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A Three-Layer Microstrip Resonator for Complex Permittivity Measurement of Medium Loss Liquids Using 3D-FDTD Simulation

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Abstract. A three-layer microstrip resonator is introduced to measure complex permittivities of medium loss liquids. The device is configured such that the first layer containing the liquid under test; a sheet of polytetrafluoroethylene (PTFE) is embedded in the middle layer, and the third layer functions as the base on which the patch is printed. The base layer is inverted on PTFE layer, and reflection coefficient is measured from 2.5 GHz to 5 GHz. The complex permittivities are extracted from the resonant frequency and the 10-dB bandwidth of S-parameter for different combinations of ethanol and methanol. Indeed, a three-layer microstrip resonator allows us to possess an affordable, and yet, high-accuracy electrical device to measure complex permittivities of medium loss liquids. FDTD method is used for analysing the structure and the results obtained by using FDTD method and the experimental data indicate a high degree of similarity.

Keywords: microstrip resonator, microwave chemistry, complex permittivity measurement, 3D-FDTD

Introduction

Complex permittivity measurement is of great significance in bio-electromagnetics, microwave chemistry and microwave engineering. Complex permittivity of some biological dilutions, which is important for millimeter-wave dosimetry studies, has been extracted by means of an open-ended coaxial probe (Zhadobov *et al*., 2012). A microwave resonator has been constructed to characterize the complex permittivity of fruitful solutions in chemistry and biology (Chretiennot *et al*., 2013) and several methods have been recently investigated to measure the dielectric of a ferroelectric composition, which is used in the electronics industry (Queffelec *et al*., 2014). The permittivity of many substances changes with frequency and quantifying of the permittivity of these materials with high resolution along with frequency, specifically microwave frequencies, is of prime concern in different industries (Sarri *et al*., 2012; Osman *et al*., 2008, Komarov *et al*., 2005). Planar circuits have always been one of the best instruments to determine the complex permittivity of materials (Chakyar *et al*., 2017, Yang *et al*., 2016; Ansari *et al*., 2015). They have great advantages including small size, light weight, low power consumption, and easy implementation. On the other hand, the number of methods applicable to measure their permittivities is reduced by the lack of particular shape in liquids. Microstrip resonators, as one type of planar circuits, have shown a good performance in the permittivity measurement of liquids. Given the importance of identification of liquids in applied sciences, resonant methods make a considerable contribution; through exploring the complex permittivity of liquids with an eligible degree of accuracy and sensitivity (Yu *et al*., 2000).

A three-layer microstrip resonator is introduced, by which the complex permittivity of liquids is determined. The resonator is composed of three substrates; the first substrate is considered to measure the sample liquid, the second substrate is fixed by a Teflon (PTFE) sheet which is used to increase the degree of freedom in choosing resonant frequency, and the last is the base layer on which the patch is inversely fabricated. The resonator measures the complex permittivity of medium loss liquids for the frequency near and below 4 GHz.

Materials and Methods

Numerical analysis. Finite-difference time-domain (FDTD) was initially proposed in 1966 by Yee (1966). This modeling technique, which solves Maxwell's

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equations in time domain, has been broadly used to simulate various electromagnetics problems (Sullivan, 2013; Taflone and Susan, 2000). FDTD method is very appropriate to model dispersive material in a wide range of frequencies (Bia *et al*., 2015; Luebbers *et al*., 1990, Yee, 1966). The S_{11} parameter of binary mixtures of ethanol-methanol, which belong to dispersive materials characterised by Debye Law (Bao *et al*., 1996) was simulated by using this time domain method.

A three dimensional FDTD code is written for the resonator. The code is implemented by MATLAB. This code has been used to validate and compare visually the results of the measurements with standard values.

Extraction of complex permittivity components. Notwithstanding, there are some equations that represent resonant frequency and Q-factor are dependent on the real ($\in'$) and imaginary ($\in''$) parts of the complex permittivity of the substrates (Gupta and Srivastava, 2012). To extract the complex permittivity components, an approximate approach was considered which is simpler and more practical than the mentioned complex equations (Gupta and Srivastava, 2012). There is almost an inverse relationship between the resonant frequency f_0 and the magnitude of $\in'$. In the same way, an inverse relationship can be considered between Q-factor and the quantity of $\in''$. Equations (1) and (2) illustrate these issues. The results of simulations and experiments presented confirm these assumptions. In the FDTD code, the values of $\in'$ and $\in''$ are dependent on frequency and are extracted from Debye function (Bao *et al*., 1996).

