The Dielectric Constant Analysis for Aqueous Characterization Using Split Ring Resonator Sensor

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***Abstract*—This paper presents a microfluidic split ring resonator sensor with planar structure to identify and analyze the real part of complex permittivity (dielectric constant). The sensor is designed based on the resonant perturbation method for high precision and optimum sensitivity. The structure device is implemented by using a split ring topology at 2.0 GHz with micro-volume (μL) sample. The split-ring excitation demonstrates significant changes in resonant frequency and shows an identical performance due to the ideal dielectric constant of the common solvent. Finally, a comparison between numbers of the ring structure is performed in order to identify the best sensing approach for the development of aqueous characterization industries.**

***Index Terms*—Dielectric Constant; Microfluidic; Material Characterization; Microwave Sensor; Split-Ring Resonator.**

I. INTRODUCTION

The development of microwave resonator sensors has become vast issue which has been used in many industries for material characterization purpose. The characteristic of materials have been studied intensively for the last decade in order to execute the initial evaluation research before come up with certain products, especially in beverage industry. Every single material has a dielectric properties which can be measured by a variety of measuring methods such as reflection method, resonator method, transmission/reflection method, and resonant perturbation method. Nowadays, a number of planar circuits, such as microstrip lines, coplanar waveguides, and stripline have been reported to effectively detect the dielectric constant of materials with high accuracy and precise measurement [1]-[4]. As a result, this finding has led to many sensing application for detection and identification, especially the discrimination of non-halal materials containing product. The identification of non-halal materials is important due to the misleading information, adulteration, mislabeling and general lack of individual awareness regarding this matter.

Liquid sensors, for example, are used to detect the alcoholic containing drinks and any materials that can cause an allergic reaction to the consumer which involved beverages quality control, utilization, and for monitoring resolve [5]-[6]. The need for sensors to determine the complex permittivity or dielectric constant of materials has gained a lot of interest. Normally, microwave sensing techniques focused on planar microwave components with the incorporation of dielectric sensitive materials. For example, liquid sensing has been presented using microwave waveguide model [7] where the dielectric response of a resonator is determined by the slit of gap on the structure and varied with a thickness of a substrate to provide high-Q. The thick structure not only has the advantage of small electrical size but also an adjustable response to two frequencies working separately. However, the design is suffers from high manufacturing cost since the structure fabrication is quite complex.

Other microwave resonator sensors have been used for liquid sensing. The dielectric response of near-field sensor has been used as an indication of the presence of liquids using a planar sensing tip structure [8]. Since the structure of the resonator is planar, a sample under test can be easily coupled to the sensor which, in turn, is potentially very low cost. However, the sensing reservoir region is a complicated structure which made by a plastic for constraining samples in order to extract the properties of liquid solvents.

Moreover, microwave passive components have been used as sensor detectors for other parameters such as surface impedance and air quality detection [9]. This sensor is an original passive microwave substrate integrated cavity resonator (SIWs) which sensing humidity environment and can apply for solvent applications. The sensing principle is referred to the dielectric constant variation due to the shifting of frequencies of the samples tested. The performance and accuracy of the sensor are very high. Yet, the structure is too complicated and costly for manufacturing process.

Based on several reviewed research, a planar split ring structures are getting more attention and popular in many areas such as microwave filters, antennas, and resonator sensors due to their low cost, simple structures, easy to manufacture, and high power capability instead of waveguide, dielectric or coaxial probe sensor which often bulky and complicated design. However, the planar resonator has low sensitivity due to low-quality factor. Therefore, the new structure of split ring resonator sensors has been studied and introduced with high Q-factor and provide high accuracy for characterization of liquid solvents. In addition, the proposed structure can be integrated with other planar circuits to form a compact microwave system with outstanding performance. The comparison of rectangular and circular SRR has been explored in [10] to investigate the sensitivity of microwave sensor. Both SRRs having equal unit cell area, are taken for the sensitivity analysis. For the best reader knowledge, it may be interesting to note that the change in resonant frequency for the circular SRR with the presence of MUT is also greater than that of the rectangular SRR. Which that means, for a given unit cell area, the circular SRR appears to be the best choice to gain high sensitivity for a given dielectric sample as compared to the rectangular SRR.

The proposed split-ring structure also shows high sensitivity, in the presence of low conductive materials, comparable to other reported microwave sensors. The model results were presented with a few types of structure and the sensing performance of the proposed structure is compared to the performance of existing planar microwave sensors and the results are discussed.

