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Research Article

A Novel Technology for Measurements of Dielectric Properties of Extremely Small Volumes of Liquids

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A high sensitivity sensor for measurement radio frequency (RF) dielectric permittivity of liquids is described. Interference is used and parasitic effects are cancellation, which makes the sensor can catch weak signals caused by liquids with extremely small volumes. In addition, we present the relationship between transmission coefficient and permittivity of liquids under test (LUT). Using this sensor, quantitative measurements of the dielectric properties at 5.8 GHz are demonstrated of LUTs. Experiments show that the proposed method only requires the volume of 160 nanoliters for liquids. Therefore, the technology can be used for RF spectroscopic analysis of biological samples and extremely precious liquids.

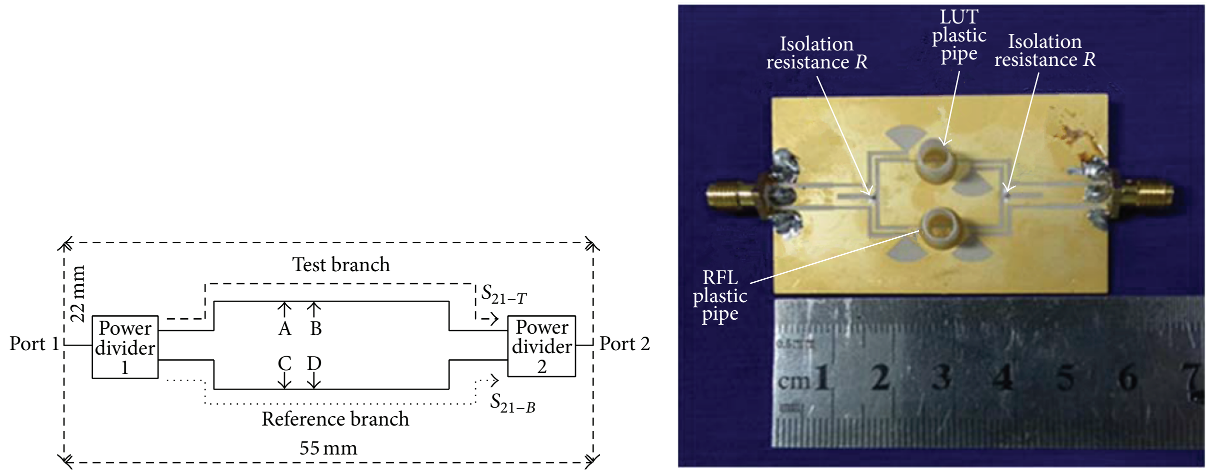
1. Introduction

RF dielectric properties of liquids of small volumes are of great interest for the development of biological and chemical fields [1–3]. Applications include dielectric studies of cells [4], medical diagnostic testing [5], and biological specimens [6] for lab-on-chip advancement. Dielectric spectroscopy that measures the dielectric properties has several advantages, such as being label-free, real-time monitoring of the samples, and being noninvasive [7]. However, application of RF dielectric properties of liquids at extremely low signal level is challenged, because low signal levels always submerge backgrounds that come from the measurement sensor [8]. One way to generate low signal is small volume sample, because large changes of the dielectric properties of samples with extremely small volumes can lead to small changes in the detected RF signals. Therefore, the sensitivity of permittivity measurement always decreases with the physical volume of the sample. At the same time, a novel technology for measurement of very small volumes of samples is particularly desirable for applications of biological and chemistry fields [9]. There have been many efforts and progress to improve measurement sensitivity and accuracy through different methods. These include transmission line [10], free space [11], and cavity techniques [12]. Nevertheless, parasitic effects [7–9] usually have a negative impact on the sensitivity of detection. The efforts are limited in counteracting parasitic effects and capturing very low signal that comes from extremely small volume [13] of the sample. So measurement of weak RF signal continues to be a technical challenge. At the same time, there also has been a difficulty in gaining dielectric properties of the liquids from the measured signals [14].

In the work, we propose a sensor for measurement of the dielectric properties of very small volumes of liquids at RF. Interference [7–9] is used to improve sensitivity of the sensor. So it can capture weak signals from extremely small volumes (nanoliter). In addition, the sensor can be used in contactless mode and possesses the quantitative extraction of the complex dielectric properties of the sample.

