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Microwave Differential CSRR Sensor for Liquid Permittivity Measurement

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Abstract
In this work, we propose a differential complementary split-ring resonator (CSRR) sensor as the resonating element for permittivity analysis of liquid samples. In comparison to conventional non-differential sensors, differential sensors are found to be immune to environmental changes. The proposed sensor operates at 2.35 GHz of the ISM band and is built on a low-cost FR4 substrate. The sensor is thoroughly optimized and validated using Ansys High Frequency Structure Simulator software. Multiple liquid samples covering a wide dielectric range of 1–111 are used to determine the sensing performance of the sensor. The sensitivity of the sensor is found to be high and on par with recent works related to differential CSRR sensors. Based on the frequency of the transmission notch observed, a fit equation is developed to determine the dielectric constant of unknown samples. The proposed differential sensor promises to be a good alternative to traditional CSRR sensors for requirements involving noise and atmospheric fluctuations.

Keywords Differential complimentary split-ring resonator · sensitivity · transmission notch · complex permittivity

Introduction

Knowledge of the complex permittivity of a material is of utmost importance for understanding the behavior of the material when subjected to an electric field. The dielectric constant may be related to other physical and chemical properties of the material as well. As such, sensors capable of measuring the dielectric constant of materials are in high demand, especially in the field of material science.

Over the years, various techniques have been proposed and used to investigate the dielectric properties of materials.[1,2] However, due to the simplicity of design, low manufacturing cost, ease of sample preparation, and the possibility of miniaturization, the resonance method has gained more popularity among the scientific community.[3] The basic principle of the resonance method is to design a resonator into which the liquid under test (LUT) is introduced such that the LUT due to its dielectric property perturbs the electric field of the resonator. The perturbation causes a change in the resonant frequency of the resonator, and by carefully studying the shift in the resonant frequency with the dielectric constant of the LUT, the sensor can be calibrated to measure the dielectric constant of an unknown sample with high accuracy. Using this principle, planar microwave resonator sensors have become the new point of interest among researchers for material characterization. Planar resonator sensors are low-cost, compact, easy to fabricate, highly accurate, simple in design, and need no sample modification to fit in the resonator.[4] Over the years, different techniques and configurations have been implemented as the sensing element of the planar sensor including the split-ring resonator (SRR) and complementary SRR (CSRR). The SRR is a pair of concentric annular rings with a split in them. The CSRR has been validated by Falcone[5] and explained by Babinet's principle. As reported in previous works, the implementation of CSRRs has been able to deliver better sensitivity compared to SRRs.[6–9] A CSRR in general increases the capacitive effect of the sensor as compared to an SRR, increasing the fringing electric field and hence better interaction with the test sample.

Although SRRs and CSRRs offer great sensitivity, in both configurations the variation of the results due to the changing environmental conditions (temperature, humidity moisture, etc.) or cross-sensitivity are not taken into account, leaving behind an important issue of concern unattended

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in most of the reported works. This creates unintentional resonant frequency shifts leading to errors in sensing.[10,11] To counter this problem, researchers have opted for a differential sensing technique. In its basic form, the differential sensor is made up of two sensing elements, such as two loaded transmission lines, with one of them serving as the reference for the other.[12] A transmission line must be symmetrically loaded or coupled with a pair of resonator elements for a sensor to be considered a true differential sensor.[13–15] In these sensors, under perfect symmetry conditions, the whole structure exhibits a single resonant frequency and transmission zero line. On introducing any asymmetry, notches at two different frequencies are observed, out of which one of them is at the original position corresponding to the symmetrical condition. This can be done by loading one of the resonators with the LUT while keeping the other unloaded. The degree of frequency difference between the two notches will depend on the asymmetry produced by the LUT and hence on the permittivity of the LUT. Since, due to any environmental perturbations, the resonant frequency corresponding to both the loaded and unloaded sensing element is going to change equally, any environmental effect can be automatically nullified. Based on this fact, Ebrahimi et al.[16] proposed an SRR-based differential sensor for permittivity measurement of solid samples. In this work, one of the resonators is loaded with a pure sample (to be taken as the reference), and the other is loaded with a defective sample. The solid samples are placed in such a way that the resonators are covered perfectly so that cross-coupling can be eliminated. Another work proposed differential sensors with stepped impedance resonators (SIRs).[17] In this work, two simple strategies for the development of differential sensors are proposed. The resonators for the differential sensor are placed in parallel and cascade connections. The authors have also provided the idea of extracting the permittivity as well as loss tangent of the samples with a theoretical study.