$$\frac{\in'_1}{\in'_2} \approx \frac{f_2}{f_1} \qquad (1)$$

$$\frac{\in''_1}{\in''_2} \approx \frac{Q_2}{Q_1} \qquad (2)$$

As reported by Bao *et al*. (1996), the changes of the real and imaginary part of the complex permittivity of ethanol-methanol binary mixtures along the intended frequency range are almost linear in connection with changes in volume fractions of these two liquids. The results are classified in the format of table and any unknown binary mixture of ethanol and methanol can be interpolated linearly from this table. Thus, the values of the real ($\in'_x$) and imaginary ($\in''_x$) part of the complex permittivity can be extracted as:

$$\frac{\in'_x - \in'_1}{\in'_2 - \in'_1} = \frac{f_1 - f_x}{f_1 - f_2} \qquad (3)$$

$$\frac{\in''_x - \in''_1}{\in''_2 - \in''_1} = \frac{BW_x - BW_1}{BW_2 - BW_1} \qquad (4)$$

Where:

constants of $\in'_1$, $\in''_1$, $\in'_2$ and $\in''_2$ are real, reference data by Bao *et al*. (1966). f_1, f_2, BW_1 and BW_2 are achieved by the FDTD code and f_x and BW_x are obtained from the experimental results.

Minimization of errors of permittivity components. Like many electrical structures, there are some errors and discrepancies between measurement values delivered by device under test and standard ones. One of the most common and not to mention easiest way to minimize these errors is equally shifting primary results to the standard values for each component of the permittivity. But this kind of gradation cannot minimize all the errors since the real part and imaginary part of the complex permittivity in ethanol-methanol binary mixtures change nonlinearly with frequency. Nevertheless, a certain frequency zone may be designated in which both parts of the permittivity approximately vary linearly in the frequency domain. The frequency range from 3.5 GHz to 4 GHz would be an overall proper choice. Therefore, discrepancies between measured and standard values decreased conspicuously. Actually, this was attained because the three-layer microstrip resonator allowed to choose an appropriate frequency domain.

Three-layer microstrip resonator configuration. Among many design challenges, the expenditure in manufacturing a device has constantly been of prime concern. Apart from cost issue, availability of the material, having appropriate features; is a key factor. In many cases, the material, which is appropriate to realize a high-accuracy measuring device, is out of reach and providing the material would not be affordable. Achieving both of these is a difficult task. The three-layer microstrip resonator, however, seems to be able to fulfill this target. The presence of two substrates beside liquid under test enhances the number of materials that can be selected as substrates in association with our demands.

Schematic diagram of the proposed microstrip resonator configuration is shown in Fig. 1. The thickness of sample layer is h_{mut}=1 mm. PTFE is set in middle layer with thickness of h_{tfln}=2 mm. The base layer is a polyester (RO4003) with relative permittivity $\in_r$=3.4 and thickness of h_{base}=0.5 mm. The cupric microstrip patch was designed in 28×20 mm^2 dimensions. The 2×10 mm^2

quarter-wavelength matched the 4×10 mm^2 microstrip transmission line to the patch. Also, SMA connector with flange jack was employed to supply the resonator. All layers were covered with a Teflon-metal enclosure; the metal portion under the structure had the duty of ground plane. Teflon layer above the resonator prevents the device from being aesthetically unpleasant. Both were jointly considered as an enclosure to protect substrates. Total dimensions of the system, as shown in Fig. 1, are 80×70×20 mm^3.

Results and Discussion

The permittivity of different binary mixtures of ethanol and methanol was constructed by the resonator. The sample layer of the structure was filled by the binary mixtures, and then reflection coefficient was measured by a vector network analyzer in the frequency range of 2.5 GHz to 5 GHz (Fig. 2). This test was performed for eleven samples in which the volume fractions of ethanol and methanol varied in a scale of 10% - from 0% to 100%. The results of the parameters were saved and then replotted in addition to FDTD results using MATLAB in order to display visually the similarity between two approaches. Figure 3 shows two specimens of these plots. Due to good assumptions in FDTD code, the simulation speed of this numerical technique would be considerably less than simulator softwares, which can be investigated later. However, the main purpose of providing this numerical method has been offering an available approach to analyze our experimental results and data in Tables 1-2 demonstrate the success of this attempt.

