A Microstrip Resonator With Slotted Ground Plane for Complex Permittivity Measurements of Liquids

Article *in* IEEE Microwave and Wireless Components Letters · May 2008

DOI: 10.1109/LMWC.2008.918894 · Source: IEEE Xplore

Changjun Liu
Sichuan University

A Microstrip Resonator With Slotted Ground Plane for Complex Permittivity Measurements of Liquids

Changjun Liu, *Member, IEEE*, and Yang Pu

***Abstract*—A novel microstrip resonator is designed to measure complex permittivities of liquids with medium loss. The enclosed resonator is based on a $\lambda/2$ open-circuit microstrip line with a slot in the ground plane. It is immersed into the liquid under test to measure the S-parameter from 2.2 to 2.6 GHz. The complex permittivities of binary liquid mixtures of methanol and ethanol are reconstructed from the resonant frequency and the unloaded quality factor. The experimental results agree with reference values. The maximum errors are 4.4% and 8.6% for the real and imaginary part of the permittivity, respectively.**

***Index Terms*—Microwave chemistry, microstrip transmission line, permittivity measurement, planar circuit.**

I. INTRODUCTION

COMPLEX permittivity measurements are important in microwave engineering, microwave material processing, microwave chemistry, and bioelectromagnetics [1]–[4]. Recently planar circuits, such as microstrip lines, coplanar waveguides, and strip lines have found their applications in complex permittivity measurements. Planar structures, which are lightweight, compact and low cost, have been successfully applied to the determination of substrate permittivities, material moisture, liquid properties, and so on [5]–[7]. Planar circuits are portable, suitable to on-line monitors, and possibly non-destructive. Those planar circuit measurements are classified into resonant methods (with high accuracy and sensitivity) and non-resonant methods (broadband measurements) [8]. Once medium/high loss materials contact a planar circuit resonator directly, the resonance condition will not hold. Therefore, the resonant measurement methods based planar circuits are usually limited to low loss materials.

In microwave chemistry, on the other hand, many liquids do not belong to low loss materials. Assuming that those complex permittivities of liquids do not vary much around the interested microwave frequency, we have proposed a novel microstrip resonator to measure complex permittivities. A $\lambda/2$ open-circuit microstrip line and an interdigital capacitor constitute the resonator, which is inside a metal enclosure. The microstrip resonator is immersed in the liquid to be characterized. Its characteristic is influenced by liquids under test through a narrow slot in the ground plane, which is under the resonant microstrip line. From measured S-parameters the resonant frequencies and the quality factors of the microstrip resonator are obtained and applied to reconstruct the complex permittivities of the liquids. Binary mixtures of methanol and ethanol were measured with the novel microstrip resonator. The reconstructed complex permittivities showed an agreement with respect to reference values.

Manuscript received August 13, 2007; revised December 6, 2007. This work was supported in part by the National Nature Science Foundation of China under Grant NSFC 60301004.

C. Liu is with the School of Electronics and Information Engineering, Sichuan University, Chengdu 610064, China (e-mail: cjliu@ieee.org; cjliu.cn@gmail.com).

Y. Pu was with Sichuan University, Chengdu 610064, China and is now with the 10th Institute, China Electronics Technology Group Corporation, Chengdu 610036, China.

