

THEORETICAL STUDY OF DESIGNING SPLIT-RING RESONATOR-BASED SENSORS FOR DIELECTRIC CONSTANT MEASUREMENT

Arz Muhammad Maitlo

M.Phil Scholar, Department of Physics and Electronics, Shah Abdul Latif University, Khairpur Mir's, Sindh, Pakistan arzsoonh@gmail.com **Correspondance Author**

Farman Ali Mangi

Department of Physics and Electronics Shah Abdul Latif University, Khairpur Mir's, Sindh, Pakistan

farman.mangi@salu.edu.pk

Ghulam Hussain Shaikh

M.Phil Scholar, Department of Physics and Electronics, Shah Abdul Latif University, Khairpur Mir's, Sindh, Pakistan ghulamshaikh861@gmail.com

Gul Hassan Sodhro

M.Phil Scholar, Department of Physics and Electronics, Shah Abdul Latif University, Khairpur Mir's, Sindh, Pakistan hassangull83@gmail.com

Aijaz Ali Shaikh

Assistant Professor, Department of Mathematics, Shah Abdul Latif University, Khairpur Mir's, Sindh, Pakistan aijaz.shaikh@salu.edu.pk

Abstract:

Dielectric constant measurement is an important topic in electronic circuit design. In this study, circular and square SRR-based sensors are proposed to overcome the limitations of conventional measurement methods. Both SRR-based sensors are loaded with a quarter-wavelength coplanar waveguide (CPW) transmission line with two ports and have a size of 35 mm x 35 mm x 1.27 mm. The transmission coefficient is used as the measurement parameter. S₂₁ resonance shifts when the material under test (MUT) is put on top of the SRR. The proposed circular and square SRR sensors are fabricated on the Rogers RO3210 substrate material with a relative permittivity of 10.2. The resonance frequency of the circular SRR is 3.31 GHz, while the square SRR resonates at 2.67 GHz. A linear relationship is found between resonance shift and dielectric constant for both proposed sensors. A good coefficient of determination is obtained, and the linear equation is used to predict the dielectric constant of Rogers RT6002, FR4, and Rogers TMM10 for validation purposes. Experiment measurement proved that the proposed circular and square SRR sensors have high accuracy in dielectric constant measurement.

Keywords: Split-Ring Resonator, Sensors, Dielectric Constant Measurement.

Introduction:

Dielectric materials have poor electrical conductivity, but they are polarizable (Islam et al., 2025). The electrical properties of these substances are explained by the dielectric constant, ϵ_r which is defined as the ratio of the permittivity of the substance to the permittivity of the free space. This parameter is important as the refractive indices and the capacitance of electronic devices are correlated to it (Luszczynska et al., 2019). Besides, it is also related to the material characteristics like water content, bulk density, biobased content, chemical absorption, and the relationship between stress and strain. The widespread usage of dielectric constant is presented in food, medicine, electronics, construction, biology, and agriculture industries (XIN, O., 2022). Therefore, the measurement of dielectric constant becomes significant (Wang et al., 2021). One of the common methods used for dielectric constant measurement is the transmission line measurement method (Al-Behadili et al., 2020). The transmission line method requires the test sample to fit firmly with the transmission line (Sato et al., 2021). The next measurement method is the open-ended coaxial probe measurement. This method measures the reflection coefficient by pressing the sensor onto the solid sample or immersing the sensor into the liquid sample (Mishra et al., 2024). The coaxial probe measurement is commonly used in dielectric constant measurement due to its simple practicality and non-destructive properties (Fontana, Canicattì,

and Monorchio, 2019). Besides, the free space measurement method is suitable for the millimeter-wave range measurement (Liu et al., 2021), while the resonant cavity method has high precision in dielectric constant measurements Albishi et al., 2021).

In recent years, split-ring resonator (SRR) and its complementary (CSRR) have gained high interest in microwave sensor design. The reason behind this is due to the good electrical properties, low profile, low radiative losses, and high-quality factor of the resonance frequency band Masrakin et al., 2023). SRR topology consists of two concentric rings with a split faced opposite each other, Samanta et al. (2021). The inductance and capacitance within the SRR enable it to behave as an LC resonator. Dielectric materials have poor electrical conductivity, but they are polarizable Javed et al., 2020). The electrical properties of these substances are explained by the dielectric constant, ϵ_r which is defined as the ratio of the permittivity of the substance to the permittivity of the free space. This parameter is important as the refractive indices and the capacitance of electronic devices are correlated to it Xu et al., 2018. Besides, it is also related to the material characteristics like water content, bulk density, biobased content, chemical absorption, and the relationship between stress and strain. The widespread usage of the dielectric constant is presented in food, medicine, electronics, construction, biology, and agriculture industries. Therefore, the measurement of dielectric constant becomes significant (Wang et al., 2021).

One of the common methods used for dielectric constant measurement is the transmission line measurement method Buragohain, 2023). The transmission line method requires the test sample to fit firmly with the transmission line Sato et al, 2021. The next measurement method is the open-ended coaxial probe measurement. This method measures the reflection coefficient by pressing the sensor onto the solid sample or immersing the sensor in the liquid sample. The coaxial probe measurement is commonly used in dielectric constant measurement due to its simple practicality and non-destructive properties. Alrayes, N., & Hussein, M. I. (2021). Besides, the free space measurement method is suitable for the millimeter-wave range measurement, while the resonant cavity method has high precision in dielectric constant measurements (Wu et al., 2022).

In recent years, split-ring resonator (SRR) and its complementary (CSRR) have gained high interest in microwave sensor design. The reason behind this is due to the good electrical properties, low profile, low radiative losses, and high-quality factor of the resonance frequency band (Oliveira et al., 2020). SRR topology consists of two concentric rings with a split faced opposite each other Ye et al., 2022). The inductance and capacitance within the SRR enable it to behave as an LC resonator. The figure below was generated online, setting up the data for the conceptual details.

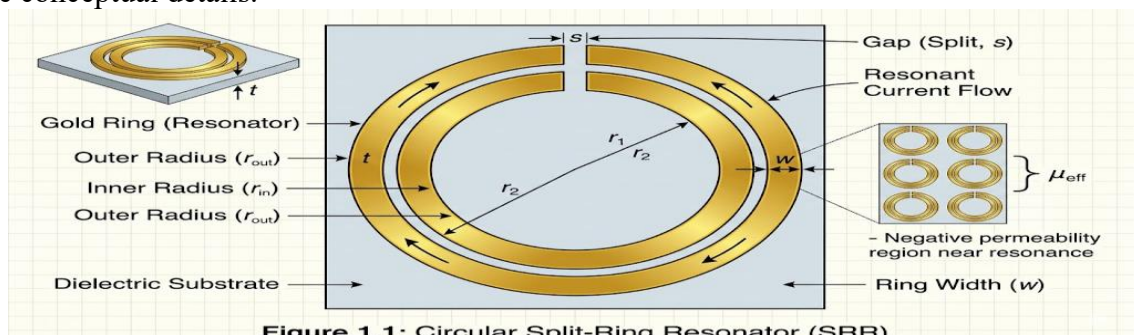


Figure 1.1: Circular Split-Ring Resonator (SRR)

Inspired by previous works, circular and square SRR-based microwave sensors are developed here for dielectric constant measurement. Both sensors are capable of measuring dielectric constants ϵ_r from 1.5 to 10.2. The resonance frequency of the SRR shifts when the material under test (MUT) is applied to the SRR sensors. The relationship between the resonance frequency shift and the dielectric constant can be used to predict the ϵ_r of unknown materials

within the testing range.

