Microstrip Patch Sensors for Complex Permittivity Measurement of Medium Loss Liquids Using 3D-FDTD

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Abstract **─** Two novel microstrip resonators are designed to measure the complex permittivity of medium loss liquids. These resonators have two layers, the first one is the sample layer and the second one is the base layer that the patch is printed on it. The base layer is suspended or inverted on the sample layer and the S-parameter is measured. The complex permittivity of the sample layer is extracted from the resonance frequency and the 3-dB bandwidth of the S-parameter. In this paper, binary mixtures of ethanol and methanol are used as sample layer. FDTD is a well-known computational method and is used for analyzing the structures. The experimental results for both of these resonators are really good and agree with reference values.

Index Terms **─** Microstrip patch resonator, microwave chemistry, permittivity measurement, 3D-FDTD.

I. INTRODUCTION

Complex permittivity measurement has high importance in microwave engineering. Since the permittivity of the materials changes a lot with frequency at high frequencies, so it is important to measure it with high accuracy in microwave frequencies. Determination of dielectric properties of materials is also important for the process control and quality control. The progress made in this direction has been covered in three books [1-3]. Over years, a number of techniques have been reported to measure the dielectric properties of materials at microwave frequency. These methods have used several media, like free-space, coaxial line, metal waveguide, dielectric waveguide, strip line, etc. The classical methods are summarized in the twin books of Hippel [4, 5]. The sensors based on waveguide and coaxial lines are bulky and not convenient for integration with electronic circuits [8-10]. Also, the volume of liquid that is needed for test in these approaches are much more than the volume of liquid which is needed for other methods like the one that is proposed in this paper. On the other hand, planar circuits, such as microstrip lines, coplanar waveguides, and strip lines have lots of advantages like low cost, easy to implementation, portability, online network monitoring and also not being destructive, so they have found their applications in complex permittivity measurements in recent years [11]. Several investigators have used microstrip patch resonators for the determination of the dielectric constant of a substrate [12-15]. Also, some of them have used microstrip patch resonators for complex permittivity measurement of liquids [16, 17]. Since it is hard to form liquids in a particular shape, so all kinds of methods of measuring permittivity are not applicable to measure their permittivities, but some methods are interesting and easy to implement. For example in [17], authors have suggested a two layer microstrip patch for investigation of complex permittivity of materials in sheet, liquid and paste forms. In this case, they have proposed some formulas for computation of total Q-factor and resonance frequency for this microstrip patch at first and then, they have explained the process of extracting the complex permittivity of low loss materials using these two parameters, total Q-factor and resonance frequency. As can be seen, the structures which have been used in this paper are very similar to those used in [17], however the adopted methods are completely different. In [17], the complex permittivity has been extracted by using some formulas, but in this paper, full-wave analysis is used to compute the complex permittivity. The planar circuit methods for measuring complex permittivity of liquids can be classified into two groups, resonant and non-resonant methods. Resonant methods are used because of their accuracy and sensitivity and non-resonant methods are used because of their broadband applications [18]. There are a lot of liquids which have medium or high permittivity and are very important in microwave chemistry, so a method is needed to measure their permittivity.

One of the most important methods of estimating the permittivity of materials including liquids in a wide range of frequency is using of formulas which need some initial parameters. One of these formulas comes from Debye theory that was introduced for the first time by Robert in 1988. According to Debye theory, the complex permittivity of a dielectric can be expressed as follows

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[1, 19]:

$$\varepsilon_r = \varepsilon_{r\infty} + \frac{\varepsilon_{r0} - \varepsilon_{r\infty}}{1 + j\beta}, \tag{1}$$

$$\varepsilon_{r\infty} = \lim_{\omega\to\infty} \varepsilon_r, \tag{2}$$

$$\varepsilon_{r0} = \lim_{\omega\to 0} \varepsilon_r, \tag{3}$$

$$\beta = \frac{\varepsilon_{r0} + 2}{\varepsilon_{r\infty} + 2}\omega\tau, \tag{4}$$

where τ is the relaxation time and ω is the operating angular frequency. Equation (1) indicates that the dielectric permittivity due to Debye relaxation is mainly determined by three parameters, ε_{r0}, $\varepsilon_{r\infty}$ and τ. As can be seen, such formulas like Debye function are really useful, since the permittivity of materials can be calculated for a wide range of frequency, but the problem is that using of such formulas needs to determine some parameters like determining ε_{r0}, $\varepsilon_{r\infty}$ and τ in Debye formula. In [19], the complex permittivity of binary mixtures of ethanol–methanol in the range from 200 MHz to 26.5 GHz have been measured and parameters including ε_{r0}, $\varepsilon_{r\infty}$ and τ have been extracted for these binary mixture for using in Debye formula.

