Ultrasensitive Planar Metamaterials for Material Characterization Using Tapered CSRR with Application to NDT of 3D Printed Structures

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***Abstract* — This paper proposes miniaturized, ultrasensitive, flexible planar metamaterials for dielectric constant measurement with a wide dynamic range of the sensing related frequency. The proposed sensors are designed using a thin-substrate microstrip line loaded with tapered complementary split ring resonator (CSRR). The sensors' configuration can be easily integrated with RFID tags for future Internet of Things (IoT) applications. The minimum transmission frequency shifts 56% as the dielectric constant of the material under test (MUT) changes from 1 to 10. Compared to similar state-of-the-art planar sensors, the proposed sensors are almost 50% more sensitive. This extraordinary sensitivity level is of great importance for the development of high-precision near-field based sensors. Sensors' performance were verified numerically and experimentally. To further demonstrate the proposed sensor's practicality, one of the proposed sensors was used to characterize 3D printed dielectric. It was also used as a crack detector for 3D printed samples designed with artificial cracks.**

***Keywords* — Dielectric measurement, Microwave sensors, Nondestructive testing, Planar metamaterial, Metasurface, Split ring resonator**

I. INTRODUCTION

Permittivity and permeability are the key parameters that govern electromagnetic wave propagation through different structures. Accurate determination of these parameters is vital for the design and analysis of electromagnetic systems. While most dielectrics have a permeability equivalent to free space permeability within RF and microwave frequency, their corresponding relative permittivities are unique and greater than one. For this reason, permittivity measurement is more crucial than permeability measurement within the specified band.

Numerous researchers have proposed different techniques to measure materials' parameters [1]. These techniques vary based on their complexity, frequency band, and preciseness. A class of the proposed techniques uses a resonant frequency method to measure homogenous materials parameters. This method is considered as the most accurate one [2]. Another class of material characterization techniques uses near field sensors. These type of sensors extract local material properties with subwavelength resolution as they are not limited by the diffraction limit [3, 4]. A novel near field sensor was introduced in [5] to measure the material's dielectric constant. The proposed sensor combines the mentioned advantages of the resonant method and near field sensing. It was designed using a planar metamaterial sensor composed of a complementary split ring resonator (CSRR) loaded to microstrip line (MTL). The design has many features which include design simplicity, low cost, and resonator's scalability.

Development of near field probes for material characterization paved the way to the development of other planar metamaterial sensors with a narrower scope such as microfluidics, biomedical, and cracks' sensors [6-12]. The sensitivity and dynamic range of a near field sensor are fundamental factors that determine its suitability for high precision measurement applications. For example, Non-Destructive Testing (NDT) transducer that is used for crack sensing needs to be sensitive enough to identify fine cracks and needs to have high resolution to distinguish between closely located ones.

This paper proposes ultrasensitive, lightweight sensors with higher sensitivity over a wide range of frequency using tapered rectangular and sectorial CSRRs etched in the ground plane of MTL. The proposed sensors can be utilized for material characterization as well as other narrower applications such as crack sensing. They can also be integrated with RFID tags for future IoT sensing applications. Table (1) below provides a sensitivity comparison between the proposed sensors and previously proposed ones. The shown frequency shifts are the encountered change in the minimum transmission frequency when the sample's dielectric constant changes from 1 to 10. The basic configuration of compared sensors is similar where a coaxial line is used to feed an MTL loaded with CSRR.

Table1. Comparison with state of the art CSRR sensors

Ref.	Freq. Band (GHz)	Resonator Type	Freq. Shift %
[5]	0.8-1.3	Double CSRR	37.5 %
[13]	1.8-2.8	Double CSRR	35.7%
[14]	1.08-1.63	Single CSRR	33.6%
[14]	2.16-3.33	Single CSRR	35.3 %
[15]	1.75-2.7	Double CSRR	35%
[16]	5.23-8.45	Double CSRR	38.1%
T.W.	5.26-12.15	Single Rectangular CSRR	56.7%
T.W.	4.02-9.16	Single Sectorial CSRR	56.1%

II. PRINCIPLES OF OPERATION

The proposed sensors are designed using electrically small resonators etched in the ground plane of the MTL. The etched resonator is called a defect, and the MTL with such defect is called a defected ground structure (DGS).

A. Defected Ground Structure (DGS)

DGS has been utilized for various sensing applications [5-16]. When the wavelength of the guided wave is much higher than the physical length of the ground plane defect (i.e., electrically small defect), lumped circuit elements can be used to model it. A lossless ground defect can be modeled by a reactive circuit composed of capacitors and inductors to account for the circulating electric and magnetic energy at resonance [5]. Its resonance can be excited by either pure electric or electric/magnetic fields depending on its geometry, electrical dimensions, and the orientation of its line of symmetry (if any) with respect to the MTL strip. To measure a material permittivity, DGS should be properly designed to ensure maximum interaction between the resonating electric energy and the material under test (MUT).