Inspired by previous works, circular and square SRR-based microwave sensors are developed here for dielectric constant measurement. Both sensors are capable of measuring dielectric constants ϵ_r from 1.5 to 10.2. The resonance frequency of the SRR shifts when the material under test (MUT) is applied to the SRR sensors. The relationship between the resonance frequency shift and the dielectric constant can be used to predict the ϵ_r of unknown materials within the testing range.

Problem Statement

The dielectric constant is important in defining a substance's ability to store energy in an electric field (Islam, M. R., Islam et al., 2022). However, the determination of the dielectric constant requires high expenses, complex design, and difficult sample preparation. The common methods used in dielectric measurement, such as the transmission line measurement method, open-ended coaxial probe measurement, free space method, and resonant cavity measurement, have their strengths and weaknesses. The transmission line method and resonant method have high accuracy in dielectric constant measurement, but the sample preparation is quite difficult. Besides, the open-ended coaxial probe method is suitable for high permittivity samples only, while the free space method is applicable for medium and high loss materials (Liu et al., 2021). Hence, this study focuses on the design of microwave sensors with the advantages of low cost, small footprint, and high accuracy.

Research Objectives

- This research aims to develop SRR-based microwave sensors with low cost, simple measurement procedures, small size, and good performance for dielectric constant measurement. Circular and square SRR-based sensors are designed in this study.
- To analyze the relationship between the resonance frequency shift Δf and the dielectric constant ϵ_r of materials. The relationship is used to determine the dielectric constant of unknown materials.

Literature Review

Method of Dielectric Constant Measurement

Various methods have been developed to measure dielectric constants. A review of the literature shows that the transmission/reflection line measurement, open-ended coaxial probe, free-space method, and resonant cavity methods are among the most popular methods employed for dielectric constant measurements. A brief illustration of these methods and their pros and cons is summarized here.

Method of Transmission/Reflection Line

Measurements using the transmission line method require a sample to be placed inside a transmission line. This method measures both the reflection and transmission coefficients. Liu et al. (2020) proposed a transmission line method to measure 3D-printing materials. The material under test (MUT) is placed into a rectangular waveguide, and the two-port S parameter is measured. However, the measurement results are susceptible to the air gap effects. This is to say that the gap between the waveguide and the MUT has to be minimized in order to obtain accurate results. Hsu et al. (2021) employed the two-port transmission/reflection line measurement to measure dielectric constants. It uses an adjustable-width line to make self-calibration and improve impedance mismatch. However, the step discontinuity of the connectors of the transmission line affects the accuracy of the measurement.

Method of Open-ended Coaxial Probe

The open-ended coaxial probe method measures the dielectric constant based on the reflection coefficient amplitude and phase (Frabetti et al., 2023). The probe is pressed onto a solid sample or immersed in a liquid sample during the measurement. Dielectric constant measurement based on the coaxial probe method has the potential for biological sensing applications (Zhu,

C., & Huang, J., 2023). Two layers of materials are measured using two coaxial probe sensors with different penetration depths. This method is independent of the measuring sample thickness, but there is an inverse problem with the admittance model. The measurement accuracy is affected by the fringing field, which is not stated in the proposed admittance model.

Split-Ring Resonator

Metamaterial is an artificial material engineered to have specific properties that are not usually found in nature (Açikel et al., 2026). The split-ring resonator (SRR) structure is capable of exhibiting the characteristics of meta-materials (Singh et al., 2021). As shown in Figure 2.1, the SRR and its complementary counterpart CSRR have similar topology -- viz., they consist of two concentric rings with slits at opposite ends. The splits of the SRR increase the electrical energy, and the loops of the SRR store the magnetic energy (Singh et al., 2024). The capacitance and inductance of the SRR structures enable it to operate as an LC resonance circuit.

Dielectric Measurement on SRR-based Sensor

A dual-band SRR-based sensor was proposed for the dielectric measurement of milk (XIN, O. (2022). The proposed SRR sensor has higher sensitivity and better resonance. The dielectric constant can be determined by a numerical model based on the resonance frequency shift. However, the proposed sensor was designed for liquid sample measurements only. Moreover, a microstrip ring resonator is presented for dielectric constant extraction (Walia, G., & Laforge, P. D., 2026). The simulation and measurement results have a good agreement up to 8.5 GHz. Other than that, the CSRR also shows good performance in dielectric constant measurement. A dual split-ring resonator-based sensor was proposed to measure the dielectric constant of the testing sample. The CSRR is integrated in the ground plane of the sensor and loaded with a microstrip line. Dielectric constants can be calculated based on the resonance frequency and magnitude of the CSRR sensor. It is to be noted that only three samples were used in the measurements. In Chuma et al. (2018), the CSRR sensor was used as a sensor to determine both the permittivity and the loss tangent of materials at 22 GHz. The shift of the resonance frequency is correlated to the dielectric constant of the MUT, while the resonant magnitude is dependent on the loss tangent of the materials. The proposed method is non-destructive, economical, and has high accuracy. It is proved by the close agreement between the measurement results and the standard values stated in the datasheet. However, some materials may not be suitable for measurement at this high-frequency range, which is 22 GHz. By characterizing the interrelation between the resonance frequency displacement and dielectric constant, the dielectric properties of materials can be determined by an SRR-based microwave sensor. In order to improve the performance of the dielectric measurement sensors for dielectric constant measurement, a circular and a square SRR-based sensor are proposed in this work. The designed sensors should have a wide measuring range, which involves more testing samples in the measurement. Besides, the measurement setup of the proposed sensors should be simple, and the operating frequency should be appropriate for the material under test (MUT), Buragohain et al., 2023).

Free Space Method

The free space method is suitable for millimeter-wave measurements. Guo et al. (2020) have used the free space method to determine the dielectric constant of liquid crystals in the millimeter-wave range. Calibration is required for this proposed method to enhance the performance of the measurement. Besides, the free space method requires a large sample size for measurements. An improved free space technique was proposed by Pieraccini et al. (2020) to measure the dielectric properties of sawdust. The size of the material used in the measurement was 60 cm x 60 cm.

