A New Microwave Oscillator-Based Microfluidic Sensor for Complex Permittivity Measurement

Chu-Hsuan Pai¹, Chao-Hsiung Tseng²
Department of Electronic and Computer Engineering, National Taiwan University of Science and Technology, Taiwan
¹vivi00077@gmail.com, ²chtseng@ieee.org

Abstract — A new microwave oscillator-based microfluidic sensor is proposed in this paper for complex permittivity measurement. A modified coplanar strip resonator is proposed as the permittivity sensing device and frequency-selective element for the oscillator design. It can concentrate the sensing electric field with a distribution consistent with the microfluidic channel. As the test liquids are placed in the sensing region, the oscillation frequency and output power are measured for complex permittivity computation. The 23-µL water-ethanol mixtures with ethanol volume fractions of 10% to 70% in increments of 20% are used as the test liquids to evaluate the sensor performance. Compared with the results obtained from the commercial dielectric probe, the maximum errors of the dielectric constant and loss tangent measured by the proposed microfluidic sensor are 9.45% and −8.84%, respectively.

Keywords — radio-frequency microfluidic sensors, complex permittivity measurement, radio-frequency permittivity sensors, liquid dielectric sensors, modified coplanar strip resonator (MCSR).

I. INTRODUCTION

Characterization of liquid permittivity in the microwave/millimeter-wave range is an effective approach to estimating the concentration of aqueous solutions and classifying the type of liquid. The permittivity measurement technique has been increasingly applied in food industrial [1], biological [2], and pharmaceutical [3] fields. Combined with microfluidics, one can precisely control the test liquid volume in a micro-litter scale for advanced applications on the microscopic scale, such as biological cell investigation [4], [5]. Over the past decade, various new microwave microfluidic sensors have been proposed in the microwave research community and are mainly categorized into the passive-type [6], [7], [8], [9] and active-type [10], [11], [12], [13], [14].

The recently developed passive-type sensors, such as the split-ring resonator (SRR) [6], microstrip LC resonator [7], complementary split-ring resonator (CSRR) [8], and substrate integrated waveguide (SIW) cavity [9], mainly focus on miniaturizing the circuit size, reducing the volume requirement of the test liquid, and improving the sensitivity. However, a vector network analyzer (VNA) is essential to build a complete sensor system for complex permittivity measurement. It is bulky, expensive, and impractical for the internet of things (IoT) or sensor network applications. Therefore, the active-type sensors using the correlators with capacitive sensors [10], the in-phase and quadrature-phase (IQ) down-conversion mixers with a capacitive sensor [11], a sensing voltage-controlled oscillator (VCO) with a phase-locked loop (PLL) [12], a VCO-based sensor with both sensing and reference VCOs [13], and a frequency-locked-loop (PLL) sensor with a frequency discriminator [14], have been proposed to get rid of using a VNA.

Although the CMOS sensing oscillators for dielectric constant measurement (real part of relative permittivity) have been proposed in [12], [13], they are only suitable to detect the test liquid in a tiny sensing area over the sensing capacitor structure of the packaged chip. For some microfluidic applications, the sensing area with a uniform electric-field distribution is required to have a layout pattern similar to that of the microfluidic channel or chamber to improve the sensor sensitivity. In addition, the limited measurement capability, i.e., only measuring the real part of permittivity, has difficulty characterizing the complete liquid properties.

This study proposes a new microwave microfluidic sensor using a sensing oscillator with a modified coplanar strip resonator (MCSR) to have a more flexible sensing field distribution for complex permittivity measurement. The system block diagram of the proposed permittivity sensor is shown in Fig. 1. A capillary tube with the test liquid is used to emulate a microfluidic channel. The inset figure shows that the tube is then placed on the MCSR along with the gap structure between the strip line and the coplanar ground to experience the electric field. In this sensor configuration, the MCSR is used as a sensing device and treated as the frequency-selective component for the feedback-loop oscillator design. A spectrum analyzer then measures the sensing oscillator to acquire the oscillation frequency and output power as different test liquids are placed on the MCSR.
II. PERMITTIVITY SENSOR DESIGN

