engineering proceedings

Proceeding Paper

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

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† Presented at the 8th International 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) to accurately measure the permittivity of biomaterials over a wide range of frequencies. This ability can be used to characterize various materials under test (MUT) such as blood, saliva, tissue samples, etc. The flexibility of the proposed sensor means that it can be used when the accessibility of the sample has technical difficulties, such as on 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 a 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 and compared to conventional rigid CSRR sensors. The proposed structure withstood the different bending positions well, and 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. *Eng. Proc.* **2021**, *10*, 26. https://doi.org/10.3390/ecsa-8-11303

Academic Editor: Francisco Falcone

Published: 1 November 2021

1. Introduction

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

Modern biosensors have played a significant part in realizing POC ideas based on the concept of reduced diagnostic 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 proved to be the ideal sensing choice, among other microwave resonators. This is due to their simple design, cost-effectiveness and compactness, as well as there label-free, portable and non-invasive nature, CMOS compatibility, and ease of sample preparation [5–10]. With recent progress in the research [5–7], planar CSRR was established as a leading instrument among a broad variety of disciplines, ranging from medical and biomedical sensing applications [7,11,12] to the oil and gas industry [13], and from material characterisation and process control to environmental monitoring [14].

A typical CSRR consists of a high-conductive metal 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 variation in resonant features versus the change in the permitivity of the materials under test (MUT) placed on the sensor surface was used to determine sensitivity for these types of sensor [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]. Nearly all the CSRR-based biosensors that have been proposed to date are rigid devices, limiting their applicability to MUTs 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 that have been 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], which both 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 unavailable to many research groups and organizations [16,17].

Here, a possible solution to this difficulty is provided with a simple, flexible, and cost-effective resonator microwave sensor using a novel manufacturing approach for non-invasive biomaterial permitivity measurements. This approach eliminates the complex microfabrication processes, lowering the 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 a 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, with circles as one of the popular ones, with small gaps on one side or two opposite sides (Figure 1a). 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 the permittivity of the 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, its most critical characteristic in the context of microwave engineering. Placing MUT on the resonator's surface changes the total effective permitivity and, 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, performed with a microstrip transmission line [9,19]. The CSRR biosensors' function can be easily evaluated by measuring the device's scattering parameters using the transmission line. 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 1b). To allow for analysis, 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].

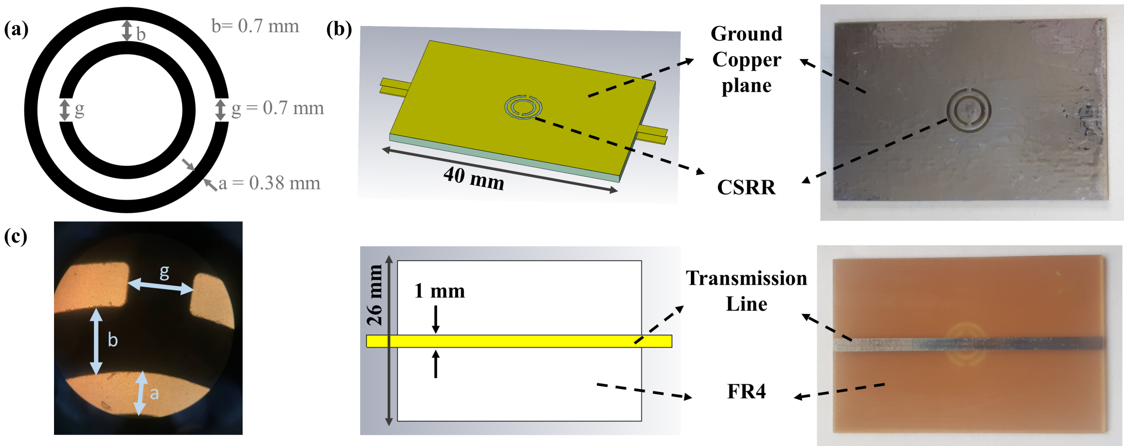

Figure 1. (**a**) Schematic of circular CSRR with design parameters. (**b**) Perspective view of simulated and fabricated model of Rigid device. (**c**) Dimensions of fabricated device.

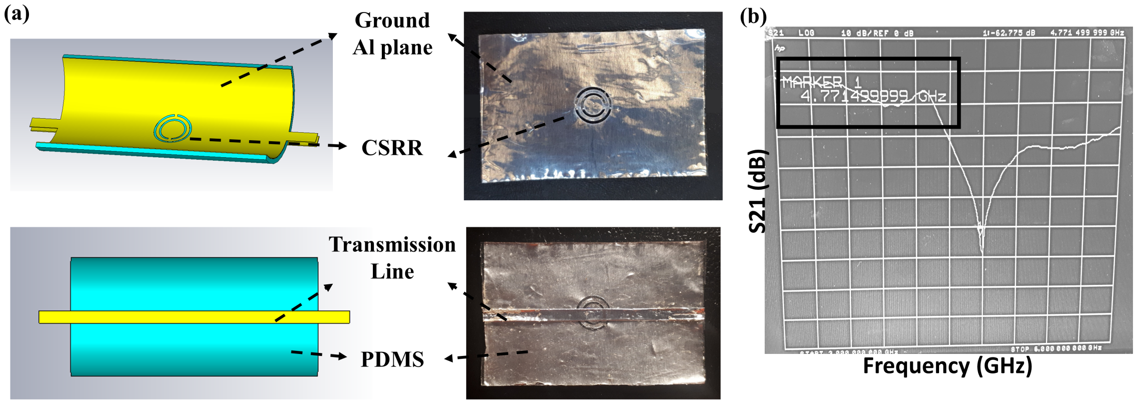

Figure 2. (**a**) Perspective view of simulated and fabricated model of flexible device. (**b**) Measured transmission coefficients as a function of frequency for flexible device without MUT.