Yamaguchi and Sato (2019) used a monostatic horn antenna to improve the free-space

measurement. The proposed method was able to improve the complex dielectric constant measurements. In loss tangent measurements, however, the developed method is limited to lossy materials only.

Resonant Method

The resonant method has high accuracy in permittivity and permeability measurements. The resonance frequency and the quality factor of an empty resonant cavity are measured, followed by the measurement of a filled cavity. The dielectric constant is then computed using the frequency and quality factor by a numerical model. A generalized two-step resonant cavity method was proposed by Jha and Akhtar (2018) to measure dielectric constants and loss tangents. The improved method has higher measurement sensitivity. Similarly, a generalized substrate integrated waveguide (SIW) cavity technique was proposed for permittivity measurement by Tiwari et al. (2018). The proposed technique is, however, restricted solely to medium-loss dielectric substrates.

It is to be noted that the resonant cavity measurement requires the sample to be filled inside the cavity. A modified cavity perturbation method was used to reduce the measurement error of a partially filled sample by Li and Li (2021). The improved formula reduces the error to 7% when the volume of the sample is above 50%.

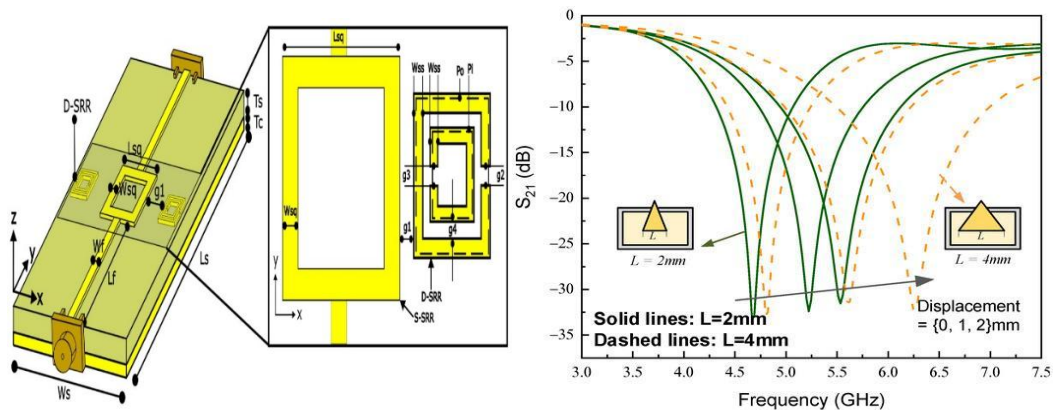
Research Methodology

Two types of SRR-based sensors are proposed for the dielectric constant measurement: one is a circular SRR-based sensor, while the other is a square SRR-based sensor. The dimensions of the SRRs are calculated based on the equations in Ahmed, S. (2025) and XIN, O. (2022), and the designs are then simulated by ANSYS High-Frequency Structure Simulator (HFSS) to get the preliminary results. The finalized designs are fabricated on a Rogers RO3210 substrate, and the experimental measurements are carried out using a vector network analyzer (VNA) for validation purposes. The transmission coefficient, S_{21} parameter for the unloaded sensor and the sensor with different materials under test (MUTs) applied onto it are recorded. Besides, the measurement results of this work are benchmarked with the open-ended coaxial probe method proposed by Khalil et al. (2023). The coaxial probe method has been chosen in this case since it provides sufficiently good accuracy, and the measurement setup is comparatively simple.

Sensors Design

Both the circular and square SRR-based sensors consist of an SRR printed on the top of the substrate and coupled with a CPW transmission line at the bottom. The sensors' resonance frequency depends on the substrate's relative permittivity, substrate thickness, and the dimensions of the SRR ring. Both sensors are printed on a Rogers RO3210 substrate, with a relative permittivity of 10.2, loss tangent of 0.003, and thickness of 1.27 mm.

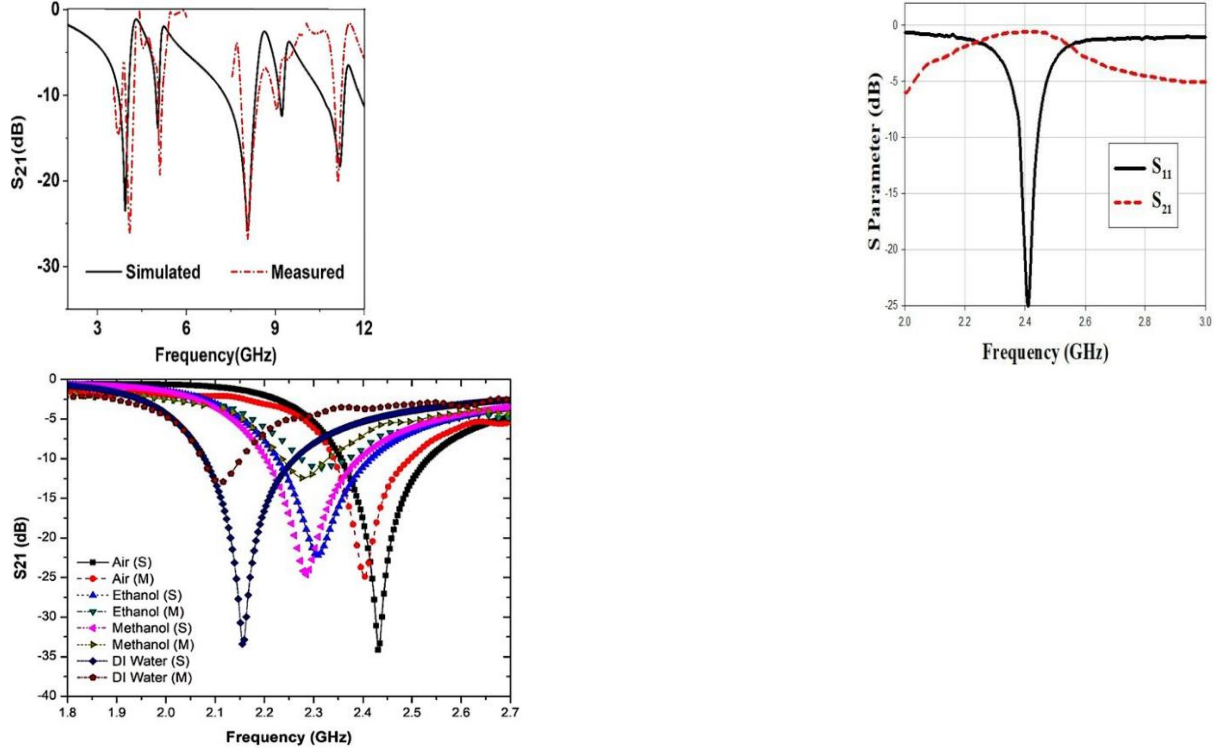
Figure 1: Proposed circular and square SRR Sensor structures