In this work, a CSRR differential sensor operating at 2.35 GHz of the industrial, scientific, and medical (ISM) band has been proposed for the permittivity characterization of LUTs. The sensor consists of two resonator elements placed in a differential arrangement, each of which consists of two concentric rings with splits in the opposite ends for high electric field concentration. The two resonators are excited by a common feedline, which is designed to transfer power without any lag so that a common transmission notch is observed under unloaded conditions. Also, the resonator elements are placed to maintain a certain distance between them to avoid coupling of the fringing field of one resonator with the other. The proposed sensor possesses a sharp and deep notch (~ 35 dB) of transmission coefficient and a high quality factor (above 200) for permittivity measurement. Samples with a very wide permittivity range of 1–111 have been used for the sensor's applicability and usability. The performance of the proposed sensor makes it a potential candidate for sensing applications which involve disturbances from environmental conditions.

Basic Principle and Design

The operating principle for a differential sensor is primarily the same as that of traditional SRRs and CSRRs. These resonators store high concentrations of an electric field at resonance behaving like a parallel resonant circuit consisting of an inductor, capacitor, and resistor of specific values. Now, if a dielectric material is allowed in the proximity of the resonator, both the capacitance and the resistance of the resonant circuit changes. This leads to the decrease of the resonant frequency (for the increase in capacitance) and the magnitude of the frequency notch. Materials with higher dielectric constant contribute to a large frequency shift and higher loss. Thus, using this principle, planar microwave resonant sensors are designed and developed using this principle. This physical phenomenon can be explained mathematically by using the perturbation equation shown below.[18,19]

$$\frac{\Delta f_{\mathrm{r}}}{f_{\mathrm{r}}} = \frac{\int_{v} \left(\Delta\varepsilon E_1 \cdot E_0 + \Delta\mu H_1 \cdot H_0\right) \mathrm{d}v}{\int_{v} \left(\varepsilon_0 |E_0|^2 + \mu_0 |H_0|^2\right) \mathrm{d}v} \tag{1}$$

This equation shows that there will be a change in the resonant frequency for any change in ε or μ from the unperturbed condition, where Δf_{r} is the resonant frequency shift, $\Delta\epsilon$ is the change in permittivity, $\Delta\mu$ is the change in the permeability, and v is the perturbed volume. E_0 and H_0 are the unperturbed fields, and E_1 and H_1 are the perturbed field distributions. Equation 1 can be obtained by using Maxwell's equations (Faraday's law of electromagnetic induction and Ampere's law) for electromagnetic fields. As such, in quasi-static resonators, a ring or loop structure behaves like an inductor because of the circulating current around the loop, generating a magnetic field. Also, a gap in the loop leads to a high concentration of electric field, thereby behaving like a capacitor. This is the basic structure of an SRR. The complementary metallic negative image of an SRR is the CSRR, in which the ring is etched from the substrate, and the gap in the loop is now a perfect line. Hence, in a CSRR, the gap behaves like an inductor, and the etched ring behaves like a capacitor. Therefore, a CSRR is more sensitive towards a dielectric material than an SRR, as it has distributed capacitance all around its perimeter. This is why for dielectric characterization the CSRR is preferred over SRR due to its large area sensitive to capacitance.

Dimension and Equivalent Circuit

The sensor was designed on an FR4 board of 1.6 mm thickness with a loss tangent of 0.03. Using standard equations available in the work by Pozar,[19] the sensor and ring dimensions were calculated for a 50 Ω transmission line. The sensor was designed, simulated, and optimized using Ansys High Frequency Structure Simulator (HFSS)[20] for the intended performance. From extensive simulation, an outer substrate dimension of 52×30 mm^2 was found to be best suited for the sensor design.

