Proceedings

Cost-Effective Flexible CSRR-Based Sensor for Noninvasive Measurement of Permittivity of Biomaterials †

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† Presented at the 8th Electronic Conference on Sensors and Applications, 1–15 November 2021; Available online: https://ecsa-8.sciforum.net/.

Abstract: A novel, cost-effective, flexible microwave sensor is proposed to facilitate point-of-care testing (POCT) methods for medical diagnosis. The sensor is based on the complementary split-ring resonator (CSRR) for accurately measuring the permittivity of biomaterials over a wide range of frequencies. This capability can be used to characterize various materials under test (MUT) such as blood, saliva, tissue samples, etc. The flexibility of the proposed sensor makes it possible to use it when the accessibility of the sample has technical difficulties, such as curved surfaces. Firstly, the optimized structure and coupling to the readout transmission line are evaluated using finite element method (FEM) simulations. Then, the prototype of the optimized structure is fabricated on thin polydimethylsiloxane (PDMS) substrate as a biocompatible economical polymer, and Aluminium is carefully chosen for the fabrication of CSRR and readout parts. The proposed flexible sensor is tested to compare to conventional rigid CSRR sensors. Not only the proposed structure withstood the different bending positions well, it is also showed an improvement in the results for curved MUT.

Keywords: Biosensor; Microwave sensor; Split-ring resonator; Biomaterial; Permittivity; Flexible

Citation: Shanehsazzadeh, F.; Azizi, N.; Kazerooni Haghighat, H.; Mashayekhi, F.; Fardmanesh, M. Cost-Effective Flexible CSRR-Based Sensor for Noninvasive Measurement of Permittivity of Biomaterials . *Journal Not Specified* **2021**, *1*, 0. https://doi.org/

Received:
Accepted:
Published:

1. Introduction

Point-of-care testing (POCT) emerges as an alternative to traditional laboratories-based diagnostic tests due to cost considerations and available medical equipment, particularly in areas of resource-limited requirements [1,2]. Simplified operation without the requirement of skilled operators, reduced analytical time and faster systematic procedures, uncomplicated and cost-effective manufacturing process, ease of use, especially in regions that have limited resources, and low energy consumption and reagent are POCT's distinct advantages [1–4].

Modern biosensors have played a significant part in realizing POC ideas based on the concept of reduced diagnostics times and processes [2]. Microwave resonator-based sensors, such as the complementary split-ring resonator (CSRR), have recently emerged as a promising technique for the fabrication of biosensors and biodevices [5,6]. For point-of-care testing, planar structures have proved to be the ideal sensing choice among other microwave resonators. This is due to their simplicity design, cost-effectiveness, compactness, label-free, portability, non-invasive nature, CMOS compatibility, and ease of sample preparation [5–10]. With recent progress in research [5–7], planar CSRR was established as a leading instrument among a broad variety of disciplines, from medical and biomedical sensing applications [7,11,12] to the oil and gas industry [13], from materials characterisation, process control to environmental monitoring [14].

A typical CSRR consists of a high-conductive metal that is fabricated on a rigid dielectric substrate surface [10]. Their design geometry and the physical parameters of the environment in which they are placed impact the resonant features of these microwave resonators. The resonant features variation versus the change in the materials under test (MUT) permittivity placed on the sensor surface is used to determine sensitivity for these types of sensors [5,6,9,12]. The air gap effect between the sample and the sensor in these structures is a common and unavoidable issue. By properly tightening the sample and the sensor together, a fraction of the error due to air gap may be reduced [5,15]. This is while nearly all CSRR-based biosensors proposed so far are rigid devices, limiting their applicability to MUT with curved surfaces such as fingers. Flexible structures can enhance the particularly crucial conditions, especially in wearable electronic applications. To the best of our knowledge, the only flexible devices proposed are the glucose monitoring device suggested by Daneshman's group in [12] and the glaucoma monitoring device proposed by Ekinici et al. in [10], where both of them used microfabrication procedures. Microfabrication processes, as is widely known, involve specialized laboratory equipment and materials such as deposition or lithographic equipment utilized by professionals. Given the expense of cleanroom treatment and the time needed, this approach is not only complex and expensive but is not even available to many research groups or organizations [16,17].

