High Quality Factor using Nested Complementary Split Ring Resonator for Dielectric Properties of Solids Sample

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Abstract **─** A Nested complementary split ring resonator (CSRR) was proposed based on planar structure. The main objective of this work is to get a higher quality factor (Q-factor) with minimal error detection of complex permittivity. The sensor operated at the 3.37GHz resonant frequency and simulated by ANSYS HFSS software. Subsequently, the designed sensor has been fabricated and tested with the presence of several material under test (MUTs) placed over the sensor. The result achieved high unloaded Q-factor, 464. There has been proof of good agreement concerning the results between theoretical, simulation, and measured parameters of error detection, which is below 13.2% real part permittivity and 2.3% the loss tangent. The proposed sensor is practically useful for the food industry, bio-sensing, and pharmacy industry applications.

Index Terms **─** Complex permittivity, loss tangent, Q-factor, Nested complementary split ring resonator (CSRR).

I. INTRODUCTION

High Q-factor in microwave resonators have attracted much attention in nonplanar sensor [1]. However, the difficulties in working with the nonplanar sensor is the complexity of the structure, expensive, bulky in circuit size as they limit their utilization in many necessary applications. Therefore, the planar microwave resonator sensor has become essential in the last few years, because the design of the structure is easily implemented and cost-effective [2],[3]. As the structure becomes simple and less expensive, the sensitivity and accuracy tend to get exhausted. Poor Q-factor and low density of E-fields are restricting their utilization and the range of materials [4], [5]. To the author best knowledge, the microstrip split ring resonator (SRR) is a well-known structure in designing a resonator, where it depends on the frequency resonant transition due to the penetration and the interaction of the resonator of electric fields [6]. The traditional single SRR has bigger sizes and higher resonance frequencies, so the other way to improve sensitivity by introduced the single complementary split ring resonator (CSRR) structure [7],[8]. It also has the benefit of reducing the size of the sensor and narrowband performance [9].

In this research, a new structure was constructed to improve the sensing performance of the device with high unloaded Q factor and high electric field density by using a multi-ring with an extended length of single CSRR. In addition, a good understanding of the good performance of the proposed sensor is crucial to obtain minimum error detection of complex permittivity. The preferred new structure resonator sensor is considered to be applied to various industries like the food industry, bio-sensing, and pharmacy.

II. CHARACTERIZATION OF SENSOR

The microstrip SRR is a well-known structure in designing a resonator, where it depends on the frequency resonant transition due to the penetration and the interaction of the resonator of electric fields [6]. Square SRR is the basic design of the square open-loop resonator that can be obtained by folding a straight open resonator (L) with a gap (C) at the end of both resonators

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represent the inductance and capacitance, respectively. The fundamental of proposed design extended capacitive feature of SRR to control the gap size without changing the area covered by the SRR as illustrated in Fig. 1.

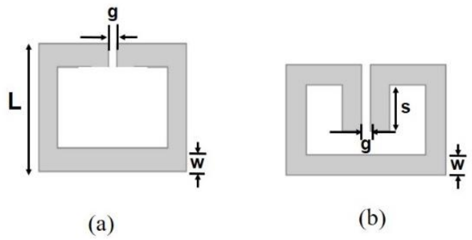

Fig. 1. (a) Split ring resonator and (b) extended length (s) of SRR gap (capacitive).

The CSRR is the different feature of the SRR. Consequently, a non-conducting element, enclosed by a conductive plane. The single CSRR structure is created by defected single SRR structure in the metal patch W_r x L_r (7.5 x 7.7 mm) as illustrated in Fig. 2 (a). The capacitance (C) of single CSRR is a non-conductive region, whereas an inductance value can define by the inductor (L) covering by a metallic gap. The CSRRs are quasi-static resonators that can be modeled using an estimated lumped element using the following equation (1) [10]:

$$f_0 = \frac{C1}{2\pi\sqrt{L_r(C_r+C)}}. \tag{1}$$

The loops and gaps can be described respectively by an inductance L_r and capacitance C_r. C_c is the coupling capacitance between 50Ω transmission line and CSRR sensor. To create a higher Q-factor and also increase the capacitance distributed leads to a lower resonance frequency, we created a new design of Nested CSRR structure as shown in Fig. 2. Besides, it can improve the high field region on the split and raise the operating frequency caused by the decrement in the value of capacitance compared to the conventional CSRR structure.

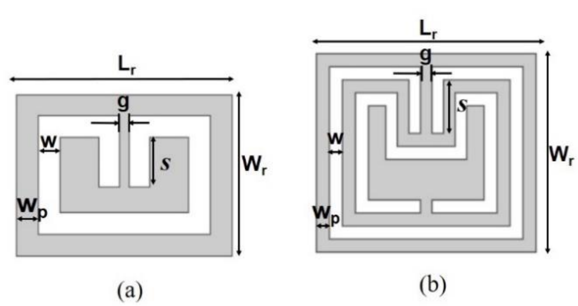

Fig. 2. Structure of proposed CSRR design: (a) conventional CSRR and (b) Nested CSRR.

