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High Accuracy Split Ring Resonator Based Sensor with Polynomial-Assisted Dielectric Characterization for Solid Material

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***Abstract*—These days, the characterization of material permittivity has gained significant interest from researchers. Even though conventional measurement techniques able to provide high accuracy of measurement, many of the devices still suffer from bulky size, expensive fabrication and complex design structures. To overcome these issues, a compact split ring resonator (SRR) based sensor was proposed for high accuracy material characterization. The proposed sensor operates at a stable resonant frequency of 3.854 GHz and utilizes multiple offset resonant frequencies combined with polynomial fitting analysis to improve dielectric constant extraction accuracy. Experimental validation using Rogers 5880, Rogers 4350, and FR4 substrates demonstrates dielectric constant accuracies of 98.67%, 88.36%, and 97.14%, respectively, while loss tangent accuracy exceeds 99% for all tested materials. The optimized 12mm x 12mm sensor on FR4 also provides stable resonance response, low loss and high Q-factor, making it suitable for low-cost and reliable microwave sensing applications.**

***Index Terms*— Dielectric Constant, High Accuracy Sensor, Material characterization, Split Ring Resonator (SRR)**

I. INTRODUCTION

In recent years, microstrip antenna technology has advanced rapidly due to its widely used in modern wireless and microwave communication systems. These antennas are commonly applied in satellite communications, radar systems, remote sensing, and portable wireless devices because of their compact design, lightweight structure, low cost and ease to integrate with planar circuits [1], [2]. Such characteristics make microstrip antennas highly attractive for compact and high-performance applications in next-generation communication technologies [3], [4].

At the same time, the accurate characterization of electromagnetic material properties, particularly complex permittivity, has become increasingly important. The dielectric constant of a material strongly affects electromagnetic wave propagation, impedance matching, and the resonant behaviour of microwave components [5], [6]. As a result, precise permittivity measurement is required to improve the performance of antennas, filters and microwave sensors [7], [8]. At higher frequencies, where small variations in dielectric properties can significantly influence overall system performance, this requirement becomes even greater to ensure the accuracy of the measurement [9], [10].

The demand for reliable and low-cost material characterization techniques has increased because of the continuous growth of wireless communication technologies. With Accurate sensing methods are needed not only for device optimization but also for material verification and quality control in industrial applications due to the advancement of high speed communication systems and microwave-based devices. [11], [12].

Resonant cavity and transmission line methods, traditional permittivity measurement techniques, able to provide high accuracy measurement. However, these techniques limited by large design structures, complicated calibration process and high fabrication cost [13], [14]. In addition, they have low compatibility with planar techniques and caused the integration process into compact microwave systems become more challenging. Although planar microwave sensors have been introduced as an alternative solution, many existing designs still face compromises between sensitivity, accuracy, and structural simplicity [15], [16].

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Recently, resonator-based sensing methods have attracted significant attention, especially those based on metamaterial-inspired structures such as SRRs. SRRs are well known for their strong electromagnetic field confinement and high sensitivity to dielectric variations, making them suitable for material characterization applications [17], [18]. Different SRR configurations, including complementary SRRs and multi-mode resonators, have been investigated to improve sensing capability and measurement performance [19], [20]. Despite these developments, several limitations remain.

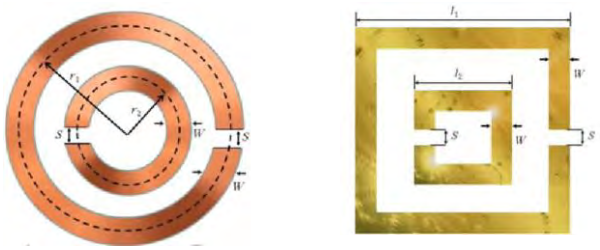
Many reported SRR based sensors depend mainly on single-resonance frequency analysis, which can reduce the reliability and accuracy of dielectric extraction, particularly for materials with nonlinear or frequency-dependent characteristics [21], [22]. Furthermore, linear approximation relationships are often used to estimate dielectric properties from resonant frequency shifts, which may produce significant errors in real measurements. Some of the microwave sensor design also has complicated structures or involved multilayer design that increase fabrication complexity and entire cost [18], [23]. When several SRR shapes such as circular, square and hexagonal geometries have been compared in term of their performance, a comprehensive analysis of their sensing stability and sensitivity is still limited [24], [25].