II. RING RESONATOR THEORY

In the last decade, the first introduction of ring resonator is in 1969, where most applications were focused on the measurements of characteristics of microstrip lines. Intensive field analyzes were developed to give an accurate and estimation of a ring resonators. In the 1980s, several applications by using ring circuits have been implemented. In the previous works, the ring circuit is blended, merged, and combined into filters, oscillators, mixers, and couplers. The integration with particulars electronic components was also realized to achieve optimum performance of the devices [11]-[12].

The ring resonator is a simple structure and it would only support wave signal that has multiple of the guided wavelength which equals to the mean circumference. The structure is simple and easy to manufacture. From that simple circuit, there is more complicated circuit is designed and created for various applications by adding a notch, slit cutting, multiple rings, integrating with other components and so on [13]. It is believed that the variations and research are still on going and not yet been exhausted. A ring resonator has higher quality factor than a straight ribbon resonator. Therefore, ring structure method has better capability to measure the properties of materials with high sensitivity and accuracy. Most of the ring resonators are design at $\mathrm{TM}_{\mathrm{mn0}}$, and the main mode is TM_{110}. The resonant condition for $\mathrm{TM}_{\mathrm{m10}}$:

Since,
$$\lambda_g = \lambda_0 \big/ (\varepsilon_{\mathrm{eff}})^{1/2} \tag{1}$$

Thus,
$$\pi(r_1 + r_2) = m\lambda_g \tag{2}$$

Where r_1 and r_2 are the ring radius for inner and outer dimensions respectively. ε_{eff} is the effective dielectric constant of a microstrip line structure which the relationship is substituted into λ_g and get the following equation [13]:

Sub,
$$\lambda_0 = \frac{\pi(r_1+r_2)}{m}\sqrt{\varepsilon_{\mathrm{eff}}} \tag{3}$$

The simulation result for the first attempt usually has a problem with the number of modes. The operating frequency of the resonator works only in the first mode. To avoid higher order modes, the geometrical of the ring resonator should satisfy the subsequent requirements:

Requirement,
$$\frac{r_1 - r_2}{r_1 + r_2} < 0.05 \tag{4}$$

Other than that, the dimension of the feedline, width, and length of the substrate, the size of the gap coupling and any related dimension of the microstrip ring resonator can be found in [14].

III. DESIGN OF THE SPLIT RING RESONATOR

A dual port microstrip planar ring resonator with operating frequency of 2.0 GHz is designed using HFSS simulation software. The dimension of the structure is calculated based on following relation [14]. The width of the ring resonator, the effective dielectric constant, and the length of the feedline can be calculated using expression (5)-(8).

$$\frac{w}{d} = \frac{8e^{A}}{e^{2A} - 2} \tag{5}$$

$$A = \frac{Z_o}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}.\left(0.23 + \frac{0.11}{\varepsilon_r}\right) \tag{6}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}.\frac{1}{\sqrt{1 + 12(\frac{d}{w})}} \tag{7}$$

$$Q = \frac{2f_c}{BW} \tag{8}$$

A coupling gap of the resonator with 0.3 mm gap dimension has shown in Figure 1 which considered in order to study the impact of resonant frequency, Q-factor and insertion loss with the present of several liquid solvents. Simulation performed with a presence of common solvents over 1-6 GHz range frequency while corresponding resonant frequency for each liquid sample has been recorded. Rogers RT5880 with thickness 3.175 mm is constructed on a dielectric of a relative permittivity 2.2 and loss tangent 0.0009. The thickness of the copper is 0.035 mm to ensure the highest possible Q-factor. The glass capillary tube is employed with dielectric constant 5.5. The inner and outer radius of the glass capillary is Qi = 0.745 mm and Qo = 0.85 mm respectively. There are few designs under study that we focus as shown in Figure 2.

