High-Sensitivity Metamaterial-Inspired Sensor for Microfluidic Dielectric Characterization

Amir Ebrahimi, Student Member, IEEE, Withawat Withayachumnankul, Said Al-Sarawi, Member, IEEE, and Derek Abbott, Fellow, IEEE

Abstract—A new metamaterial-inspired microwave microfluidic sensor is proposed in this paper. The main part of the device is a microstrip coupled complementary split-ring resonator (CSRR). At resonance, a strong electric field will be established along the sides of CSRR producing a very sensitive area to a change in the nearby dielectric material. A micro-channel is positioned over this area for microfluidic sensing. The liquid sample flowing inside the channel modifies the resonance frequency and peak attenuation of the CSRR resonance. The dielectric properties of the liquid sample can be estimated by establishing an empirical relation between the resonance characteristics and the sample complex permittivity. The designed microfluidic sensor requires a very small amount of sample for testing since the cross-sectional area of the sensing channel is over five orders of magnitude smaller than the square of the wavelength. The proposed microfluidic sensing concept is compatible with lab-on-a-chip platforms owing to its compactness.

Index Terms—Complementary split-ring resonator (CSRR), dielectric characterization, metamaterial, microfluidic sensor.

I. INTRODUCTION

MICROWAVE sensors are very attractive choices for many of electronic, biomedical and industrial applications [1], [2]. They offer many advantages including high sensitivity, robustness and low fabrication and measurement costs [3]. These advantages make them preferable choices for microfluidic and biosensing applications [4], [5]. High sensitivity and accurate identification of chemical and biological liquid samples using microwave dielectric and cylindrical resonators have been studied and demonstrated [5]–[9]. In these applications, the resonance frequency changes and the transmission characteristics at resonance are used for determination of the complex permittivity. Notably, a relatively large device size makes these types of sensors unsuitable for integrated systems. In [10], a compact microwave sensor is designed for broadband microfluidic permittivity measurement with complicated mathematical post-processing. In [11], a new K-band microfluidic device was proposed based on a quarter-wavelength resonator designed on coplanar waveguide. It employs a change in the resonance frequency for dielectric characterization. Despite the compactness and high sensitivity, the quality factor of the resonance is moderate, affecting the measurement accuracy for a small change in the dielectric properties.

Recently, a new microwave sensing platform is being developed using the concept of metamaterials [12], [13]. Metamaterials are artificially engineered materials made of sub-wavelength resonators that can manipulate the electromagnetic waves in a way causing some exotic electromagnetic properties [14]. Metamaterial inspired devices are suited to sensing applications since they offer improved compactness and a high Q-factor that is very sensitive to environmental changes [15]. Various types of new or improved microwave and terahertz sensors have been introduced so far using this new concept for different sensing applications such as displacement [16]–[18], rotation [17], [19] thin-film sensing [20]–[22], and strain sensing [23], [24]. Further to that, there are a few studies on metamaterial-based microfluidic characterization. In [25] and [26] microfluidic channels were designed to deliver the fluid sample to an array of resonators causing a significant modification of the resonance frequency. Nevertheless, this configuration requires a large amount of liquid sample for identification. In addition, a left handed planar medium formed, by using a spiral-resonator coupled microstrip line was designed together with a microfluidic channel for liquid sensing [27]. This device shows a bandpass response that is not accurate for dielectric characterization. Recently, we proposed a metamaterial-based microfluidic sensor with a single split-ring resonator (SRR) coupled microstrip line [28]. The microfluidic channel was considered in the gap area of the SRR where there is a very strong and localized electric field on resonance. Applying the liquid sample to this capacitive gap modifies the resonance frequency and quality factor from which the complex permittivity of mixtures can be determined. However, the sensitivity of the device was not enough to discriminate small changes in the permittivity of the sample as the maximum resonance frequency shift was reported to be around 100 MHz for a permittivity change of 80 [28].