Explanation: These figures have been taken from Ahmed, S. (2025). Dielectric Constant

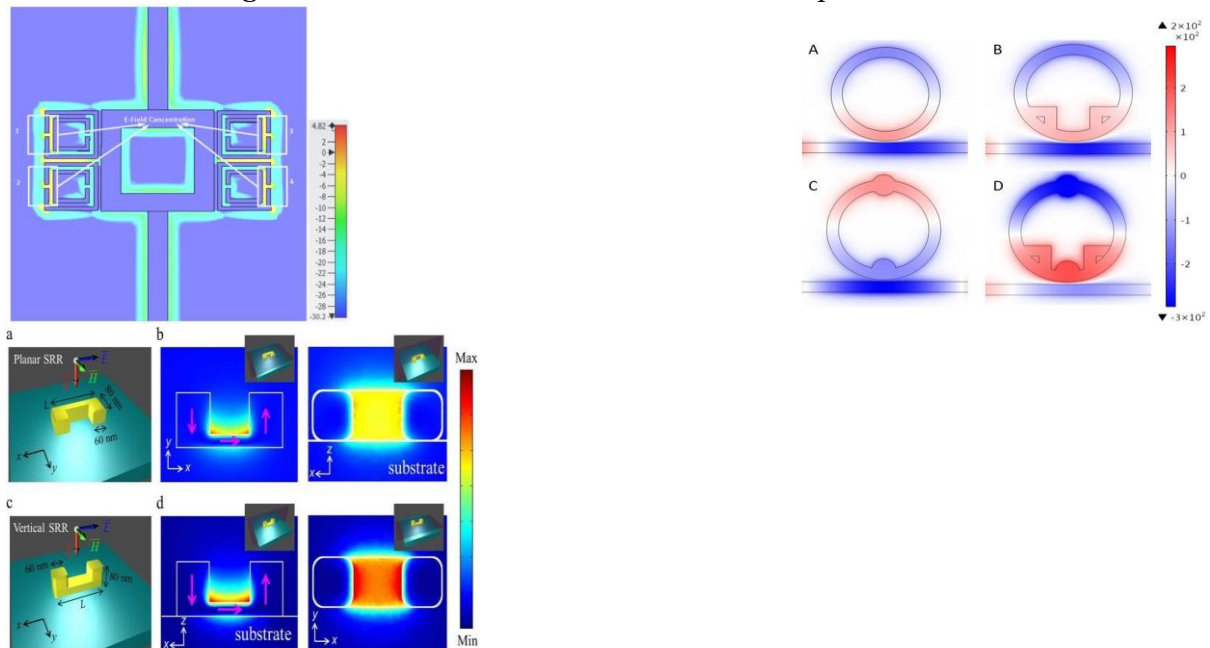
Measurement Sensor Based on SRR Configuration, which presents the geometry of the proposed circular and square SRR-based dielectric sensors. Both sensors are fabricated on Rogers RO3210 substrate with dimensions of 35 mm × 35 mm × 1.27 mm. The CPW transmission line excites the resonator and enables two-port S-parameter measurements.

Figure 2: Simulated S21 Response of Circular and Square SRR Sensors



Explanation: Watson et al. (2015, June) defined the simulated transmission coefficient (S21) response of both sensors, which is shown. The circular SRR resonates at 3.31 GHz, while the square SRR resonates at 2.67 GHz. A deep resonance notch confirms strong electromagnetic coupling and proper resonator operation.

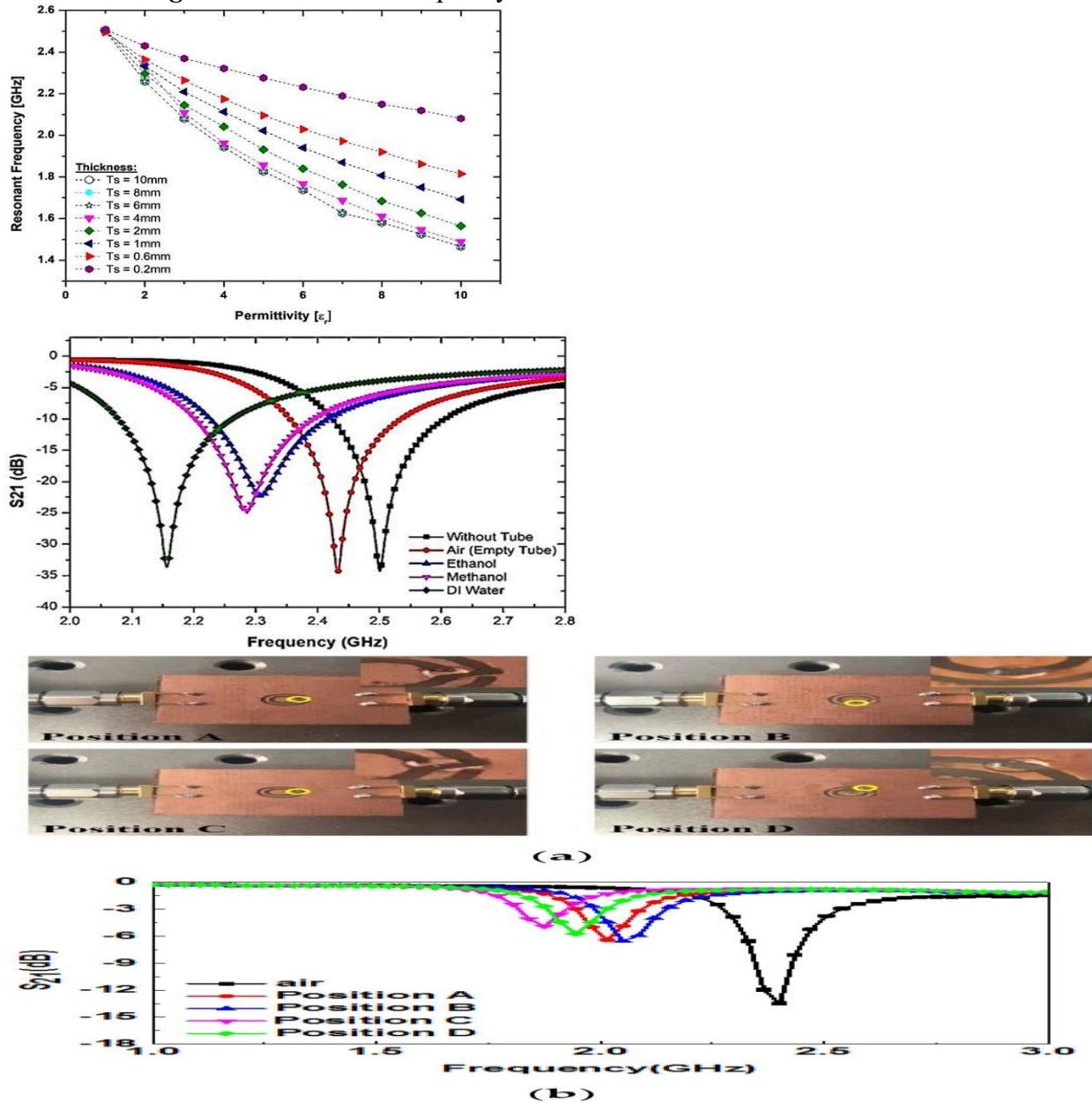
Figure 3: Electric Field Distribution of the Proposed Sensors



Explanation: Figure 3 shows the electric field distribution at the resonance frequency. The

maximum electric field is concentrated around the split gap region of the SRR. This high field confinement enhances the interaction between the resonator and the material under test (MUT), leading to improved dielectric sensitivity (Withayachumnankul et al., 2011).