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LMWC.2008.918894

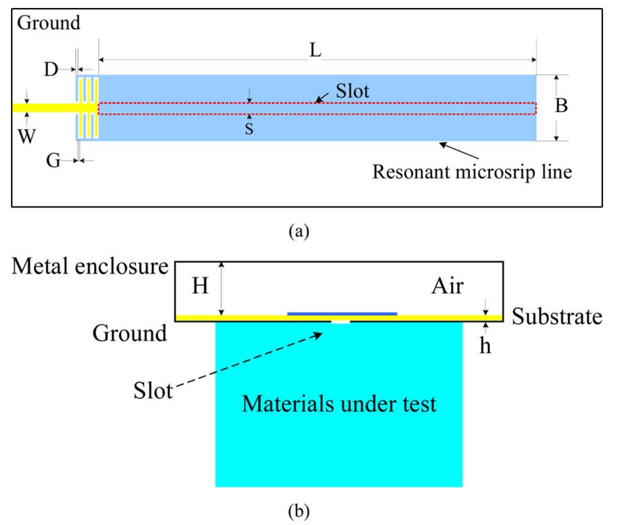
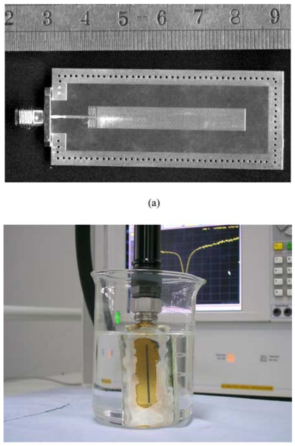


Fig. 1. Top and cross view of the microstrip resonator (a) top view of the microstrip resonator and (b) cross view of the microstrip resonator.

II. STRUCTURE OF THE MICROSTRIP RESONATOR

We have designed the microstrip resonator working at 2.4 GHz, as shown in Fig. 1. The substrate is RT/Duroid 5880 with relative permittivity $\varepsilon_r = 2.2$ and thickness $h = 0.254$ mm. The resonant microstrip line is designed with a width of $B =$ 6.0 mm, resulting in a characteristic impedance of $Zc = 9.6\ \Omega$. It is put into a metal enclosure with $H = 3.0$ mm. The metal enclosure is connected to the ground plane at all four sides. The total enclosed microstrip resonator is 60 mm $\times$ 25 mm $\times$ 3.5 mm. Both radiation loss and conductor loss are minimized in the above configuration. The metal enclosure protect liquids from directly contacting to the resonant microstrip line and avoids the potential erosion as well. Epoxy adhesives are used to keep liquids from seeping between the substrate and the enclosure.

The microstrip resonator is connected to a SMA adapter. The coupling between the 50 Ω feed line and the resonant microstrip line is performed by an interdigital capacitor, which consists of three pairs of fingers. The finger widths and finger gaps are $D = 0.20$ mm and $G = 0.15$ mm, respectively. The length of



(a)

(b)

Fig. 2. Microstrip resonator and the measurement system (a) photo of the microstrip resonator (without the metal enclosure) and (b) photo of the resonator immersed in a solution.

the resonant microstrip line is $L = 39.8$ mm. The microstrip resonator is working at the under-coupled condition at about 2.4 GHz.

A narrow slot with width $S = 1$ mm is fabricated in the ground plane under the resonant microstrip line. The slot is completely immersed in the liquids to be characterized during measurements. The SMA connector is kept away from liquid solutions. The resonant frequency shift and the quality factor variation reflect the complex permittivities of the liquids under test. The microstrip resonator and the measurement system are shown in Fig. 2.

III. Reconstruction Method of the Complex Permittivity

The unloaded quality factor Q_0 of a $\lambda/2$ open-circuit microstrip line is

$$Q_0 = \frac{\beta}{2\alpha} \tag{1}$$

where α is the attenuation factor and β is the propagation constant. The resonant frequency f_0 is dependent on the phase velocity v_p

$$f_0 = \frac{v_p}{2l_{eff}} \tag{2}$$

where l_{eff} is the effective length of the resonant microstrip line. Here the attenuation factor α, the propagation constant β, and the phase velocity v_p are relevant to the complex permittivity of the liquid under test. So far there are two equations with two unknowns (the real and imaginary part of the complex permittivity $\varepsilon = \varepsilon' - j\varepsilon''$). Thus, the complex permittivity can be obtained from the measurements of the resonant frequency f_0 and the unloaded quality factor Q_0.