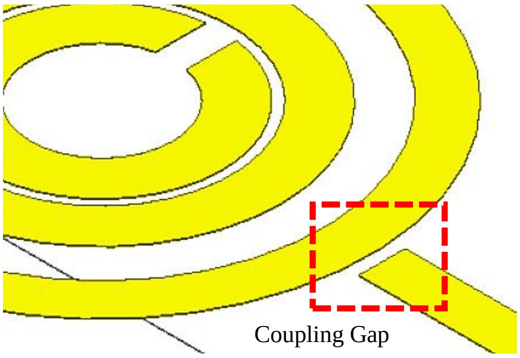
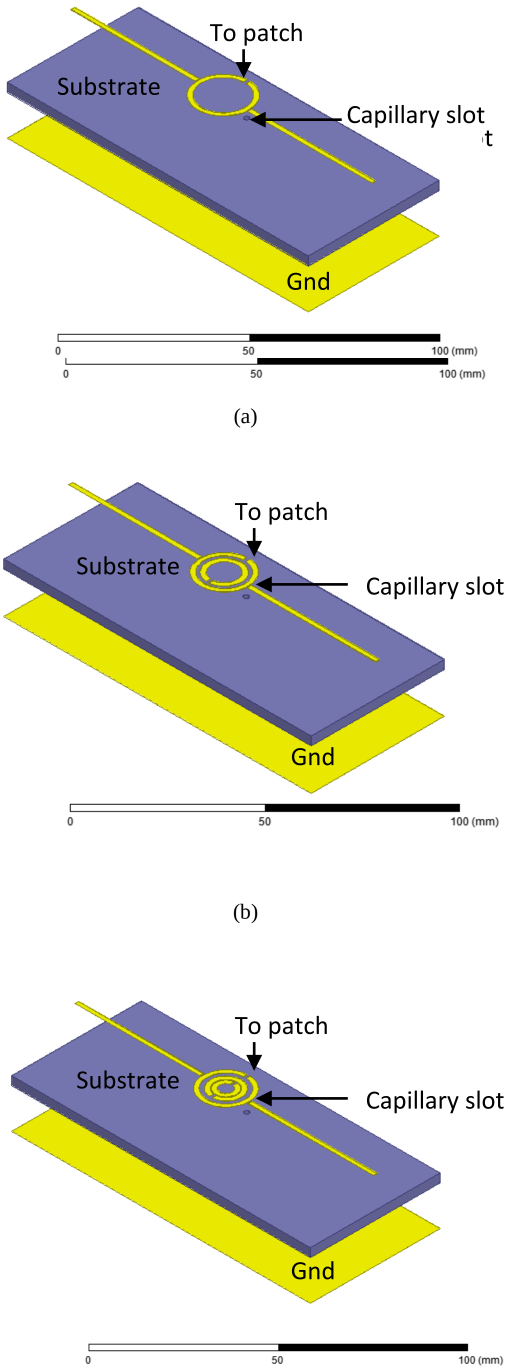


Figure 1: Coupling gap of the multi-split ring resonator



(a)

(b)

(c)

Figure 2: Split-ring resonator sensor structure with loose coupling peripheral. (a) Single ring. (b) Double ring. (c) Multi-ring.

The loose coupling of split-ring resonator sensor is presented with the integration of glass capillary of 5.5 dielectric constants in order to maximize the potential of the sensor in characterizing materials. The design structure has many benefits over the conventional split-ring resonator (SRR) for characterization of solvents properties and the plan structure also potentially develop the intensity of electric fields distribution at sensing region. The resonator structure was reformed at a sensing region where capillary tube was placed in the gap of outer ring structure (if more than single ring structure) to optimize the amount of electric flux in the presence of common solvents and at the same time increased the volume of E-fields due to the polar nature of solvents characteristic.

At this point, the sensor was manufacture at very high Q-factor in order to perform with the extremely small volume of samples 2.5 μL. So that the selection dimension of the capillary was chosen at small standard size μL volume.

IV. RESULTS AND DISCUSSION

Simulation result of split ring resonator sensor with a loose coupling which has a different number of ring are illustrated in Figure 3. Coupling gaps of 0.3 mm, are used to improve the performance of the planar ring resonator. From the simulation results, it can be observed that the Q-factor and insertion loss have significant change due to the increases number of ring on the structure and the polarization of electric flux on the capillary hole is maximum towards the split structure. This is due to the capacitance strength value. The simulation involves calculating quality factor and E-fields of each design structures when encapsulated several aqueous solvents such as water, ethanol, and methanol. The performance of the resonator is verified by simulation for comparative study. As we compare results among current designs, the performance in terms of the quality factor, frequency shifting and insertion loss of the sensors have difference performance due to the measurement uncertainties of the gaps, substrate, capillary and thickness of the bare copper.