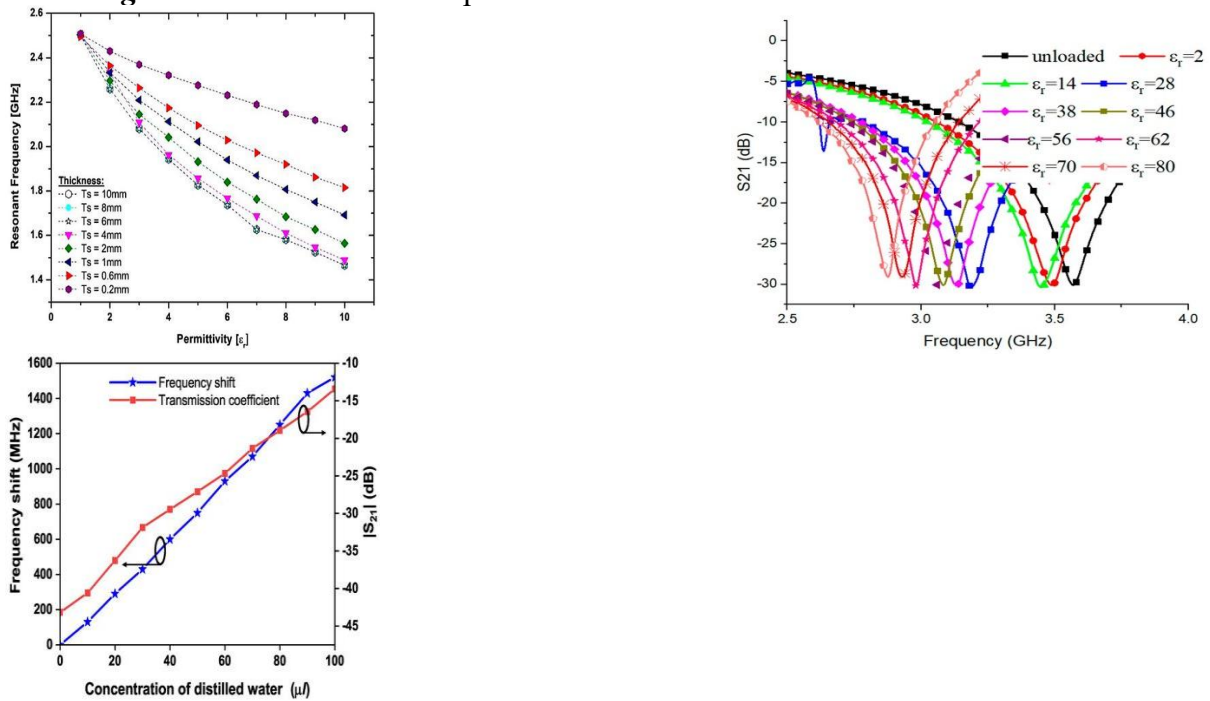
Figure 4: Resonance Frequency Shift with Different MUT Materials



Explanation: Haq et al. 2019 said that when MUT samples are placed on top of the SRR, the resonance frequency shifts toward lower frequencies due to increased effective permittivity. Higher dielectric constant materials produce larger frequency shifts, which are given separately as follows:

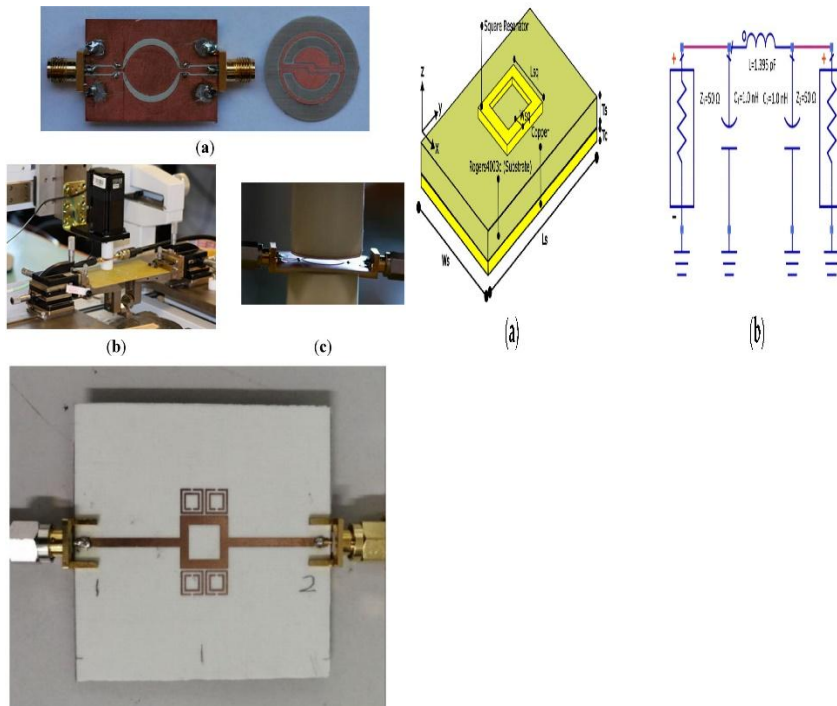
Material	Dielectric Constant	Circular SRR Shift	Square SRR Shift
Air	1.0	3.31 GHz	2.67 GHz
Rogers RT6002	2.94	Slight shift	Slight shift
FR4	4.4	Moderate shift	Moderate shift
Rogers TMM10	9.2	Large shift	Large shift

Figure 5: Linear Relationship between Resonance Shift and Dielectric Constant



Explanation: Ahmed, S. 2025, illustrates the figure above that linear relationship between resonance frequency shift and dielectric constant for both circular and square SRR sensors. A high coefficient of determination (R^2) confirms excellent linearity and reliable dielectric prediction performance. The dielectric prediction equation can be represented as: $\epsilon_r = a(\Delta f) + b$ where ϵ_r is the dielectric constant, and Δf is the resonance frequency shift.