In this paper, a complementary split-ring resonator (CSRR) is used instead of a SRR, to provide a larger area of fringing electric field that increases the effective interaction area with the sample. The proposed sensor determines the complex
The resonance occurs when the electric energy stored in the difference between the capacitive plate and the ground plane. This electric field excites the CSRR inducing a voltage microstrip and an electric field pointing towards the ground plane at a distance $c$ from its edge. Since the CSRR is etched in ground plane and is mainly excited by the electric field of the microstrip line, the whole coupled structure can be modelled by the lumped element circuit in Fig. 1(b) [29]. In the equivalent circuit model, the parallel combination of $L_C$, $C_C$ and $R_C$ models the CSRR, where $C_C$ stands for the capacitor between the square-shaped metallic plate and the ground plane, $L_C$ stands for the inductance of the metallic inductive path of width $g$ connecting the capacitive plate to ground, and $R_C$ models the equivalent loss associated with the CSRR [30]. Here, $L$ and $C$ model the inductance and capacitance of the microstrip line, respectively.

When the microstrip is fed with a microwave signal, it develops a quasi-TEM electromagnetic wave propagation mode described by a magnetic field circulating around the microstrip and an electric field pointing towards the ground plane. This electric field excites the CSRR inducing a voltage difference between the capacitive plate and the ground plane. The resonance occurs when the electric energy stored in the $C$ and $C_C$ capacitors equals to magnetic energy of the inductive strip of $L_C$. As shown in Fig. 2, at resonance, a strong electric field will be established across the gap between the capacitive plate and ground. The electric field is stronger across the lower edge of the square-shaped CSRR making this region very sensitive to dielectric changes. Therefore, a microfluidic channel is laid across the lower edge of the CSRR. The resonance can be observed as a notch in the transmission coefficient of the structure as illustrated in Fig. 2. From the circuit model of Fig. 1(a), the resonance frequency can be defined as [30]

$$f_0 = \frac{1}{2\pi \sqrt{L_C(C + C_C)}} \tag{1}$$

and the quality factor of the resonance is

$$Q = R \sqrt{\frac{C + C_C}{L_C}} \tag{2}$$

It is worth noting that the capacitor $C_C$ is affected by the dielectric materials near the gap between the CSRR and ground. So, it can be approximated by

$$C_C = C_0 + \epsilon_{sam}C_e, \tag{3}$$

where, $C_0$ models the capacitive effects of the dielectric substrate, channel walls and surrounding space excluding the channel cavity and the term $\epsilon_{sam}C_e$ denotes the capacitive effect of the liquid sample loaded into the microfluidic channel. Here, $C_e$ is the capacitance of the empty channel. Now, if the complex permittivity of the liquid sample is considered to be $\epsilon_{sam} = \epsilon_{sam}' + j\epsilon_{sam}''$, from (1)–(3), both of the resonance frequency and the quality factor will be functions of the liquid sample permittivity or

$$f_0 = F_1(\epsilon_{sam}',\epsilon_{sam}''), Q = F_2(\epsilon_{sam}',\epsilon_{sam}''). \tag{4}$$

The above discussion indicates that the resonant characteristics of the microstrip coupled CSRR device are dominated by the complex permittivity of a liquid sample. Therefore, by analyzing this dependency, we can determine the complex permittivity of an unknown liquid sample simply by measuring the transmission resonance characteristics.
III. Fabrication Process

The designed device has been fabricated on Rogers RO6002 microwave substrate with a relative permittivity of 2.94 for allowing significant fringing field in the sensing area and hence increasing the sensitivity. The substrate thickness is 0.508 mm. The copper metalization for the ground plane and microstrip line is 18 μm.

As mentioned before, the microfluidic channel is positioned along the lower edge of the CSRR. The material used for channel is polydimethylsiloxane (PDMS) since it is inexpensive, widely available, biocompatible, durable, and easy to process [10], [11]. For channel fabrication, a mold has been prepared on a silicon substrate by using a thick photoresist mask and chemical etching. Then, a PDMS layer is deposited on the prepared mold and cured at 80 °C. Finally, the PDMS channel is peeled off and attached to the microstrip coupled CSRR. The channel is manually positioned to the lower side of CSRR where the fringing electric field is strongest and therefore, the sensitivity to the dielectric property changes is maximum. The height, width and length of the channel are 0.06 mm, 0.7 mm and 14 mm, respectively. Fig. 3 shows the bottom view and cross section of the structure when the channel is attached to the substrate.