In addition, SRR based sensors inherently suffer from several practical limitations. These structures generally exhibit relatively low quality factor (Q-factor) values, producing broader resonance responses that reduce frequency resolution and sensing precision [19], [20]. Their performance is also highly sensitive to fabrication tolerances, where small variations in gap size, conductor width, or etching accuracy can cause measurable shifts in resonant frequency. Compared to circular geometries, square SRR structures may also provide less uniform electromagnetic field confinement, reducing interaction efficiency with the material under test (MUT), especially for materials with low dielectric contrast [24], [25]. Moreover, relying solely on single-frequency analysis further limits the robustness of dielectric characterization. These issues highlight the need for improved sensor designs and more advanced analysis methods to enhance measurement reliability and accuracy.

To overcome these limitations, this paper presents a high accuracy SRR based microwave sensor that analyze the shifted resonant frequencies set using a polynomial fitting assisted technique for dielectric constant characterization. By utilizing 2nd and 3rd order polynomial analysis, the proposed sensor able to determine the nonlinear relationship between resonant frequency shifts and permittivity properties more effectively, leading to increase the accuracy of material characterization [21], [22]. In addition, a comparative study of different SRR geometries is performed to identify a configuration with better sensing stability and performance. The proposed sensor employs a compact planar structure with the SRR integrated into the ground plane, allowing simple fabrication and easy integration with standard microwave circuits.

II. Design and Method

Different shapes of SRR were designed and simulated to obtain the most suitable resonator performance at desired frequency. Designing of split ring resonator by using different shapes (circular, square and hexagon) and different sizes create different resonant frequencies as shown in Fig. 1 and Fig. 2. Therefore, the resonant frequency of different shapes and sizes of split ring resonator can be used to determine the relationship between resonant frequency, sizes and shapes of split ring resonator.



(a) (b)

Fig. 1: (a) Circular SRR (C-SRR) (b) Square SRR (S-SRR)

Average loop length,
$L_{1,2} = 2\pi r^{1,2} - S$
Resonant frequency for single loop, $f_{1,2} = \frac{c}{2L_{1,2}\sqrt{\varepsilon_{eff}}}$

Average loop length,
$L_{1,2} = 4l_{1,2} - S - 4W$
Resonant frequency for single loop, $f_{1,2} = \frac{c}{2L_{1,2}\sqrt{\varepsilon_{eff}}}$

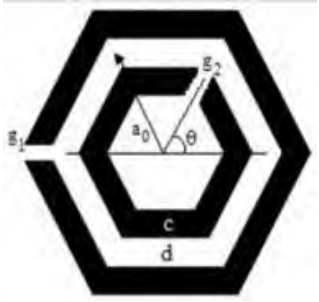


Fig. 2: Hexagon SRR (H-SRR)

Resonant frequency for single loop,

$$f_o = \frac{1}{\left(2\pi\sqrt{(2a_{eq}\,.\,L_{Net}.\,C_{Net})}\right)}$$

$$N = 6, a_{eq} = 2a\left(\sin\left(\frac{\pi}{2}\right)\right) - \frac{g}{N}$$

$$L_{Net} = 0.00508\left(2.030\log_{10}\frac{4l}{c} - 2.636\right)$$

$$C_{Net} = \frac{\left(Nsin\left(\frac{\pi}{N}\right) + \beta\right)^2 - \left(\frac{\Delta}{a}\right)^2}{2\left(Nsin\left(\frac{\pi}{N}\right) + \beta\right)}$$

Fig. 3 illustrates the equivalent circuit model of the proposed SRR structure, while the resonant frequency equations for the different SRR geometries are expressed as follows:

