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COMPUTER MODELING OF MICROWAVE STRIPLINE RESONATORS FOR NON-INVASIVE SENSING

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Microwave stripline resonators of rectangular and double rectangular shapes for non-invasive sensing have been designed and investigated experimentally and numerically. The resonator of single rectangular shape has had a resonance at about 4.32 GHz for S_{21} and the resonator of double rectangular shape has had resonances at about 3.5 GHz for S_{21} and 5.85 GHz for S_{11}. The simulation results for the sensitivity of the single rectangular and double rectangular resonators were -0.023 $dB/(mg/dL)$ (glucose concentration) and 0.0143 $dB/(mg/dL)$ (NaCl concentration), respectively. The electromagnetic field distribution of the resonators was visualized and compared using computer simulation software HFSS. The obtained data have shown the accuracy of resonators as a non-invasive sensor for biophysical applications.

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Introduction. The application of the electromagnetic waves and the development of miniaturized devices operating in the microwave ranges for non-invasive sensing is an up-to-date task. Nowadays, non-invasive microwave sensing is a promising technique. It is used in plural applications such as environmental monitoring, healthcare industry, food industry, etc. [1–3]. Important benefit of non-invasive sensing technique lies in its real-time, non-destructive and safe character, particularly, in the healthcare industry [4]. When the resonator is used as a sensor, the material under test (MUT) to be measured is brought into contact with the sensing zone in the resonator and, therefore, the transmission and reflection parameters of system change depending on the complex relative permittivity of the MUT [5]. These devises are of various type of geometric structure and can be utilized for non-invasive sensing applications and to monitor the electromagnetic properties of materials [6,7].

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In the study we have designed and optimized two microwave stripline resonators of rectangular and double rectangular shapes for non-invasive measurements of the D-glucose and sodium chloride concentrations in aqueous solution. The single rectangular and double rectangular resonators have had resonant frequencies at about 4.3 GHz and 3.5 GHz, respectively. With these resonators we have measured the shifts of the transmission (ΔS_{21}) and reflection (ΔS_{11}) parameters due to changes in concentrations of the solvents, namely, D-glucose and sodium chloride. The optimization of the sensor and calculations of S-parameters were implemented by using simulation software based on Finite element method (HFSS).

Design, Fabrication and Operating Principle. The microwave resonators were modeled as single rectangular and double rectangular shaped structures. The real images and geometry of prepared resonators are shown in Fig. 1. Ceramic substrates of the resonators were coated from both upside and downside by thin layer of silver paste of about 50 μm thickness and then patterned by using a laser patterning technique on upside. The geometry of the resonators was optimized by using HFSS to obtain high metering sensitivity. The optimized parameters were chosen as follows: $h = 1$ mm; $w = 0.1$ mm; $s = 2$ mm; $l = 3$ mm. To achieve more accurate simulation results, the upper side and downside of the substrates were set to Finite Conductivity, and silver with a thickness of 50 μm was chosen as a conductor. Note that in simulation the radiation boundary with PML layer was chosen as an outer boundary in order to completely eliminate the feedback of electromagnetic waves toward system. The simulated results were obtained by applying the Multipole Debye Model Input function for the glucose and NaCl solutions to derive accurate results [8].

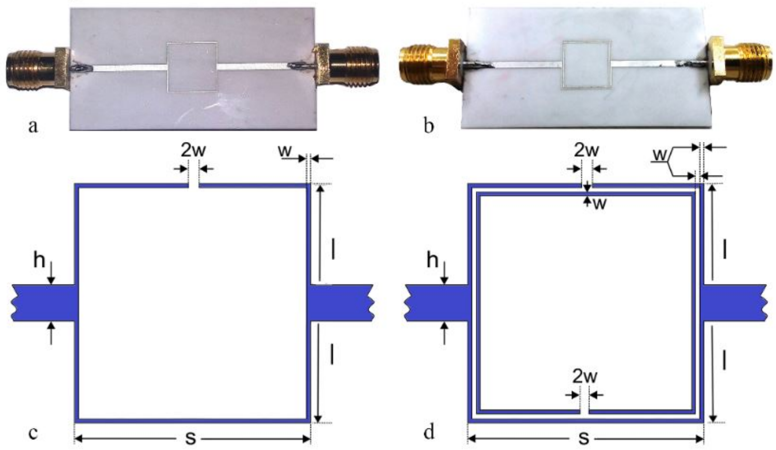

Fig. 1. The real images of prepared (a) single rectangular and (b) double rectangular resonators. The structural geometry of (c) single rectangular and (d) double rectangular resonators.

The glucose aqueous solution with glucose concentration ranging from 0 (ultrapure water) to 250 mg/dL by step of 50 mg/dL was chosen as a MUT. Concentration of sodium chloride aqueous solution changed from 0 to 500 mg/dL in increments of 100 mg/dL. The simulations for glucose and NaCl measurements were performed using single rectangular and double rectangular shaped resonators, respectively. During the simulation the MUT volume was kept constant (300 μL) and within the quartz flask to get closer to the experiment.