2. Sensor Fabrication

Figure 1(a) shows a schematic of the proposed structure. We can see that the sensor consists of two branches and two identical Wilkinson power dividers [15]. The two branches are composed of 180-degree reverse-phase and in-phase CPW-(coplanar waveguide-) slot-line back-to-back balun [16]; one branch is filled with LUT; the other is filled with referenced liquid (RFL). An incoming microwave signal from port 1 is separated evenly into the two branches by the first power



(a) (b)

Figure 1: (a) Schematic of the proposed high sensitive sensor. (b) Fabricated sensor with plastic pipes.

divider; then signals will propagate to the two admittances and finally arrive to the second power divider [17].

Therefore, interference is used to improve measurement sensitivity greatly, which has been reported at radio frequency in [7–9]. If the two branches are filled with identical samples, the transmission S_{21} is close to zero. Otherwise, small differences of the two dielectric properties will lead to large relative changes of S_{21} between LUT and RFL. The sensor is designed by CPW (coplanar waveguide) and slot-line. A prototype is fabricated on an AD1000 substrate (relative permittivity is 10.2; substrate thickness is 1.6 mm). The characteristic impedances of ports 1 and 2 are chosen as 50 ohm, for the convenience of process; the input/output characteristic impedance of the baluns is chosen as 75 ohm. Therefore, the even mode characteristic impedance of quarter wavelength section of the power divider and isolation resistance are 86.6 and 150 ohm, respectively. For the convenience of sample solution injection, LUT and RFL plastic pipes are attached on the sensor. The fabricated sensor with SMA connectors and plastic pipes is shown in Figure 1(b).

3. Dielectric Properties Extraction Method

Assuming that S_{21-T} and S_{21-B} are the signal transmission coefficients of the two branches, then the signal transmission coefficient from port 1 to port 2 can be expressed as

$$S_{21} = S_{21-T} + S_{21-B}. \tag{1}$$

If T_1 and T_2 express transmission coefficients of sections of A-B and C-D, then

$$S_{21} = S_{21-Tr} \times T_1 + S_{21-Br} \times T_2, \tag{2}$$

where S_{21-Tr} and S_{21-Br} are the rest of signal path components except the A-B and C-D sections, respectively. For the convenience of test, two identical plastic pipes whose diameter and height equal 2 mm and 4 mm are glued at the A-B and C-D sections. And, for the REL cell,

$$T_2 = \frac{2Z_0}{2Z_0 + Z_{2(\omega)}}, \tag{3}$$

where Z_0 is the characteristic impedance of transmission line and $Z_{2(\omega)}^{-1} = G_{2(\omega)} = j\omega C_1 + j\omega C\varepsilon_2$. C_1 is the parasitic capacitance and C is the capacitance of the liquid channels, which can change with variations of samples filled in the channel. If ε_2 and σ_2 are the complex permittivity and conductivity of the sample in the REL channel, respectively [18], then

$$\varepsilon_2 = \varepsilon_2' + j\left(\varepsilon_2'' - \frac{\sigma_2}{\varepsilon_0\omega}\right). \tag{4}$$

Similar relationship applies to LUT; the change of dielectric properties of it can change C and G with an amount of ΔC and ΔG. Therefore, we have

$$T_1 = T_2 + \Delta T. \tag{5}$$

From formulas (2) and (5), we obtain

$$S_{21} = S_{21-Tr} \times (T_2 + \Delta T) + S_{21-Br} \times T_2. \tag{6}$$

Furthermore, $S_{21-Tr} \times T_2 + S_{21-Br} \times T_2 = 0$. For our channels, $T_{1,2} \ll 1$, so

$$\begin{aligned} S_{21} &= S_{21-Tr} \times \Delta T \\ &= S_{21-Tr} \times 2Z_0 \frac{Z_{2(\omega)} - Z_{1(\omega)}}{\left[2Z_0 + Z_{1(\omega)}\right]\left[2Z_0 + Z_{2(\omega)}\right]} \\ &\approx 2Z_0 j\omega S_{21-Tr}(\varepsilon_1 - \varepsilon_2)C, \end{aligned} \tag{7}$$

where ε_1 and ε_2 are permittivity of LUT and RFL, respectively. Expression (7) shows that the difference of dielectric properties is direct relationship to the measured S_{21} of the sensor,

Table 1: Measurement results for methanol, M-E, M-P, and n-propanol.