In this paper, 2 resonators are introduced to find the complex permittivity of the medium loss liquids, i.e., suspended and inverted patch resonators. Using the scattering responses of these structures, permittivity of medium loss liquids is extracted.

II. MICROSTRIP PATCH RESONATORS AS SENSORS

Figure 1 shows the simple schematic of the resonators used in our study. They have two layers, the first layer is the liquid under test and the second layer is the substrate that the patch is printed on it. The first layer is called the sample layer and the second layer is called the base substrate. The thickness, dielectric constant, and loss tangent for the base layer are known but for the sample dielectric are unknown. Taconic RF-35 with relative permittivity of 3.5 is used as substrate for the base layer. The sample thickness (h_{sam}) is 2 mm and the base thickness (h_{base}) is 1.524 mm. The dimensions of the patch for both of these patch resonators are the same and is 35 mm×25 mm. The ground is the empty metallic cavity that should be filled with the liquid under test. The ground of the cavity should be large enough not to infect the parameters of our structure, so its dimension is 10 cm×10 cm. The feed of the microstrip resonator is connected to a SMA adapter and the SMA connector should be kept away from the liquid solutions. The cavity is filled with the sample and the base layer is put on it, then the S_{11}-parameter of the resonator is measured. The resonance frequency and 3-dB bandwidth of the structures are calculated from measured data. When the sample is changed, the resonance frequency and the 3-dB bandwidth changes too, so the resonance frequency shift and the 3-dB bandwidth variation reflect the complex permittivity of the liquid under test.

As can be seen in Fig. 1, for one of these resonators, the base layer is suspended on the patch and for the other one the base layer is inverted on the patch. Suspended patch resonator is used to measure the complex permittivity of medium loss liquids for the frequency about 2.3 GHz and inverted patch resonator is used to measure the complex permittivity of medium loss liquids for the frequency about 480 MHz. Ethanol and methanol are two types of liquids which have medium loss. Therefore, binary mixtures of ethanol and methanol with different volume fractions are used as material under test for the sample layer. In [19], complex permittivity of these two types of liquids is measured and the parameters which are needed in Debye function are specified for different volume fractions of their binary mixtures in the room temperature. It is worth to say that the data which have been reported in [19] is used as reference for this paper and the results of this paper have been compared with them.

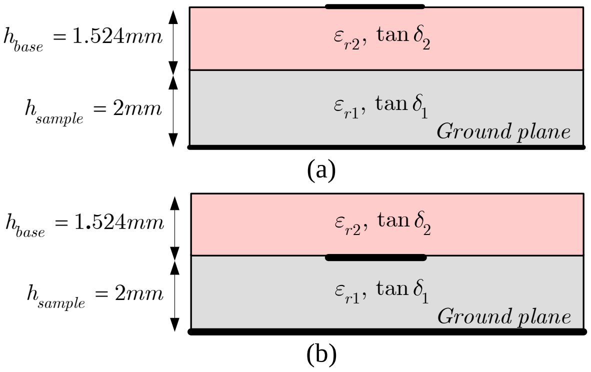


Fig. 1. Microstrip patch resonator structures as a sensor: (a) suspended patch resonator, and (b) inverted patch resonator.