The outermost ring had an inner radius (r_{2i}) of 4.25 mm and an outer radius (r_{2o}) of 5.25 mm, while the innermost ring had an inner radius (r_{1i}) of 2.25 mm and an outer radius (r_{1o}) of 3.25 mm. The split gap in each ring was 1 mm, and the feed width was also 1 mm. The sensor was in a splitter configuration, as shown in Fig. 1, with two transmission lines separated by a distance of 17 mm to reduce cross-coupling between the resonators. The circular structures on the feed line just below each resonator were to maximize the quality factor for the sensor.

The equivalent circuit model of the differential sensor was obtained using Keysight Advanced Design System (ADS) software[21] and is shown on the right-hand side of Fig. 1. Since there are two CSRR sensors, each one is loaded with the 50 Ω transmission line bifurcated from the single transmission lines; the equivalent model depicts the same. For unloaded conditions, the resonant frequency of the sensor is given by[19,22]

$$f_{0,\text{unloaded}} = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{2}$$

where L_r represents the equivalent inductance of the CSRR resonator, and C_r represents the equivalent capacitance. A cylindrical sample holder with an inner radius of 3.75 mm and height of 4 mm was placed over one of the resonators. Acrylonitrile–butadiene–styrene (ABS) was used for the sample holder, as it is easy to fabricate using a three-dimensional (3D) printer and introduces very little change in the resonant frequency of the sensor. The sample holder was placed on the region with maximum electric field intensity, as shown in Fig. 2.

When the LUT is loaded in the resonator, due to its dielectric nature, the concentrating field is perturbed. As the resonator itself was built on a dielectric substrate, the inclusion of another dielectric effectively increases the overall dielectric behavior. This leads to an increase in the overall capacitance of the dielectric resonator.[23] Thus, in Eq. 2, in addition to C_r, we need to include the capacitance of the LUT denoted by C_{LUT}, and the total capacitance of the resonator is $(C_r + C_{\text{LUT}})$. Hence, in the presence of an LUT, the resonant frequency of the differential sensor can be obtained as

$$f_{0,\text{loaded}} = \frac{1}{2\pi\sqrt{L_r(C_r + C_{\text{LUT}})}} \tag{3}$$

Results and Analysis

In this work, we have obtained the transmission notch S_{21} to measure the shift in resonant frequency. As mentioned, we inserted 100 µl of the LUT into the sample holder using a micropipette, and the corresponding frequencies were noted. After each measurement, the sample holder was cleaned and dried until the resonant frequency and the transmission notch returned to the original position under unloaded condition. This process was repeated for all samples. The change in resonant frequency of the sensor against each LUT is shown in Fig. 3.

The liquids used for the investigation were acetonitrile ($\varepsilon' = 36.64$), hydrogen peroxide ($\varepsilon' = 74.6$), distilled water ($\varepsilon' = 80.1$), and formamide ($\varepsilon' = 111$).[24–26] The liquids were selected based purely on easy availability and a wider range

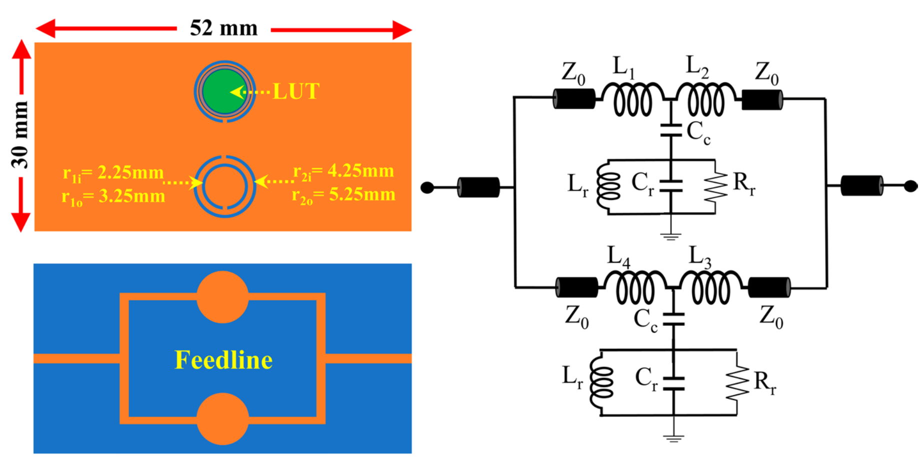

Fig. 1 CSRR differential sensor and its equivalent circuit model.