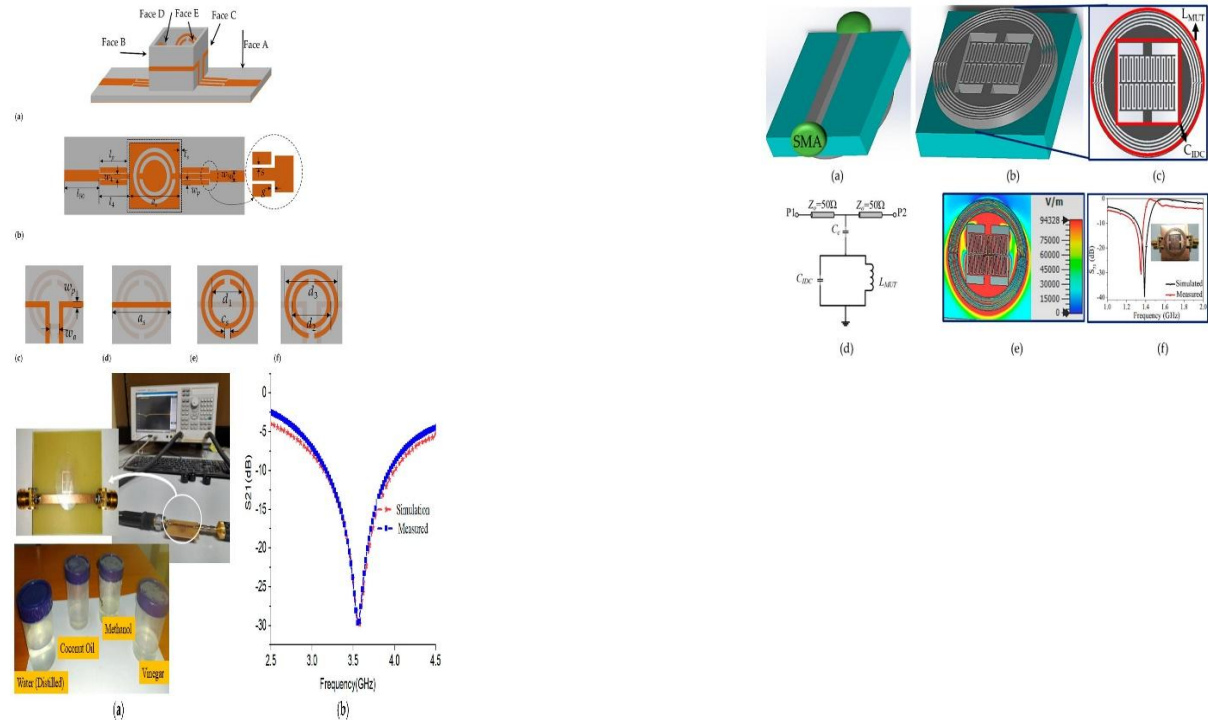
Figure 6: Fabricated Prototype and Experimental Measurement Setup



Explanation: Harnsoongnoen, S. 2019 presented the fabricated sensor prototypes and the experimental measurement setup using a Vector Network Analyzer (VNA). The MUT samples

are placed directly above the SRR region to evaluate the dielectric sensing performance experimentally.

Figure 7: Comparison between Measured and Predicted Dielectric Constants



Explanation: Cao et al. 2024 and Ahmed, S. 2025 predicted that dielectric constants obtained using the linear fitting equations closely match the actual values of Rogers RT6002, FR4, and Rogers TMM10. The small percentage error demonstrates high sensor accuracy and reliability, as shown in the table below.

Material	Actual ϵ_r	Predicted ϵ_r	Error (%)
Rogers RT6002	2.94	2.98	1.36%
FR4	4.4	4.31	2.04%
Rogers TMM10	9.2	9.08	1.30%

Summary of Results

The circular and square SRR designs are simulated by ANSYS HFSS, and they are then fabricated for validation. As shown by the results, the experimental measurements agree well with the simulation results. Both results exhibit a linear relationship between the resonance frequency shift and the dielectric constant, with R^2 above 0.99. The linear equation obtained from the measurement is applied to predict the dielectric constant ϵ_r of Rogers RT6002, FR4, and Rogers TMM10, with standard values of 2.94, 4.4, and 9.2, respectively. For circular SRR measurements, the differences found between the measurement results and the standard dielectric constant for the three substrate materials are 4.76%, 0.45%, and 3.59%, respectively, while the percentage error between the square SRR measurement and the referenced values are 3.40%, 0.00%, and 1.20%.

In conclusion, the proposed SRR-based microwave sensors show high accuracy in measuring MUTs with dielectric constants from 1.5 to 10.2. This research presents an alternative measurement method with the strengths of small size, high sensitivity, and a simple measuring setup.

Research Overview

This research is carried out to design and develop split-ring resonator-based microwave sensors for dielectric constant measurement. Split-ring resonator (SRR) with good electrical properties and good sensitivity towards the surrounding permittivity is implemented in the proposed sensors.

There are two types of SRR sensors proposed in this work, which are circular and square SRR-Based sensors. Both SRRs have a similar footprint and load a CPW transmission line. The proposed sensors are fabricated on the Rogers RO3210 substrate with a relative permittivity of 10.2 and a size of 35 mm x 35 mm x 1.27 mm. The material under test (MUT) is put on the SRR structure to determine the shift of the transmission coefficient resonance. The correlation between the resonance frequency shift and dielectric constant can be explained by a linear regression model. The simulation and measurement results proved that the circular and square SRR sensors have high accuracy in dielectric constant measurements. The SRR-based sensors have the advantages of a small footprint, high accuracy, and non-destructive.

Recommendations

In this work, circular and square SRR-based microwave sensors are proposed to measure the dielectric constant of an unknown material. The working of the proposed sensors is based on the change of resonance frequency with respect to the variation of the dielectric constant ϵ_r of materials. After a thorough study, the recommendations for future work are proposed here.

Future studies should emphasize the impedance matching of the transmission line. The problem of the impedance mismatch may affect the performance of sensors. The efficiency of the SRR-based microwave sensors can be improved by a good return loss, as more power can be delivered from the source to the load. Besides, the measuring range of the proposed sensors can be increased to a higher value, which allows the sensors to measure MUTs with a higher dielectric constant. The orientations of the SRR rings could be adjusted to optimize the performance of the SRR. Moreover, the different shapes of the SRR structure can be implemented into the proposed microwave sensors. The comparison and analysis of the results of different types of SRRs may help to enhance the measurement accuracy, sensitivity, and the overall performance of the proposed sensors.

Conclusion

The proposed circular and square SRR-based dielectric sensors successfully measured dielectric constants with high sensitivity and accuracy. The circular SRR exhibited higher operating frequency and stronger resonance characteristics, while the square SRR showed stable linear behavior. Both sensors demonstrated clear resonance shifts as the dielectric constant of the MUT samples increased. Experimental results validated the simulation outcomes, confirming the effectiveness of the proposed sensors for Microwave dielectric characterization applications.