Referring to the sensor configuration shown in Fig. 1, the MCSR simultaneously plays the role of a liquid sensing device and a frequency-selective resonator for the oscillator design. Fig. 2 (a) shows the three-dimensional structure of the MCSR with the physical dimensions indicated in Fig. 2 (b). It is designed at 1.8 GHz on a 20-mil RO4003C substrate, with a dielectric constant of 3.55 and a loss tangent of 0.0027. The MCSR is mainly a half-wavelength transmission-line (TL) resonator, and a portion of the TL is replaced by a conductor strip with a coplanar ground plane. In addition, the ground-defected structure on the bottom conductor layer is placed beneath the strip line and coplanar ground to concentrate the electric-field distribution into the sensing gap. The radio-frequency (RF) energy couples into this resonator via bilateral interdigital capacitors. Fig. 2 (c) shows the electric-field distribution simulated by the ANSYS High-Frequency Structure Simulator (HFSS) on the virtual plane, which is placed on the surface of MCSR. As expected, the electric field concentrates on the sensing gap. Since the appearance of the electric-field sensing area of the MCSR is similar to the capillary tube shown in Fig. 1, it provides an advantage to penetrate a stronger electric field into the test tube for sensitivity improvement. The measured S-parameters of the MCSR are shown in Fig. 2 (d), and the resonance frequency is located at 1.77 GHz.

Based on the feedback-loop oscillator configuration, the MCSR sensing oscillator is designed according to the design procedures in [15] and fabricated on a RO4003C substrate. Fig. 3 (a) shows the circuit photograph of the proposed sensor. The design comprises the MCSR, an RF amplifier, and connecting microstrip lines. The MCSR has been designed as shown in Fig. 2. An Infineon BFP405 bipolar junction transistor (BJT), biased at $V_{cc} = 2.2 \text{ V}$ and $I_c = 10 \text{ mA}$, is used as an amplifier to compensate the loss contributed from the MCSR and satisfy the loop gain requirement of the Barkhausen oscillation criterion. Similarly, the connecting microstrip lines were designed to fulfill the loop phase requirement. The output spectrum measured by the Agilent spectrum analyzer N9010A is shown in Fig. 3 (b). The oscillation frequency of the MCSR oscillator is located at 1.82 GHz, with an output power of 2.96 dBm.

III. EXPERIMENTAL RESULTS

A. Sensor Calibration

Fig. 4 shows the permittivity measurement setup for the proposed microfluidic sensor. A three-dimensional (3D) printing plastic holder is fabricated to fix the position of the capillary tube stably on the sensing gap. The sensor output is connected with the Agilent EXA N9010A spectrum analyzer to acquire the oscillation frequency and output power. Before performing the permittivity measurement, one should first calibrate the proposed microfluidic sensor to obtain the equations relating the measured oscillation frequency, $f_{osc}$, and output power, $P_o$, to the dielectric constant, $\varepsilon_r$, and loss tangent, $\tan \delta$, respectively. Here, the complex relative permittivity $\varepsilon$ of the liquid under test (LUT) is defined as
The complex permittivity can be divided by $\varepsilon'$ to define the loss tangent as $\tan \delta = \varepsilon'' / \varepsilon'$ [16]. Referring to Fig. 2 (b), since the length of the sensing gap is 22 mm, and the inner radius of the capillary tube is 1.15 mm, the LUT volume for permittivity measurement is approximately 23 $\mu$L.

