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A High *Q*-Factor Microwave Sensor Based on Metamaterial Structure for Solid Characterization

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ABSTRACT

This study introduces the conceptual development and evaluation of a microwave sensor based on a split ring resonator as a metamaterial structure, aimed at achieving enhanced *Q*-factor for solid characterization. The proposed configuration utilizes the resonant characteristic inherent to metamaterials and exploits the substantial coupling between electromagnetic fields to facilitate high *Q*-factor deriving sharp resonance at 2.16 GHz for solid detection. The suggested sensor is simulated in HFSS software for common substrates used in antenna fabrication, such as FR-4 and Rogers. The results demonstrate that variations in the different dielectric constant and height of solid under test (SUT) cause corresponding shifts in the resonant frequency. Due to the high *Q*-factor, this design provides widespread applications like new material detection and quality control processes industries. The *Q*-factor of proposed sensor is 42.2 at 2.16 GHz. In addition, the sensor sensitivity and dimensions are 1.63%, $0.28\lambda_0 \times 0.28\lambda_0 \times 0.02\lambda_0$ where λ_0 indicates the wavelength in free space, respectively.

1 | Introduction

In recent years, microwave sensors have been widely used in various industries, including healthcare for non-invasive diagnostics [1, 2], agriculture for soil moisture measurement [3], food industry [4] and dielectric detection [5]. Quantitative analysis of permittivity profiles and associated electromagnetic field behaviours in single and multi-layered structures [6–8] remains a critical area of scientific investigation. The relative permittivity of solid and liquid materials can be characterized through various measurement techniques such as metamaterial structure [9], optical method [10], microwave sensor [11] and magnetic induction [12]. Metamaterial-based permittivity measurement techniques utilize subwavelength artificial structures exhibiting engineered electromagnetic properties like negative refractive index or near-zero permittivity to achieve superior field confinement and sensitivity [13]. Metamaterials have been extensively applied in fields ranging from graphene electronics [14] to telecommunications, where their implementation in MIMO antenna systems [15–17]. In addition, Spectroscopic ellipsometry and THz time-domain spectroscopy have emerged as powerful tools for non-invasive dielectric characterization, resolving complex permittivity with femtosecond temporal resolution and micrometer spatial precision across the optical spectrum [18]. Meanwhile, magnetic induction-based characterization techniques derive complex permittivity values in conductive media by analysing frequency dependent eddy-current perturbations, typically implemented through synchronized impedance analyser measurements from 0.1 to10 MHz [19].

Unlike low frequency capacitive methods, microwave sensor approaches including microstrip ring resonators such as split ring resonator (SRR), complimentary split ring resonator (CSRR) and cavity perturbation techniques [20, 21] enable broadband

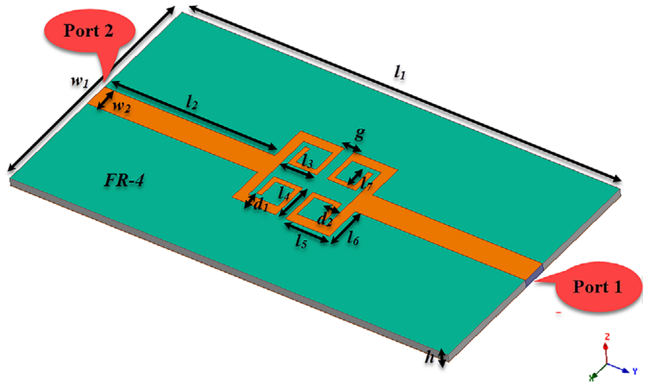

FIGURE 1 | The planar view of the sensor. l1 = 90 mm, l2 = 35 mm, l3 = 6 mm, l4 = 8 mm, l5 = 9 mm, l6 = 7.5 mm, l7 = 5 mm, w1 = 50 mm, w2 = 5 mm, d1 = 1 mm, d2 = g = 2 mm, h = 1.6 mm.

dielectric characterization with enhanced sensitivity to both real and imaginary permittivity components at GHz frequencies. SRRs and CSRRs both improve microwave sensor sensitivity but differ in operation. SRRs respond to frequency shifts, while CSRRs react to transmission zeros, enabling tailored material analysis. Transmission line and SRR coupling makes electromagnetic hot spots via field confinement, dramatically boosting *Q*-factor, sensor sensitivity and detection capability [22]. Microwave frequency metamaterial sensors offer an economical platform for wireless, non-destructive, contactless and real-time detection applications. Illustrated implementations include biological analyte monitoring like glucose [23], chemical substance analysis for instance, ethanol, methanol [19] with *Q*-factor 31, 19.34 and sensitivity of 0.2%, 1.37% at 2.45 GHz and 4.5 GHz, respectively.