The forward problem is to compute the resonant frequency and the unloaded quality factor when the permittivity of the under test liquid is given. Both of them are obtained by a two-dimensional finite difference time domain (2D-FDTD) method [9], which is efficient in electromagnetic simulation. It takes about a few dozens of seconds in a personal computer to obtain the resonant frequency and the unloaded quality factor of the resonator. A calibration of the resonator is performed in air in order to determine the two initial parameters, i.e., the equivalent length and the loss of the microstrip resonator, required by the 2-D-FDTD program. Based on the measured resonant frequency and the unloaded quality factor at 2.4 GHz, these two parameters are determined from the calibration.

The inverse problem is to reconstruct the complex permittivity from the measured resonant frequency and unloaded quality factor. A classical Newton-Raphson method is applied to solve the nonlinear equations of (1) and (2). The required Jacobian matrix is approximated by a finite difference method. Then, the complex permittivities of liquids under test are retrieved from measured results. The inverse problem is not seriously ill-posed, and the convergent results are reached usually within ten iterations in the Newton–Raphson method.

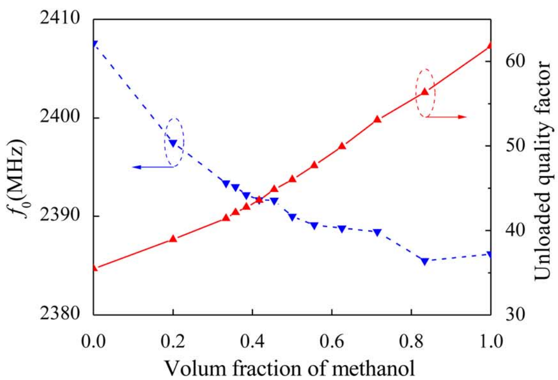
IV. Measurements and Results

We chose binary mixtures of methanol and ethanol with different volume fractions as liquids under test. The binary mixtures at 30 °C were filled into a 500 mL glass beaker, in which the microstrip resonator was immersed for measurements. Then the $|S_{11}|$ parameters of the microstrip resonator from 2.2 GHz to 2.6 GHz were measured ten times by an Agilent E8362B vector network analyzer. Air bubbles are hard to adhere to the slot, since the resonator is vertical to the surface of infiltrate liquids during measurements. The photo in Fig. 2(b) shows the measurement system. The resonant frequency f_0 and the unloaded quality factor Q_0 are accurately determined from the measured $|S_{11}|$ parameters by a weighted least-square curve fitting procedure [10], [11]. The measured resonant frequencies and calculated unloaded quality factors are shown in Fig. 3(a).

The complex permittivities of the binary mixtures, as shown in Fig. 3(b), are obtained from the reconstruction method in Section III. The reconstructed complex permittivities agree with the reference values obtained from Bruggeman's formula [12]. The maximum relative errors of ε' and ε'' are 4.4% and 8.6%, respectively. The proposed microstrip resonator is suitable to measure permittivities within the range $\varepsilon' < 20$ and $\varepsilon'' < 12$, in which the relative error is reduced to less than 4%. When either the real or imaginary part of the permittivity is high, less electromagnetic fields leak out through the slot in the ground plane of the resonator. The resonant frequency is not sensitive to the variation of either the real or imaginary part of the permittivity. Therefore, large measurement errors are obtained with high volume fraction of methanol.

V. Conclusion

An enclosed microstrip resonator with a slot in the ground plane has been designed and fabricated for complex permittivity measurements. Binary mixtures of methanol and ethanol with different volume fractions have been measured with the novel microstrip resonator. The measured complex permittivities agree with respect to the reference values. The maximum relative error of 8.6% appears when $\varepsilon'' \approx 13$. The suitable permittivity measurement range for the proposed resonator is within $\varepsilon' < 20$ and $\varepsilon'' < 12$, in which the relative error is less than 4%.



