Differential microwave sensor based on microstrip lines loaded with a split-ring resonator for dielectric characterization of materials

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Abstract. In this work, we propose a microwave sensor that allows the characterization of dielectric materials based on a differential configuration. A microstrip permittivity sensor of the surrounding material is proposed using a split ring-resonator to measure differentially. The geometry was optimized and was numerically analyzed using CST STUDIO. The numerical analysis of the metamaterial unit cells is carried out first, to determine the operating band. After that, the metamaterial cell was employed to design the differential microstrip permittivity sensor. The obtained results reveal that the proposed sensor has the capability to characterize different materials whose relative dielectric permittivity’s are in the range of 9.8 to 80 with great performance. The device has a total size of 86 mm × 60 mm and operates around 3 GHz. In this band, the sensor reaches a sensibility of 2.89 MHz and a Q-factor of 70.15. Thus, this work shows a compact, reusable, label-free, and non-destructive microwave sensing device and paves the way for high accuracy sensing of the dielectric properties of different materials due to its high- Q-factor as well as high sensitivity.

1. Introduction
In recent years, the measurement of the dielectric permittivity of materials has aroused strong interest in many industrial applications due to the fact that the dielectric permittivity of bulk materials can be related to other important parameters such as density, concentration, temperature and humidity [1,2]. Thus, the characterization of this parameter is a powerful way to develop applications or devices to solve problems in medicine, biology, security, food industry, chemical, among others [3–8].

Several microwave methods had been explored to measure the dielectric permittivity of liquids and solids, the main techniques include the free space technique, and the use of resonators, parallel plate capacitors, and microstrip technology [1,2]. However, microwave devices based on microstrip technology emerge as an interesting alternative because they are inexpensive, easy to construct, have simple integration setups with electronic components, and are versatile in comparison with other microwave methods. Likewise, the devices based on the resonant technique offer higher accuracy and high-quality factor (Q-Factor). Moreover, this kind of sensor determines the dielectric properties of the sample under test (SUT) by simply measuring the shift in the resonant frequency, the phase change, and the Q-Factor of the sensor as a function of the dielectric permittivity [5,9,10]. Then, the combination of both characteristics had been explored in the past to achieve high-performance microwave sensing devices. Many kinds of resonant structures such as split-ring resonators (SRRs), step impedance
resonators, substrate integrated waveguide (SIW) resonators and others have been employed to date to measure dielectric permittivity [5,11–13]. However, the measurement of this property could be affected by environmental conditions such as humidity or temperature fluctuations, which can induce cross-sensitivity that entails measurement errors.

To avoid these systematic errors due to cross-sensitivity, some interesting alternatives had been proposed. The first one explores the use of materials that are not sensitive to environmental changes, but these materials are expensive in most cases. The second one explores the use of a differential configuration, which compares the stimulus that suffers two identical sensors subject to the same external factors. This alternative could be used in combination with microstrip technology to obtain compact devices that offer the possibility to compensate environmental changes. For example, A. Ebrahimi, et al. [14], in 2018, present a microwave sensor using a pair SRRs. In this configuration, the authors load a microstrip line with two identical SRRs on its sides. Thus, a differential permittivity sensor was analyzed and employed to compare a SUT with a reference sample. Simultaneously, Paris-Velez, et al. Reported a differential permittivity sensor based on a pair of uncoupled microstrip lines, which are loaded with open complementary split-ring resonators (OCSRRs) [10]. Then, the authors implement this configuration to measure the dielectric changes in mixtures of ethanol and deionized water. Thus, they demonstrate that this kind of configuration is more sensitive and versatile. Other configurations based on Magnetic resonators composed of capacitive and inductive structures [15], Rat-Race couplers [16], and dumbbell-shaped defect ground structures [13] have been recently reported, demonstrating that sensors based on differential configuration are an interesting option when you want to override the effects of the environment.

Therefore, we propose a differential permittivity sensor based on a microstrip coupler loaded with a couple of SRRs, one in each branch. This sensor initially operates at 3.5 GHz. In comparison with other previous studies, the proposed structure has some important advantages. The aim of this work is to demonstrate that the proposed sensor presents a high sensitivity when it is used to measure dielectric changes, and it offers a differential measurement, which can be used to obtain a more stable solution.

2. Methodology and materials

This section details the methodology to analyze the resonator used to verify that it has metamaterial characteristics. Subsequently, the design of the proposed configuration to measure permittivity changes is presented. Finally, the principle of operation of this device is explained to ensure a better understanding of the work.