III. FDTD METHOD

Finite-difference time-domain (FDTD) is a popular computational electrodynamics modeling technique. This method is easy to understand and also easy to implement in software. Since it is a time-domain method, solutions can cover a wide frequency range with a single simulation run. The FDTD method belongs to the general class of grid-based differential time-domain numerical modeling methods. The time-dependent Maxwell's equations in partial differential form are discretized using central-time central-space scheme. The resulting electric field vector components in a volume of space are solved at a given instant in time, then the magnetic field vector components in the same volume are solved at the next instant, and the process is repeated over and over until the desired transient or steady-state electromagnetic field behavior is fully evolved [6, 7]. In this paper, the structures are simulated by 3D-FDTD method and 2 different CADs are written in C++ programming language, so it takes little time to run the codes for simulation of the structures.

Discretization of Maxwell's equations are done using well-known Yee algorithm. For example, Ampere-Maxwell equation (in 2D format) can be expressed as:

$$\begin{aligned}\frac{D_z^{n+\frac{1}{2}} - D_z^{n-\frac{1}{2}}}{\Delta t} &= \frac{1}{\sqrt{\varepsilon_0\mu_0}}\left\{\frac{H_y^n\left(i+\frac{1}{2},j\right) - H_y^n(i-\frac{1}{2},j)}{\Delta x}\right. \\ &\left.- \frac{H_x^n\left(i,j+\frac{1}{2}\right) - H_x^n(i,j+\frac{1}{2})}{\Delta y}\right\}.\end{aligned} \tag{5}$$

In preparation of the software code, it is important to consider the effect of complex permittivity or conductivity of the dielectric. In this case, the frequency-domain's relation between D and E, i.e.:

$$\tilde{D}(\omega) = \varepsilon\tilde{E}(\omega) + \frac{\sigma}{j\omega\varepsilon}\tilde{E}(\omega), \tag{6}$$

is converted to time domain and then discretized as:

$$E^n \approx \frac{D^n - \sigma\Delta t\sum_{i=0}^{n-1}E^i}{\varepsilon + \sigma\Delta t}. \tag{7}$$

Another important thing which must be taken into account is employing a perfect matched layer (PML) in our code. A lossy material is used as this absorbing layer which can be represented by the following discretized scheme:

$$\begin{aligned}\frac{\partial D_z}{\partial t} + \frac{\sigma_D}{\varepsilon_0}D_z &\approx \frac{D_z^{n+\frac{1}{2}} - D_z^{n-\frac{1}{2}}}{\Delta t} \\ &+ \frac{\sigma_D}{\varepsilon_0}.\frac{D_z^{n+\frac{1}{2}} + D_z^{n-\frac{1}{2}}}{2} \\ &= D_z^{n+\frac{1}{2}}\frac{1}{\Delta t}\left\{1 + \frac{\sigma_D\Delta t}{\varepsilon_0}\right\} \\ &- D_z^{n-\frac{1}{2}}\frac{1}{\Delta t}\left\{1 - \frac{\sigma_D\Delta t}{\varepsilon_0}\right\},\end{aligned} \tag{8}$$

in which we have used $D_z \approx \frac{D_z^{n+\frac{1}{2}} + D_z^{n-\frac{1}{2}}}{2}$.

IV. EXTRACTION OF COMPLEX PERMITTIVITY

In this paper, the structures are simulated by 3D-FDTD method. The forward problem is to compute the resonance frequency and the 3-dB bandwidth of resonators when the permittivity of the liquid under test is given. To compute the resonance frequency and 3-dB bandwidth of the structures, 2 CAD programs are written to simulate 2 structures. For each structure, the code is run for many different cases of complex permittivity for the sample layer, so a database is created of the resonance frequency and 3-dB bandwidth of the structure for different cases of sample layer. The reverse problem is to measure the resonance frequency and 3-dB bandwidth of resonator in presence of the sample layer and then recognizing the permittivity of the sample by using the database which has been prepared before. As if, each CAD for each structure was run for about 300 different cases of complex permittivity of sample layer and as if it takes about 2 minutes to run each code for one case, it took about 10 hours to create the database for each structure. At first, it may seem that making a database for each structure takes a long time, but it should be considered that this database is created just once and is used forever.