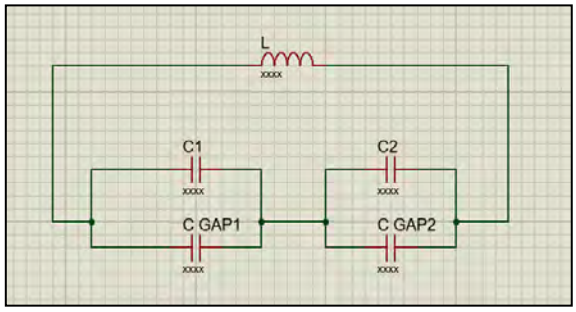


Fig. 3: Equivalent circuit of the SRR

For Circular - SRR :

$$f_0 = \frac{1}{2\pi\sqrt{LC_{eq}}} = \frac{1}{2\pi\sqrt{L_T\left[\frac{(\pi r_0 - g)C_{pul}}{2} + \frac{\varepsilon_0 ct}{2g}\right]}}$$

For Square - SRR :

$$f_0 = \frac{1}{2\pi\sqrt{L_T C_{eq}}} = \frac{1}{2\pi\sqrt{L_T\left[\left(2a_{avg} - \frac{g}{2}\right)C_{pul} + \frac{\varepsilon_0 ch}{2g}\right]}}$$

For Hexagon- SRR :

$$f_0 = \frac{1}{2\pi\sqrt{L_T C_{eq}}} \frac{1}{2\pi\sqrt{L_T\left[\frac{(3a_{avg} - g_1)C_{pul}}{2} + \frac{\varepsilon_0 ch}{2g_1}\right]}}$$

Among them, L_T is the total inductance of split ring resonator, and C_{eq} is the equivalent capacitance of the structure, calculated according to the equivalent circuit. C_{pul} is the capacitance per unit length, r_o (C-SRR) and a_{avg} (S-SRR and H-SRR) between the rings are the distance from the center of the two components of the SRR. C_{pul} is calculated as

$$C_{pul} = \frac{\sqrt{\varepsilon_e}}{c_0 Z_0}$$

where $c_o = 3 \times 108\, ms^{-1}$ is speed of light. ε_e is the effective permittivity of the substrate and Z_0 is the total impedance. The total inductance of the structures, L_T is computed as

$$L_T = 0.00508l\,(2.303log10\,\frac{4l}{d} - \boldsymbol{\theta})$$

where, l and d are the wire length and width, respectively. The constant $\boldsymbol{\theta}$ varies with wire geometry and is given as 2.45 (Circular SRR), 2.85 (Square SRR) and 2.64 (Hexagonal SRR).

III. Results and Discussions

The resonant characteristics of S-SRR, C-SRR and H-SRR with different radius and metallic strip width, c, are investigated through analytical computation and full-wave simulation. The resonant frequencies of the proposed SRR structures are initially estimated using theoretical equations and subsequently verified through simulation results to evaluate the accuracy and behaviour of each geometry under dimensional variations. Different SRR shapes produce sharp resonant characteristics because current distribution and electromagnetic field confinement is altered and optimized within the resonator structure.

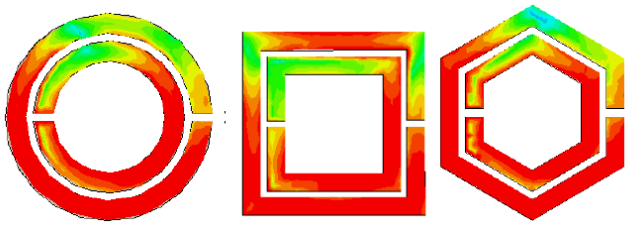


Fig. 4 C-SRR, S-SRR, H-SRR

Fig. 4 present investigation of the surface current distributions analysis for different SRR structures. In current distribution analysis, red colour and green colour represent the highest current density and the lowest current density, respectively. From the observation, it shows that each SRR geometry has different current concentration patterns, particularly between the split gap and ring edges. These differences give significant impact to the resonant behaviour, quality factor, and electromagnetic coupling capability of the resonator. The surface current distributions in the circular and hexagonal structures are smoother and have more uniform current flow compared to the square SRR. S-SRR has stronger field concentration at the sharp corners compare to other area. Therefore, detailed analysis of the SRR geometry and current distribution is required to optimize the SRR performance and improve the overall effectiveness of the proposed sensor design.