In this paper, the water-ethanol mixtures with ethanol volume fractions (EVF) from 0% to 80%, namely 0%, 20%, 40%, 60%, and 80%, were used as the calibration liquids. After injecting the calibration liquids into the capillary tube, $f_{osc}$ and $P_o$ were measured and listed in Table 1. Since the sensor used a tiny near field to sense the test liquid and the frequency shift was about only 0.28% of the oscillation frequency, the sensing oscillator was still in the stable region in the measurement. According to the microfluidic oscillator sensors in [12], [13], [17], the oscillation frequency and output power variations for different LUTs can be further related to the real part of permittivity, $\varepsilon_r$, and loss tangent, $\tan \delta$, of the known calibration liquids, respectively. The complex permittivities of the calibration liquids, measured by the Keysight N1501A Dielectric Probe Kit in combination with the E5071C Vector Network Analyzer, were also summarized in Table 1 for performing the curve fitting. Fig. 5 (a) plots the calibration $\varepsilon_r$ shown in Table 1 versus $f_{osc}$ and fitted by a 3-order polynomial equation as

$$\varepsilon_r = -12.27 \left(\frac{f_{osc} - 1.78846}{0.003455}\right)^3 + 28.41 \left(\frac{f_{osc} - 1.78846}{0.003455}\right)^2 - 24.87 \left(\frac{f_{osc} - 1.78846}{0.003455}\right) + 34 \quad (1)$$

Similarly, Fig. 5 (b) plots the calibration $\tan \delta$ shown in Table 1 versus $f_{osc}$ and fitted by a 3-order polynomial equation as

$$\tan \delta = 0.06552 \left(\frac{P_o - 3.485}{0.148}\right)^3 + 0.07113 \left(\frac{P_o - 3.485}{0.148}\right)^2 - 0.3604 \left(\frac{P_o - 3.485}{0.148}\right) + 0.3189 \quad (2)$$

Hence, based on (1) and (2), the measured $f_{osc}$ and $P_o$ of the proposed microfluidic permittivity sensor successfully relate to the $\varepsilon_r$ and $\tan \delta$ of the test liquid.

**B. Permittivity Measurement**

To verify the proposed microfluidic permittivity sensor, the water-ethanol mixtures with EVFs from 10% to 70% in increments of 20%, namely 10%, 30%, 50%, and 70%, were used as the LUTs. By injecting the LUTs into the capillary tube on the MCSR shown in Fig. 4, one can acquire the $f_{osc}$ and $P_o$ corresponding to the liquid concentrations from the spectrum analyzer. The measured $\varepsilon_r$ and $\tan \delta$ results can be calculated by substituting the measured $f_{osc}$ and $P_o$ into (1) and (2). Fig. 6 showed the measured $\varepsilon_r$ and $\tan \delta$. In addition, the reference results measured by the dielectric probe kit were illustrated for comparison. The exact measured values using the proposed microfluidic permittivity sensor and the dielectric probe kit are in good agreement with those obtained by the dielectric probe kit.

Table 1. Measured $f_{osc}$ and $P_o$ of Proposed Sensor for Different Water-Ethanol Calibration Liquids

<table>
<thead>
<tr>
<th>EVF (%)</th>
<th>$f_{osc}$ (GHz)</th>
<th>$P_o$ (dBm)</th>
<th>cal. $\varepsilon_r$</th>
<th>cal. $\tan \delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.78547</td>
<td>3.64</td>
<td>77.76</td>
<td>0.0868</td>
</tr>
<tr>
<td>20</td>
<td>1.78591</td>
<td>3.60</td>
<td>66.16</td>
<td>0.1256</td>
</tr>
<tr>
<td>40</td>
<td>1.78679</td>
<td>3.54</td>
<td>53.74</td>
<td>0.2021</td>
</tr>
<tr>
<td>60</td>
<td>1.78756</td>
<td>3.48</td>
<td>39.02</td>
<td>0.3104</td>
</tr>
<tr>
<td>80</td>
<td>1.79053</td>
<td>3.42</td>
<td>24.40</td>
<td>0.4975</td>
</tr>
</tbody>
</table>

Table 2. Measurement Comparisons of Water-Ethanol Mixtures for Proposed Sensor and Commercial Dielectric Probe