Here the possible solution to this difficulty with a simple, flexible, and cost-effective resonator microwave sensor using a novel manufacturing approach for non-invasive biomaterial permittivity measurements is provided. This approach eliminates complex microfabrication processes, lowering total costs and making it a viable choice for POCT outside of hospitals or health centers for outpatient monitoring, as well as revitalizing medical and health care in resource-limited locations. Furthermore, the suggested device is built from thin polydimethylsiloxane (PDMS) substrate as an inexpensive biocompatible and flexible polymer, making it applicable when the sample accessibility has technical challenges, such as curved surfaces or liquid samples such as saliva or urine. The proposed sensor is designed and simulated using the numerical electromagnetic solver, the Computer Simulation Technology (CST). The proposed sensor is tested in terms of flexibility and sensitivity using in-vitro setups and is compared with the typical rigid CSRR sensors. In comparison to the standard SRR, there is a substantial improvement in sensitivity and performance. The structures and results are described in the following.

2. Materials and Methods

CSRRs typically consist of one or more rings etched out from a flat conductive layer. The rings can be in different shapes, such as circles as one of the popular ones, with small gaps on one side or two opposite sides (Figure 1 (a)). A circuit can model the CSRR's electrical behavior with equivalent resistance, capacitance, and inductance. The gaps can be interpreted as capacitors (C), and the rings can be considered as inductors (L) and resistors (R) [6,18]. Accordingly, the resonance frequency can be calculated with $f_0 = a/2\pi\sqrt{L \times C}$ while $C \propto \varepsilon_0 \varepsilon_r$, where ε_0 and ε_r are permittivity of free space and relative permittivity of the resonator's environment, respectively [7,9]. Therefore, it can be stated that the sensor's resonance frequency is inversely associated with the MUT's relative permittivity as its most critical characteristic in the context of microwave engineering. Placing MUT on the resonator's surface changes the total effective permittivity; consequently, the sensor's resonance frequency, which can be utilized as a sensing parameter to distinguish different materials [5,10,12].

An electric field (E) perpendicular to the CSRR plane is required to excite the structure, done with a microstrip transmission line [9,19]. The CSRR biosensors' function can be easily evaluated by measuring the device's scattering parameters by using the transmission line. So typically, the sensor comprises a substrate including metal layers on both sides, one as a ground layer from which the rings are etched out, and the other as a transmission line on the opposite side (Figure 1 (b)). To be analyzed, the biosensor is connected to the vector network analyzer (VNA) through coaxial cables and SMA connectors. Then the transmission spectra S_{21} is measured, which strongly depends on the frequency. Notably, when compared to other scattering parameters, the influence of sample material permittivity is more significant on the S_{21} behavior [5,18,19].

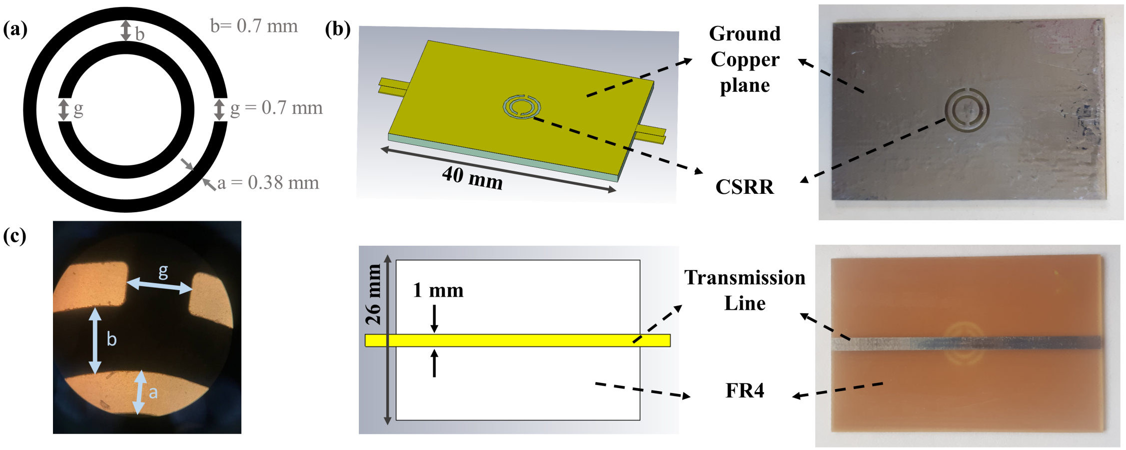


Figure 1. (**a**) Schematic of circular CSRR with design parameters. (**b**) Perspective view of simulated and fabricated model of Rigid device. (**c**) Dimentions of fabricated device.