As mentioned before, the complete results including amounts of measured and simulated resonant frequency and 10-dB bandwidth of all samples and errors of ϵ' and ϵ'' have been provided in Tables 1-2. The errors have been extracted according to equations (3) and (4) and also have been accomplished by minimization method, explained in second section (Minimization of

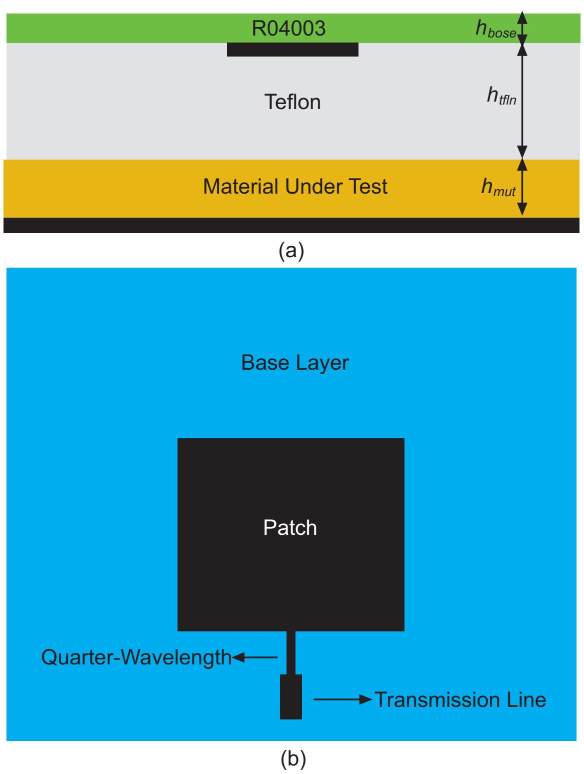

Fig. 1. Configuration of the three-layer microstrip resonator from (a) lateral view and (b) top view.

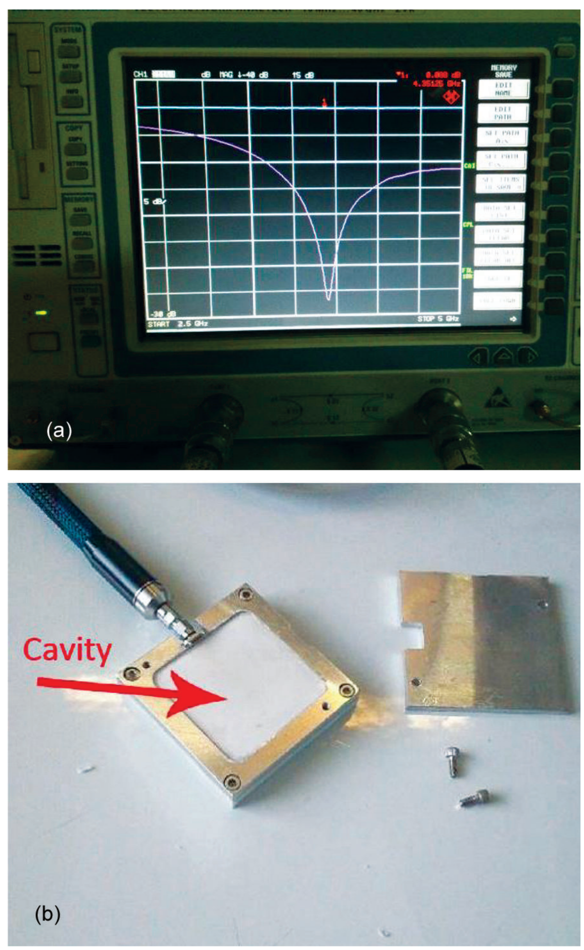

Fig. 2. Photo of (a) the measurement system and (b) the microstrip resonator.

errors of permittivity components). The considerable achievement obtained by the new resonator was regarding the errors of the imaginary ($\in''$) part of the complex permittivity in the binary mixtures which keep limited. The resemblance between the 10-dB bandwidths of the two curves in Fig. 3 demonstrates this claim. Capability in choosing a proper resonant frequency, which varied between 3.5 GHz and 4 GHz, in a three-layer microstrip resonator led to acquire such an improvement. In this frequency area, both components of the complex permittivity showed almost linear changes with respect to changes in volume fractions of ethanol-methanol. In future works, the effect of feed system and matching can also be considered on the accuracy of measurements in the three-layer microstrip resonator by applying different types of feeding techniques.

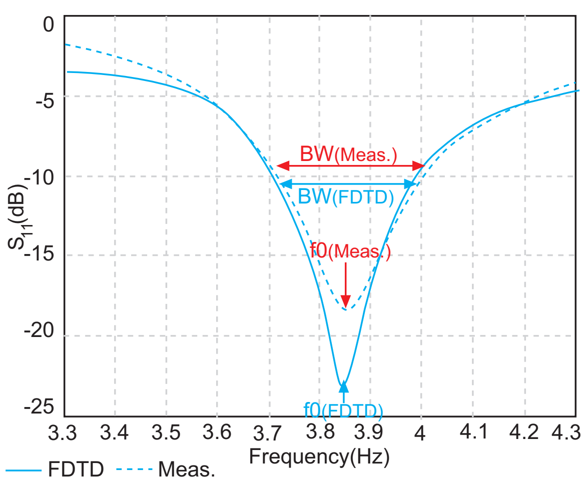

Fig. 3. Measured and simulated curves of reflection coefficient for binary mixture of ethanol 80% - methanol 20%.