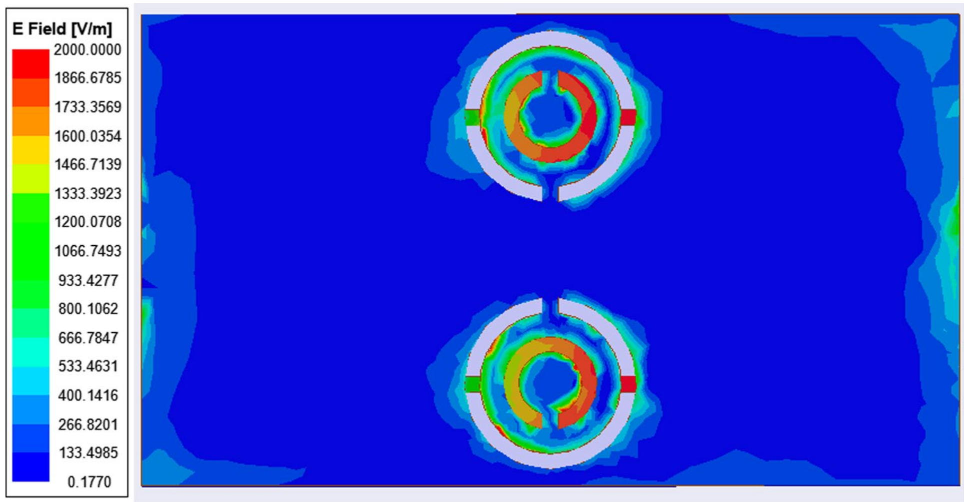

Fig. 2 Distribution of the electric field intensity of the sensor.

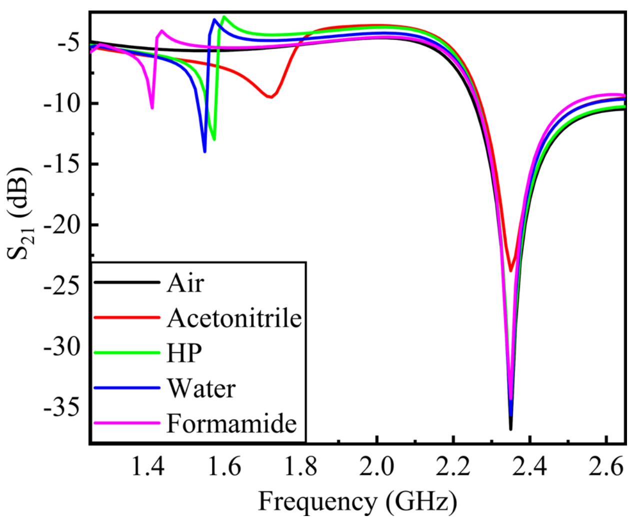

Fig. 3 Transmission coefficient for the LUTs.

to be covered for the investigation. The sensor was found to resonate at 2.35 GHz under unloaded conditions with a quality factor above 200. This high quality factor represents the sensor's ability to resolve any two closely spaced samples, which shows its accuracy and applicability. The sensor was found to exhibit a good amount of shift, leading to higher sensitivity.

