CSRR-Based Microwave Sensor for Measurement of Blood Creatinine Concentrations Levels

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Abstract: Present treatment protocols for non-communicable diseases put a socioeconomic strain on healthcare systems in many low-income to middle-income countries. Currently, this situation has highlighted the clinical need for effective diagnosis, prevention and treatment of non-communicable diseases, such as chronic kidney disease (CKD). The emerging paradigm of non-invasive and continuous monitoring of biological parameters of interest is critical to better screening as well as monitoring of afflicted patients. In this work, non-invasive, continuous monitoring of renal function using a complementary split ring resonator (CSRR) microwave sensor is investigated, as the basis for more effective management of CKD. The results of the investigation suggest that the CSRR sensor was sensitive to changes in the relative permittivity of the material under test (MUT), which modelled a portion of the human. The relative permittivity in turn, being dependent upon the concentration levels of analytes of interest such as Creatinine, highlights the potential applicability of CSRRs as a sensor module for CKD monitoring.

Keywords: complementary split ring resonator, chronic kidney disease, non-invasive continuous monitoring, complex permittivity measurement.

1. Introduction

Non-communicable diseases (NCDs) have globally become a prevalent problem, accounting for more than 60% of the mortality worldwide. NCDs impose socioeconomic consequences to low-income countries as 80% of NCD deaths occur in such countries [1, 2]. The World Health Organization (WHO) has necessitated that cost-effective preventive measures, which have an immediate impact on the burden at population level, are required in low-income to middle-income countries [3]. Non-invasive technology offers potentially low-cost and less painful alternative in support of more effective management of NCDs [4]. This technology, in the form of wearable sensors or lightweight portable devices, confers advantages in the healthcare management of NCDs by facilitating continuous monitoring of the patient's health. This introduces a paradigm shift in diagnostics as practitioners can better and progressively diagnose a patient.

In chronic kidney disease, an NCD, blood creatinine levels increase due to impaired filtration and distal tubule secretion of creatinine. However, creatinine clearance measurement is both cumbersome and error-prone. Indirect estimation of the estimated glomerular filtration rate (eGFR), the typical measure of renal function, from the serum creatinine concentration [5], has resulted in imprecise estimation of creatinine excretion and hence impairs chronic kidney disease management [6, 7]. Such factors motivate the need to develop a sensor for non-invasive and continuous monitoring of blood creatinine concentrations, as a preventive measure to mitigate the occurrence of end stage renal failure.

The non-invasive planar sensor, based on a circular complementary split ring resonator (CSRR), has been found to be sensitive for the permittivity measurement of a specimen kept in contact with the sensor at resonant frequency [8]. In reference [8], the authors investigated the effect of changes in relative permittivity (ε_r), in a range of 1-10, on the magnitude of the transmission coefficient, S_{21}. This work aims to recreate a 3D model of this sensor in the COMSOL Multiphysics® software using the RF Module, instead investigates the applicability of the reflection coefficient (S_{11}). The human skin is incorporated into the geometry, with the relevant material properties, as the specimen in contact with a circular CSRR. The material properties, relative permittivity, relative permeability and conductivity were set to the values in the frequency range (1-10 GHz) [9] for wave excitation at the lumped port on a micro-strip copper line below the plane of the CSRR. This frequency range is representative of the acceptable range for medical applications [10] and provides for the requirements on the penetration depth into the skin tissue for detecting blood permittivity changes. Changes in blood analyte concentrations, within the skin, provide a platform for detecting changes in the dielectric properties of blood due to the effect of an applied electric field [11]. As such, these changes in dielectric properties of blood are simulated by parameterizing the blood relative permittivity over the frequency sweep of 1 to 10 GHz for a relative permittivity range of 1 to 100. The effect of the latter on S-parameter magnitude is investigated in reflection mode. A wide relative permittivity range is investigated to account for all the possible changes in the dielectric properties of blood that can occur in vivo.

2. Background & Motivation

In RF and microwave engineering, the accurate determination of complex permittivity with microwave planar circuits is important to understanding material properties. This can be implemented by several techniques, inter alia:

1. The coaxial probe method, which uses a cut-off section of the transmission line of an open ended coaxial probe. The material is measured by immersing the probe into a liquid or touching it to the flat face of a solid [12]. A reflected signal (S_{11}) is obtained and can be related to ε_r but requires extensive, time-consuming full-wave analysis [13].
2. Free-space methods, which use antennas to focus microwave energy at or through a slab of material without the need for a test fixture [14]. Measurement of relative permittivity over a wide frequency band is achieved; however, this method is mostly applicable to larger sample sizes and is limited in measuring thin and electrically small samples [15].
3. Transmission line methods, which involve placing the sample inside a portion of an enclosed transmission line, usually a rectangular waveguide or coaxial airline. The relative permittivity is measured from both the reflected (S_{11}) and transmitted (S_{21}) signals [16]. This is method is more cost-effective than the free-space method but lacks accuracy in measuring the dielectrics of low-loss samples [17].
4. Resonant methods, which use cavities which resonate at certain frequencies upon perturbation. A piece of sample material affects the centre frequency (f) of the cavity, from which the material dielectrics can be obtained at a single frequency. The resonant method is the most accurate means of material parameter determination [18].