In Tables 1-2 the errors of the real and imaginary part of the complex permittivity have been given as:

$$\text{Error}_{\in^x}\ (\%) = \frac{\in^x_{data} - \in^x_{meas}}{\in^x_{data}} \times 100 \quad \text{........... (5)}$$

Where:

$\in^x_{data}$ is the permittivity component retrieved from (Bao *et al*., 1996), and $\in^x_{meas}$ is obtained from measured results and equations (3) and (4).

In order to indicate improvement in measuring the complex permittivity of the binary mixtures of ethanol and methanol, the measured results by the three-layer microstrip resonator has been compared to the result of

Table 1. Results of measured and simulated resonant frequency of samples and measurement errors of ($\in'$)

Material under test	f_0(GHz)-FDTD	f_0(GHz)-Measurement	Error ($\in'$)
Ethanol 1.0 - Methanol 0.0	3.886	3.907	0.7%
Ethanol 0.9 - Methanol 0.1	3.868	3.889	1.2%
Ethanol 0.8 - Methanol 0.2	3.851	3.873	0.8%
Ethanol 0.7 - Methanol 0.3	3.838	3.859	2.9%
Ethanol 0.6 - Methanol 0.4	3.830	3.854	-1.2%
Ethanol 0.5 - Methanol 0.5	3.819	3.843	-1.5%
Ethanol 0.4 - Methanol 0.6	3.811	3.835	-1.2%
Ethanol 0.3 - Methanol 0.7	3.804	3.828	-2.8%
Ethanol 0.2 - Methanol 0.8	3.800	3.824	-2%
Ethanol 0.1 - Methanol 0.9	3.795	3.819	-1.8%
Ethanol 0.0 - Methanol 1.0	3.789	3.813	-1.6%

Table 2. Results of measured and simulated 10-dB bandwidth of samples and measurement errors of ($\in''$)

Material under test	BW(MHz)-FDTD	BW(MHz)-Measurement	Error ($\in''$)
Ethanol1.0 -Methanol0.0	426	427.3	2.8%
Ethanol0.9-Methanol 0.1	419	420.1	1.6%
Ethanol0.8-Methanol 0.2	405.1	406.9	0.7%
Ethanol0.7-Methanol 0.3	392.9	395.1	0.3%
Ethanol0.6-Methanol 0.4	380.4	382.5	0.8%
Ethanol0.5-Methanol 0.5	364.1	367.6	-1.1%
Ethanol0.4-Methanol 0.6	353	358.5	-3.2%
Ethanol0.3-Methanol 0.7	346	351	-1.8%
Ethanol0.2-Methanol 0.8	336	342	-4.1%
Ethanol0.1-Methanol 0.9	331	334.5	-0.7%
Ethanol0.0-Methanol 1.0	322.9	326.8	-0.9%

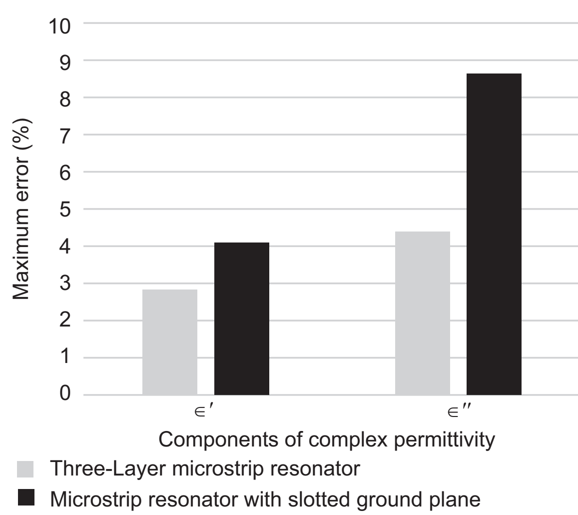

Fig. 4. Maximum measurement errors for the real and imaginary part of the complex permittivity in the three-layer microstrip resonator and a microstrip resonator with slotted ground plane.

a microstrip resonator with slotted ground plane (Liu and Pu, 2008), and the maximum errors of the real and imaginary part of the complex permittivity measured by both instruments have been plotted in Fig. 4.

Conclusion

A three-layer microstrip resonator was demonstrated in order to measure the complex permittivity of binary mixtures of ethanol-methanol. FDTD simulations and measurements were applied to illustrate the accuracy of the structure. The maximum measurement errors for the real and imaginary part of the complex permittivity were produced 2.9% and 4.1%, respectively, indicating the high quality of this resonator. In fact, the presence of this configuration allowed us to choose its operating frequency and materials used in the resonator. The former increased the precision of measurements; the later decreased the expenditure of the structure.

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