LUT	ε'	Reference [19]	Relative error (%)	ε''	Reference [19]	Relative error (%)
Methanol	31.013	30.279	2.42	−8.126	−7.904	−2.81
M-E	22.287	21.734	2.54	−10.025	−9.818	−2.11
M-P	17.556	17.915	−2.01	−10.356	−10.212	−1.41
Ethanol	13.986	14.403	−2.89	−9.389	−9.524	1.42
n-Propanol	8.126	7.910	2.73	−7.669	−7.831	2.07

where C is lossless in expression (7), since the tubes and the substrate (Rogers TMM10) have very low dielectric loss in design frequency (5.8 GHz).

If considering nonidealities of the two power dividers and small differences in the size of the two channels, the transmission coefficient S_{21} can be written as follows:

$$\begin{aligned} S_{21} &= 2Z_0 j\omega \left[S_{21-Tr}\left(\varepsilon_1 - \varepsilon_2\right) C\right] + S_{21-Tr}\left[\varepsilon_1 \Delta C \right. \\ &\quad \left. + \Delta C_1\right] + \left(S_{21-Tr}T_2 + S_{21-Br}T_1\right)\left(C\varepsilon_1 + C_1\right) \\ &= \left[S_{21-Tr}\Delta C + \left(S_{21-Tr}T_2 + S_{21-Br}\right) C \right. \\ &\quad \left. + 2Z_0 j\omega S_{21-Tr} C\right]\varepsilon_1 + S_{21-Tr}\Delta C_1 + \left[S_{21-Tr}T_2 \right. \\ &\quad \left. + S_{21-Br}T_1\right] C_1 - 2Z_0 j\omega S_{21-Tr} C\varepsilon_2 = M\varepsilon_1 + N\varepsilon_2 \\ &\quad + P, \end{aligned} \tag{8}$$

where C_1 is parasitic capacitance and lossless in (7) and ΔC, ΔC_1 are changes of channel and parasitic capacitances, respectively. In the work, deionized water is chosen as RFL. So coefficients of M, N, and P can be determined from the tested S_{21} of two liquids with known permittivity.

4. Results and Discussions

On the basis of the proposed method, transmission parameters of S_{21} are tested with a network analyzer. During experiments, deionized water is the RFL, and methanol, ethanol-propanol, M-E, and M-P are chosen as tested liquids. M-E (M-P) is mixtures of methanol and ethanol (methanol and n-propanol) with identical mole fraction. Measurements were performed at room temperature of 25°C. The magnitude of S_{21} is shown in Figure 2. The measurement results demonstrate convincingly the theoretical analysis noted above. That is, the transmission coefficients of the sensor have inevitable connection with the permittivity difference between the RFL and LUT.

The transmission of S_{21} is about −70 dB, when the two channels are placed with the same materials (deionized water). It also exhibits a strong dependence on the dielectric properties of LUT.

We chose deionized water (~80) and acetone (~20.5) as calibration liquids and permittivity of LUT is computed from the measured S_{21}, accordingly from (8). The results are shown in Table 1. We can see that the measured results are in good agreement with reference [19].

One way to illustrate the sensitivity of the proposed method is shown in Figure 3, which compare the amplitude

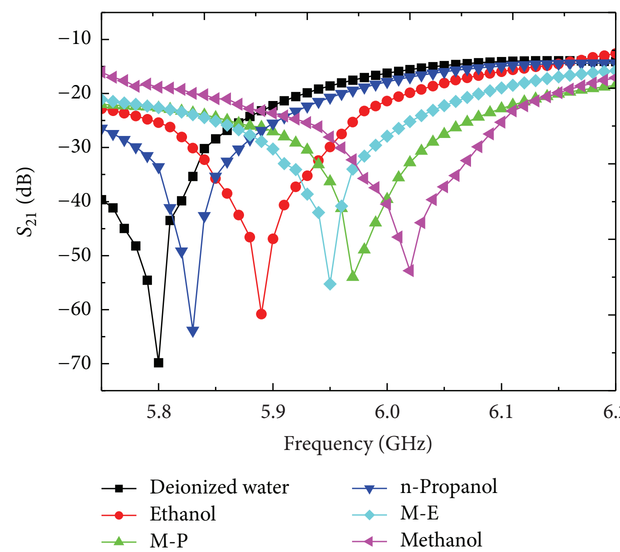


Figure 2: Measured S_{21} for different LUT under the RFL which is deionized water.

of S_{21} for different LUTs. In the process of this experiment, the A-B section which is reference channel is filled full in deionized water, and the LUT channel residing in the C-D section is filled in ethanol with different molar concentration, respectively. From Figure 3, the maximum S_{21} changes are ~0.22 dB for shielded coplanar waveguide (S-CPW) [14] method. However, the proposed method exhibits large S_{21} changes for the same permittivity difference between LUT and RFL, which indicates high sensitivity. The dielectric constant values obtained in [19] are used.