<table>
<thead>
<tr>
<th>EVF (%)</th>
<th>$\varepsilon_r$</th>
<th>$\tan \delta$</th>
<th>rel. $\varepsilon_r$</th>
<th>error</th>
<th>ref. $\tan \delta$</th>
<th>error</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>78.52</td>
<td>9.45</td>
<td>71.74</td>
<td>9.45%</td>
<td>0.0991</td>
<td>1.75%</td>
</tr>
<tr>
<td>30</td>
<td>60.30</td>
<td>9.23</td>
<td>60.16</td>
<td>0.23%</td>
<td>0.1478</td>
<td>2.76%</td>
</tr>
<tr>
<td>50</td>
<td>44.01</td>
<td>9.82</td>
<td>46.78</td>
<td>-5.92%</td>
<td>0.2604</td>
<td>6.24%</td>
</tr>
<tr>
<td>70</td>
<td>28.01</td>
<td>9.51</td>
<td>30.55</td>
<td>-8.32%</td>
<td>0.4072</td>
<td>9.79%</td>
</tr>
</tbody>
</table>

Fig. 5. (a) Calibration $\varepsilon_r$ versus $f_{osc}$ and (b) Calibration $\tan \delta$ versus $P_{out}$ with fitting polynomial curves.

Fig. 6. Measured $\varepsilon_r$ and $\tan \delta$ of the water-ethanol mixtures using the proposed microfluidic sensor.
the measurement performance, the accuracy of measuring $\varepsilon_r$ is better than this work. Although the PLL-based sensors in [12] and [13] can improve the sensitivity and need a smaller LUT volume simultaneously, they did not have the capability of measuring $\varepsilon''$ or $\tan \delta$.

IV. CONCLUSION

A new microwave oscillator-based microfluidic sensor was proposed, designed, and experimentally verified to measure the complex permittivities of water-ethanol mixtures. To flexibly fit the layout pattern of the microfluidic channel, an MCSR sensing device is proposed in this paper to concentrate the electric field in a narrow gap and treated as a frequency-selective element for the sensing oscillator design. The maximum measured errors of $\varepsilon_r$ and $\tan \delta$ of the water-ethanol mixtures were well controlled below 10% compared to the results measured by a commercial dielectric probe kit. In the future, a frequency demodulator will be developed to transfer the sensing oscillator’s the frequency shifts and power variations to I/Q channel voltages for data manipulation.

ACKNOWLEDGMENT

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REFERENCES


Table 3. Performance Comparison of Active Liquid Permittivity Sensors from Literature and the Proposed Microfluidic Permittivity Sensor

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Sensor technology</th>
<th>LUT (Volume)</th>
<th>$\varepsilon_r$ error</th>
<th>$\tan \delta$ or $\varepsilon''$ error</th>
</tr>
</thead>
<tbody>
<tr>
<td>[10] 1-8</td>
<td>capacitive sensor with correlators</td>
<td>ethyl acetate (250 $\mu$L)</td>
<td>$&lt; 1.32%$</td>
<td>–</td>
</tr>
<tr>
<td>[11] 0.5-3</td>
<td>interdigital capacitor with IQ mixers</td>
<td>isopropanol-methanol (150 $\mu$L)</td>
<td>$&lt; 1.5%$</td>
<td>$&lt; 1.5%$ ($\varepsilon''$)</td>
</tr>
<tr>
<td>[12] 7-9</td>
<td>PLL-based sensing oscillator</td>
<td>6 different chemicals (20 $\mu$L)</td>
<td>$&lt; 3.5%$</td>
<td>–</td>
</tr>
<tr>
<td>[13] 10.4</td>
<td>PLL-based sensing oscillator</td>
<td>methanol-ethanol (20 $\mu$L)</td>
<td>$&lt; 1.5%$</td>
<td>–</td>
</tr>
<tr>
<td>[14] 5.798</td>
<td>FLL-based sensor</td>
<td>water-ethanol (100 $\mu$L)</td>
<td>$&lt; 2.66%$</td>
<td>$&lt; 9.94%$ ($\tan \delta$)</td>
</tr>
<tr>
<td>This work</td>
<td>oscillator-based sensor</td>
<td>water-ethanol (23 $\mu$L)</td>
<td>$&lt; 9.45%$</td>
<td>$&lt; 8.84%$ ($\tan \delta$)</td>
</tr>
</tbody>
</table>