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Dielectric Constant Measurement Sensor Based on SRR Configuration

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***Abstract*—This paper presents design of a microwave sensor (MW sensor) based on circular split ring resonator (SRR) and coplanar waveguide (CPW) transmission line with two ports. The proposed sensor is used to measurement dielectric constant characteristics for different dielectric materials. The overall dimensions of the proposed sensor configuration are of 30x30 mm^2. The measurement parameter is the transmission coefficient (S_{21}). When the material under tested (MUT) is placed over the split ring resonator, the transmission coefficient respose shifts, caused by the change of dielectric constant of the system is measured, which depends on the dielectric constant. Rogers (RO3210) substrate material with dielectric constant of 10.2 and height of 1.27 mm is utilized as substrate for the proposed sensor. The resonance frequency of the proposed circular SRR sensor is 5.33 GHz. For suggested sensor, there is a non-linear relationship between the dielectric constant and transmission coefficient response shift. The dielectric constant is predicted using the non-linear equation, and a good coefficient of determination is achieved.**

***Index Terms*—microstrip patch, coplanar waveguide, split ring resonator, sensor and dielectric constant.**

I. INTRODUCTION

Dielectric substrate materials, also known as the relative permittivity are polarizable but have low electrical conductivity. The dielectric constant, ε_r, which is the ratio of the substance's permittivity to that of the free space ($\varepsilon_r = \frac{\varepsilon}{\varepsilon_o}$), explains the electrical characteristics of these materials. The dielectric constant ε_r is widely used in the fields of biology, agriculture, electronics, food, and medicine. As a consequence, it is crucial to measure the dielectric constant. The dielectric constant is essential in evaluating a substance's ability to store energy in an electric field [1,2,3]. The moisture content can be detected using the dielectric constant (ε_r) measurement, it is noticed that dielectric constant εr is decreased as increasing of moisture by Trabelsi and Nelson [4]. The blood glucose level may be predicted using another application of dielectric constant (ε_r). This approach enables non-invasive blood glucose monitoring. As in [5,6,7], a rise in the dielectric constant is seen as the glucose concentration decreases.

There are several techniques for determining dielectric constants. For example, the transmission/reflection line measurement [8,9]. With this approach, the transmission and reflection coefficients are measured simultaneously. The dielectric constant is measured in the second technique using the amplitude and phase of the reflection coefficient in an open-ended coaxial probe[10,11]. By pushing the sensor against a solid sample or submerging it in a liquid sample, this technique determines the reflection coefficient. Because of its easy use and non-destructive characteristics, the measurement of coaxial probe is frequently employed in relative permittivity measurements. The free space approach is the third method [12,13]. In the free space approach, two antennas that are usually on opposing sides are linked to a vector network analyzer (VNA). For millimeter wave measurements, the free space approach is appropriate.

Permittivity and permeability may be measured with great precision using the resonant technique. An empty resonant chamber is first measured for its resonance frequency and quality factor, then a filled chamber is measured. Although the resonant and transmission line methods are highly accurate in measuring dielectric constant, sample preparation is challenging. Furthermore, only high permittivity samples can be used with the open-ended coaxial probe approach, whereas medium and high loss materials can be used with the free space method.

Therefore; the primary focus of this research [14, 15] is on creating microwave sensors that are inexpensive, have a small footprint, and have high accuracy. This paper develops a compact circular SRR-based microwave sensor with coplanar wave guide for measuring dielectric constants. In order to ascertain the dielectric constant of unknown materials within the testing range, it seeks to examine the link between dielectric constant (ε_r) and resonance frequency shift (Δf).

This work is organized as flows: section 2 and 3 is related to split ring resonator (SRR) and coplanar waveguide (CPW) background theory. Design the structure of the proposed sensor is presented in section 4. Analyses and discussion are introduced in the section 5. Finally, summary of this work is concluded in section 6.

II. SPLIT RING RESONATOR

A man-made material created to possess certain characteristics that are not typically found in the environment is known as metamaterial. The split-ring resonator (SRR) configuration has the potential to display the properties of metamaterials. The SRR is made up of two concentric rings with openings at opposing ends. The SRR's splits raise the electrical energy, while its loops store the magnetic energy. The SRR structures' capacitance and inductance cause them to function as an LC resonance circuit [16, 17, 18].

The SRR has been widely used in microwave sensors [19], filter designs [20], and antenna designs [21] due to its benefits of cheap cost, compact size, and excellent electrical features. The SRR is implemented to improve the radiation efficiency of the antenna. The literature indicates that an SRR-based antenna has a larger bandwidth and higher gain than a typical microstrip patch antenna.