COMPARISON OF DIFFERENT SIZE FOR VARIOUS SHAPES

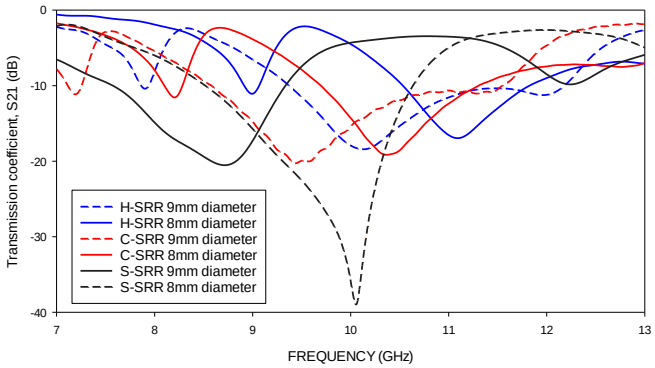


Fig. 5: Comparison of S-parameters between different shapes, ring widths, and diameters of SRRs

Fig. 5 shows the performance comparison of the designed sensor with different SRR geometries and SRR sizes. Based on the simulated results, both the H-SRR and C-SRR demonstrate better stability in resonant frequency characteristics when the SRR size is varied. In contrast, the square SRR exhibits larger resonance deviations under the same dimensional variations, indicating higher sensitivity to geometrical changes. The improved stability observed in the H-SRR and C-SRR structures can be attributed to their more uniform current distribution and smoother electromagnetic field confinement, which contribute to consistent resonant behaviour.

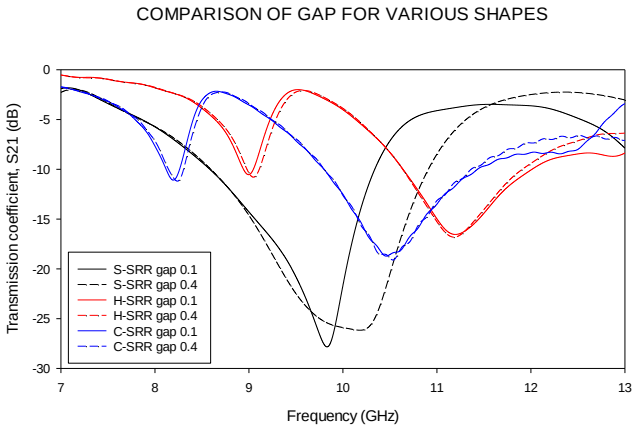


Fig. 6: Comparison of S-parameters between different shapes and split gap dimension of SRR

The performance comparison for different split gap in the SRR structure is presented in Fig. 6. From the observation, the H-SRR and C-SRR has similar trends and maintain stable resonant responses compared to the S-SRR as the gap size varies. The S-SRR shows more significant resonance shifting and performance fluctuation due to the stronger field concentration at the sharp edges and corners. In addition, the C-SRR produces a deeper resonance characteristic than the H-SRR, showing stronger electromagnetic coupling and higher resonance quality. A deeper resonance is required as it enhances the sensitivity and detection capability of the sensor.

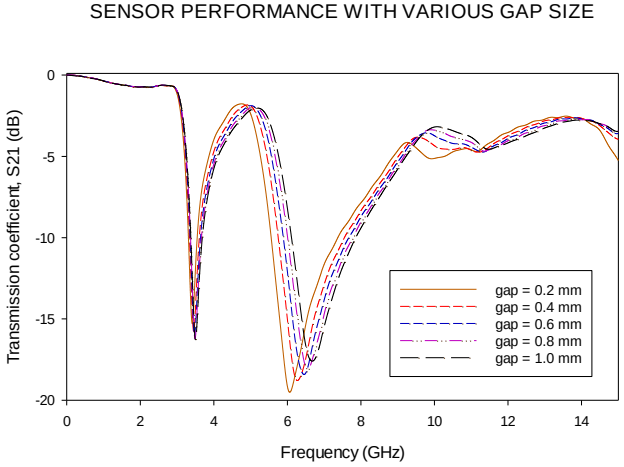
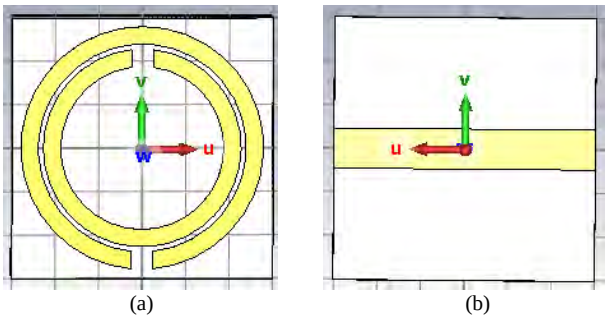