There are 2 points that should be considered. The first one is that the complex permittivity of samples are frequency dependent and the resonance frequency of each structure will changes by the change in complex permittivity of the sample, but when the CAD of each structure is run to solve the forward problem and making the database, it is supposed that the complex permittivity of the samples are constant. This supposition is right if the change in the real part and imaginary part of complex permittivity of samples is negligible or the change of resonance frequency by the change of complex permittivity of the samples is not considerable. The second considerable point is that there is a frequency shift between the resonance frequency of measurement and FDTD simulation as will be seen. As mentioned before, the method of reconstructing the complex permittivity of the sample is to measure the S_{11}-parameter of the resonator in presence of the sample and extracting the resonance frequency and 3-dB bandwidth of S_{11}-parameter, then comparing these information with the ones which have been prepared as database before and extracting the real and imaginary parts of the complex permittivity of the sample. But the frequency shift between measurement and simulation will cause a great error in extracting the sample permittivity. There is a solution for this problem and decreasing the error. The solution is to find the mean of frequency shifts for different samples and then subtracting this mean from the resonance frequency of each sample that its complex permittivity is unknown, then doing the process of finding the sample permittivity by referring to the database.

In the following part, results of simulation and measurement for both patch resonators are introduced. Section V.A reports the results of measurement and simulation for suspended resonator and Section V. B. reports the results of measurement and simulation for inverted resonator.

V. RESULTS OF MEASUREMENT AND SIMULATION

A. Suspended patch resonator

In this section, a suspended patch resonator is suggested. This suspended patch resonator is used to reconstruct the permittivity of medium loss liquids. The shape and dimensions of the structure are shown in Fig. 2. The binary mixtures of ethanol and methanol are used as samples. The proposed structure is designated to work at frequency of about 2.3 GHz. The patch dimensions are 35 mm×25 mm and the feed dimensions are 30 mm × 4 mm.

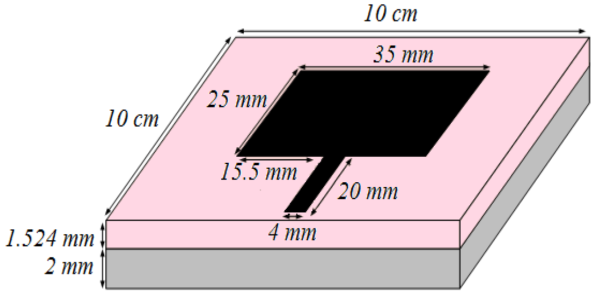
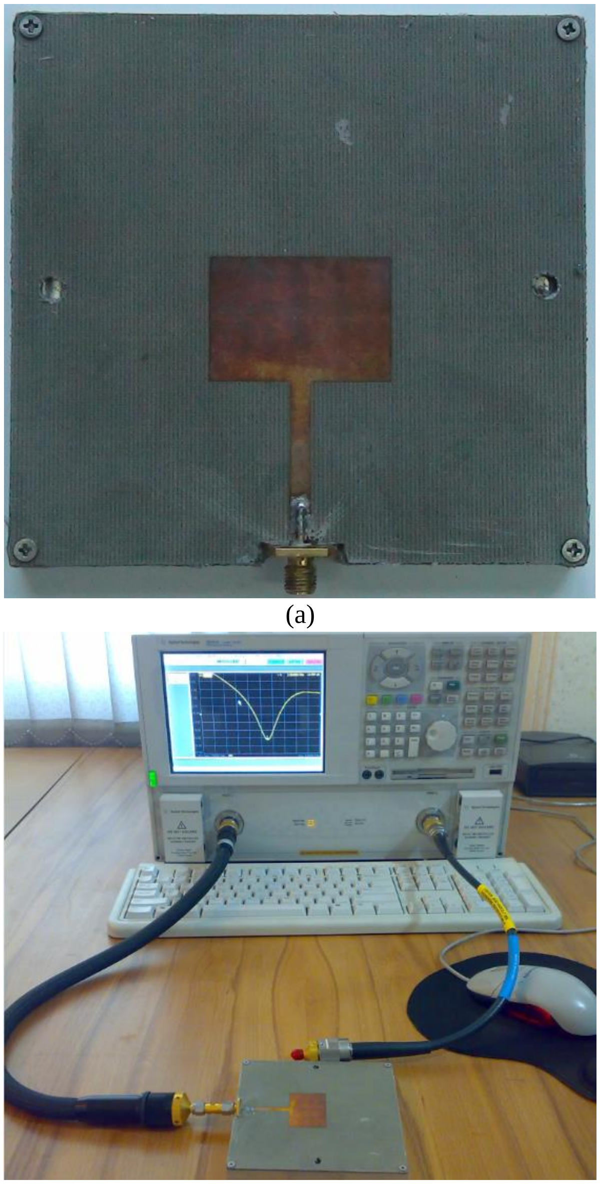


Fig. 2. Suspended patch structure.