Split-ring resonators (SRR) and their complementary (CSRR) have garnered significant attention in microwave sensor design in recent years. This is because of the resonance frequency band's high quality factor, low profile, minimal radiative losses, and favorable electrical characteristics [22, 23]. Two concentric rings with split faces opposite one another make up the SRR topology. The SRR can function as an LC resonator because of its internal capacitance and inductance. Here, microwave sensors based on square and circular SRRs are created for measuring dielectric constant. The dielectric constants ε_r that can be measured by both sensors range from 1.5 to 10.2. When the material under test (MUT) is placed over the proposed sensors, the resonance frequency of the SRR changes [24, 25].

The equation below can be used to calculate a circular SRR's resonance frequency:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

Where L and C are determined from the following formula

$$L = 0.0021l \, log\left(\frac{4l}{c} - \gamma\right) \quad \mu\text{H} \tag{2}$$

$$C = \frac{\varepsilon_o ct}{2g} + (\pi r_o - g)\left(\frac{C_{pul}}{2}\right) \quad \text{PF} \tag{3}$$

Where l is the length of the ring
ε_o is the absolute permittivity
w is the width of the ring
c is free speed light
γ is the propagation conatant
t is the metal thickness and
g is the gap between the split
C_{pul} is the capacitance per unit length

The SRR acts similarly to an LC circuit. The self-inductance of the SRR structure is represented by the Ls in the diagram. The total capacitance between the rings is defined by C_o, where $Co=2\pi \, r_o \, C_{pul}$, where r_o is the average radius of the rings and C_{pul} is per-unit length capacitance. The resulting capacitance is given by $C_s=C_o/4$.

III. COPLANAR WAVEGUIDE

CPWs are widely used in microwave and RF circuits because of their ease of integration with active devices and ability to support planar structures. **A** coplanar waveguide consists of a central conductor strip with two ground planes on the same plane of a dielectric substrate. The design of CPW depends on width of center patch, gap between center conductor and ground planes, thickness of substrate (h) and dielectric constant of the substrate material (ε_r) . The characteristic impedance of a CPW can be calculated by:

$$Z_0 = \frac{30\pi}{\sqrt{\varepsilon_{eff}}}\frac{K(k\prime)}{K(k)} \tag{4a}$$

Where K(k) and K(k') are complete elliptic integrals of the first kind

$$k = \frac{W}{W+2S} \tag{4b}$$

$$k' = \sqrt{1-k^2} \tag{4c}$$

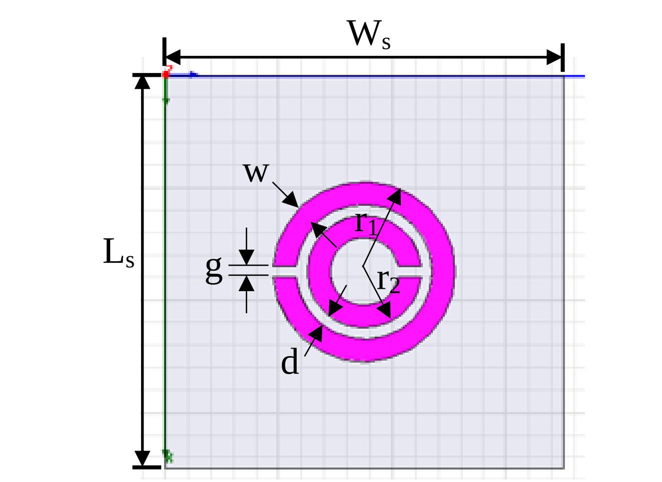
$$\varepsilon_{eff} \approx \frac{\varepsilon_r + 1}{2} \tag{4d}$$

IV. DESIGN OF PROPOSED SENSOR

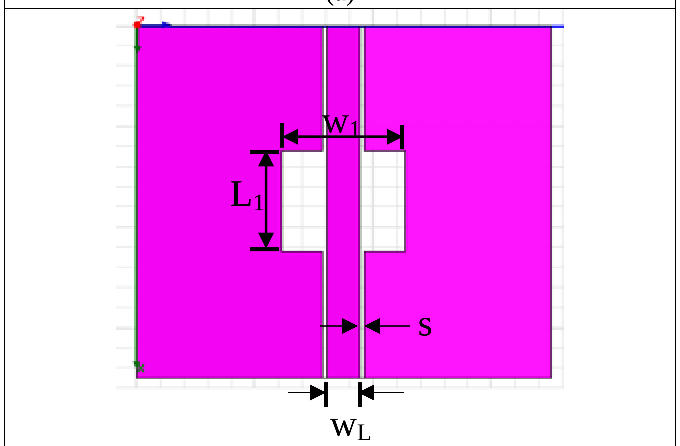
The simulation methodology for the circular SRR-based sensor's design configuration is all covered in this section. The sensors are constructed using an SRR that is coupled to a coplanar waveguide (CPW) transmission line. It is discussed theoretical formulations and sensor simulation. Based on the equations, the SRRs are sized, and the designs are simulated by Ansys High-Frequency Structure Simulator (HFSS) in order to obtain the initial findings. The unloaded sensor's transmission coefficient (S_{21}) parameter is measured, as well as the sensor with various materials under test (MUTs) placed on it.