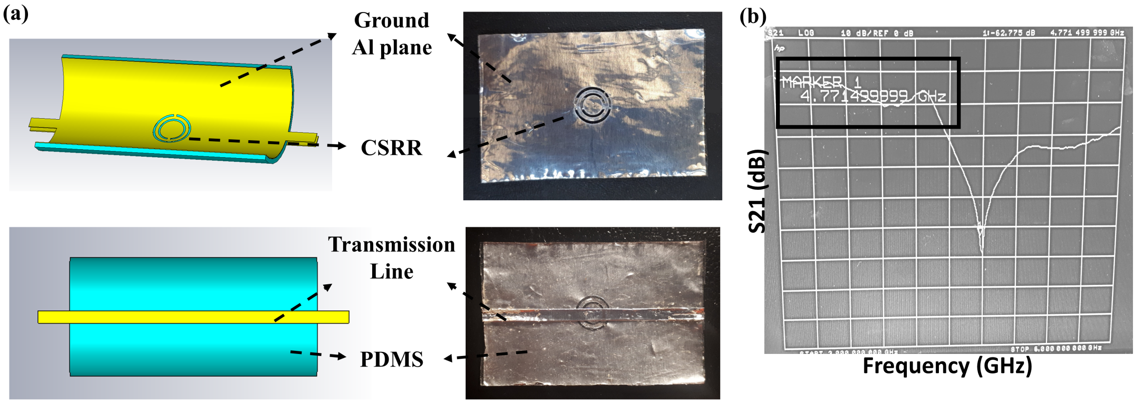


Figure 2. (**a**) Perspective view of simulated and fabricated model of flexible device. (**b**) Measured transmission coefficients as a function of frequency for flexible device without MUT.

Since the objective sensors operate at different resonance frequencies, the results should be normalized to the relevant frequency to allow a more realistic performance comparison. In this regard, the quantity that helps us is their sensitivity, defined as the relative frequency shift vs. permittivity changes of MUT for a given volume. Because the tests are performed on similar materials, we choose parameter S defined as $S = \Delta f / f_0$ where $\Delta f = f - f_0$ to compare different devices. Here f and f_0 indicate the resonant frequencies in the cases with and without MUT, respectively [5,7,12].

The primary goal of this work is to examine the fabrication process and performance of a flexible CSRR-based biosensor to reduce the air gap effect between the sample and the sensor, which is a common yet unavoidable problem. A rigid structure is also considered to compare its performance as the standard technology to that of the flexible one. So, it is fabricated on a conventional printed circuit board (PCB) for the experimental investigation, see Figure 1 (b). The ground copper plane is printed on one side of the FR4 substrate, with the rings etched out of it, and the copper transmission line is printed on the other side. The shape of the CSRR is chosen to be circular based on Ansari et al. comprehensive sensitivity study [5], which reveals that the circular CSRR gives higher sensitivity than the rectangular CSRR with the same unit area. The dimensions and configuration of the device are shown in Figure 1 (a), (b), and (c).

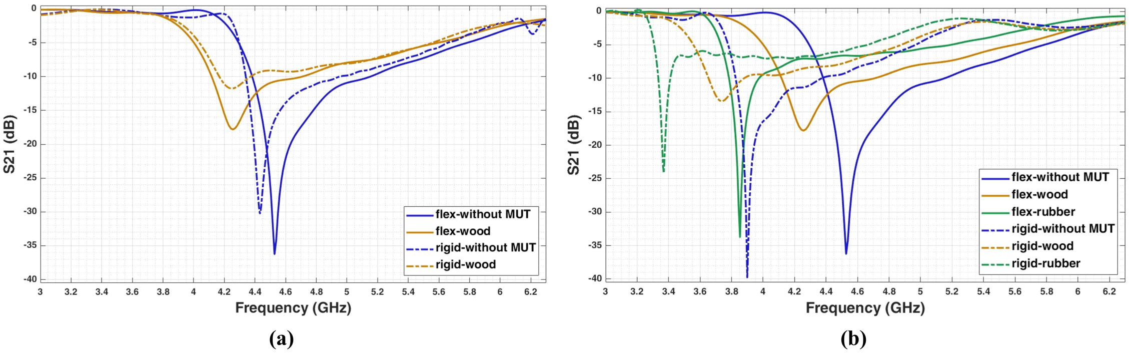
As illustrated in Figure 2 (a), the proposed flexible device is fabricated from Polydimethylsiloxane (PDMS) as its substrate and Aluminum as the metal parts. Because of PDMS's biocompatible nature and mechanical impedance near to that of soft tissues, it has been widely used in biomedical applications [17,20]. Aluminum tape is chosen to implement the ground plane and transmission line in this structure because it is not only inexpensive and readily available, but it can also withstand various bending positions without damage. After that, to make patterns on Aluminum tape, a conventional laser engraver was used. The suggested methodology eliminates traditional microfabrication procedures, which are complicated and expensive to fabricate microfeature-sized designs. Therefore, the proposed flexible biosensor is low-cost and easy to use, proper for POCT applications.