Top view of the structure and measurement setup is shown in Fig. 3. The sample liquid is injected into the cavity by a syringe via two holes that are created in the substrate on both sides of the patch. The resonance frequency and 3-dB bandwidth of the structure are calculated from the measured data. When the sample is changed, the resonance frequency and the 3-dB bandwidth changes too, so the resonance frequency shift and the 3-dB bandwidth variation reflect the complex permittivity of the liquid under test. Figure 4 (a) is the measurement data and shows the change in the resonant frequency and quality factor when the liquid sample changes. It must be noted that in this figure eth(x) & meth(y) introduces a mixture of x% ethanol and y% methanol.

The results of simulation and measurement are depicted in Fig. 4 (b). It shows a good agreement between simulation and measurement, but there is a frequency shift between simulation and measurement which is almost constant. The mean of frequency shifts is 121.36 MHz that can be treated as mentioned before. It seems one of the most common origins for the error is that we have not used a full-wave model for the SMA connector. Also, it is seen that putting an absorbing layer in a proper distance above the circuit under test will slightly affect the results. Actually, this seems to be another reason for the difference of simulation and measurement results. It should be noted that the resonance frequency changes from 2.25 GHz to 2.41 GHz. The real and imaginary part of complex permittivity of the liquid samples are frequency dependent and will change during this frequency band, but this change is little and negligible. Therefore, in the FDTD code, the complex permittivity of our sample is supposed to be constant.



(a)

(b)

Fig. 3. (a) Top view of fabricated patch for suspended patch resonator, and (b) measurement setup.

B. Inverted patch resonator

In this section, an inverted patch resonator is proposed. This inverted patch resonator is used to reconstruct the permittivity of medium loss liquids. The shape of the structure are shown in Fig. 1 (b). Again, the binary mixtures of ethanol and methanol are used as samples. The proposed structure is designated to work at frequency of about 480 MHz. The patch dimensions are 35 mm×25 mm and the feed dimensions are 30 mm× 4 mm. Figure 5 (a) is the measurement data and shows the change in the resonance frequency and quality factor when the liquid sample changes. In this figure eth(x) & meth(y) introduces a mixture of x% ethanol and y% methanol.

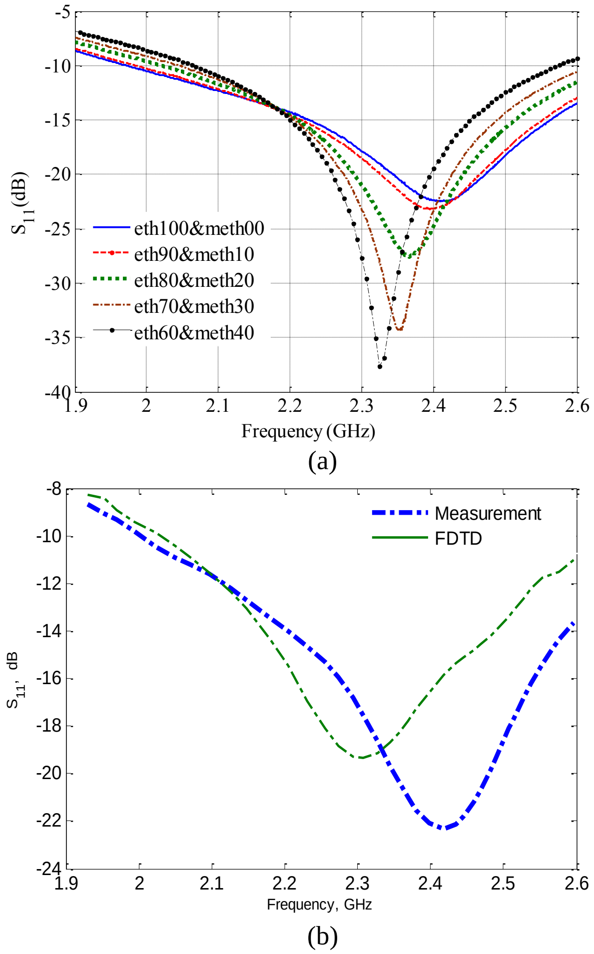


Fig. 4. (a) Measurement data of different samples for suspended patch resonator, and (b) comparison of S_{11} of measurement and 3D-FDTD simulation for ethanol 100%.