The proposed circular sensor, which is consisted of an SRR and CPW, an SRR is printed on the surface of the substrate and connected to a CPW transmission line at the bottom as shown in figures 1(a and b). The resonance frequency of the sensors is determined by the dimensions of the SRR ring, the substrate thickness, and the relative permittivity of the substrate. The suggested sensor is designed using a Rogers RO3210 substrate, which has a thickness of 1.27 mm, a relative permittivity of 10.2, and a loss tangent of 0.003. The 3D geometrical parameters and design layout of the circular SRR sensor are shown in Figure 1(c). The equivalent LC circuit of the circular SRR is depicted in figure 1(d).

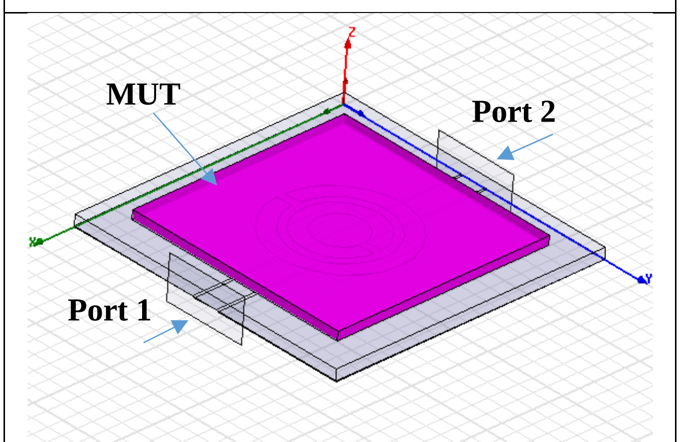
The maximum distribution of the electric field is concentrated on the center of the line and SRR while the minimum electric field distribution is appearing on both sides of ground plane, as depicted in Figure 1(e). To achieve precise sensing information, MUT must be located over SRR with most concentration of electric field. MUT has dimensions of 25*25 mm^2 and its dielectric constant ε_r is various in the range of 2.2-10.2. The optimized dimensions of proposed sensor are displayed in Table 1.



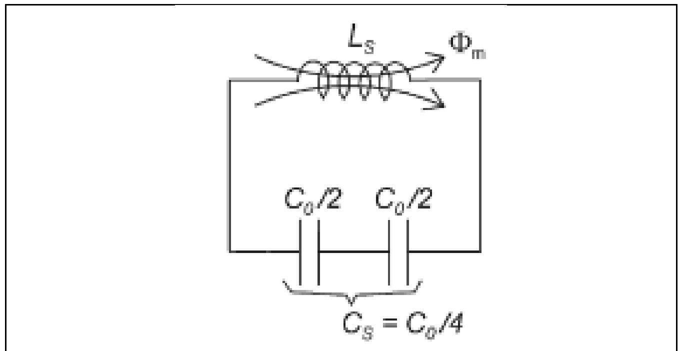
(a)



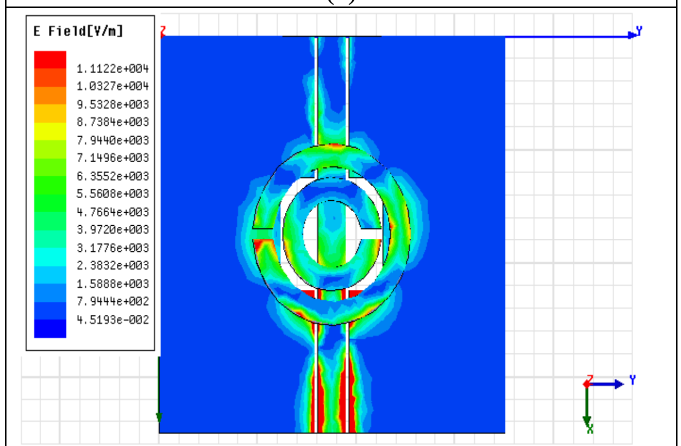
(b)



(c)



(d)



(e)

Fig. 1. Sensor geometry (a) surface and (b) bottom surfaces of the circular SRR (c) 3D geometry (d) equivalent circuit of SRR (e) electric distribution.