2.1. Metamaterial unitary cell

Figure 1(a) shows the proposed metamaterial unit cell. This metamaterial cell consists of a unique circular split ring resonator with a gap (g) equal to 2 mm, an internal radio (r) of 4.5 mm, and an outer radio (R) of 5.8 mm. The ring resonators are made of copper lines with a metal thickness of 35 µm. The performance of the proposed unit cell was numerically evaluated using two floquet ports to study its electromagnetic performance, while perfect electric condition (PEC) and perfect magnetic boundary conditions (PMC) were imposed on the metamaterial unit cell, see Figure 1(a). The structure was excited using a uniform plane wave, which is propagated on the z-axis with an open-end boundary condition, visible in Figure 1(a). Likewise, PEC was used in z-direction, a PMC was defined in the XY plane, while the electromagnetic wave was propagated in x-direction. Therefore, the E-field of the incident wave is polarized along x-axis, while the H-field is polarized along the y-axis.

Therefore, the Nicolson Rose Weir (NRW) method was employed to extract and get the permeability and permittivity of the proposed structure from the scattering parameters (S-parameters). This numerical analysis was carried out from 2 GHz to 4 GHz. The obtained results are illustrated in Figure 1(b). The simulations show the real and imaginary parts of the permeability and permittivity of our resonator. Likewise, the results reveal that the proposed SRR presents a negative behavior for the real part of the permeability from 3.2 GHz to 3.49 GHz. In a similar way, the imaginary part of the permittivity has negative values from 3.2 GHz to 3.33 GHz. On the other hand, the real part of the permittivity and the
imaginary part of the permeability both remain positive in the studied frequency range. Thus, we can affirm that this structure presents a typical behavior of a single negative (SNG) metamaterial resonator [17–19].

2.2. Microwave sensor design

Figure 2 illustrates the proposed microwave sensor, which is based on a differential configuration. In this case, a resistive power divider is employed to split the input power into two identical branches. The lower arm is known as the reference arm, while the upper arm is the sensor arm, and it is used to measure the dielectric permittivity of the SUT. Both arms were designed using a standard microstrip line with an impedance of 100-Ω. Likewise, these microstrip lines are loaded with a circular SRR (the inset of Figure 2 shows the structure with more details). As shown in section 2.1 this metamaterial structure was optimized to resonate at 3 GHz and the resonator was set at a distance of 2 mm from the microstrip line to ensure a good power coupling [20,21]. The SRR structure was selected to design the sensing region of the proposed sensor due that these types of structures help to increase the capacitance of the microstrip circuit, and the E-Field in this point is confined. Thus, the gap of this structure allows for a more sensitive area [18]. To model and characterize the performance of this sensor a container with a cylinder shape and diameter of 2 mm was placed on the gap of the SRR.

On the other hand, the numerical analysis of the proposed configuration was carried out using CST microwave studio, which is a software based on the standard finite-difference time-domain (FDTD) method. The substrate material considered in this study was a Rogers 4003C with a relative dielectric permittivity (ε_r) of 3.55, a thickness of 1.52 mm and a tangent of losses of 0.0027. In addition, a thin layer of copper of 35 µm was employed in the construction of the microstrip lines and the ground plane. Table 1 summarizes the most important geometrical parameters of the proposed microwave sensor configuration.

| Parameter | Value (mm) | Parameter | Value (mm) |
|-----------|------------|-----------|------------|
| W         | 86.0       | d         | 0.2        |
| L         | 60.0       | s         | 4.4        |
| lb        | 54.9       | g         | 2.0        |
| ls        | 5.2        | R         | 5.8        |
| a         | 15.4       | r         | 4.5        |
| wa        | 28.4       | hc        | 4.0        |
| wb        | 30.8       |           |            |
2.3. Working principle
The working principle of the proposed microwave sensor is based on mode conversion, which occurs when the sensing branch is loaded with a different material, thus the balanced condition of this configuration is broken. Then, this sensor presents two different situations: the first one is when the configuration is balanced, it occurs when both branches are surrounded by the same material, and the phase difference between both two paths is zero. For this reason, only one resonant peak is detected in the transmission spectrum associated with the natural resonance of the SRR. Conversely, when the sensing branch is in contact with a material and the reference branch is in the presence of a different one, such difference is detected through mode conversion. This mode conversion is induced by the phase difference between the waves that travel through the two paths. In this condition, a second zero in the transmission response of the proposed device is obtained. Then, a variation on the relative permittivity of a SUT could be measured using the difference between the two transmission zeros. This aspect helps obtain a self-referenced sensor configuration. Likewise, these kinds of sensors are immune to external noise due to thermal or humidity changes. Therefore, it is a robust configuration that can provide greater reliability and better stability than other previously reported alternatives.

3. Results and discussion
First, the proposed microwave device illustrated in Figure 2 was simulated using CST STUDIO without a sample to corroborate the initial performance of this sensor device. Figure 3(a) shows the response of the $S_{21}$ parameter between 2.6 GHz and 3.4 GHz. It is clear from this spectrum that the proposed microwave device has a dip at 3 GHz of $-16$ dB. On the other hand, the spectrum reveals a single resonant peak due to both resonators (reference arm and sensing arm) having the same structure and the surrounding media for both being air ($\varepsilon_r=1$) [12,13]. Therefore, both SRRs resonate at the same frequency. So, it can be said that the device is balanced in this case. In addition, the E-Field distribution of the sensor was included at 3 GHz. From Figure 3(b) is easy to corroborate that the E-field intensity is higher in the gap region.