The conclusions drawn from the findings of the development of split-ring resonator-based sensors are presented. The conclusions are based on the research objectives, problem statement, and the outcomes of the study. Besides, the recommendations are also described in the following section.

References

- Açıkel, C., Helvacı, E., Öner, B. B., & Alp, I. O. (2026). Negative-Refractive-Index Behavior in A Periodic Photonic Metamaterial: Unit-Cell Topology Tailoring for Broadband Response. *Journal of the European Optical Society-Rapid Publications*, 22(1), 20. <https://doi.org/10.1051/jeos/2026018>
- Ahmed, S. (2025). Dielectric Constant Measurement Sensor Based on SRR Configuration. *Academic Journal of Electrical and Computer Engineering*, 1(02), 45-

50. <https://doi.org/10.31272/ajece.28>
- Al-Behadili, A. A., Mocanu, I. A., Codreanu, N., & Pantazica, M. (2020). Modified Split Ring Resonators Sensor For Accurate Complex Permittivity Measurements of Solid Dielectrics. *Sensors*, 20(23), 6855. <https://www.mdpi.com/1424-8220/20/23/6855>
- Albishi, A. M., Alshebeili, S. A., & Ramahi, O. M. (2021). Three-dimensional Split-Ring Resonators-Based Sensors For Fluid Detection. *IEEE Sensors Journal*, 21(7), 9138-9147. <https://ieeexplore.ieee.org/abstract/document/9335054/>
- Alrayes, N., & Hussein, M. I. (2021). Metamaterial-based Sensor Design Using Split Ring Resonator and Hilbert Fractal for Biomedical Application. *Sensing and Bio-Sensing Research*, 31, 100395. <https://doi.org/10.1016/j.sbsr.2020.100395>
- Buragohain, A., Das, G. S., Beria, Y., Kalita, P. P., & Mostako, A. T. T. (2023). Highly Sensitive DS-CSRR-Based Microwave Sensor for Permittivity Measurement of Liquids. *Measurement Science and Technology*, 34(12), 125134. <https://iopscience.iop.org/article/10.1088/1361-6501/acf336/meta>
- Cao, L., Meng, F., Özdemir, E., Loth, Y., Richter, M., Wigger, A. K., & Roskos, H. G. (2024). Interdigitated Terahertz Metamaterial Sensors: Design with the Dielectric Perturbation Theory. *Photonics Research*, 12(6), 1115-1128. <https://opg.optica.org/prj/fulltext.cfm?uri=prj-12-6-1115>
- Chuma, E. L., Iano, Y., Roger, L. B., & Fontgalland, G. (2018, August). Using Metamaterial Complementary Split-Ring Resonators for Measuring Dielectric Constants and Loss Tangents at 22 GHz. In *2018, the 3rd International Symposium on Instrumentation Systems, Circuits and Transducers (INSCIT)* (pp. 1-5). IEEE. <https://ieeexplore.ieee.org/abstract/document/8546699>
- Fontana, N., Canicattì, E., & Monorchio, A. (2019, July). An Application of the Virtual Transmission Line Model of an Open-Ended Coaxial Probe for Dielectric Properties Characterization Of Biological Tissues. In *2019, IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting* (pp. 341-342). IEEE. <https://ieeexplore.ieee.org/abstract/document/8888294>
- Frabetti, A. C. C., Garnault, T., Curto, H., Thillier, A., Boillereaux, L., Rouaud, O., & Curet, S. (2023). Dielectric Properties of Low Moisture Foods Measured By Open-Ended Coaxial Probe and Cavity Perturbation Technique. *European Food Research and Technology*, 249(11), 2861-2873. <https://link.springer.com/article/10.1007/s00217-023-04333-7>
- Guo, C., Wang, H., & Fan, S. (2020). Squeeze free space with nonlocal flat optics. *Optica*, 7(9), 1133-1138. <https://doi.org/10.1364/OPTICA.392978>
- Haq, T. U., Ruan, C., Zhang, X., & Ullah, S. (2019). Complementary Metamaterial Sensor for Nondestructive Evaluation of Dielectric Substrates. *Sensors*, 19(9), 2100. <https://www.mdpi.com/1424-8220/19/9/2100>
- Harnsoongnoen, S. (2019). Microwave Sensors Based on Coplanar Waveguide Loaded with Split Ring Resonators: A Review. *Applied Science and Engineering Progress*, 12(4), 224-234. <https://ph02.tci-thaijo.org/index.php/ijast/article/view/232469>
- Hsu, Y. W., Shen, S. J., Chen, C. A., Qiu, S. H., & Chen, H. H. (2021, October). Broadband Measurement of Dielectric Constant on FR-4 PCB by Using Discontinuous Microstrip Lines. In *2021 International Symposium on Antennas and Propagation (ISAP)* (pp. 1-2). IEEE. <https://ieeexplore.ieee.org/abstract/document/9614543>
- Islam, M. R., Islam, M. T., Hoque, A., Bais, B., Alsaif, H., Islam, M. S., & Soliman, M. S. (2025). Quad-Band Split Ring Resonator-Based Sensor for Microwave Sensing Application. *Scientific Reports*, 15(1), 6888. <https://www.nature.com/articles/s41598-025-90245-3>