The results and errors of the test with different volume fractions of ethanol and methanol are listed in Table 1. The first column is the type of the sample. The second and fourth columns are respectively the actual values of ε' and ε'' at resonance frequency which are calculated by using the Debye function according to the data that are reported in [19]. Finally, the third and the fifth columns are the measurement errors compared to the values listed in the second and forth columns. The results show that the errors of ε' reconstruction is negligible, but the errors of ε'' reconstruction is more than ε' reconstruction, but it is acceptable.

The simulation and measurement results are depicted in Fig. 5 (b). It shows a good agreement between simulation and measurement, but there is a frequency shift between simulation and measurement and it is almost constant. The mean of frequency shifts is 37.61 MHz which can be treated as stated in the previous section. The results and errors of the test with different volume fraction of ethanol and methanol are listed in Table 2. The results show that the ε' extraction error is quite low, but that of ε'' is more, although it is satisfying.

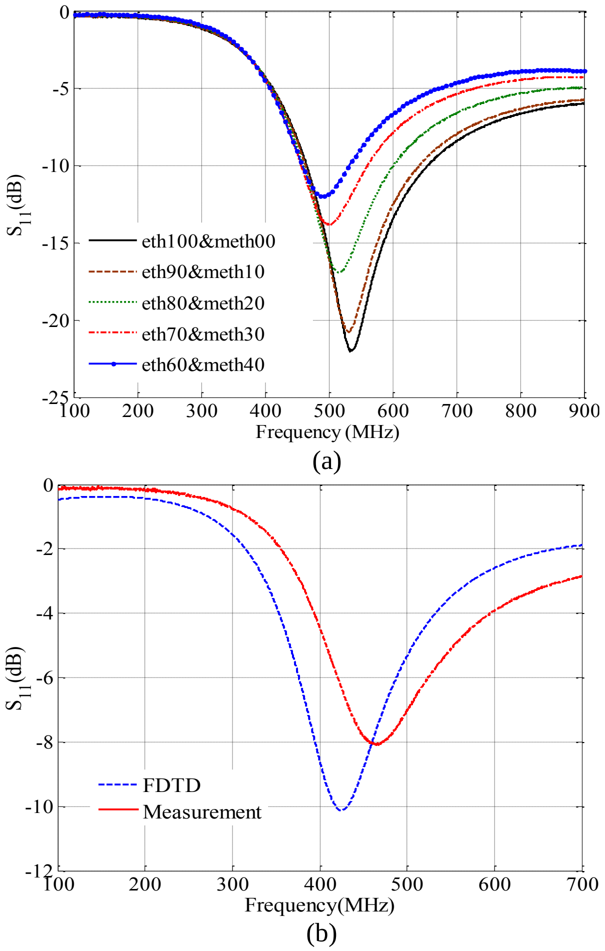


Fig. 5. (a) Measurement data of different samples for inverted patch resonator, and (b) comparison of S_{11} of measurement (----) and 3D-FDTD simulation (—).

VI. COMPARISON OF PATCH RESONATORS AS SENSORS

Two types of microstrip patch resonator are shown in Fig. 1. Both of these two patch resonators have low Q-factor as compared to the metallic cavity resonators like the one that is used in [15], but the S_{11}-parameter is deep enough to extract the accurate resonance frequency and 3-dB bandwidth from the measured S_{11}-parameter. For these two resonators, the size of the patch is determined by the operating frequency. Also, the total substrate thickness, between patch and ground plane has a strong influence on the total Q-factor of the patch cavity. By comparing the Fig. 4 and Fig. 5, it can be seen that the S_{11}-parameter of the suspended patch resonator is much deeper than the S_{11}-parameter of inverted patch resonator, so in this case, the resonance frequency of the suspended patch resonator can be distinguished more accurately than resonance frequency of the inverted patch resonator. On the other hand, the difference between the resonance frequency of the simulation and measurement for the inverted patch is less than that for the suspended patch resonator. It means that the simulation results are closer to the measurement results for the inverted patch resonator compared to the suspended patch resonator.