Sensitivity Analysis

When one of the resonators was loaded with LUT, the sensor provided sensing based on the change of relative permittivity of the capacitive region of the sensor. For the differential sensor, the sensitivity can be defined as the ratio of the change in frequency under loaded and unloaded conditions to the change in the dielectric constant of the loaded sensor to air or the unloaded condition. The sensitivity is given by[27]

$$S_{\text{diff}} = \frac{\Delta f_{\text{diff}}}{\Delta \varepsilon_{\text{diff}}} = \left| \frac{f_{\text{diff}}^{\text{loaded}} - f_{\text{diff}}^{\text{unloaded}}}{\varepsilon_{\text{diff}}^{\text{loaded}} - \varepsilon_{\text{diff}}^{\text{unloaded}}} \right| \tag{4}$$

where $f_{\text{diff}}^{\text{loaded}}$ and $f_{\text{diff}}^{\text{unloaded}}$ are the differential resonant frequencies for asymmetrical loading and symmetrical unloaded condition, respectively, while $\varepsilon_{\text{diff}}^{\text{loaded}}$ and $\varepsilon_{\text{diff}}^{\text{unloaded}}$ are the respective dielectric constants for the same.

Since the sensors proposed by different researchers operate at different resonant frequencies and the shift per unit dielectric constant also changes with the frequency of operation, a normalized form of sensitivity was used to properly compare the sensitivity of the sensors. The normalized form of the sensitivity is defined as

$$S_{\text{diff, norm}}(\%) = \frac{\Delta f_{\text{diff}}}{f_0 \cdot \Delta \varepsilon_{\text{diff}}} \times 100\% \tag{5}$$

where f_0 is the resonant frequency for the unloaded condition for the differential sensor.

For sensitivity analysis of the proposed sensor, we need to calculate the difference in the resonant frequency of the unloaded and loaded condition with respect to the change in the dielectric constant of the sample and air (unloaded case). When the sample is loaded in the differential resonator, one of the resonant frequencies remains at the original unloaded position, and the other shifts to a lower value. We calculate this frequency difference and then the difference in the dielectric constant of the loaded sample and air. From this data, we can calculate the sensitivity by simply dividing the change in resonant frequency by the change in dielectric constant. This procedure is repeated for all the samples. Finally, the average sensitivity is calculated, and then normalized sensitivity can be obtained by dividing the average sensitivity by the unloaded resonant frequency. The sensitivity analysis of the proposed sensor is shown in Table I.

Table I Sensitivity analysis of the proposed sensor

Sample	Resonant frequency (f)	Dielectric constant (ε')	Δf_{diff} (MHz)	$\Delta\varepsilon'_{\text{diff}}$	Sensitivity (S_{diff}) (MHz)	$S_{\text{diff,avg}}$ (MHz/ε')	$S_{\text{diff,norm}}$ (%)
Air	2.35	1	–	–	–	11.675	0.496
Acetonitrile	1.725	36.64	625	35.64	17.54		
Hydrogen peroxide	1.575	74.6	775	73.6	10.53		
Water	1.55	80.1	800	79.1	10.11		
Formamide	1.4125	111	937.5	110	8.52		

Table II Comparison of the proposed work with some recently reported differential works

Refs.	f_0 (GHz)	$S_{\text{diff, avg}}$ (MHz/ε')	$S_{\text{diff, norm}}$ (%)	ε' range	Substrate used	Topology
28	0.87	0.79	0.91	1–24.3	Rogers RO3010	SRR
23	1.5	0.42	0.028	1–24.3	–	Spiral SRR
29	2.45	2.117	0.086	8.22–79.5	Rogers RO4350	Inductor/capacitor (LC) resonator
30	1.618	10.12	0.626	1–24.3	–	Microstrip CSRR
31	3	2.89	0.096	9.8–80	Rogers 4003C	SRR
32	1.02	2.856	0.28	1–24.3	–	Circular spiral resonator (CSR)
This work	2.35	11.675	0.496	1–111	FR4	CSRR

The average sensitivity of the sensor was found to be 11.675 MHz, and the normalized sensitivity was 0.496%. Although these values may not be high compared to regular microwave planar sensors,[22] for differential sensing of LUTs, the sensitivity exhibited by the sensor is quite high. A few recently submitted works on differential resonators are compared with this work for the sensitivity comparison in Table II.