Another way of measurement sensitivity is defined as the relative change of interference frequency along with volume of different LUTs. Figure 4 shows the test results of sensitivity on the basis of dielectric properties of LUTs calculated above. Five sampling valves of permittivity correspond to five LUTs; they are methanol, M-E, M-P, ethanol, and n-propanol. It can be seen that the larger the volume of LUTs, the higher the sensitivity when the LUTs remain the same. So the sensitivity of the measurement increases with volumes of LUTs. However, the volumes of the channel will not affect the sensitivity of the sensor if volume is greater than or equal to 160 n L as can be seen from Figure 4, because two curves (V = 140 nanoliters and V = 160 nanoliters) have already overlapped. That is, the volume of the LUT only requires 160 n L. Compared with [13], the proposed method is much more sensitive. At the same time, the detector requires

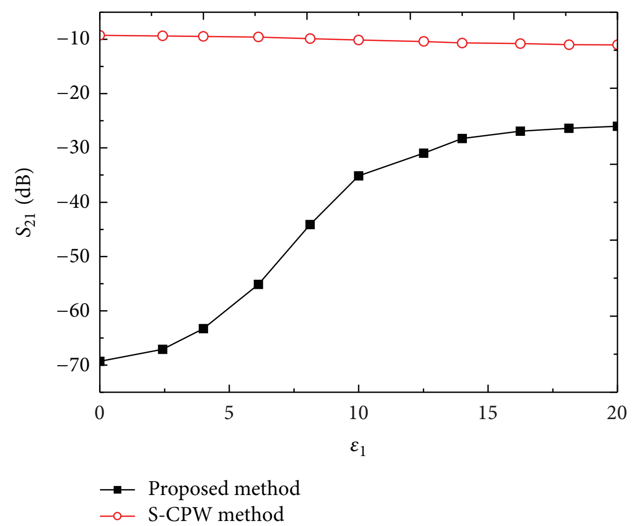


FIGURE 3: The scattering parameters S_{21} change with various differences of permittivity for two methods.

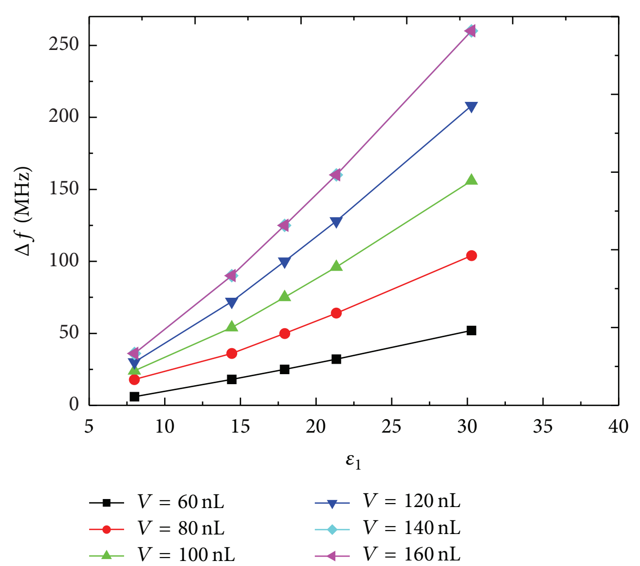


FIGURE 4: Variation of cancellation frequency with permittivity of LUT calculated by the proposed method.

the smallest volume of 160 nanoliters. It is also shown that the proposed method is very high sensitive for detecting signal generated by liquids with extremely small volumes. In previous work, an extremely small sample (~200 nanoliters) has been realized in [20]. Compared with it, a smaller sample volume has been required by using the proposed method.

5. Conclusion

In summary, a high sensitive sensor for measurement permittivity with very small volumes of liquids is demonstrated. There are two attractive features of the proposed method: the measurement is very high sensitive and permittivity of liquids can be carried out with small volume. Therefore, the sensor can be used for measurement dielectric spectrum for biological samples or extremely precious liquids. At the same time, we analyze deeply the relationship between transmission coefficient and dielectric properties of LUT. There are some issues that need to be studied, such as bandwidth and miniaturization.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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