According to the Tables 1 and 2, for both of the resonators, the ε'' reconstruction error is more than that of ε'. It can be seen that the error of ε' reconstruction is really low and negligible, but the error of the ε'' reconstruction is more but it is also acceptable. The mean of the ε' reconstruction error for inverted patch resonator is 1.81%, but the mean of the ε' reconstruction error for the suspended patch resonator is 1.2%, so it can be concluded that ε' reconstruction process for both of the patch resonators are accurate, but it is more exact for the suspended patch resonator. The mean of the ε'' reconstruction error for the inverted patch resonator is 6.73%, but the mean of ε'' reconstruction error for the suspended patch resonator is 8.12%. Therefore, it can be derived that ε'' reconstruction process is not as accurate as ε' reconstruction process, but it is good enough to be accepted.

It is worth to compare the results of this paper and the results in [16], because in [16] a microstrip resonator with a slot in its ground plane is enclosed in a metallic cavity and is used to reconstruct the complex permittivity of binary mixtures of ethanol and methanol in a frequency band around 2.4 GHz. In that paper, it is mentioned that the maximum relative errors of ε' and ε'' are 4.4% and 8.6%, respectively. In this paper, the maximum relative errors of ε' and ε'' for suspended patch resonator are 3.8% and 12.26% and for inverted patch resonator are 4.18% and 12.43%. In this case, it can be concluded that the ε' reconstruction in this paper is more accurate than the one in [16], but the ε'' reconstruction in [16] is more exact than the one in this paper. Also, it should be considered that the mean error for ε' extraction in this paper is really lower than that of [16] and there is a big difference between them. On the other hand, the mean error for ε'' extraction in [16] is lower than the mean error for ε'' reconstruction in this paper but there is a small difference between them. Therefore, the advantage of this paper on [16] is that the ε' reconstruction process in this paper is greatly more accurate than the one in [16].

According to the discussion above, both of the patch resonators are proper for the permittivity measurement of medium loss liquids in the frequency band about their resonance because the simulation results are really close to the measurement results. Furthermore, the permittivity extraction errors for both of these resonators are low and acceptable.

Table 1: Real and imaginary part of complex permittivity of samples and errors for suspended patch resonator

Material Under Test	ε'	Error of ε'	ε''	Error of ε''
Ethanol 100% - methanol 00%	8.0359	1.29%	7.693	5.20%
Ethanol 90% - methanol 10%	8.774	0.95%	8.544	5.80%
Ethanol 80% - methanol 20%	10.12	0.20%	9.565	7.30%
Ethanol 70% - methanol 30%	11.31	1.30%	10.44	9.03%
Ethanol 60% - methanol 40%	12.54	0.96%	11.01	10.00%

Table 2: Real and imaginary part of complex permittivity of samples and errors for inverted patch resonator

Material Under Test	ε'	Error of ε'	ε''	Error of ε''
Ethanol 100% - methanol 00%	21.45	3.72%	9.098	5.07%
Ethanol 90% - methanol 10%	23.42	3.93%	8.941	3.80%
Ethanol 80% - methanol 20%	24.97	4.18%	8.027	3.45%
Ethanol 70% - methanol 30%	26.1	1.34%	7.626	2.26%
Ethanol 60% - methanol 40%	27.5	0.90%	7.33	5.72%

VII. CONCLUSION

Two double layer microstrip resonators have been designed and fabricated for complex permittivity measurements of liquids. Complex permittivity of binary mixtures of ethanol and methanol with different volume fractions have been measured with the novel microstrip resonators. Both of these resonators were used to measure the complex permittivity of medium loss liquids. For both of these patch resonators, the simulation results are similar to the measurement results. The error of ε' extraction for both of these patch resonators are really low and negligible. The error of ε'' extraction is a little more than that of ε', but it is also acceptable. In this case, it can be concluded that both of these resonators are good for permittivity measurement in the frequency range about their resonance frequency.