The dielectric constant is dependent on the frequency. Consequently, the resonant frequency selected needs to meet the features of the sensor related to their application and also based on structured approaches such as topology, material, and size. The optimization of the proposed design parameters with patch size W_r x L_r (10 x 8.5 mm) are tabulated in Table.1

Table 1: Parameters of CSRRs

Sensor	**Frequency (GHz)**	**Parameter (mm)**			
		g	w	w_p	l_a
Conventional CSRR	4	0.4	1	1	2.3
Nested CSRR	3.37	0.4	0.5	0.5	2.1

Figure 3 shows the simulated insertion loss of the both sensor by HFSS 15.0 software. The conventional CSRR resonator resonates at 4 GHz with producing 214 unloaded Q-factor. While the proposed Nested CSRR sensor resonates at 3.37 GHz noticed that the good result of unloaded Q-factor has been increased twice with the value 464 compared with conventional CSRR. Besides, the Nested CSRR structure is designed in such a way as to improve the high field region on the split and raise the operating frequency caused by the decrement in the value of capacitance compared to the conventional CSRR structure. It creates a strong, localized electric fields within the gap is highly sensitive to dielectric samples.

The unloaded Q-factor can be calculated from equation (2), where the resonant frequency, f_r and the frequency bandwidth, Δf of the resonant peak at -3dB power points are calculated from S-parameter [11].

$$Q = {}^{2f_r}/_{\Delta f}. \tag{2}$$

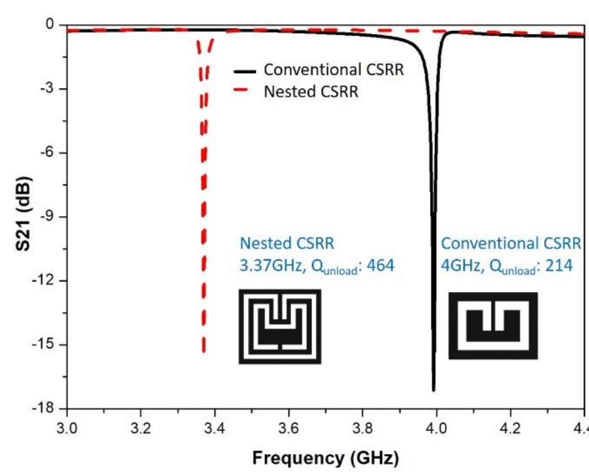

Fig. 3. Comparison of the resonant frequency and unloaded Q-factor conventional and Nested CSRR.

The main advantages of the proposed Nested CSRR are supporting a high Q-factor when compared with other stopband frequencies of the sensors as presented in Table 2. The narrow band with insertion loss over -15dB has noted that the Q-factor that obtains more than 400 is greatly sensitive to any type of substance attached to the sensing area.

Table 2: Comparison between different sensors (stopband frequency) with the proposed sensor

Ref.	Sensing Element	Sensing Elements	
		Feq. (GHZ)	Q-Factor
[11]	Aligned Gap MSRR	5	240
	Centre Gap MSRR	5	150
[10]	CSRR	2.65	80
[12]	Asymmetric (aSRR)	4.67	102
	Symmetric (sSRR)	4.82	82
[13]	CSRR – Loaded Patch	4.72	43
[14]	SRR	5	68
This Work	**Conventional CSRR**	**4**	**214**
	Nested CSRR	**3.37**	**464**

III. SENSING PERFORMANCE

A. Dielectric detection area and sensitivity analysis

The shifting of the frequency of resonance relies on the reaction among the dielectric materials and the electric field distribution of the sensor. This interaction creates perturbation toward the electrons of the material under test (MUT) in the electric flux density causing a change in the frequency of the resonance together with the Q-factor. The phenomenon occurs due to the properties of the material in terms of the complex permittivity and the loss tangent. The MUT can be placed over the sensor on the area that has the supreme concentration of the E-flux density surrounding the sensor structure as shown in Fig. 4.

Optimized dimensions of the Nested CSRR structure are as follows: the gap between the feed line and sensor, g_f = 0.2 mm, substrate sized Ls x Ws = 60mm x 24mm and feed line width = 2.9mm are illustrated in Fig. 5. While MUT is placed over the sensor in a rectangular shape with sample size (8.5 x 11) mm based upon the strength of the E-flux density. It is avoids depositing the sample in some places, leading to the high levels of inaccuracy [11]. In addition, the preparation of the sample size is simple.