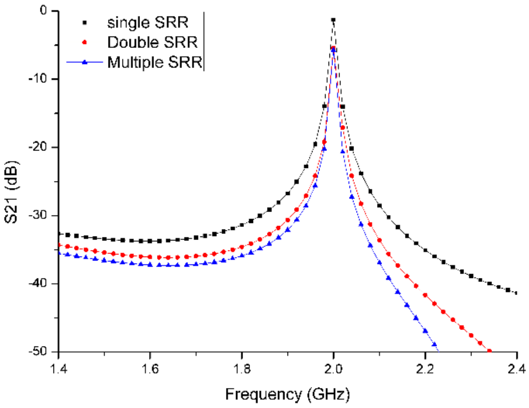


Figure 3: Resonant frequency of the planar ring resonator sensor

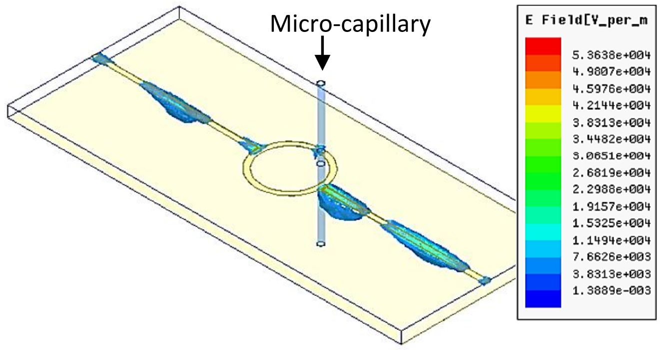
The insertion loss of single split ring resonator is observed better than double and multi rings structure which is -1.27 dB instead of -5.42 dB, and -5.72 dB respectively. This is due to the less radiation loss at split gaps area of the sensor. The maximum electric fields are constrained to the capacitance strength region of the close ring. However, when the split gap is implemented on the ring structure, the frequency boundary is disturbed and produce radiation leakage all over the cavity. Therefore, the insertion loss of the resonator increased dramatically proportional to the width of the gaps. The performance of the resonator structure is shown in Table 1.

Table 1
The performance of planar ring resonator sensor

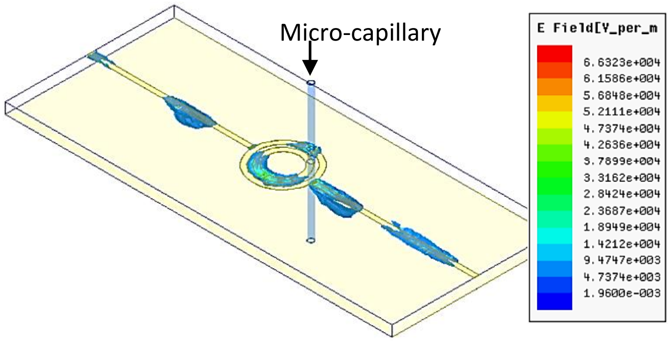
No. of Rings	Frequency (GHz)	Q-factor	S_{21} (dB)
Single	2.0	404	-1.27
Double	2.0	421	-5.42
Multi	2.0	430	-5.72

Referring to Table 1, the multiple split-ring resonator has high Q-factor compared to another two structures. This is related to the even mode discussed by Ali. A. Abduljabar [15]. On even mode state, the negative maximum electric fields distribution occurred at the gaps structure between the outer capillary regions. This will help to reduce the bandwidth of the frequency range. Thus, the sensitivity of the structure design is enhanced for accurate measurements.

The overall structure designs has been simulated and the electric fields distribution is presented as shown in Figure 4 to validate the sensitivity performance at sensing region (capillary slot channel). Until then, the most sensitive sensor is simulated with the presence of several common solvents to detect the dielectric constant and compared with theoretical expectation for verification purposed.



(a)



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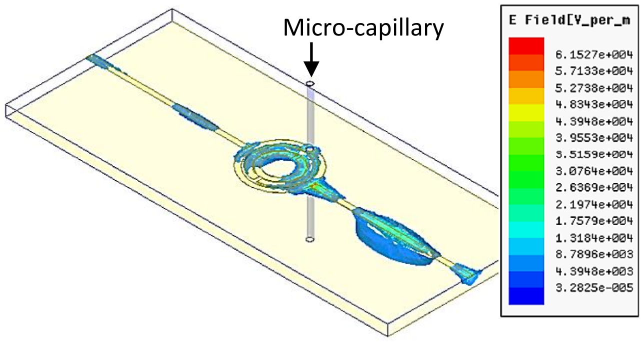

(c)

Figure 4: The electric flux density of split ring resonator sensors. (a) Single SRR, (b) Double SRR, (c) Multiple SRR.

Multiple SRR is said to be most sensitive sensor among the design due to the high electric flux density on medium channel and high Q-factor. High Q-factor is referring to lossless device and accurate measurement. Therefore, MSRR is simulated using several solvents to identify the dielectric constant of MUT as shown in Figure 5.

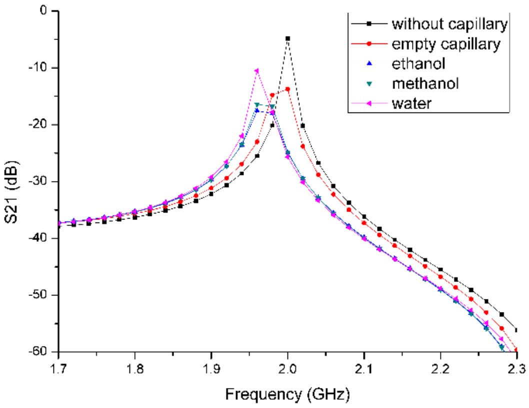

Figure 5: The simulation result of MSRR with the presence of common solvents.