Both rigid and flexible structures are modeled in the CST studio suite for the simulation phase to acquire the two-port scattering parameters in the specified frequency band with and without MUT. After analyzing the simulation results, they are fabricated to compare experimentally. Figure 1 and Figure 2 show the overall structure of both devices in simulation and experiment.

3. Results

For evaluating the proposed structure, the simulation results were first compared. By using the suggested model for rigid and flexible sensors in CST Microwave Studio, S_{21} profile and sensitivity of sensors for different materials such as wood and rubber as reference samples are analyzed. Firstly, to consider the influence of device flexibility in analyzing samples with curved surfaces, two devices with similar characteristics such as geometry and material (PDMS and Al) in flat (rigid) and bend (flexible) structures were simulated. The results with and without MUT are shown in Figure 3 (a). The frequency change in the sensor's transmission spectra is obvious by positioning a specific volume of wood as MUT on the resonator's surface. In this case, the sensitivity of rigid and flexible devices are 0.042 and 0.062, respectively, corresponding to 48% sensitivity improvement. Consequently, as expected, the flexible structure performs better for samples with curved surfaces.

Following that, two structures with identical dimensions and materials to that of the fabricated devices, a flexible Al-PDMS sensor and a rigid Cu-FR4 device, were simulated. It is worth noting that due to fabrication faults, there is a slight variation between f_0 of two devices, which is also taken into account in the simulation. The results of both devices for different MUT are compared in Figure 3 (b). Rigid sensor sensitivity for wood and rubber samples was 0.040 and 0.136, respectively, whereas these were 0.060 and 0.149 for the flexible sensor. Here, there are also a 50% and 9.6% improvement in sensitivity for flexible structure for wood and rubber, respectively.



(a) (b)

Figure 3. Simulation of S_{21} as a function of frequency for (**a**) rigid and flexible devices with similar characteristics such as geometry and material (PDMS and Al). (**b**) a flexible Al-PDMS sensor and a rigid Cu-FR4 device.

Now that the simulation results are desirable, the fabricated flexible device was examined in practice. During the test phase, it was necessary to place the flexible biosensor on a curved surface to check its performance in the bent position. Flexible sensors were tested on curved surfaces with various bending angles to ensure that bending does not damage the biosensors and that their sensing performance stays unaltered. Then, the S_{21} parameter was measured experimentally by connecting the device to the VNA via SMA connectors. The sensor response is steady and reproducible. Also, based on experimental results, the resonant frequency for bent flexible biosensor was 4.77GHz (Figure 2 (b)) which is close to the simulation results. Even though a frequency shift in the device's transmission spectra was observed by positioning MUT, it should be optimized to improve sensitivity.

4. Discussion

In this study, a novel, cost-effective, flexible complementary split ring resonator was proposed to facilitate POCT. We provided simulation and experimental results for studying the effects of flexibility of sensor on its sensitivity. The results showed that the proposed structure can improve sensitivity for the samples with curved surfaces. This capability can be used to characterize various MUT such as blood, saliva, or when the accessibility of the sample has technical difficulties, such as curved surfaces. A comparison between traditional rigid microwave resonators and the proposed sensor was provided here to present a meaningful understanding of sensitivity enhancement in the proposed sensor.

In microwave resonator sensors, the electromagnetic fields interact with the MUT, which is how the sensing mechanism works. It has been demonstrated in the literature that the substrate stores a significant amount of electromagnetic energy; hence, increasing the intraction of MUT with substrate is predicted to enhance its electromagnetic interactions with the resonator, resulting in improved sensitivity [7]. With this argument, we predicted that a flexible sensor could provide better results than a flat sensor for curved specimens. This hypothesis was confirmed by the obtained results. Despite the fact that flexible microwave resonators provide acceptable results, there are still a number of difficult challenges to overcome.

Author Contributions: Conceptualization, F.SH.; methodology, F.SH.,N. A., H. K. H. and F.M; software, N. A. and H. K. H.; investigation, F.SH., N. A. and H. K. H.; resources, M.F.; data curation, F.SH., N. A. and H. K. H.; writing—original draft preparation, F.SH and N.A.; writing—review and editing, F.SH.,N. A. and F.M; supervision, F.SH, and M.F.; project administration, F.SH. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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