The suggested sensor demonstrates multifunctional capabilities, with primary application in precise permittivity characterization of solid materials especially dielectric substrates, which is a crucial parameter in antenna fabrication. The sensor exhibits a sensitivity of 1.63%, with a *Q*-factor of 42.2 at 2.11 GHz.

2 | Sensor Design

The broad applicability of microwave sensors in industries necessitates enhancements in *Q*-factor, sensitivity and miniaturization to meet evolving performance requirements. The proposed sensor structure, illustrated in Figure 1, incorporates two meandered line

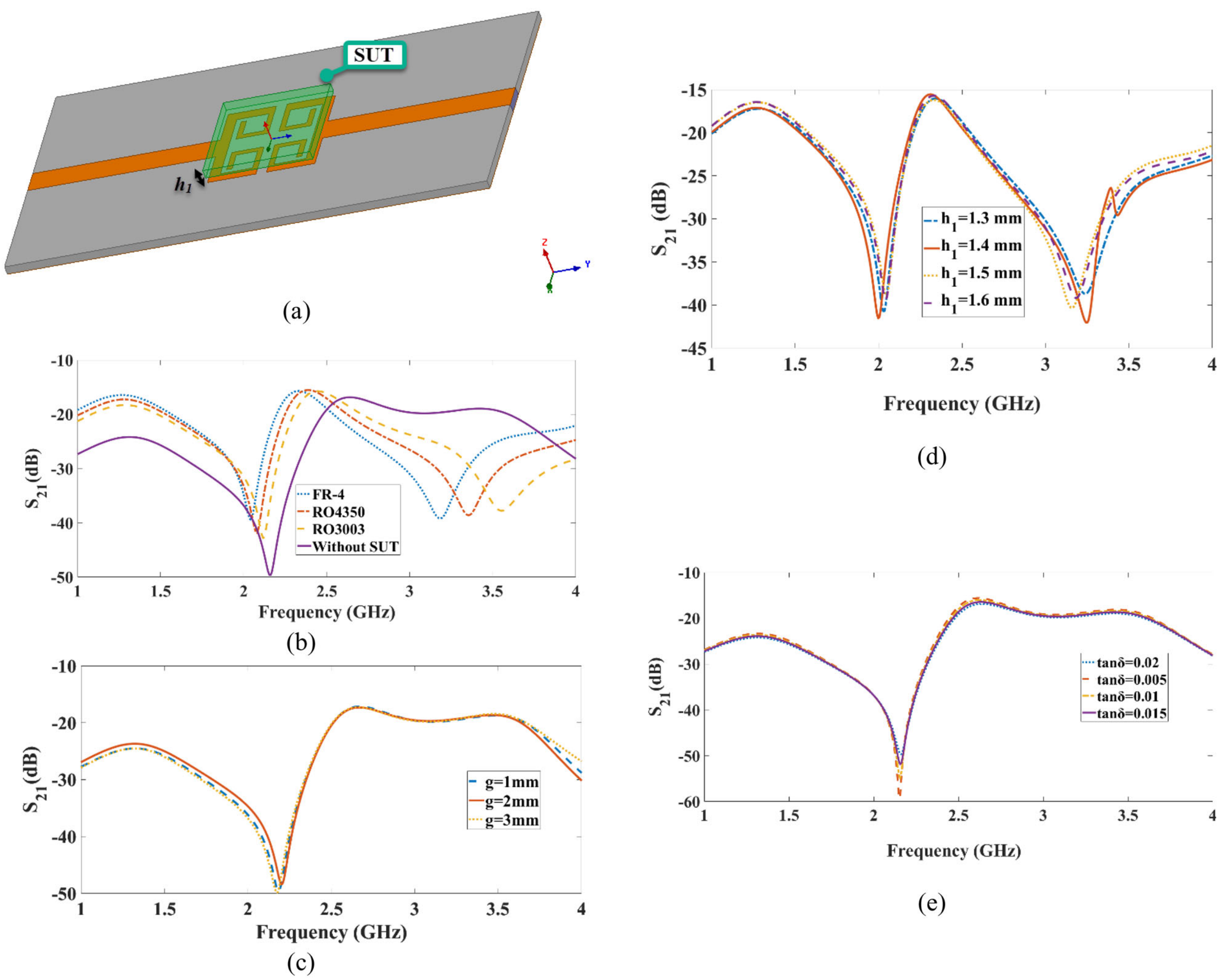

FIGURE 2 | (a) Sensor design with SUT; (b) Influence of SUT on S_{21} (dB); (c) Gap effect on S_{21} (dB); (d) SUT thickness effect on S_{21} (dB); (e) Substrate tanδ effect.