TABLE I

THE OPTIMIZED DIMENSIONS OF PROPOSED SENSOR (IN MM)

parameters	**R_1**	**R_2**	**w**	**g**	**L_s**
values	8	5	2	1	30
parameters	**d**	**W_s**	**W_1**	**L_1**	**w_L**
values	1	30	10.4	10	2.8

V. SIMULATION OF PROPOSED SENSOR

The proposed sensor is modeled in the form of SRR and CPW. The performance of the proposed sensor is evaluated by simulation in HFSS software. An 3D electromagnetic simulation program is used to design, develop, and simulate high-frequency electronic components such as antennas, microwave components, and sensors, is used to model the planned circular SRR-based sensor. Seven sets of materials having dielectric constants (ε_r) ranging from 2.2 to 10.2 are chosen in order to correlate the dielectric constant ε_r with the resonance frequency shift Δf.

The sample is taken on the upper surface of SRR, as seen in Figure 1(c). Table 1 presents the correlation between the magnitude of S_{21}, resonance frequency, shift Δf and the dielectric constant ε_r of material. However, for the proposed sensor with MUT having a permittivity value of ε_r=10.2 the proposed sensor displays its lowest frequency response at 4.7 GHz. On the other hand, the proposed sensor with MUT having a permittivity value of 2.2 demonstrates higher frequency response at 5.2 GHz. The resonance frequency of the unloaded sensor is known as f_0 (5.33 GHz), the resonance frequency at each dielectric constant ε_r is recorded as f_r, and the resonance shift Δf is calculated by $\Delta f = f_r - f_0$. The resonance frequency of the transmission coefficient shifts towards a lower value when MUT is applied. This is because the capacitance of the SRR structure is affected by the increasing permittivity of its surroundings. In order to investigate the performance of the proposed sensor, Figure (٢) shows the change in resonance frequency of the proposed sensor and transmission coefficient $S_2$١ for all cases, with and without MUT . It is noticed that S_{21} is shifted to left (lower band frequency) when MUT has dielectric constant greater than previous material. The shift in resonance frequency can be exploited to detect permittivity.

Figure 3(a) shows the relationship between dielectric constant and frequency using matlab program. While Figure 3(b) represents the relationship between dielectric constant and frequency using origin program. It is clear that the relationship between resonance frequency of S_{21} and dielectric constant is non-linear relationship. The mathematical expression of all above is given in equation (5).

$$\varepsilon_r = 10.988f^2 - 124.33f + 351.56 \tag{5}$$

Figure 4 describes the relationship between the amplitude of S_{21} and frequency.

TABLE II

SEVERAL MATERIALS ARE USED IN SIMULATION

Material types	S_{21}	f	Δf	ε_r
Without MUT	-27.63	5.33	0	1
Duroid	-25.5	5.2	0.13	2.2
Roger RO3003	28.9	5.13	0.2	3
Epoxy FR4	-22.8	5.01	0.32	4.4
Porcelain	-25	4.936	0.394	5.7
Marble	-20.61	4.77	0.56	8.3
Roger TMM 10	-22.73	4.73	0.6	9.2
Rogers RO3210	-22.1	4.7	0.63	10.2