Fig. 7: Resonant frequency of different gap size



(a) (b)

Fig. 8 (a) Top View and (b) Bottom View

Fig. 7 shows the transmission coefficient response of the proposed SRR sensor for different gap sizes. The resonant frequency at 3.854 GHz demonstrates greater stability against gap variation compared to the resonance near 6 GHz, which exhibits larger frequency shifts. This indicates that the lower-frequency resonance is less sensitive to fabrication tolerance and dimensional deviation. The SRR size was optimized and reduced to 5.6 mm to achieve resonance at 3.854 GHz while maintaining compactness as shown in Fig. 8. Lower-frequency operation offers several advantages, including reduced conductor and dielectric losses, lower noise sensitivity, improved resonance stability, and more reliable dielectric characterization performance for microwave sensing applications.

After the optimization completed, the proposed sensor was simulated using multiple MUTs with different dielectric constant values to investigate the resonant response behaviour. Different resonance frequencies were generated for each MUT because each MUT has a unique permittivity value. The produced resonance shifts were carefully observed and analyzed. The relationship between the shifted resonance frequency and the dielectric constant of the MUTs is extracted and generated. The results demonstrated a clear resonance frequency shift for each material, confirming the high sensitivity of the proposed sensor with different dielectric constant.

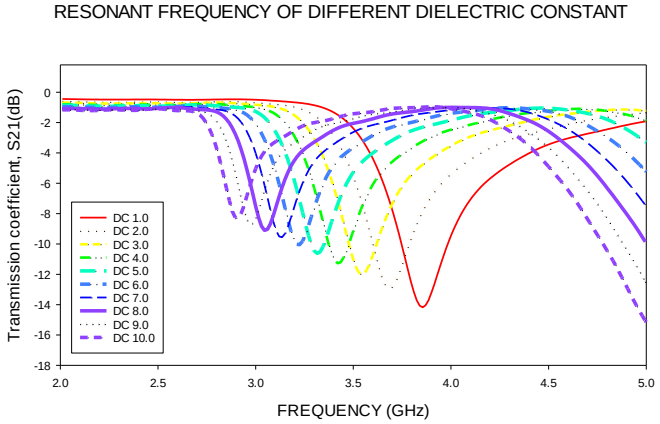


Fig. 9: Resonant frequency of different dielectric constant

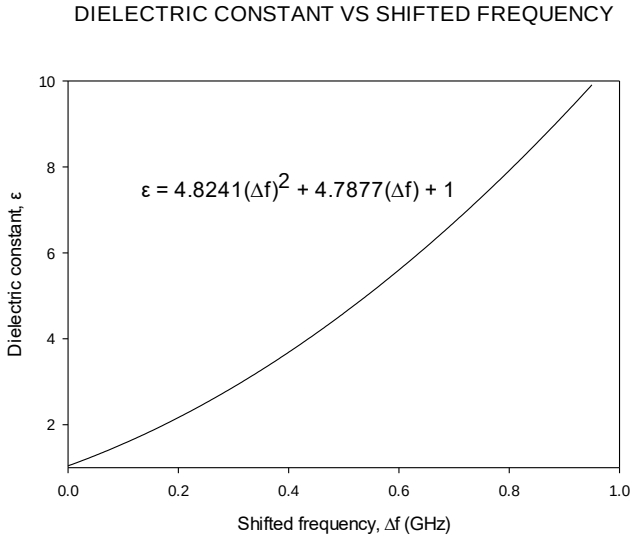


Fig. 10: Shifted frequency of different dielectric constant

Fig. 9 and Fig. 10 shows the resonance frequency shifting response respected to the initial resonance frequency against the

dielectric constant of MUT in polynomial equation form. These graphical representations provide significant insight into the dielectric characteristic of the MUTs and their impact on the resonant properties of the resonator.