The PDMS channel ensures a constant volume and shape of the liquid sample across the sensing area. It should be mentioned that the device response might be influenced by the position of the channel but it should not be an issue since the channel position is kept unchanged during all measurements.

In a similar manner to [28], the measurements are carried out based on a stop-flow technique. A binary solution of distilled water and ethanol is used as a liquid sample for testing since it provides a broad range of the complex permittivity at the low microwave frequency range [31]. Teflon tubes, together with a syringe, connected to the inlet and outlet of the channel are used for filling and draining the channel. The fabricated and assembled sensor is shown in Fig. 4 together with the measurement setup. During the measurements, a very low pressure is applied to the syringe to avoid channel deformation. In each step, the channel is firstly filled with the liquid sample and then the flow is stopped for measurement. The resonance frequency and peak attenuation parameters are then recorded to characterize the liquid test samples. As seen in Fig. 5, the resonance frequency and peak attenuation are maximum when the channel is not attached to the sensor. By adding the PDMS channel, the resonance frequency is shifted down with a small decrease of peak attenuation since a part of the CSRR is covered with the PDMS.

IV. Device Characteristics

A. Initial Measurements

For investigating the effect of the complex permittivity \( \epsilon'_{\text{sam}} + j \epsilon''_{\text{sam}} \) on the resonance frequency and peak attenuation, a set of experiments has been performed using binary mixtures of distilled water and ethanol. The dielectric properties of water-ethanol mixture was accurately studied in [31]. The accurate complex permittivity of the test fluid samples
The complex permittivity of unknown liquid samples can be determined using matrix inversion. Inverting (10) leads to
\[
\begin{bmatrix}
\Delta f_0 \\
\Delta\epsilon'_{\text{sam}}
\end{bmatrix}
= \begin{bmatrix}
-0.00528 & 0.000256 \\
-0.00045 & -0.292
\end{bmatrix}
\begin{bmatrix}
\Delta f_0 \\
\Delta\epsilon'_{\text{sam}}
\end{bmatrix},
\] (10)

By comparing the coefficients in (6), it will be found that the effect of \( \epsilon' \) on the resonance frequency is approximately 20 times larger than the effect of \( \epsilon'' \). On the other hand, the impact of \( \epsilon'' \) on the peak attenuation is 650 times higher than the influence of \( \epsilon' \).

### Table I

Complex Permittivity of Water-Ethanol Mixture at 1.9 GHz

<table>
<thead>
<tr>
<th>Water Fraction%</th>
<th>( \epsilon' )</th>
<th>( \epsilon'' )</th>
<th>( \Delta\epsilon' )</th>
<th>( \Delta\epsilon'' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>16.5</td>
<td>12.3</td>
<td>-30.5</td>
<td>-2.7</td>
</tr>
<tr>
<td>30</td>
<td>31.5</td>
<td>15.55</td>
<td>-15.5</td>
<td>0.55</td>
</tr>
<tr>
<td>50</td>
<td>47</td>
<td>15</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>70</td>
<td>61</td>
<td>12.8</td>
<td>14</td>
<td>-2.2</td>
</tr>
<tr>
<td>90</td>
<td>72</td>
<td>10.6</td>
<td>25</td>
<td>-4.4</td>
</tr>
</tbody>
</table>

From [28], [31] are listed in Table I. For the first set of measurements, the volume fraction of water is changed from 10% to 90% with a step size of 20% and at each step, the resonance frequency and peak attenuation of the sensor are recorded giving a data set of 5 samples. The measurement results of the resonance frequency and maximum attenuation for the 5 test samples are shown in Fig. 6. As seen, the resonance frequency is shifted from 1.875 GHz down to 1.57 GHz as the water volume fraction increases from 10% to 90%. The peak attenuation is minimum when the water volume fraction is 30%. It is worth noting that the observed nonlinearity in the peak attenuation with respect to the water content follows the nonlinear loss function of water mixture [28], [31].