REFERENCES

[1] E. Nyfors, and P. Vainikainen, *Industrial Microwave Sensors*. Artech House, USA, 1989.

[2] H. Baltes, W. Gopel, and J. Hesse (Eds.), *Sensors Update*. Wiley Inc, Germany, vol. 7, 2000.

[3] L. F. Chen, C. K. Ong, C. P. Neo, V. V. Varadan, and V. K. Varadan, *Microwave Electronics, Measurement and Materials Characterization*. John Wiley & Sons, USA, 2004.

[4] A. V. Hippel, *Dielectric Materials and Application*. Artech House, USA, 1995.

[5] A. V. Hippel, *Dielectrics and Wave*. Artech House, USA, 1995.

[6] A. Taflove, and S. C. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method*. Artech House, USA, 2000.

[7] Dennis M. Sulivan, *Electromagnetic Simulation Using The FDTD Method*. IEEE Press, 2000.

[8] S. I. Ganchev, N. Qaddoumi, S. Bakhtiari, and R. Zoughi, "Calibration and measurement of dielectric properties of finite thickness composite sheets with open-ended coaxial sensors," *IEEE Trans. on Instrument, and Meas*, vol. 44, pp. 1023-1029, 1995.

[9] U. C. Hasar, "Permittivity determination of fresh cement-based materials by an open-ended waveguide probe using amplitude-only measurements," *Progress In Electromagnetics Research, PIER 97*, pp. 27-43, 2009.

[10] R. Huang and D. Zhang, "Application of mode matching method to analysis of axisymmetric coaxial discontinuity structures used in permeability and/or permittivity measurement," *Progress In Electromagnetics Research, PIER 67*, pp. 205-230, 2007.

[11] P. Queffelec and P. Gelin, "Influence of higher order modes on the measurements of complex permittivity and permeability of materials using a microstrip discontinuity," *IEEE Trans. Microw. Theory Tech*, vol. 44, no. 6, pp. 816-824, 1996.

[12] D. Shimin, "A new method for measuring dielectric constant using the resonant frequency of a patch antenna," *IEEE Trans. Microw. Theory Tech*, vol. 34, no. 9, pp. 923-931, 1986.

[13] Y. K. Verma and A. K. Verma, "Accurate determination of dielectric constant of substrate materials using modified Wolff model," *IEEE MTT-S Int. Microw. Symp. Dig*, pp. 1411-1414, 2000.

[14] M. Bogosanovich, "Microstrip patch sensor for measurement of the permittivity of homogeneous dielectric materials," *IEEE Trans. on Instrument, and Meas*, vol. 49, no. 5, pp. 1145-1148, 2000.

[15] A. K. Verma and Nasimuddin, "Determination of dielectric constant and loss-tangent of substrate sheet using microstrip patch resonator," *Microw. Opt. Technol. Lett*., vol. 35, no. 3, pp. 175-179, 2002.

[16] L. Changjun and P. Yang, "A microstrip resonator with slotted ground plane for complex permittivity measurements of liquids," *IEEE Microw. Wireless Compon. Lett*, vol. 18, no. 4, pp. 257-259, 2008.

[17] A. K. Verma, Nasimuddin, and A. S. Omar, "Microstrip resonator sensors for determination of complex permittivity of materials in sheet, liquid and paste forms," *IEE Proc. Microw. Antennas Propag*., vol. 152, no. 1, pp. 48-54, 2005.

[18] J. Hinojosa, K. Lmimouni, S. Lepilliet, and G. Dambrine, "Very high broadband electromagnetic characterization method of film-shaped materials using coplanar waveguide," *Microw. Opt. Technol. Lett.*, vol. 33, pp. 352-355, 2002.

[19] Z. Bao, M. L. Swicord, and C. Davis, "Microwave dielectric characterization of binary mixtures of water, methanol, and ethanol," *Journal of Chemical Physics*, vol. 104, pp. 4441-4450, 1996.

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