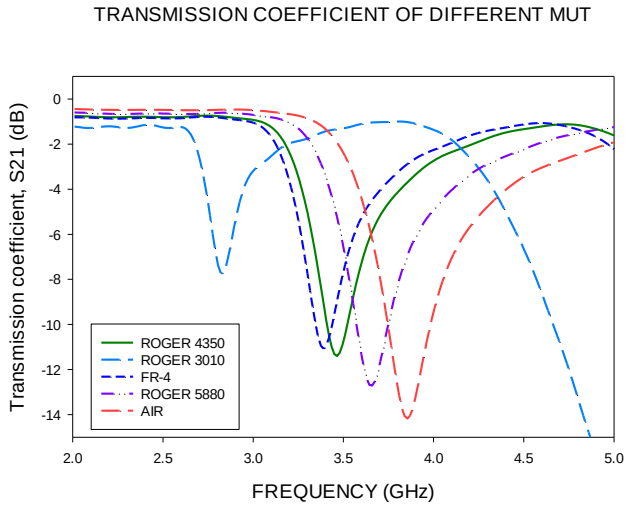


Fig. 11: Resonant frequency of different material under test (MUT)

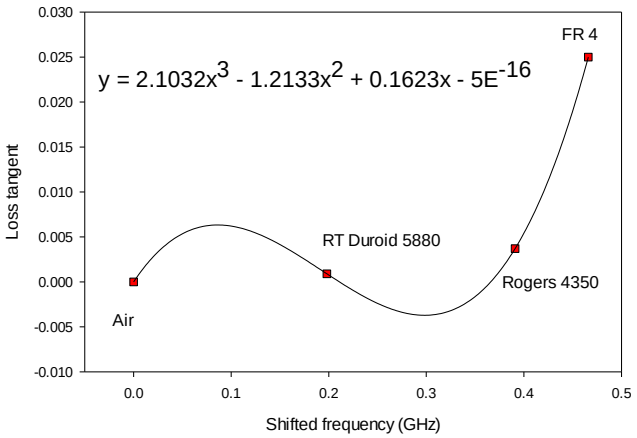


Fig. 12: Shifted frequency of different loss tangents

In Fig. 11, different MUT, such as Roger 5880, Roger 4350, Roger 3010, and FR4, were analyzed. The shift in resonant frequency for each MUT is being examined and studied. The observation shows that each MUT produces significant impacts on the resonant frequency. This variation is taken for further consideration and analysis to accurately characterize the dielectric constant of each material. Such characterization is essential for optimizing the application of these materials in high frequency electronic circuits and improving their performance in real engineering scenarios.

Fig. 12 shows the polynomial curve of the loss tangent against the shifted frequency for different MUT. To further characterize the relationship between resonance response and dielectric properties, 2nd order and 3rd order polynomial equations were extracted from the plotted graph using equation (1) and equation (2) to estimate the dielectric constant and loss tangent of the measured MUTs, respectively. The exact polynomial equations are presented together with the plotted graphs as reference equations for the proposed sensor design.

$$y = Ax^2 + Bx + C \quad (1)$$

$$y = Ax^3 + Bx^2 + Cx + D \quad (2)$$

The C-SRR then fabricated successfully on FR4 substrate and measured to verify the simulation result. Fig. 13 shows the fabricated C-SRR microwave sensor from top and bottom view.

(a) (b)

Fig. 13: (a) Front View and (b) Back View

Fig. 14 presents the comparison between the simulated and measured resonance responses for different MUTs. The simulation and measurement trendlines show strong agreement for all investigated MUTs, demonstrating that the developed microwave sensor is reliable and capable of accurately predicting the resonant behaviour of the proposed sensor. The high similarity between simulation and measurement also validates the effectiveness of the fabricated prototype under practical measurement situation.