#### B. Mathematical Model Derived from Measurements

Based on the measurement results of the five test samples, a simple model is derived for resonance frequency shift and peak attenuation variations as a function of the complex permittivity. This simplified model can be defined as
\[
\begin{bmatrix}
\Delta f_0 \\
\Delta S_{21}
\end{bmatrix}
= \begin{bmatrix}
m_{11} & m_{12} \\
m_{21} & m_{22}
\end{bmatrix}
\begin{bmatrix}
\Delta\epsilon'_{\text{sam}} \\
\Delta\epsilon''_{\text{sam}}
\end{bmatrix},
\] (5)

where, \( \Delta\epsilon'_{\text{sam}} = \epsilon'_{\text{sam}} - \epsilon'_{\text{ref}}, \Delta\epsilon''_{\text{sam}} = \epsilon''_{\text{sam}} - \epsilon''_{\text{ref}} \) and \( \Delta f_0 = f_0_{\text{sam}} - f_0_{\text{ref}} \) with subscript (sam) for the sample under test and (ref) for the reference mixture. Here, the mixture with a 50% water fraction is considered as the reference. The unknown parameters of the matrix can be determined from the data available from the measurement results of Fig. 6, together with the reported complex permittivity in Table 1. The benefit of this model is that all the fabrication tolerances of the device are fully taken into account. The coefficients of the model in (5) are over determined by test datasets. So, the least-squares method explained in [28] can be used to approximate the coefficients. This method yields the following matrix that relates the resonance frequency and maximum attenuation changes to the complex permittivity
\[
\begin{bmatrix}
\Delta f_0 \\
\Delta S_{21}
\end{bmatrix}
= \begin{bmatrix}
-0.00528 & 0.000256 \\
-0.00045 & -0.292
\end{bmatrix}
\begin{bmatrix}
\Delta\epsilon'_{\text{sam}} \\
\Delta\epsilon''_{\text{sam}}
\end{bmatrix}.
\] (6)

### Table II

Complex Permittivity of Water-Ethanol Mixture at 1.9 GHz

<table>
<thead>
<tr>
<th>Water Fraction%</th>
<th>( \epsilon' )</th>
<th>( \epsilon'' )</th>
<th>( \Delta\epsilon' )</th>
<th>( \Delta\epsilon'' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>9</td>
<td>10</td>
<td>-38</td>
<td>-5</td>
</tr>
<tr>
<td>20</td>
<td>24</td>
<td>13.6</td>
<td>-23</td>
<td>-1.4</td>
</tr>
<tr>
<td>40</td>
<td>39</td>
<td>15.6</td>
<td>-8</td>
<td>0.6</td>
</tr>
<tr>
<td>60</td>
<td>53</td>
<td>14.6</td>
<td>-6</td>
<td>-0.4</td>
</tr>
<tr>
<td>80</td>
<td>67</td>
<td>13.4</td>
<td>20</td>
<td>-1.6</td>
</tr>
<tr>
<td>100</td>
<td>79.5</td>
<td>9</td>
<td>32.5</td>
<td>-6</td>
</tr>
</tbody>
</table>

Considering the samples of Table I
\[
\begin{align*}
\frac{\Delta\epsilon'}{\epsilon''_{\text{max}}} & \approx 28, \\
\frac{\Delta\epsilon''}{\epsilon'_{\text{max}}} & \approx 0.176.
\end{align*}
\] (7)

So, by neglecting \( m_{12} \) and \( m_{21} \) the maximum errors of \( \Delta f_0 \) is
\[
\frac{m_{12}\Delta\epsilon''}{m_{11}\Delta\epsilon'} \approx 0.9\%,
\] (8)

and the maximum error in \( \Delta S_{21} \) can be obtained as
\[
\frac{m_{21}\Delta\epsilon'}{m_{22}\Delta\epsilon''} \approx 4.3\%.
\] (9)

From (8) and (9) it can be inferred that the contributions of \( \epsilon'' \) on the resonance frequency shift and \( \epsilon' \) on the peak attenuation changes are negligible. So, the characteristic matrix of (6) can be simplified as
\[
\begin{bmatrix}
\Delta f_0 \\
\Delta S_{21}
\end{bmatrix}
= \begin{bmatrix}
-0.00528 & 0.000256 \\
-0.00045 & -0.292
\end{bmatrix}
\begin{bmatrix}
\Delta\epsilon'_{\text{sam}} \\
\Delta\epsilon''_{\text{sam}}
\end{bmatrix}.
\] (10)