The radiation pattern of the resonator sensor shows positive feedback through the capillary hole. The principle of electromagnetic wave propagation is based on resonant perturbation method. The resonant frequency of the structure is disturbed by the dielectric properties of samples due to the polar nature of the sample. The presence of solvents interferes the electromagnetic energy constrains inside the cavity, even though the volume of sample is extremely low. At this point, the properties of materials (liquid) can be determined by shifting of the resonant frequency of each known permittivity solvents. Moreover, the equation to identify unknown materials properties can be extracted from this particular results.

The sensor structure is design at 2.0 GHz without integrating the capillary. When capillary was inserted into the cavity, the frequency shifted to low frequency. This is due to the dielectric properties of glass materials. Water, methanol, and ethanol have a relative permittivity of 81.0, 32.7, and 24.5 respectively. The presence of these liquids disturbed the propagating of the electromagnetic wave inside the cavity and at the same time, the frequency was shifted the lower frequency range.

Multiple rings structure has slightly different response compared to single and double structure in term of sensing capability. However, the electric fields distribution pattern is maximum in the gap area of the outer ring. The capillary affects resonant frequency once it placed into the cavity. The glass capillary can only be placed on outer split ring for the best accuracy. The performance of multiple split ring resonator sensor has been compared critically with existing SRR design in microfluidic characterization applications as presented in Table 2.

Comparing the performance of proposed sensor with existing research works, this sensor has high potential values in terms of simple structure, ease fabrication, and low cost manufacturing process. In Ali A. Abduljabar [15], Muhammed Said Boybay [16], and Nora Meyne [17], the authors presented the split ring resonator methods which are most popular technique since the last decade. This technique promising high Q-factor, high accuracy and efficient performance with identical results. The enhancement of the design structure is analyzed in order to improve the measurement sensitivity for a minimum volume of samples. For example, Muhammed Said Boybay [16] introduced complementary split-ring resonator (CSRRs) which is gain high accuracy and eliminates the extensive sample preparation procedure needed in resonance based methods. However, the radiation loss of the structure is high and working only for the high volume of samples. Besides, Nora Meyne [17] has presented the enhancement of split-ring resonator by using dielectric resonator coupling. As the result, high Q-factor can be extracted with more than 300 at low concentration of liquid samples. At the same time, the analysis of water content can be determine based on resonant frequency shifting of different liquid concentration. Yet, the size of the structure is large and provide high cost of manufacturing.

Apart from that, Ali A. Abduljabar and his research members have demonstrated improvement of the conventional split-ring resonator by introducing double split ring resonator (DSRR) to increase the amount of electric flux on sensing region. The design has a compact size and making it suitable for a lab-on-a-chip approach. The high Q-factor has been shown around 200-300 with small frequency shifting. However, the design is too complicated. It is using the coaxial port with different modes of the structure. Every single conventional resonator has their own advantages and disadvantages. Therefore, based on the weakness of the previous design structure, we introduced a planar microstrip resonator sensor based on the split ring geometrical structure and simple coupling implementation but with high capacitance effect, maximum electric flux, high sensitivity (Q > 400), easy to fabricate and low cost of manufacturing.

Table 2
The comparison of conventional planar sensor with proposed structure

Type of Sensors	**Frequency (GHz)**	**Q-factor**	**Insertion loss (dB)**
Double split ring resonator (DSRR) [15]	3.0	250	-11.52
Complementary split ring resonator (CSRRs) [16]	0.8-1.3	370	-20.0
Couple SRR-DR Sensor [17]	11.0	335	-18.5
Microfluidic Planar Resonator (MPR) [18]	20.0	96	-17.77
Multiple split-ring resonator [This work]	2.0	430	-5.72

V. CONCLUSION

A microstrip planar resonator sensor based on split ring structure for accurate dielectric measurement of microfluidic solutions has been designed and simulated. The effectiveness of the designs with the characterization of liquid solvents is determined by using HFSS simulation software. The loose coupling increases the capacitance strength of the ring structure and provides high sensitivity with Q-factor more than 400 for accurate measurement. The presence of common solvents inside the cavity is response identically as theoretical expectation. The proposed structure shows better performance in terms of the quality factor, resonant shifting, electric fields distribution, and insertion loss compared to conventional planar resonator sensor for characterization of materials.

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