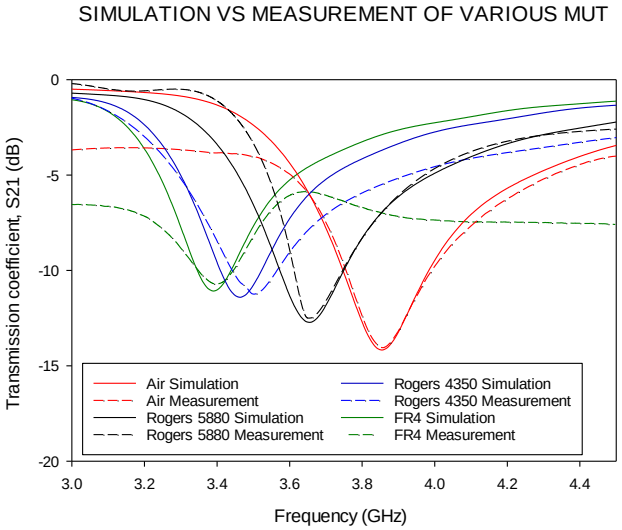


Fig. 14: Comparison between measurement and simulation of various MUT

TABLE I
COMPARISON OF MEASUREMENT AND SIMULATION VALUE

	Air	Rogers 5880	Rogers 4350	FR4
Simulation (GHz)	3.854	3.656	3.463	3.388
Measurement (GHz)	3.858	3.651	3.508	3.399
Error (%)	**0.104%**	**0.137%**	**1.299%**	**0.325%**

Table I summarizes the comparison recorded data between the simulated and measured resonant frequencies for the different MUTs. Based on the results, the measured resonant frequencies show strong agreement with the simulated values, demonstrating the reliability and accuracy of the fabricated sensor design and simulation sensor. From the data, resonance frequencies is confirming decrease as the dielectric constant of the MUT increases, which is consistent with the theoretical

behaviour of microwave resonator sensors where higher permittivity materials increase the effective capacitance and resonance shifting toward lower frequencies.

The percentage error between simulation and measurement remains relatively small for all tested materials, ranging from 0.104% to 1.299%. The lowest error is contributed by air, while the highest deviation observed from Rogers 4350. Nevertheless, the overall inconsistency is still within an acceptable range for microwave sensing applications. These minor differences may contributed by fabrication error, soldering impact, variation in substrate properties and environmental conditions during experimental validation. Overall, the results confirm that the proposed sensor achieves good measurement accuracy and stable resonant performance for dielectric characterization applications.

These insignificant errors can be attributed to a range of sources, including production flaws, the effects of soldering, and intrinsic losses in measuring equipment. These inaccuracies highlight the difficulties in establishing perfect consistency between theoretical simulations and experimental results. However, the high similarity between simulation and measurement results confirms the proposed simulation design and its predictive ability. This thorough comparison is essential for optimizing simulation models and increasing the correctness of future experimental designs in sensors.

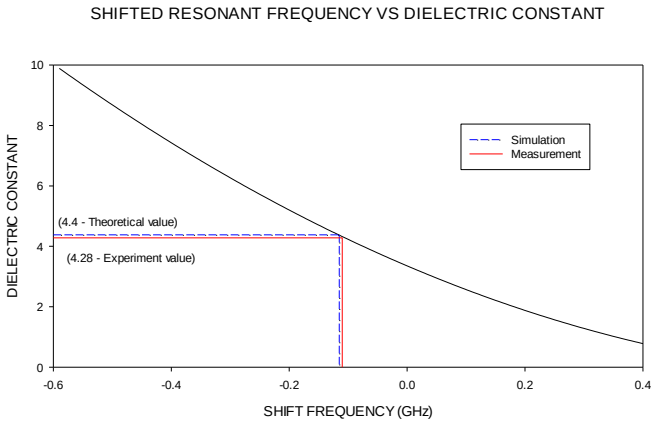


Fig. 15: Dielectric constant of FR4

Fig. 15 shows the graphical relationship between the dielectric constant and shifted resonance frequency of the investigated MUTs. Based on the plotted graph, the shifted frequency increases consistently as the dielectric constant increases, indicating that the proposed sensor is highly responsive to permittivity variations. The graph also demonstrates a stable and predictable trendline, which confirms the effectiveness of the proposed sensor for dielectric characterization and material identification applications.

