1}$$

where $\Delta f = f_0 - f_1$, and N is a coefficient depending on geometry of a resonator and a measured sample as well as on the position of the sample in the resonator. For some particular cases, N can be found analytically; for a rectangular sample in the rectangular resonator with the TE_{10n} mode, in accordance with [14], it is equal to:

$$N = \begin{cases} \dfrac{4abL^3}{n^2\pi^2 b_1 d^3 (a_1 - \frac{a}{2\pi}\sin\frac{2\pi a_1}{a})}, & \text{for position 1} \\[2ex] \dfrac{abL}{b_1 d (a_1 - \frac{a}{2\pi}\sin\frac{2\pi a_1}{a})}, & \text{for position 2} \\[2ex] \dfrac{12abL^3}{n^2\pi^2 b_1 d^3 (a_1 - \frac{a}{2\pi}\sin\frac{2\pi a_1}{a})}, & \text{for position 3} \end{cases} \tag{2}$$

provided that the sample is located in one of the three positions with respect to the resonator shorting wall: at the half wavelength in the node of the electric field (position 1), at the quarter wavelength in the antinode (position 2), and in contact with the shorting wall in the node (position 3).

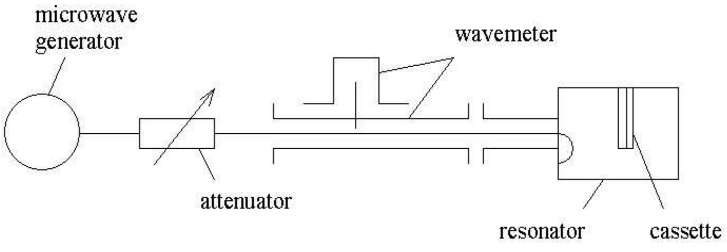

Fig. 2. Principal layout of the experimental setup.

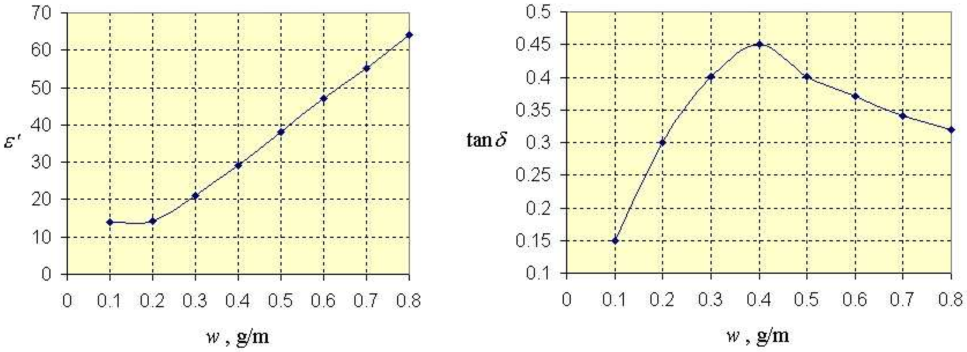

Fig. 3. Measured dielectric constant and loss factor of a movie-film as functions of the film's moisture contents (adapted from [13]).

Complex permittivity of a piece of a movie-film was determined with the use of the described technique; the results are shown in Fig. 3. When calculating N, formula (2) for position 2 was used. It was measured that $f_0 = 2.970$ GHz, and $Q_0 =$ 3,500. The graphs in Fig. 3 are shown versus an artificial parameter w, which represents the water contents on the surface of the film. The accuracy of the technique was estimated as 5 and 14% for ε' and tanδ respectively.

COMPUTER MODEL AND DISCUSSION

The EM processes in the rectangular resonator used in this experiment has been simulated by *QuickWave-3D*. When discretizing the structure, the cubic 6 mm cells were used in air. The cell sizes within the Teflon cassette and the film were 2.5 x 6 x 6 mm and 0.5 x 6 x 6 mm respectively. In order to compute f_0, we have performed eigenvalue analysis of the structure with the special lumped source technique implemented in *QW3D*. With the pulse excitation, it was found that $f_0 = 2{,}975$ MHz.

With the sinosoidal excitation at f_0, the electric field in the horizontal plane of the empty resonator has been computed and visualized (Fig. 4). The mode has been identified as the TE_{103}, and the exact locations of the cassette in positions 1-3 specified. For instance, when experimentally determining ε' and tanδ, in order to eligibly use formula (2) for position 2, the cassette should be placed at $L_1 = L_{1m} = 152$ mm. However, referring to the conditions of the measurements, it is necessary to note that in [13] that requirement was not scrupulously followed.

The patterns presented at Fig. 5 show how the electric field structure varies with increasing of the water contents when the cassette is located at L_{1m}. The computation has been made assuming that ε' and tanδ of the film depends on w in accordance with the data shown in Fig. 3. It is seen that the distortion of the field is notable even for moderate water contents ($w = 0.5$ g/m) and becomes stronger for higher w. Computation has also confirmed the anticipated fact that with certain displacement of the cassette from position 2 (towards 1 or 3), the distortion of the field structure becomes weaker. This principally validates the basic assumption of the perturbation technique in its considered implementation, but also reveals its substantial limitation.