Since the objective sensors operate at different resonance frequencies, the results should be normalized to the relevant frequency to allow for a more realistic performance comparison. In this regard, the quantity that helps us is their sensitivity, defined as the relative frequency shift vs. permitivity changes in MUT for a given volume. As the tests are performed on similar materials, we chose 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. It was fabricated on a conventional printed circuit board (PCB) for the experimental investigation; see Figure 1b. The ground copper plane was printed on one side of the FR4 substrate, with the rings etched out of it, and the copper transmission line was printed on the other side. The shape of the CSRR was chosen to be circular based on Ansari et al.'s comprehensive sensitivity study [5], which reveals that the circular CSRR provides a higher sensitivity than the rectangular CSRR with the same unit area. The dimensions and configuration of the device are shown in Figure 1a–c.

As illustrated in Figure 2a, the proposed flexible device was fabricated with polydimethylsiloxane (PDMS) as its substrate and aluminum as the metal parts. Due to 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 was chosen to implement the ground plane and transmission line in this structure because it is not only inexpensive and readily available, but 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 when fabricating microfeature-sized designs. Therefore, the proposed flexible biosensor is low-cost and easy to use, suitable 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 for an experimantal comparison. Figures 1 and 2 show the overall structure of both devices in the simulation and experiment.

3. Results

To evaluate the proposed structure, the simulation results were first compared. By using the suggested model for rigid and flexible sensors in CST Microwave Studio, the 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 when 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 3a. The frequency change in the sensor's transmission spectra can be seen by positioning a specific volume of wood as MUT on the resonator's surface. In this case, the sensitivity of the rigid and flexible devices is 0.042 and 0.062, respectively, corresponding to a 48% sensitivity improvement. Consequently, as expected, the flexible structure performs better for samples with curved surfaces.

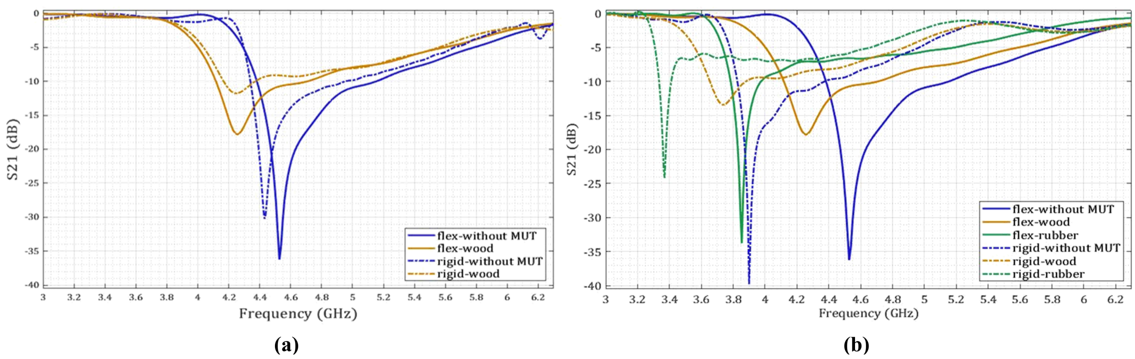

Figure 3. Simulation of S_{21} as a function of frequency for (**a**) rigid and flexible devices with similar characteristics, such as geometry and material (PDMS and Al). (**b**) a flexible Al-PDMS sensor and a rigid Cu-FR4 device.

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 was a slight variation between the 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 3b.The rigid sensor sensitivity for wood and rubber samples was 0.040 and 0.136, respectively, whereas the sensitivities were 0.060 and 0.149 for the flexible sensor. Here, there are also a 50% and 9.6% improvements in sensitivity for flexible structure for wood and rubber, respectively.

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 dos not damage the biosensors and that their sensing performance remained unaltered. Then, the S_{21} parameter was measured experimentally by connecting the device to the VNA via SMA connectors. The sensor response was steady and reproducible. Based on the experimental results, the resonant frequency for bent flexible biosensor was 4.77 GHz (Figure 2b) 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 studying the effects of the flexibility of a sensor on its sensitivity. The results showed that the proposed structure can improve sensitivity for the samples with curved surfaces. This ability can be used to characterize various MUTs, such as blood and saliva, or when the accessibility of the sample has technical difficulties, such as on curved surfaces. A comparison of traditional rigid microwave resonators and the proposed sensor was provided 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]. Using 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.S.; methodology, F.S., N.A., H.K.H. and F.M.; software, N.A. and H.K.H.; investigation, F.S., N.A. and H.K.H.; resources, M.F.; data curation, F.S., N.A. and H.K.H.; writing—original draft preparation, F.S. and N.A.; writing—review and editing, F.S., N.A. and F.M.; supervision, F.S. and M.F.; project administration, F.S. 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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