B. Resonator Type

Conventional straight line resonators are not suitable for the design of a miniaturized sensing platform as they require relatively longer resonating current path. On the contrary, a curved resonator such as spiral, split ring resonator (SRR) and CSRR forces the induced resonating current to circulate within a smaller physical area. The spiral resonator has more than one current path within its structure, which dramatically reduces the resonator's electrical size. However, such structure split the confined electric energy within its turns, which reduces its efficiency for permittivity sensing. SRR is a C shape resonator which confines the resonating electrical energy within its slit only. In contrast, its complement (CSRR), confines its resonating electrical energy within a subsection of its circumference with an equivalent area larger than the SRR slit. Since both particles (SRR and its complement) capture relatively low energy, the size of the sensing area should determine the resonator to be utilized for sensing applications. For this reason, CSRR is used as the sensor resonator in this paper.

C. Integration with RFID Tag

IoT is an emerging field that sets a new paradigm for future sensing networks. RFID tag loaded with multiple sensors is considered as IoT technology enabler and an indispensable element in future wireless sensing networks. Chip-less RFID tag uses the electromagnetic properties of various structures to perform data encoding without the need for an IC chip. Data encoding is usually performed by loading the RFID tag with electrically small resonators as they consume limited energy with high efficiency [18]. Development of planar sensors that are compatible with RFID technology extend their usability and practicality. The resonators of the proposed sensors can be utilized with chip-less RFID tags for sensing applications.

D. Sensors Design

The proposed sensing platform is composed of a 30mm-by-30mm MTL loaded with a tapered CSRR. Two sensor topologies were designed. The first one is a tapered rectangular CSRR while the second one is a tapered sectorial CSRR. Fig. 1 shows the top view of the proposed sensors. The substrate layer was removed from the figure to clarify the alignment of the MTL signal strip with respect to the etched resonators' splits. The length and width of each side of the rectangular CSRR are 6 mm and 2.2 mm, respectively with a 1.6 mm split width. The length of the longer arc of the tapered sectorial CSRR is 9 mm. The width of each edge of the sectorial CSRR is 2 mm with a split width of 2mm as well. Both CSRR were etched in a ground plane of the MTL. The MTL is fed with coaxial cable with 50-ohm impedance. The MTL signal strip is designed with a 0.267 mm strip width. The used substrate is a liquid crystal polymer (LCP) substrate with a 0.116 mm thickness and a dielectric constant of 2.9. This ultra-thin substrate is used to increase the DGS fundamental resonance frequency which consequently increases the dynamic range. On the other hand, tapering CSRR decreases its equivalent inductance and capacitance. These two factors increase the dependence of the sensor's resonance frequency on the loaded MUT dielectric constant.

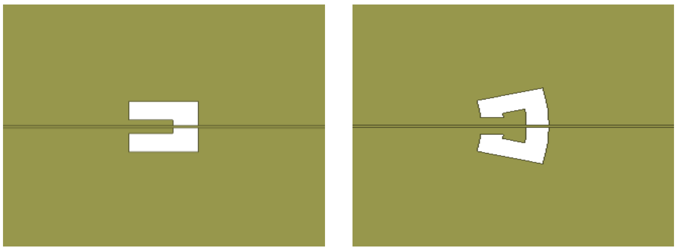
(a) (b)

Fig.1. Top view of designed rectangular (a) and sectorial (b) CSRR sensors

III. SIMULATIONS AND MEASUREMENTS

A. Simulation Results for Sensitivity and Dynamic Range

The main goal of this study is to design an ultrasensitive planar sensor with a wide dynamic range of the sensing related frequency. To verify the performance of the proposed sensors, full-wave numerical simulation package ANSYS HFSS was used. The simulation setup consists of the planar sensor with MUT placed underneath the MTL ground plane in direct contact with the etched resonator. The MUT dielectric constant was varied from 1 to 10 with a 0.25 step. Fig.2 shows the percentages of the change in the minimum transmission frequency with respect to the dielectric constant variation, while fig.3 shows the corresponding dynamic range in GHz for the specific dielectric constant variation. Rectangular and sectorial CSRR based sensors achieved 56.7% and 56.1% frequency shift with a corresponding 6.89 GHz and 5.14 GHz dynamic range, respectively.