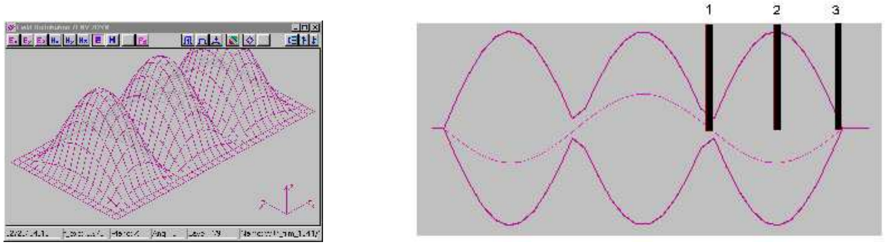

Fig. 4. Modeling results: the magnitude of the electric field in the empty resonator in the absence of the cassette (left) and the three positions of the cassette for formula (2) (right).

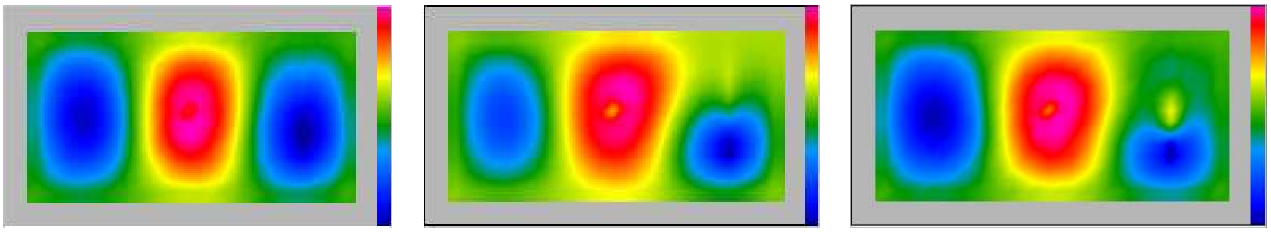

Fig. 5. Patterns of instantaneous electric field (vertical component) in the resonator with the sample (cassette with the film) at $L_1 = 152$ mm (position 2) computed for $w = 0.2$, 0.5, and 0.8 g/m (from left to right).

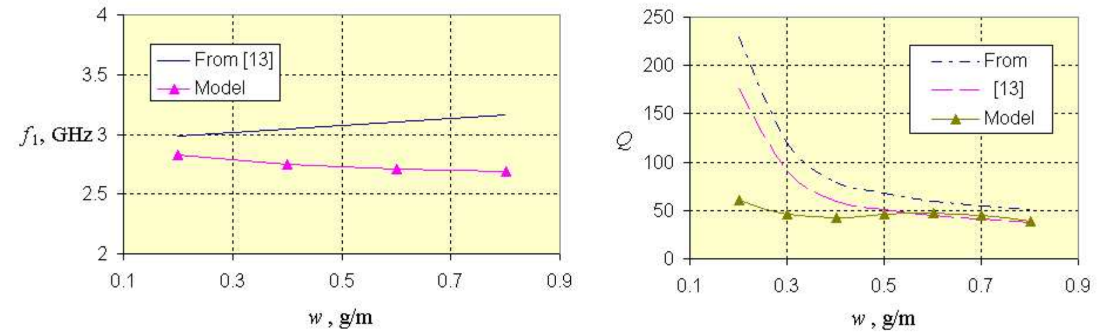

Fig. 6. Resonant frequency (left) and Q-factor (right) of the resonator with the cassette and the film as function of the film's moisture contents: calculated from measurements in [13] and computed with the use of the *QW3D* model for L_1 = 152 mm.

The resonator with the cassette located at L_{1m} has been simulated towards getting f_1 and Q_1. These parameters were computed for different ε' and $\tan\delta$ determined in [13] for various w. The results of computations are shown in Fig. 6 along with the curves for f_1 and Q_1 calculated with (1) and (2) for position 2 and ε' and $\tan\delta$ at the endpoints of the 5% and 14% ranges of accuracy of the experimental determination. It is seen that the considered version of the perturbation method is very sensitive to the position of the cassette. When it is in position 2 and the water contents increases, the resonant frequency decreases and the Q-factor drops from about 60 to 40. When the sample is not exactly there (like in [13]), the behavior of f_1 and Q_1 may transform dramatically, e.g., become like functions shown in Fig. 6.

The presented analysis suggests that if the cassette is placed outside the field maximum, the accuracy of determination of ε' and $\tan\delta$ for larger w is higher. In this case, however, N cannot be found from (2). Clearly, modeling accompanying measurements could easily generate correction formulas for (2) specifying N at any L_1.

CONCLUSIONS

The results of modeling of the experimental setup for determination of ε' and $\tan\delta$ of the wet movie-film by the perturbation technique [13] have confirmed the validity of the key concept of the method (a weak distortion of the field in the presence of the measured sample) only for the low loss film (insignificant water content on its surface) unless the measured sample is located away from the maximum of the electric field. In experimental determination of the dielectric constant and loss factor, orientation on the results of numerical modeling of the field distribution, resonant frequencies and Q-factor can lead to a notable improvement of the accuracy of measurement and specify limitations of the method in the considered experimental setup.

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