resonators (dimensions specified in Figure 1), terminated with 50 Ω SMA connectors serving as the sensor feed. Two parallel metamaterial elements arranged in line with the transmission lines. The gap between the meandered line SRR assess the capacitance, while the SRR lengths define inductances. Proposed sensor from top to bottom consists of three layers of SRR layer, substrate and ground, respectively. The design utilizes FR-4 substrate ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$), selected for its cost-effectiveness and suitable dielectric properties.

3 | Simulation Results and Discussion

The placement of the SUT on the sensor surface is demonstrated in Figure 2a. Figure 2b presents the S_{21} parameter evaluation for materials with ε_r = 3, 3.66, 4.4 and $\tan\delta$ = 0.0013, 0.004, 0.02, demonstrating resonant frequency shifts proportional to permittivity variations. As illustrated in Figure 2c, the effects of gap variations were investigated, confirming their significance in capacitor specification definition and energy storage functionality. Furthermore, Figure 2d reports the transmission characteristics of the proposed sensor across varying SUT thicknesses.

Moreover, as illustrated in Figure 2e, reducing the loss tangent sharpens the resonance null, thereby enhancing the quality factor of the sensor. This improvement occurs because lower dielectric losses minimize energy dissipation, resulting in a more pronounced and stable resonant response.

A positive relationship between stored energy and *Q*-factor is derived in Equation (1), confirming that energy storage enhancement elevates quality factor [25]. The terms f_{unloaded}, $f_{\varepsilon r}$ and f_0 denote the sensor's resonant frequency without SUT, with SUT and the bandwidth's centre frequency, respectively. Increasing permittivity yields greater Δf, leading to improved *Q*-factor and sensitivity per Equation (3), with results validated in Figure 2b.

TABLE 1 | *Q*-factor and sensitivity according to various SUT.

Material	Permittivity	Loss tangent	*Q*-factor	Sensitivity (%)
FR-4	4.4	0.02	40.8	1.63
RO 4350	3.66	0.0037	41.6	1.39
RO 3003	3	0.0013	42.2	1.15
Without SUT	1	—	43.2	—

$$Q = \frac{f_0}{\text{BW}_{3\text{dB}}} = \frac{1}{R}\sqrt{\frac{L}{C}} = 2\pi f_r \times \frac{\text{energystored}}{\text{powerloss}} \quad (1)$$

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (2)$$

$$S = \frac{f_{\text{unloaded}} - f_{\varepsilon_r}}{f_{\text{unloaded}}(\varepsilon_r - 1)} \quad (3)$$

Table 1 presents the measured quality factors and sensitivities, which exhibit dependencies on resonance frequency and SUT properties as derived in Equations (1)–(3).

The E-field distribution which has demonstrated in Figure 3 reveals the sensor's performance under 1 W excitation and unloaded resonator condition, achieving 1.5×10^4 V/m peak intensity at 2.16 GHz. This aligns with the SRR-metamaterial coupling described in Equation (1), where energy conservation and