Complementary split ring resonators (CSRR) are electrically small structures designed with a loop and a gap that separate the loop in two parts. CSRR sensors have been implemented as a non-invasive, portable and low cost means of dielectric measurement of low-loss materials, with more ease in sample preparation [19]. CSRR sensors function as near-field probes implemented on the ground plane of micro-strip lines, which excites the sensors with a dielectric MUT inserted below the ground plane. Research has been extensively conducted to investigate the dielectric response of blood to an applied electric field, especially for the development of a sensor module to detect blood glucose changes. Much of the research has suggested that changes in electrical properties can be correlated to detectable changes in blood glucose concentration levels. To the best of the authors' knowledge, this has not been investigated for creatinine levels and renders a study to understand if a similar relationship exists for blood creatinine. With the advent of planar technology development in healthcare [20], a CSSR-based microwave sensor for blood creatinine level detection provide an excellent platform to develop a module, which adopts an Internet of Things (IoT) approach necessary to target the difficulties involved in NCD management. As such, the aim of this study is to simulate the response of a CSRR sensor to the change in dielectric constant or relative permittivity of blood to translate to the development of a physical sensor module for in vivo blood creatinine detection.

3. Use of COMSOL Multiphysics®

A 3D model of a CSRR-based sensor was built in the COMSOL Multiphysics® software. The RF module was used as the selected physics, given the electrical size (L_c) is greater than the limit of $L_c > \lambda/100$, to excite a microstrip line below the plane of the CSRR sensor over a narrow frequency band of 1 to 10 GHz via a Frequency Domain study, which was employed under the conditions that the material properties (ε_r) are constant with respect to electrical field strength and the changes in the latter, is sinusoidal at a known frequency or range of frequencies. The microstrip line bridges the gap between the top and ground perfectly conducting planes and is set as a lumped port in the study to mitigate reflection during wave propagation. The electric field is thus assumed to be uniform in magnitude between the bounding faces with the height and width (2.91 mm) of the lumped port face smaller than the wavelengths in the surrounding medium for the tested 1-10 GHz band. The lumped port boundary condition thus allows for material property changes to be detected solely from the perturbation due to relative permittivity changes from an overlying material under test (MUT). As the impact of creatinine concentration on the effective relative permittivity of serum has not as extensively investigated as glucose, at least not for the frequency range investigated, a parametric sweep over a relative permittivity range from 1-100 (in steps of 5) was iterated with the default *Robust* setting to detect the response of the CSRR centre frequency due to relative permittivity change. This change is related to the concentration of the MUT. Therefore, the response of the CSRR change in resonance can be used to track changes in MUT concentrations. The material parameters for blood, in the tested frequency range, were incorporated into the study. The *Finer* mesh option, the computational cost limit for the system used, was chosen to ensure the densest mesh was available for the solver to ensure the numerical solutions for ε_r were close to the actual solution. Remeshing, though recommended for variations in material properties, was not required given the narrow frequency band used for the study. The surrounding air was modelled as a perfectly matched layer to simulate a real-life application of the sensor with FR4 as the substrate material.

4. Methodology

The CSRR sensor was modelled as shown in Figure 1. The sensor dimensions were based upon previous work by Ansari et al. [8]. A full analysis of the dielectric parameters of the CSRR sensor was performed to ascertain the parameters that correlate best with changing permittivity of the MUT over the sensor.

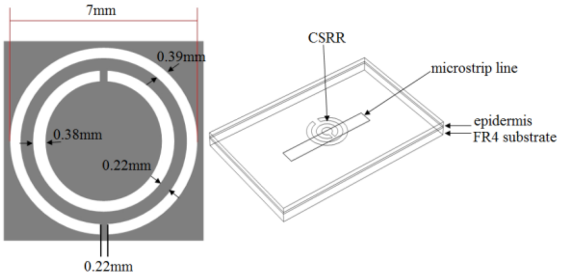

Figure 1. Labelled CSRR model used in simulations showing the respective components. Dimensions of the CSRR are shown to the left of the model.