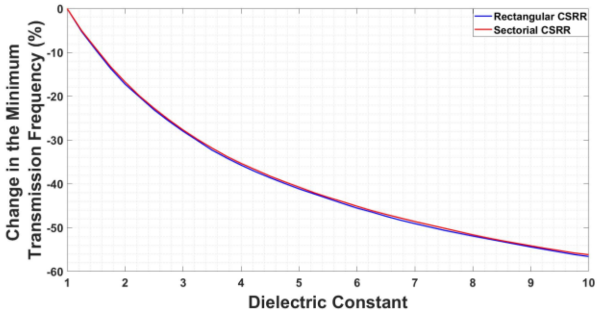

Fig.2. Change in the minimum transmission frequency for the rectangular (blue) and sectorial (red) CSRR based sensors

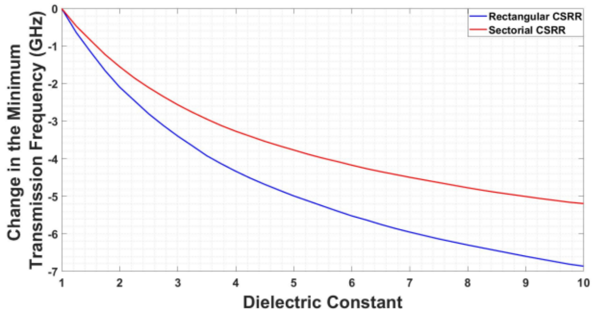

Fig.3. Change in the minimum transmission frequency for the rectangular (blue) and sectorial (red) CSRR based sensors

B. Experimental Measurements

Two sensor prototypes were fabricated using flexible LCP substrate. Three cubic dielectric samples with cube height of 5mm and approximate dielectric constant of 3, 6, and 10 were prepared to verify the numerical results. The samples were prepared using Roger substrates RO3003, RO3006, and RO3010. For each substrate, the copper layer was removed using a chemical solution. After that, five 15mm-by-15mm layers of the copper free substrates were stacked vertically to have a sample height of approximately 5mm. Fig.4 shows the fabricated sensors and dielectric samples.

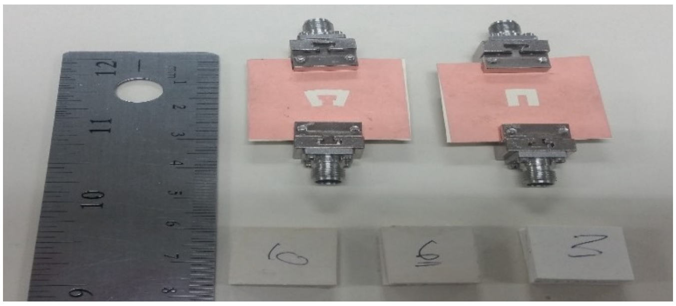

Fig.4. Fabricated sectorial and rectangular CSRR based sensors and dielectric samples

Each sensor was connected to the VNA ports. The free space fundamental resonance frequency was first recorded for each sensor. After that, each of the three samples was loaded to the sensors with direct contact to the tapered CSRR. Fig.5 and fig.6 show the results of the measured transmission coefficient with the simulated ones. Both results are in very good agreements.

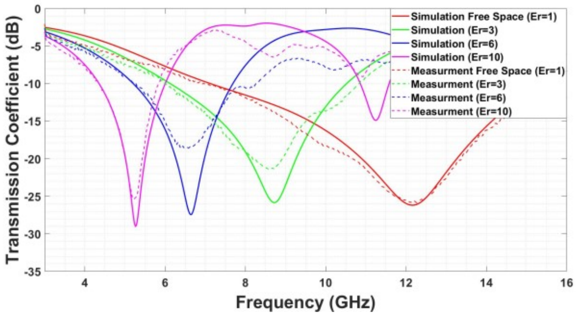

Fig.5. Simulation (solid line) and measurement (dashed line) results for the rectangular CSRR based sensor

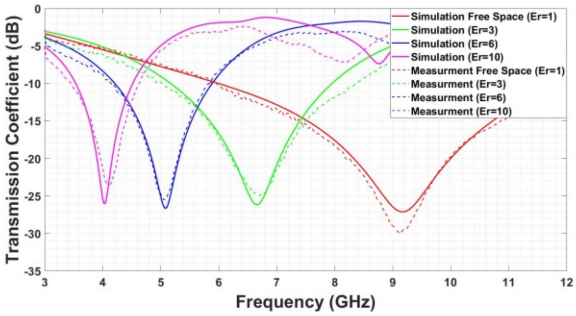

Fig.6. Simulation (solid line) and measurement (dashed line) results for the sectorial CSRR based sensor