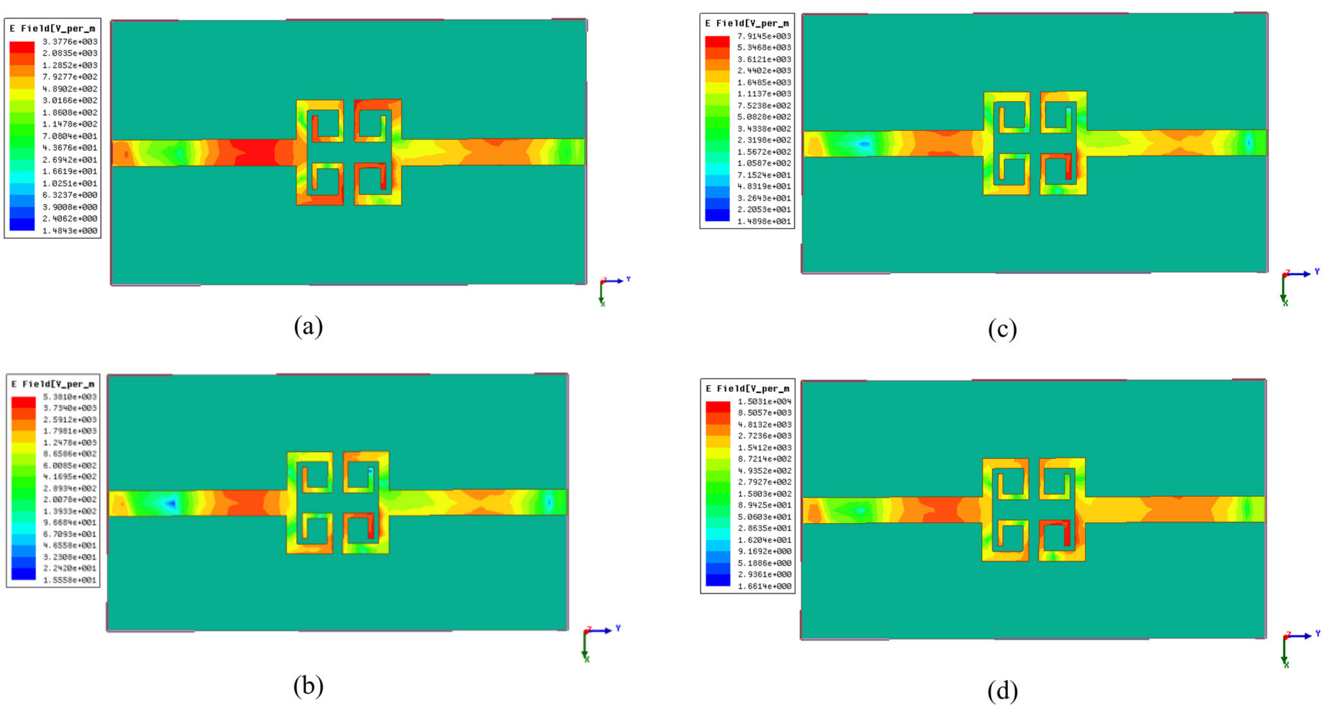

FIGURE 3 | The E-field distribution of suggested sensor. (a) f = 2.04 GHz; (b) f = 2.08 GHz; (c) f = 2.11 GHz; (d) f = 2.16 GHz.

TABLE 2 | Comparison of suggested sensor with pervious works.

Ref.	Size ($\lambda_0{}^3$)	Freq. (GHz)	Q-factor	Sensitivity (%)
[22]	0.28 × 0.2 × 0.02	4.5	19.34	1.37
[23]	0.31 × 0.24 × 0.09	2.45	31	0.2
[26]	0.65 × 24 × 0.02	5.515	11.278	1
This work	0.28 × 0.28 × 0.02	2.16	42.2	1.63

Q-factor improvement are achieved through engineered shielding effects.

Comparative analysis in Table 2 evaluates the proposed sensor improvements over existing designs in miniaturization, frequency operation, Q-factor, sensitivity.

4 | Conclusion

This work presents a microwave sensor based on SRR metamaterials, comprising two meandered line resonators coupled in parallel and fed by 50 Ω SMA ports in a line with transmission lines. The design employs an FR-4 substrate positioned between the ground plane and SRR layer. Full-wave electromagnetic simulations in HFSS validated the sensor's performance, supplemented by parametric studies quantifying the influence of geometric dimensions on resonant characteristics. Comparative analysis in Table 2 depicts a significant improvement in Q-factor over previously reported microwave sensors. High Q-factor sensors are indispensable for applications demanding accuracy, low noise and minimal energy loss.

Author Contributions

Mahdi Ghafourivayghan: conceptualization, methodology, software, formal analysis, validation, investigation, data curation, writing – original draft preparation, writing – review & editing. **Sergey Shabunin:** formal analysis, validation, investigation, data curation, writing – review & editing, supervision, funding acquisition. **Mohammad Alibakhshikenari:** conceptualization, resources, supervision, methodology, writing – review & editing, project administration, funding acquisition. **Patrizia Livreri:** validation, writing – review & editing, data curation. **Takfarinas Saber:** conceptualization, conceptualization, methodology, software, visualization, writing – review & editing, supervision.

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The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data available on request from the authors.

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