The dielectric properties or complex permittivity of materials have different values. Since the material dielectric properties are determined by its molecular structure with the polarization of electrons, two or more substances can be discriminated [15]. In the electric field, if the molecular structure changes, so will the dielectric properties. The situation related to the dimensionless relative complex permittivity ε_r that can be expressed as the following equation 3 [16], where; dielectric constant, ε' and dielectric loss factor, ε''.

$$\varepsilon = \varepsilon' + j\varepsilon''. \tag{3}$$

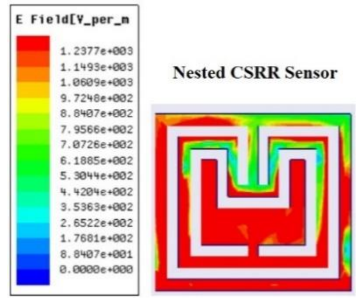

Fig. 4. E-flux density around the sensor structure.

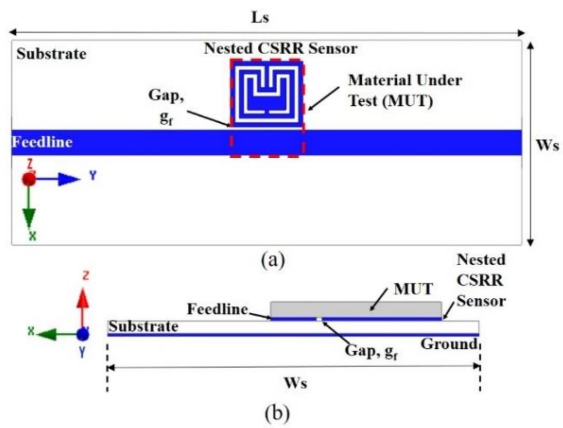

Fig. 5. The geometrical diagram of Nested CSRR sensor. (a) Top view of the sensor with MUT position (z-axis), and (b) side view structure (y-axis).

B. Sensor experimental validation

The proposed sensor is manufactured on Roger RT/Duriod 5880 substrate (ε_r = 2.2) for a height of 0.787mm and 0.07mm conductor thickness. It has 0.0009 of tangent loss and operates along 60mm feedline with a two-port Nested sensor based on characteristic impedance of 50Ω as shown in Fig. 6. The frequency of resonance along with the resonance frequency shift is observed at various dielectric MUTs such as Roger 5880, Roger 4350 and FR4 to verify the suggested sensor and evaluate their potential in dielectric sensing.

Fig. 6. The fabricated of Nested CSRR sensor.

Table 3: Measured complex permittivity of Nested CSRR sensor

MUT	Fre. (GHz)	Ideal *ε_r	Ideal Tan δ	Measured Data at 3.37GHz			
				ε_r’	Error (%)	Tan δ	Error (%)
Air	3.367	1	0	1.131	13.06	0	0
Roger 5880	3.214	2.2	0.0009	2.327	5.75	0.00092	2.2
Roger 4350	3.061	3.66	0.004	3.785	3.41	0.00402	0.7
FR4	2.89	4.4	0.02	4.518	2.68	0.0201	0.3

*ε_r is references permittivity (standards).

In Fig. 7, the measurement of the frequency response measured using the Vector Network Analyzer (VNA) shows a good agreement compared with simulated results. Despite that, there is a clear trend of decreasing peak amplitude of measurement results which contribute to the reduction of sensor sensitivity. In the perturbation technique, permittivity depends on the frequency. The sample was analyzed while placed on the sensor and it shows an interaction between the electric field and MUT will cause a shift in the resonant frequency [11]. The shifting of response is a reflection of the dimension error uncertainties which may slightly be different during the fabrication process. The quality factor and insertion loss clearly show the reduction of amplitude for measured results.

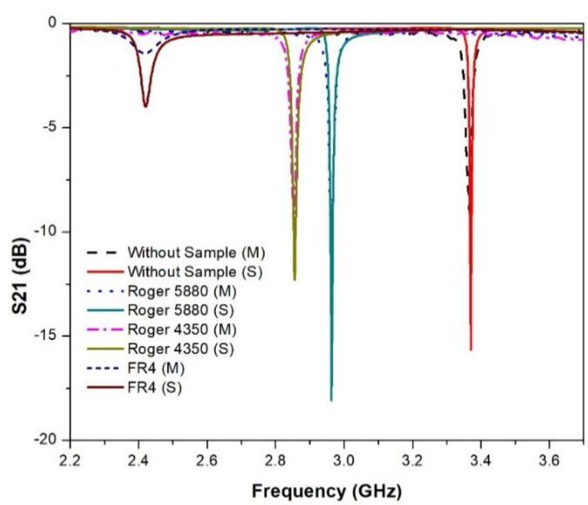

Fig. 7. Comparison of simulated and measured Nested CSRR sensor with the presence of solid samples.