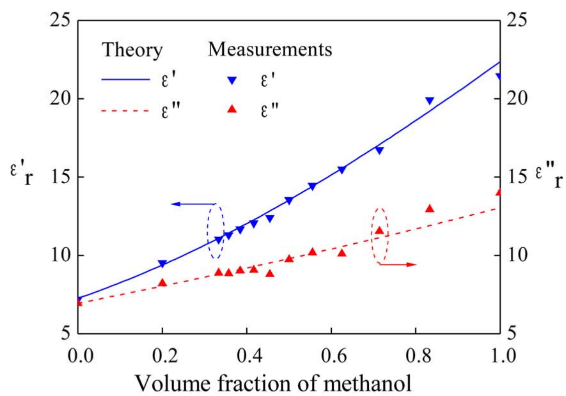


Fig. 3. Measured results of binary mixtures of methanol and ethanol. The volume fraction of methanol to mixture varies from 0% to 100%. (a) Measured resonant frequencies and quality factors. (b) Reconstructed complex permittivities.

Besides the advantages of planar circuits, the microstrip resonator is able to protect potential erosion from solutions under test in microwave chemistry research. The calibration of the microstrip resonator is easy to perform.

ACKNOWLEDGMENT

The authors wish to thank Dr. W. Menzel, Institute of Microwave Techniques, Ulm University, Germany, for his suggestions and discussions, and Editor-in-Chief Dr. G. Ponchak and the Reviewers for their valuable comments.

REFERENCES

[1] I. Waldron, S. N. Makarov, S. Biederman, and R. Ludwig, "Suspended ring resonator for dielectric constant measurement of foams," *IEEE Microw. Wireless Compon. Lett.*, vol. 16, no. 9, pp. 496–498, Sep. 2006.

[2] S. N. Makarov, S. D. Kulkarni, A. G. Marut, and L. C. Kempel, "Method of moments solution for a printed patch/slot antenna on a thin finite dielectric substrate using the volume integral equation," *IEEE Trans. Antennas Propag.*, vol. 54, no. 4, pp. 1174–1184, Apr. 2006.

[3] K. Huang, X. Cao, and C. Liu, "Measurement/computation of effective permittivity of dilute solution in saponification reaction," *IEEE Trans. Microw. Theory Tech.*, vol. 51, no. 10, pp. 2106–2111, Oct. 2003.

[4] L. Yan, K. Huang, and C. Liu, "A noninvasive method for determining dielectric properties of layered tissues on human back," *J. Electromagn. Waves Appl.*, vol. 21, no. 13, pp. 1829–1843, Oct. 2007.

[5] 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, Jun. 1996.

[6] A. K. Verma, Nasimuddin, and A. S. Omar, "Microstrip resonator sensors for determination of complex permittivity of materials in sheet, liquid and paste forms," *Proc. Inst. Elect. Eng.*, vol. 152, pp. 47–54, 2005.

[7] J. Hinojosa, "S-parameter broad-band measurements on-microstrip and fast extraction of the substrate intrinsic properties," *IEEE Microw. Wireless Compon. Lett.*, vol. 11, no. 7, pp. 305–307, Jul. 2001.

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

[9] F. Liu, J. E. Schutt-Aine, and J. Chen, "Full-wave analysis and modeling of multiconductor transmission lines via 2-D-FDTD and signal-processing techniques," *IEEE Trans. Microw. Theory Tech.*, vol. 50, no. 2, pp. 570–577, Feb. 2002.

[10] D. Kajfez, "Linear fractional curve fitting for measurement of high Q factors," *IEEE Trans. Microw. Theory Tech.*, vol. 42, no. 7, pp. 1149–1153, Jul. 1994.

[11] D. Kajfez, "Random and systematic uncertainties of reflection-type Q-factor measurement with network analyzer," *IEEE Trans. Microw. Theory Tech.*, vol. 51, no. 2, pp. 512–519, Feb. 2003.

[12] T. Sato, A. Chiba, and R. Nozaki, "Composition-dependent dynamical structures of monohydric alcohol-water mixtures studied by microwave dielectric analysis," *J. Molec. Liquids*, vol. 96–97, pp. 327–339, 2002.