4.1. Model Details

The dimensional and material details which were used in building the model are captured in Table 1.

4.2. Resonant Frequency Analysis

The sensor was excited by the normal component of an electric field in the Frequency Domain study node. The MUT, or rather a material block with the electrical properties of blood, covers the entire area of the CSRR to ensure effectiveness in perturbation by the electric field is achieved. The S-parameter (S_{11}) plots were generated to detect the resonant frequency (f_r) or the centre frequency change due to the MUT placed over the CSRR. The resonant frequency corresponding to each change in permittivity, or indirectly to concentration changes in blood effecting a change in dielectrics, is obtained from the S_{11} plots and correlated to the variation in ε_r.

Table 1: Dimensional and Electrical Parameters used in simulations

Component	Shape & Dimensions	Electrical Parameters
Air (*perfectly matched layer*)	Sphere: radius = 110 mm	σ = 0 S/m ε_r = 1 μ = 1
Substrate (FR4)	Primitive Block: width = 40 mm depth = 26 mm height = 0.8 mm	σ = 0.004 S/m ε_r = 4.5 μ = 1
Epidermis (Blood)	Primitive Block: width = 40 mm depth = 26 mm height = 1 mm	σ = 0.8 S/m ε_r = 1- 100 μ = 1

4.3. Loss Tangent Analysis

Permittivity describes the interaction of a material with an electric field is given as a complex quantity:-

$$\varepsilon = \varepsilon' - j\varepsilon'' \qquad (1)$$

The real part of permittivity (ε') is a measure of how much energy from an external electric field is stored in a material. The imaginary part of permittivity (ε'') is the loss factor and measures how dissipative or lossy a material is to an external electric field.

The relative permittivity or dielectric constant is the ratio of ε' and ε_0 ($\varepsilon_r = \frac{\varepsilon'}{\varepsilon_0}$). The loss factor includes the effects of both dielectric loss and conductivity, represented as the loss tangent or the relative "lossiness" of a material is the ratio of the energy lost to the energy stored:-

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\sigma}{\varepsilon'\omega} = \frac{\sigma}{\varepsilon_0\varepsilon_r\omega} \qquad (2)$$

σ is the conductivity of the MUT or rather the blood input into the parameters of the material block over the ground plane comprising the CSRR. ω is the angular frequency of the electromagnetic wave generated from the excitation of the lumped port set at the micro-strip line. The loss tangent was correlated to ε_r and the reflection detected at the 2.65GHz resonant frequency of the unloaded CSRR sensor ($S_{11,\ 2.65GHz}$).

5. Results and Analysis

Figures 1 to 6 capture the shift in resonance frequency of the CSRR due to the presence of the epidermis, parameterized with the electric properties of blood, acting as a perturbation to the applied electric field on the plane of the sensor. A resonance shift is detectable for relative permittivities ranging from 5 to 25, however, for ranges 30 to 100, the resonant frequency tend to overlap while the S_{11} parameter varies in depth with changes in the relative permittivity of the epidermis (blood). The latter trend was observed at the 2.65 GHz frequency, which is the resonant frequency of the unloaded CSRR sensor, for the provided dimensions, exposed to air.

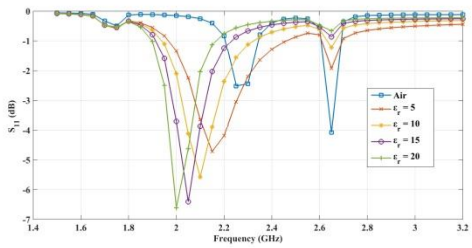

Figure 2. S_{11} vs. frequency for relative permittivities, ε_r of the overlying epidermis $\in$ (5, 20). The S-parameter response for air is shown as the unloaded condition.

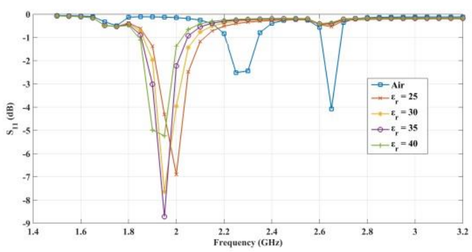

Figure 3. S_{11} vs. frequency for relative permittivities, ε_r of the overlying epidermis $\in$ (25, 40). The S-parameter response for air is shown as the unloaded condition

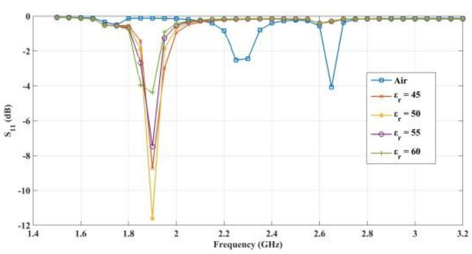

Figure 4. S_{11} vs. frequency for relative permittivities, ε_r of the overlying epidermis $\in$ (45, 60). The S-parameter response for air is shown as the unloaded condition.