The complex permittivity of unknown liquid samples can be determined using matrix inversion. Inverting (10) leads to
\[
\begin{bmatrix}
\Delta\epsilon'_{\text{sam}} \\
\Delta\epsilon''_{\text{sam}}
\end{bmatrix}
= \begin{bmatrix}
-189.39 & 0 \\
0 & -3.424
\end{bmatrix}
\begin{bmatrix}
\Delta f_0 \\
\Delta S_{21}
\end{bmatrix},
\] (11)

which can be used for determining the complex permittivity of unknown liquid samples simply just by measuring the resonance characteristics.
V. EXPERIMENTAL RESULTS AND VALIDATION

In order to verify the presented sensor model in (11), the water ethanol mixture is used again. This time, the volume fraction of water is changed from 0% to 100% with the step size of 20% giving 6 data sets of measurement results. The measured transmission responses of the sensor for these sets of samples are shown in Fig. 7 together with the extracted resonance frequency and peak attenuation. As seen, the corresponding frequency shift for 0%–100% of the water volume fraction is around 400 MHz, showing 4 times higher sensitivity with respect to our previous design [28] with a 100 MHz frequency shift. The model presented in (11) is used to determine the $\Delta\epsilon'$ and $\Delta\epsilon''$ for each couple of measured resonance frequency and peak attenuation, where 50% water-ethanol mixture is considered as the reference. Then, the complex permittivity of each sample can be calculated as

$$\epsilon'_\text{sam} = \epsilon'_\text{ref} + \Delta\epsilon'_\text{mod}$$  \hspace{1cm} (12)  

$$\epsilon''_\text{sam} = \epsilon''_\text{ref} + \Delta\epsilon''_\text{mod}$$  \hspace{1cm} (13)

with a subscript ‘mod’ for the values obtained from (11). For comparison, the obtained complex permittivity values of the samples are plotted against the exact values in Fig. 8. This figure shows an acceptable accuracy of the simplified model of (11). The small disagreements between the measured and literature values of complex permittivity may potentially arise from the measurement uncertainties or the simplified linear approximation of the sensing model. The accuracy can be increased by using a higher order approximation. The device can also be tested with other sets of liquid samples covering wider ranges of complex permittivity values to produce a more accurate sensing model.

VI. CONCLUSION

A simple and efficient concept for a microwave microfluidic sensor is proposed and validated. By exploiting the advantage of a microstrip-coupled CSRR, a very strong electric field is produced in a small area, resulting in a high sensitivity to the dielectric property of surrounding materials. A PDMS microfluidic channel has been attached along the lower edge of CSRR to deliver the fluidic sample to the sensing area where the cross section of the sensing channel is small as $2 \times 10^{-5} \lambda_0^2$. Binary mixtures of water-ethanol have been used to characterize the sensor. Measurement results show a good accuracy when using the proposed microfluidic sensor and the parameter estimation model. The proposed concept promises a high sensitivity and accurate microfluidic sensing at low microwave frequencies. Owing to its compact structure, the device has the potential to be integrated with system-on-a-chip.

ACKNOWLEDGMENT

The authors would like to acknowledge Pevel Simcik and Ian Linke of the University of Adelaide and Simon Doe and Dipankar Chugh of Ian Wark Research Institute for their technical assistance in fabricating and assembling the sensor. Thanks are also given to South Australian ANFF node at Ian Wark Research Institute of the University of South Australia for providing us with the nanofabrication facility.

REFERENCES


[14] Amir Ebrahimi (S’09) was born in Babol, Iran, on September 11, 1986. He received the B.Sc. degree in electrical engineering from the University of Mazandaran, Babol, in 2008, and the M.Sc. degree in electronic engineering from the Babol University of Technology, Babol. From 2009 to 2012, he was a Research Assistant with the Integrated Circuits Research Laboratory, Babol University of Technology, Babol, Iran. He is currently pursuing the Ph.D. degree in electrical and electronic engineering with the University of Adelaide, Australia. His research interests include metamaterial-inspired microwave devices, microwave circuit design, microwave filters, and frequency selective surfaces. Mr. Ebrahimi is a recipient of the International Postgraduate Research Scholarship of Australia Postgraduate Award, and the Australian National Fabrication Facility Award for fabricating high performance microwave microfluidic sensors in collaboration with the Ian Wark Research Institute, University of South Australia.