The result reveal that, the resonance frequency shift is regarded as data that is related to the dielectric properties or permittivity of the MUT (ε_r). Thus, by using data shifts of resonance frequencies are present in Fig. 8, the curve fitting (CF) technique based on 3rd order polynomial function is modelled. The technique approach is carried out for evaluating the real permittivity value.

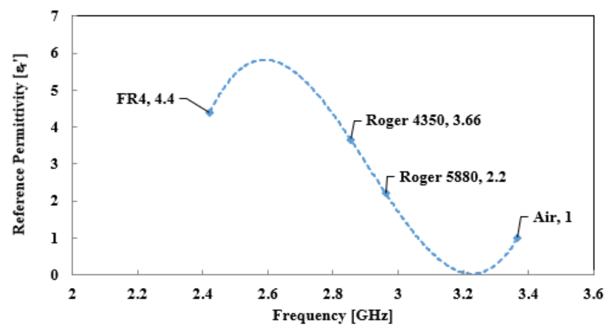

Fig. 8. Polynomial fit of real permittivity, ε_r.

From the curve fitting technique, an expression of the relationship between the frequency, f and permittivity, ε_r of the MUT can be derived with an expression as follows:

$$\varepsilon_r' = 45.386f^3 - 432.06f^2 + 1361f - 1415.9. \quad (4)$$

The polynomial fitting technique is used to identify the real permittivity and loss tangent of the MUT in measurement based on ideal value. This technique can also determine the dielectric constant of the unknown sample. According to the improvement in the consistency factor associated with the perturbation theory, the loss tangent matched the frequency response bandwidth of 3dB. The relationship of loss tangent (tan δ) and resonant frequency shifting (Δf) is present in Fig. 9.

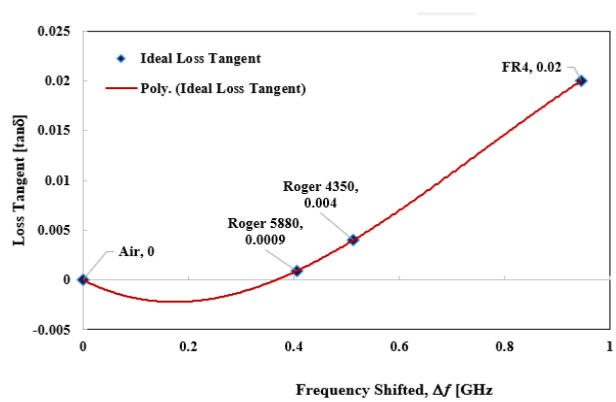

Fig. 9. Polynomial fit of loss tangent.

Table 4: The comparison of various band-stop sensors for measured complex permittivity

Methods	**Roger 5880 [% Error]** [11]			**FR4 [% Error]** [17]		**Roger 4350 [% Error]** [18]	
	ε_r'(*M1)	ε_r'(*M2)	Tan δ	ε_r'	Tan δ	ε_r'	Tan δ
Other	12.7	15.9	-	0.43	4.5	0.43	-
This Work	5.75		2.2	2.68	0.3	3.41	0.7

*M1- Method 1, *M2 - Method 2

The diagram is illustrated from that specific data collection for regards to the ideal tangent loss to develop expression from the CF technique. It can be noticed that the distribution of $tan\,\delta$ with the Δf is not constant and the outcome is represented by the equation 5. Nevertheless, the correlation between both parameters can be represented as a polynomial expression of 3rd order to produce an effective numerical equation:

$$\text{Tan}\,\delta = -0.0278|\Delta f^3| + 0.0777|\Delta f^2| - 0.0248|\Delta f| - 7^{-15}. \quad (5)$$

The real permittivity (ε_r'), loss tangent (tan δ) and percentage error for complex permittivity of Nested CSSR are listed in Table 3. In view of the results obtained, the percentage of error of the real part permittivity and loss tangent is below 13.2% and 2.3% respectively. The comparison of the percentage of the error complex permittivity is tabulated in Table 4, where the extracted data of each sample is compared within SRR sensors in the electrical characteristics (stopband frequency). It is noted that all measurement results are obtained through the proposed method within reasonable floating ranges. The accuracy and suitability of the measurement apparatus were validated when the maximum error in the reorganized values of all these samples with their reference data is usually discovered to be <6%. The slight geometry mismatching between the simulated and the fabricated devices and also the possibility of the air gap between the sample and the sensor serves to be an example of factors that contribute to the error.

VI. CONCLUSION

In this work, Nested CSRR sensor was designed using the planar structure for the characterization of complex permittivity of solid samples. High unloaded Q-factor 464 at 3.37GHz was found compared to the conventional proposed sensor. The results of complex permittivity indicate less than 13.2% error detection of real part permittivity and 2.3% the loss tangent extract from the polynomial equation based on the substitution frequency values. The sensor is potential for the multichannel sensing and can be applied for the food industry, bio-medical and pharmacy industry applications.

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