- Islam, M. R., Islam, M. T., M M. S., Bais, B., Almalki, S. H., Alsaif, H., & Islam, M. S. (2022). Metamaterial Sensor Based On Rectangular Enclosed Adjacent Triple Circle Split Ring Resonator with Good Quality Factor for Microwave Sensing Application. *Scientific reports*, 12(1), 6792. <https://www.nature.com/articles/s41598-022-10729-4>
- Javed, A., Arif, A., Zubair, M., Mehmood, M. Q., & Riaz, K. (2020). A low-cost Multiple Complementary Split-Ring Resonator-Based Microwave Sensor for Contactless Dielectric Characterization of Liquids. *IEEE Sensors Journal*, 20(19), 11326-11334. <https://ieeexplore.ieee.org/abstract/document/9102273>
- Jha, A. K., Tiwari, N. K., & Akhtar, M. J. (2018). Novel Microwave Resonant Technique for Accurate Testing of Magnetic Materials. *IEEE Transactions on Microwave Theory and Techniques*, 67(1), 239-248. <https://ieeexplore.ieee.org/abstract/document/8574994>
- Khalil, M. A., Yong, W. H., Islam, M. T., Hoque, A., Islam, M. S., Leei, C. C., & Soliman, M. S. (2023). Retracted Article: Double-Negative Metamaterial Square Enclosed QSSR for Microwave Sensing Application in S-Band with High Sensitivity and Q-factor. *Scientific Reports*, 13(1), 7373. <https://www.nature.com/articles/s41598-023-34514-z>
- Li, Y., Li, H., Xiao, Y., Cao, L., & Guo, Z. S. (2021). A Compensation Method for Nonlinear Vibration of Silicon-Micro Resonant Sensor. *Sensors*, 21(7), 2545. <https://www.mdpi.com/1424-8220/21/7/2545>
- Liu, X., Peng, L., Liu, Y. F., Yu, W. S., Zhao, Q. X., Jiang, X., & Ruan, C. (2020). Ultrabroadband all-Dielectric Transmitarray Designing Based on Genetic Algorithm Optimization and 3-D Print Technology. *IEEE Transactions on Antennas and Propagation*, 69(4), 2003-2012. <https://ieeexplore.ieee.org/abstract/document/9210882>
- Liu, Y., Liu, J., Xia, H., Zhang, X., Fontes-Garfias, C. R., Swanson, K. A., & Shi, P. Y. (2021). Neutralizing Activity of BNT162b2-elicited Serum. *New England Journal of Medicine*, 384(15), 1466-1468. <https://www.nejm.org/doi/full/10.1056/NEJMc2102017>
- Masrakin, K., Ibrahim, S. Z., Rahim, H. A., Azemi, S. N., Soh, P. J., & Tantivivat, S. (2023). Microstrip Sensor Based on Ring Resonator Coupled With Double Square Split Ring Resonator For Solid Material Permittivity Characterization. *Micromachines*, 14(4), 790. <https://www.mdpi.com/2072-666X/14/4/790>
- Mishra, P., Singh, B. P., & Agrawal, V. V. (2024). Deciphering Split Ring Resonators: Understanding Theoretical Validation and Simulation Implications. *Engineering Research Express*, 6(3), 035319. <https://ieeexplore.ieee.org/abstract/document/9127130>
- Pieraccini, S. (2020). Uncertainty Quantification Analysis in Discrete Fracture Network Flow Simulations. *GEM-International Journal on Geomathematics*, 11(1), 12. <https://link.springer.com/article/10.1007/s13137-020-0148-0>
- Samanta, S. K., Pradhan, R., & Syam, D. (2021). Theoretical Approach to Verify the Resonance Frequency Of A Square Split Ring Resonator. *Journal of the Optical Society of America B*, 38(10), 2887-2897. <https://opg.optica.org/josab/abstract.cfm?uri=josab-38-10-2887>
- Sato, Y., Atarashi, K., Plichta, D. R., Arai, Y., Sasajima, S., Kearney, S. M., & Honda, K. (2021). Novel Bile Acid Biosynthetic Pathways are Enriched in The Microbiome of Centenarians. *Nature*, 599(7885), 458-464. <https://www.nature.com/articles/s41586-021-03832-5>
- Simonsohn, U., Simmons, J. P., & Nelson, L. D. (2015). Better P-curves: Making P-curve Analysis More Robust to Errors, Fraud, And Ambitious P-Hacking, a Reply to Ulrich

- and Miller (2015). <https://psycnet.apa.org/buy/2015-53127-004>
- Singh, N., Khan, T., Kumar, S., Kanaujia, B. K., Choi, H. C., Kim, K. W., & Kishk, A. A. (2024). Ultra-Thin Flexible Rectenna Integrated With Power Management Unit for Wireless Power Harvester/Charging of Smartwatch/Wristband. *Scientific Reports*, 14(1), 7447. <https://www.nature.com/articles/s41598-024-57639-1>
- Tiwari, N. K., Singh, S. P., & Akhtar, M. J. (2018). Novel Improved Sensitivity Planar Microwave Probe for Adulteration Detection in Edible Oils. *IEEE Microwave and Wireless Components Letters*, 29(2), 164-166. <https://ieeexplore.ieee.org/abstract/document/8595436>
- Walia, G., & Laforge, P. D. (2026). Reflected Group Delay of a Capacitively Coupled Resonator for Characterization of Dielectric Constant and Loss Tangent of Microstrip Substrates. *IEEE Access*. <https://ieeexplore.ieee.org/abstract/document/11394772>
- Wang, C., Wang, Z., Wang, G., Lau, J. Y. N., Zhang, K., & Li, W. (2021). COVID-19 in early 2021: Current Status and Looking Forward. *Signal transduction and targeted therapy*, 6(1), 114. <https://www.nature.com/articles/s41392-021-00527-1>
- Watson, A. M., Padilla, A., Holloway, C. L., Bright, V. M., & Booth, J. C. (2015, June). High-Q on-chip Microwave Resonator for Sensitive Permittivity Detection in Nanoliter Volumes. In *2015, Transducers-2015 18th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS)* (pp. 1665-1668). IEEE. <https://ieeexplore.ieee.org/abstract/document/7181262>
- Withayachumnankul, W., Fumeaux, C., & Abbott, D. (2011). Metamaterial-Inspired Multichannel Thin-Film Sensor. *IEEE Sensors Journal*, 12(5), 1455-1458. <https://ieeexplore.ieee.org/abstract/document/6062377>
- Wu, W. J., & Zhao, W. S. (2022). A Quality Factor Enhanced Microwave Sensor Based on Modified Split-Ring Resonator For Microfluidic Applications. *IEEE Sensors Journal*, 22(23), 22582-22590. <https://ieeexplore.ieee.org/abstract/document/9928055>
- XIN, O. (2022). Design and Development of Split-Ring Resonator-Based Sensors for Dielectric Constant Measurement. http://eprints.utar.edu.my/5161/1/fyp_EIA_2022_OZX.pdf
- Xu, K., Liu, Y., Chen, S., Zhao, P., Peng, L., Dong, L., & Wang, G. (2018). Novel Microwave Sensors Based on Split Ring Resonators for Measuring Permittivity. *IEEE Access*, 6, 26111-26120. <https://ieeexplore.ieee.org/abstract/document/8356624>
- Yamaguchi, Y., & Sato, Y. (2019). Error Reduction Processes Using Multiple Measurements and Numerical Analysis for Complex Dielectric Constant Measurement with Monostatic Horn Antenna. *Measurement Science and Technology*, 30(4), 045013. <https://iopscience.iop.org/article/10.1088/1361-6501/ab05b5/meta>
- Ye, W., Wang, D. W., Wang, J., Wang, G., & Zhao, W. S. (2022). An Improved Split-Ring Resonator-Based Sensor for Microfluidic Applications. *Sensors*, 22(21), 8534. <https://www.mdpi.com/1424-8220/22/21/8534>
- Zhu, C., & Huang, J. (2023). Coaxial Cable Sensing: Review and Perspective. *IEEE Transactions on Microwave Theory and Techniques*, 72(3), 1790-1809. <https://ieeexplore.ieee.org/abstract/document/10229976>