C. Characterization of 3D Printed Dielectric

The sectorial sensor is especially useful in the characterization of unknown dielectric with or without defects. 3D printed dielectric produced by Formlabs was selected for characterization. A defect-free rectangular cubic sample was printed using Form2 3D printer. The model of the used dielectric material is (Clear Resin 1L-RS-F2-GPCL-04). An experimental procedure similar to the one discussed in the previous section was followed to measure the transmission coefficient and then to estimate the sample dielectric constant. The obtained minimum transmission frequency was compared to results reported in fig.3 and fig.6. The dielectric constant of the 3D printed dielectric matched the frequency shift of the simulated 2.75 dielectric constant MUT. Figure.7 shows the transmission coefficient of a simulated cubic MUT with a 2.75 dielectric constant and measured transmission coefficient of the printed sample. The good agreement between the two results supports the estimated dielectric constant.

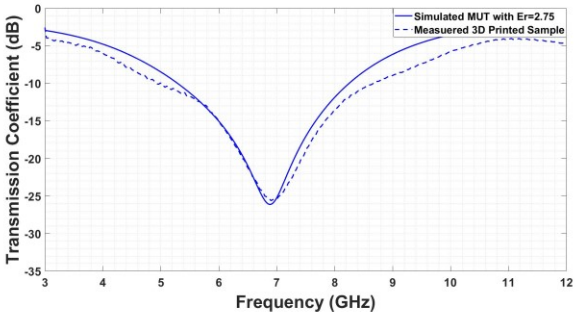

Fig.7. Transmission coefficient of the simulated MUT (solid line) and the measured one for a 3D printed sample (dashed line)

E. *NDT of 3D Printed Samples*

Encouraged by the previous results, the sectorial CSRR based sensor was used as an NDT near field sensor. At resonance, the electric field concentration is maximum at the curved edge of the resonator, which is opposite to the resonator's split. Material's cracks are curved defects in nature as they follow grain boundaries. Thus utilization of such curved edge resonators will facilitate the detection of parallel and/or perpendicularly oriented cracks with respect to the resonator axis. Three 3D printed samples were designed with longitudinal slots to simulate longitudinal surface cracks as shown in fig.8, which also includes a defect-free sample (reference sample). Two of the four samples have one crack each with similar depth (3mm) and different width (500um and 1mm, respectively). The third sample has two cracks with a 1-mm width and a 3-mm depth each and separated by 1-mm. Fig.9 shows the measured transmission coefficient for the three samples as well as the reference case and free space. The sensor was able to detect a 500-um width longitudinal surface crack with a 277 MHz shift in the minimum transmission resonance frequency from the reference case, which corresponds to a 12% frequency shifts.

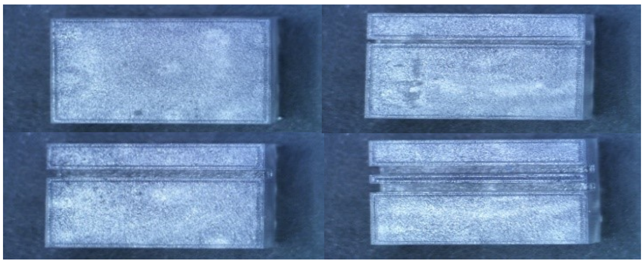

Fig.8. Four 3D printed samples

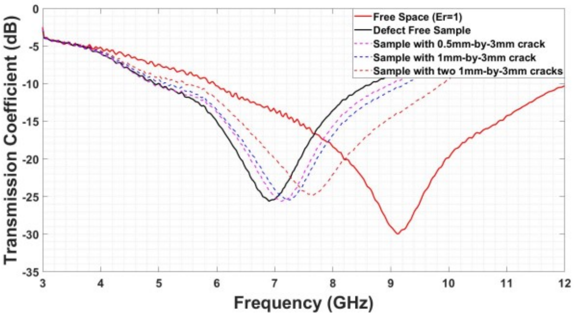

Fig.9. Measured transmission coefficient of free space (solid-red), defect free sample (solid-black) and cracked 3D printed samples (dashed lines)

IV. CONCLUSION

In this paper, two planar metamaterial sensors with high sensitivity and dynamic range were proposed. Simulation and experimental results verified their superiority over previously reported similar sensors. The proposed sensors feature a potential for a wide range of near-field based sensors. Resonator's path width tapering concept proved to enlarge sensor sensitivity and should be explored more and employed in the design of an ultrasensitive thin-substrate planar sensor. It should be noted that the proposed sensing platforms are compatible with RFID technology which ease their utilization for the emerging IoT applications.

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