Withawat Withayachumnankul received the B.Eng. (Hons.) and M.Eng. degrees in electronic engineering from the King Mongkut’s Institute of Technology Ladkrabang, Thailand, in 2000 and 2002, respectively. From 2006 to 2008, he was an Australian Endeavour International Postgraduate Research Scholarship and University of Adelaide Scholarship for Postgraduate Research. He is currently pursuing the Ph.D. degree with the School of Electrical and Electronic Engineering, University of Adelaide. He received the IEEE/LEOS Graduate Student Fellowship and the SPEE Scholarship in Optical Science and Engineering. He is currently an ARC Post-Doctoral Research Fellow with the School of Electrical and Electronic Engineering, University of Adelaide, and an Associate Professor with RMIT University, Australia. His research interests include metamaterials, plasmonics, and terahertz spectroscopy.

Said Al-Sarawi (M’92) received the B.Eng. degree (1st Class Hons.) in marine radio communication and in marine electronics and communication from the Arab Academy for Science and Technology, Egypt, in 1987 and 1990, respectively, and the Ph.D. degree in mixed analog and digital circuit design techniques for smart wireless systems with special commendation in electrical and electronic engineering from The University of Adelaide, Australia, in 2003. He was awarded The University of Adelaide Alumni Postgraduate Medal (formerly Culross Prize) for outstanding academic merit at the postgraduate level. He received the Commonwealth Postgraduate Research Award (Industry). He received the Graduate Certificate in Education (Higher Education) with the same university in 2006. Currently, he is the Director of the Centre for Biomedical Engineering and a Founding Member of the Education Research Laboratory, Babol University of Technology, Babol. From 2009 to 2012, he was a Research Assistant with the Integrated Circuits Research Laboratory, Babol University of Technology, Babol, Iran. He is currently pursuing the Ph.D. degree in electrical and electronic engineering with the University of Adelaide, Australia. His research interests include microwave-based biosensors, optical properties of metamaterials, and nanophotonics.
Derek Abbott (M’85–SM’99–F’05) was born in London, U.K., in 1960. He received the B.Sc. (Hons.) degree in physics from Loughborough University, U.K., in 1982, and the Ph.D. degree in electrical and electronic engineering from the University of Adelaide, Australia, in 1995, under K. Eshraghian and B. R. Davis. From 1978 to 1986, he was a Research Engineer with the GEC Hirst Research Centre, London. From 1986 to 1987, he was a VLSI Design Engineer with Austek Microsystems, Australia. Since 1987, he has been with the University of Adelaide, where he is currently a Full Professor with the School of Electrical and Electronic Engineering. He holds over 800 publications/patents and has been an invited speaker at over 100 institutions. He is a fellow of the Institute of Physics (IOP). He has received a number of awards, including the South Australian Tall Poppy Award for Science in 2004, the Premier’s SA Great Award in Science and Technology for outstanding contributions to South Australia in 2004, and the Australian Research Council Future Fellowship in 2012. He has served as an Editor and/or Guest Editor for a number of journals, including the IEEE Journal of Solid-State Circuits, the Journal of Optics B (IOP), Microelectronics Journal (Elsevier), Chaos (AIP), Smart Structures and Materials (IOP), Journal of Optics B (IOP), Fluctuation Noise Letters (World Scientific), and is currently on the editorial boards of the PROCEEDINGS OF THE IEEE, the IEEE PHOTONICS JOURNAL, and PLoS ONE. He has co-edited Quantum Aspects of Life, Imperial College Press, co-authored Stochastic Resonance (Cambridge University Press) and Terahertz Imaging for Biomedical Applications (Springer-Verlag).

His interests are in the area of multidisciplinary physics and electronic engineering applied to complex systems. His research programs span a number of areas of stochastics, game theory, photonics, biomedical engineering, and computational neuroscience.