Using the 2nd order and 3rd order polynomial equations extracted from the plotted graph, the dielectric constant and loss tangent values of each MUT were calculated and recorded accurately. The extracted values show good agreement with the reference dielectric properties, indicating that the proposed polynomial fitting method provides reliable prediction accuracy for material characterization. Minor deviations may be caused by fabrication tolerance and measurement uncertainty during the experimental process.

TABLE II
SENSOR PERFORMANCE FOR VARIOUS MUT

		Air	Rogers 5880	Rogers 4350	FR4
Simulation (GHz)		3.854	3.656	3.463	3.388
Measurement (GHz)		3.858	3.651	3.508	3.399
Shifted Freq (GHz)		0.004	0.203	0.346	0.455
Dielectric Constant	**Reference**	1	2.2	3.66	4.3
	Measured	1.02	2.17	3.23	4.18
Accuracy (%)		98.08	98.67	88.36	97.14
Loss Tangent	**Reference**	0	0.0009	0.02	0.022
	Measured	6.00E-16	0.000899	0.0199	0.02199
Accuracy (%)		100.00	99.89	99.50	99.95
BW (MHz)		180	195	180	195
Q-Factor		42.83	37.62	38.50	34.85
Sensitivity (MHz/εr)		na	169.2	130.1	137.9

Table II shows the performance validation of the proposed microwave sensor through comparison between simulated and measured values for various MUTs, namely air, Rogers 5880, Rogers 4350, and FR4. The measured resonant frequencies highly similar with the simulated results, indicating good agreement between simulation and experimental validation. The resonance frequency gradually shifts toward lower frequencies as the dielectric constant increases, confirming the sensor's capability in characterizing materials with different dielectric properties. The highest shifted frequency is observed for FR4 with 0.455 GHz, followed by Rogers 4350 and Rogers 5880, while air shows only a minimal shift of 0.004 GHz due to its low permittivity.

The proposed sensor able to determine the dielectric constant with high accuracy and validate the reliability of the proposed sensor. High dielectric constant accuracy values achieved for air, Rogers 5880, FR4 and Rogers 4350 are 98.08%, 98.67%, 97.14% and 88.36%, respectively. This fluctuation may be caused by fabrication tolerance, substrate inconsistency, or measurement uncertainty. Similarly, the extracted loss tangent values demonstrate excellent agreement with reference values, achieving accuracies above 99% for all MUTs.

Proposed microwave resonator provides bandwidth ranges between 180 MHz and 195 MHz and the Q-factor varies from 34.85 to 42.83. Air as MUT produces the highest Q-factor due to lower dielectric losses. Compared to FR4, the determined Q-factor is the lowest because of its higher loss characteristic. The sensitivity of the proposed sensor also good, with the highest sensitivity obtained for Rogers 5880 at 169.2 MHz/εr, followed by FR4 and Rogers 4350. Overall, the results confirm that the proposed sensor provides stable resonant characteristics, high accuracy, and good sensitivity for dielectric characterization applications.

IV. CONCLUSION

In conclusion, the proposed SRR based microwave sensor successfully characterized the dielectric properties of different materials with high accuracy and stable performance. The sensor demonstrated strong agreement between simulation and measurement results for Air, Rogers 5880, Rogers 4350, and FR4 substrates. The measured dielectric constant achieved

accuracy of 98.67% for Rogers 5880, 88.36% for Rogers 4350, and 97.14% for FR4, while the loss tangent measurement exceeded 99% accuracy for all tested materials. The optimized SRR structure provided stable resonance characteristics, good sensitivity, compact size, and improved tolerance against fabrication variation. In addition, the use of polynomial fitting analysis improved the reliability of dielectric characterization compared to conventional single-frequency methods. Overall, the proposed sensor offers a low-cost, compact, and easy-to-fabricate solution for high-accuracy microwave material characterization and sensing applications.

AUTHOR CONTRIBUTIONS

Misran conceptualized the research work, conducted the overall investigation, supervised the project development, and prepared the manuscript draft as the main corresponding author. Meor Said and Othman contributed to the development of the methodology framework, experimental design, and technical validation of the proposed system. Subari and Babale were responsible for data processing, analysis, interpretation of experimental results, and performance evaluation. Setumin contributed to the review and refinement of the manuscript, particularly in data interpretation and technical presentation. All authors reviewed and approved the final version of the manuscript.

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