Determination of Permittivity from the Fit Equation

From the results of the measurement of the transmission notch frequency, the resonant frequency of the sensor against the corresponding dielectric constant value of the LUT was fitted. As it is usually not possible to find actual LUTs with equally spaced dielectric values, the behavior of the resonant frequency shift is not in a regular fashion with respect to the corresponding dielectric of LUTs. Also, it has been seen that as we gradually approach higher dielectric values, the frequency shift decreases accordingly. Therefore, although it is thought that the variation of resonant frequency with dielectric constant should be a linear function, the best fit is shown to be polynomial, especially for a large number of samples and higher dielectric LUTs. The second-order polynomial fitting was adopted in this work, as it provides a higher R-squared value, which indicates a better fit. We have also employed other higher-order polynomial regression to fit our data, but it was observed that this results in overfitting of the data. That is why the second-order polynomial fitting was used as an optimal fitting of the data in this work.

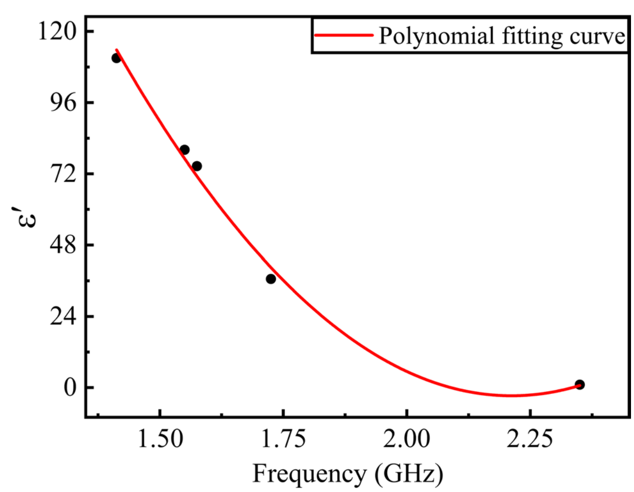

Fig. 4 Fitting curve for the LUTs.

The value of the dielectric constant for each of the samples has been taken as per that available in the literature. The fit indicates a very close relation between frequency and dielectric constant, as shown in Fig. 4. From this we have developed a fit equation (Eq. 6) given as follows:

$$\varepsilon' = 182.24f^2 - 806.25f + 888.98\left(R^2 = 0.987\right) \tag{6}$$

where f is the resonant frequency exhibited by the sensor when a particular liquid is inserted into the sample holder. By substituting the value of f (to be obtained from a vector network analyzer) in the above equation, the dielectric constant of the unknown sample can be calculated.

Discussion and Conclusion

Microwave sensors in their regular single-element form may be susceptible to errors due to environmental effects during experimentation. In this article, to counter this problem, a CSRR-based differential microwave sensor has been designed using the HFSS electromagnetic simulation tool. The sensor is designed to operate in the licensed free ISM band of 2.35 GHz. The sensor works on the principle of displacement of resonant frequency when a LUT is allowed to interact with the resonator unit. The real challenge in designing a differential sensor is to minimize the mutual coupling between the two elements, as the loading of one of the sensing elements might also disturb the field pattern of the unloaded resonator. This in turn effectively shifts the transmission notch of the unloaded reference element which may cause error in the analysis. The design presented here has been optimized to minimize this effect of mutual coupling without increasing the footprint of the sensor or increasing the complexity of the sensor. The performance of the sensor was validated using four liquid samples covering a wide range of permittivity values ($\varepsilon' = 1$ to 111). The sensitivity per unit dielectric constant of the sensor was found to be 11.675 MHz, whereas the normalized sensitivity was found to be 0.496%. The quality factor of the sensor was also higher than 200, indicating the possibility of high resolving power when used as a sensor. The samples with known properties of permittivity were chosen to develop a relation between the dielectric constant and the respective changes in frequency, which will be further used to estimate the dielectric constant of unknown samples. Finally, a fit equation has been developed to calculate the dielectric constant of any unknown sample from the knowledge of the resonant frequency. The advantage of the proposed sensor is its simple design and inexpensive cost which will ensure its reproducibility in bulk. The proposed sensor will be an ideal candidate for dielectric constant measurement where there may be high fluctuations in environmental conditions.

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Conflict of interest The authors declare that they have no conflict of interest.

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