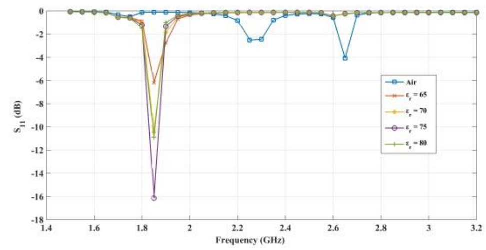

Figure 5. S_{11} vs. frequency for relative permittivities, ε_r of the overlying epidermis $\in$ (65, 80). The S-parameter response for air is shown as the unloaded condition.

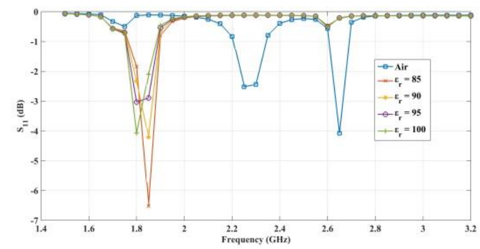

Figure 6. S_{11} vs. frequency for relative permittivities, ε_r of the overlying epidermis $\in$ (85, 100). The S-parameter response for air is shown as the unloaded condition.

The reflection obtained in the loaded condition ($S_{11,\ 2.65\ GHz}$) is plotted versus ε_r (Fig. 7). The goodness of fit results obtained from MATLAB curve fitting tool indicates that the change in reflection with respect to air (unloaded condition) can be used as a parameter to distinguish between changes in relative permittivities of blood. The loss tangent (tan δ) plot (Fig. 8) also shows a good correlation with ε_r, in a decreasingly exponential form and thus can also be used as a parameter to distinguish concentration changes of blood analytes due to changing ε_r, given the relationship of ε_r with the loss tangent as explained above. The $S_{11,\ 2.65GHz}$ vs. tan δ plot (Fig. 9) highlights the best goodness of fit ($R^2 = 0.9873$) for using the CSRR sensor as a module for blood-creatinine concentration detection.

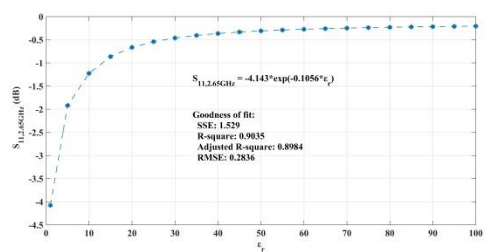

Figure 7. $S_{11,\ 2.65GHz}$ (S_{11} at 2.65 GHz) vs ε_r of the overlying epidermis for the CSRR sensor.

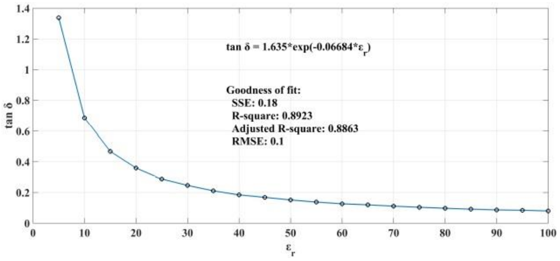

Figure 8. Loss tangent response of the overlying epidermis (tan δ) vs ε_r.

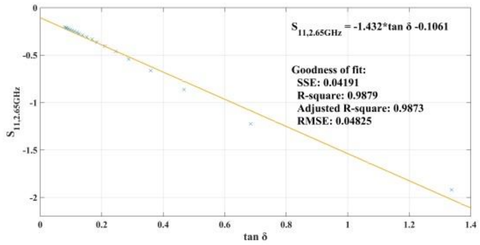

Figure 9. $S_{11,\ 2.65GHz}$ (S_{11} at 2.65 GHz) vs the loss tangent response of the overlying epidermis (tan δ).

6. Conclusion

The simulation results show the propensity of microwave engineering to monitor relative permittivity changes for a MUT acting as a disturbance to an applied electric field on the planar surface of a microwave sensor. CSSRs are sensitive to changes in relative permittivity, as evident in the correlation response of changes in the electrical parameters due to MUT, with general the electrical properties of the human epidermis, for the M-band frequency range investigated. These results, as such, motivate future steps to physically develop a prototype sensor module incorporated with a voltage-controlled oscillator (VCO), sensitive to the observed changes in electrical parameters, as part of a frequency sensitizer system [12].

7. References

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