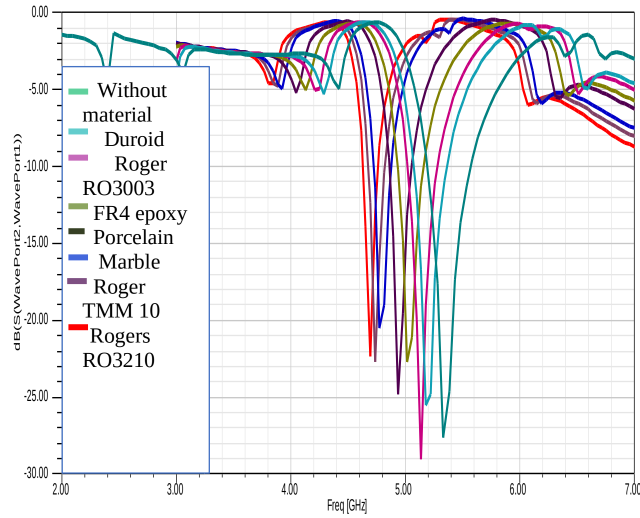
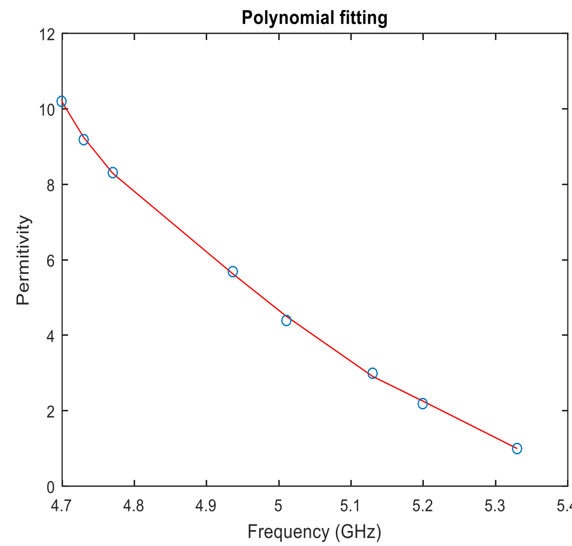
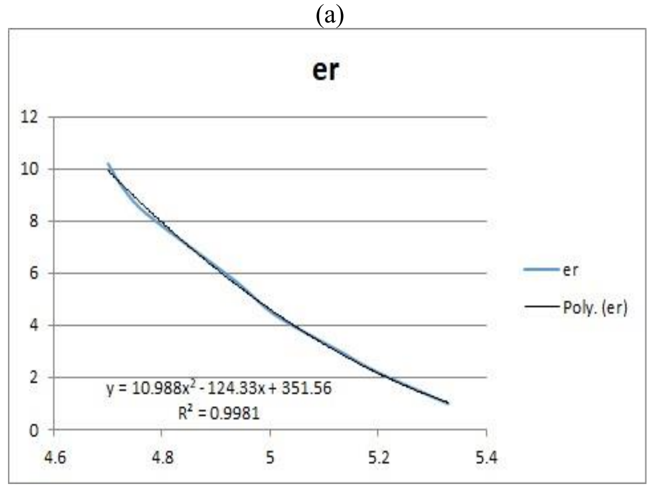


Fig. 2. S_{21} for various material with different values of dielectric constant.



(a)



(b)

Fig. 3. Relationship between dielectric constant and frequency using a) Matlab Program b) Origin program

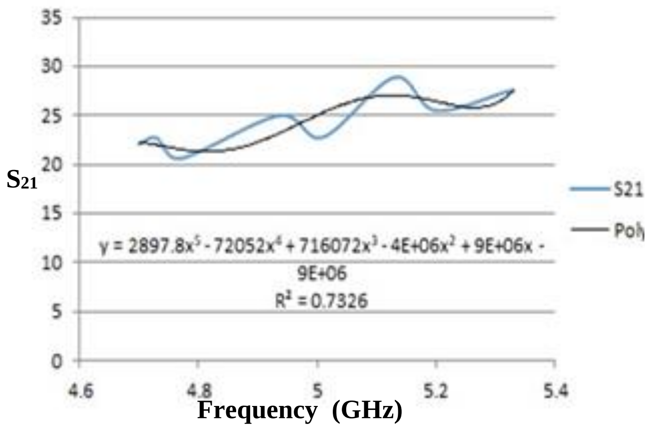


Fig. 4. Relationship between amplitude of S_{21} and frequency

TABLE III
COMPARISON WITH OTHER REFERENCES

References	**Sensor type**	***f (GHz)***	Substrate	**Application**
[22]	Rectangular patch	10	FR-4	Liquid detection
[24]	Rectangular patch antenna	2.9	silicone	saline detection in liquids
[25]	Circular ring monopole	2.4	Epoxy	Sugar detection
[26]	Rectangular patch with slots	2	Cellulose paper	Liquid detection
The proposed sensor	SRR with CPW	5.33	FR-4 epoxy	Dielctric constant

VI. CONCLUSION

In this work, design and development of circular split-ring resonator (SRR)-based sensors (planar MW sensor) for dielectric constant Measurement is achieved successfully, which demonstrates the potential of metamaterial-inspired structures in precise permittivity sensing applications. A new equation is obtained to measure the relative permittivity of different materials using SRR metamaterials and coplanar waveguide. The proposed sensing principle is based on shifting of S_{21} response with different MUT. by leveraging the unique electromagnetic properties of circular SRRs. The proposed microwaves sensor technique has advantages of compact size and achieves high sensitivity and selectivity in measuring dielectric constants, making it suitable for various fields such as material science, biomedical diagnostics, and quality control in industrial processes in the future.

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