As mentioned in section 2.3, any asymmetrical perturbation in the SRR of the sensing arm can induce a mode conversion, so, the transmission spectra will present two dips. Therefore, we can use this working principle to characterize the dielectric permittivity of any SUT. Thus, a simulation process was achieved to study the performance of this microwave sensor when the dielectric relative permittivity ($\varepsilon_r$) values of the SUT are varied. Figure 4(a) shows the obtained results of the magnitude of the $S_{21}$ parameter when the dielectric permittivity of the sample is varied from 9.8 to 80. Now, we can observe the presence of a new resonant peak, whose resonant frequency shifts towards lower frequencies. On the other hand, one peak remains almost constant at 3 GHz for all loaded samples. These results corroborate the capability of this novel structure to give a differential measurement. In fact, this sensor can be self-referenced measurements are always taken with respect to the reference peak. Another advantage of this configuration is that the magnitude of the resonant peak is consistent for all samples, making it easy to implement in real applications.
Figure 3. (a) Frequency response of the proposed differential microwave sensor at the balanced condition, (b) E-Field distribution at 3 GHz.

An analysis of the sensitivity and Q-Factor of the sensor was carried out using the obtained spectra in Figure 4(a). Figure 4(b) reveals that the proposed differential configuration exhibits high sensitivity. In fact, the resonant frequency change from 2.975 GHz to 2.826 GHz when the dielectric constant varies from 9.8 to 80. Thus, the sensitivity ($\Delta f/\Delta \varepsilon_r$) of this sensor is 2.89 MHz/$\varepsilon_r$. In addition, the exponential adjustment of the obtained results is expected due that these kinds of sensors tend to saturate for high dielectric permittivity values. The quality factor was also evaluated for each sample. Table 2 summarized the obtained results, and evidence that this important parameter remains stable between 64.99 and 70.15. This result tells us again that the shape of the resonance peak is maintained throughout the measurement range.

Figure 4. (a) Simulated frequency responses of the proposed differential microwave sensor of different samples under test values, (b) simulated sensitivity of the differential microwave sensor.

| Permittivity ($\varepsilon_r$) | Q-factor |
|-------------------------------|----------|
| 9.8                           | 64.99    |
| 18.5                          | 68.24    |
| 27.3                          | 68.64    |
| 36.1                          | 68.95    |
| 44.9                          | 69.18    |
| 53.7                          | 69.05    |
| 62.4                          | 69.42    |
| 71.2                          | 69.86    |
| 80.0                          | 70.15    |
Finally, Table 3 presents a comparison between the performance of the proposed differential microwave sensor and other configurations reported in the literature. In general, the operating principle and the technology of all compared works are the same, i.e., the author employs microstrip/planar sensors to measure the dielectric constant of liquid or solid materials in microwave region in all cases. Also, these configurations use the differential method to obtain more stable devices. It is evident that the proposed configuration presents a high sensitivity in comparison with previous reports. Likewise, the proposed configuration could be employed in the characterization of a wide range of materials as it can characterize materials with a relative permittivity of 9.8 to 80.

**Table 3.** Comparison with other differential planar and microwave sensors. The size is reported in mm, while the sensitivity (S) is reported in MHz/Δεr.

| Resonator | Size | S      | Range of SUT | Frequency | Reference |
|-----------|------|--------|--------------|-----------|-----------|
| Circular SRR | 1.62 λg × 1.13 λg | 2.89 | 9.8 – 80 | 3.0 | This work |
| Split ring resonators | 0.57 λg × 0.79 λg | 0.79 | NA | 0.87 | [22] |
| Open complementary SRRs | 0.41 λg × 0.29 λg | 1.8 | 28 – 81 | 0.9 | [10] |
| Dumbbell-shaped defect ground structures stepped | 0.87 λg × 0.54 λg | 1.03 | 13 – 81 | 1.05 | [13] |
| Stepped impedance resonators | NA | 0.536 | 1–11.2 | 4.0 | [12] |

*NA No value, * λg is the guided wavelength.

### 4. Conclusions

A differential microwave sensor based on a pair of transmission lines loaded with split ring resonators has been proposed and numerically investigated in this work. The operating principle of the sensor was analyzed and demonstrated using full-wave simulations. The main relevant characteristics of the proposed structure are that this sensor device has the capability to detect dielectric changes in a wide variety of materials whose relative permittivity is between 9.8 and 80 with high sensitivity. Likewise, the proposed sensor is compact, and the required amount of a given sample is small. Finally, the Quality Factor of this structure was evaluated, and it corroborated that this configuration has a stable resonant peak, which is desirable in real implementations. Therefore, the proposed sensor is an excellent candidate to develop devices for biological, medical, industrial, and other applications where material characteristics are a key aspect.

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