The computer models in HFSS for single and double rectangular resonators and simulated electromagnetic near-field distributions are represented in Fig. 2. For glucose concentrations the simulation was done by single rectangular resonator and for NaCl concentrations by double rectangular resonator as shown in Fig. 2 (a) and (b). The electric field intensity was concentrated around the gap of the single rectangular resonator and between the two gaps of double rectangular resonator as shown in Fig. 2 (c) and (d). The magnetic field intensity was concentrated around the metal edges of the single rectangular resonator and between metal edges of the double rectangular resonator as shown in Fig. 2 (e) and (f).

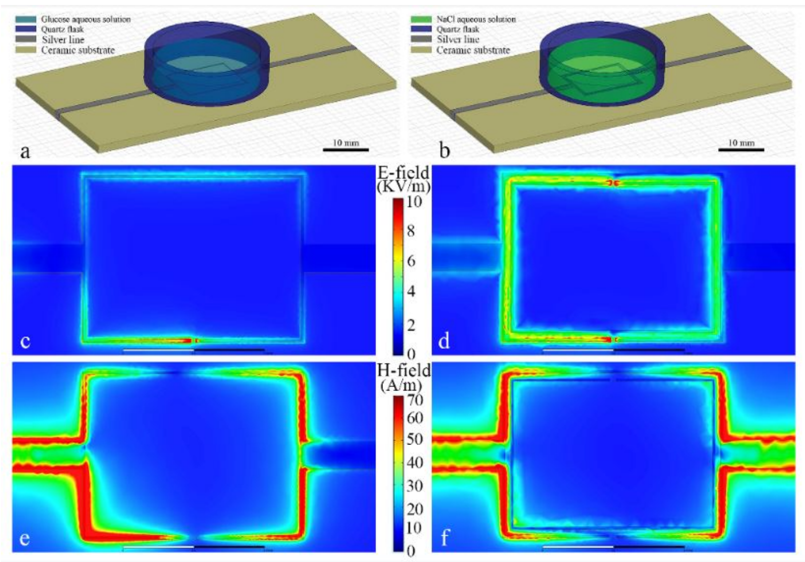

Fig. 2. The computer models in HFSS for (a) single rectangular and (b) double rectangular resonators. Simulated electric field distribution for (c) single rectangular and (d) double rectangular resonators and simulated magnetic field distribution for (e) single rectangular and (f) double rectangular resonators without MUT.

Results and Discussion. The measured and simulated transfer parameters for single and double rectangular resonators without MUT are presented in Fig. 3 (a) and (b), respectively. The obtained data for simulation and experiment are close enough and, in general, the behaviors of measured and simulated S-parameters are in good agreement. The single rectangular resonator has had resonance frequency at about 4.3 GHz (experiment: 4.32 GHz vs. simulation: 4.35 GHz) for S_{21} and double rectangular resonator has had two picks of resonance frequency at about 3.5 GHz (3.50 GHz in experiment vs. 3.53 GHz in simulation) for S_{21} and at about 5.85 GHz (5.82 GHz in experiment vs. 5.87 GHz in simulation) for S_{11}. Note that for single rectangular resonator the S_{21} amplitude variation was $\Delta S_{21}=S_{21}^{exp.}-S_{21}^{sim.}=5.63\ dB$ at

4.32 *GHz*, and for double rectangular resonator the S-parameter amplitude variation was $\Delta S_{21}=S_{21}^{exp.}-S_{21}^{sim.}=0.4\ dB$ at 3.5 *GHz* and $\Delta S_{11}=S_{11}^{exp.}-S_{11}^{sim.}=3.62\ dB$ at 5.85 *GHz*.

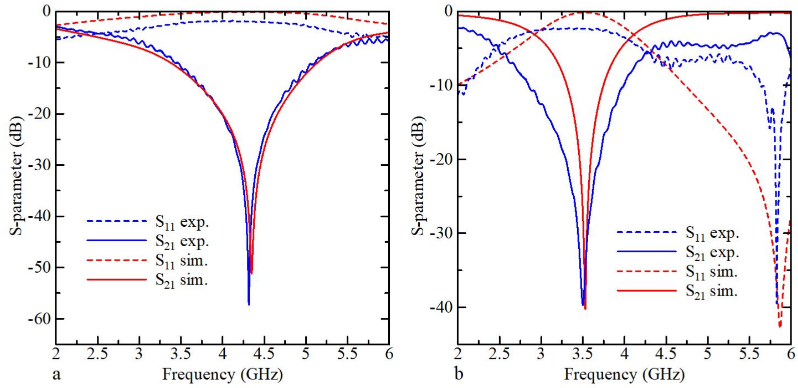

Fig. 3. The obtained experimental and simulation S-parameters without MUT for (a) single rectangular resonator and (b) double rectangular resonator.

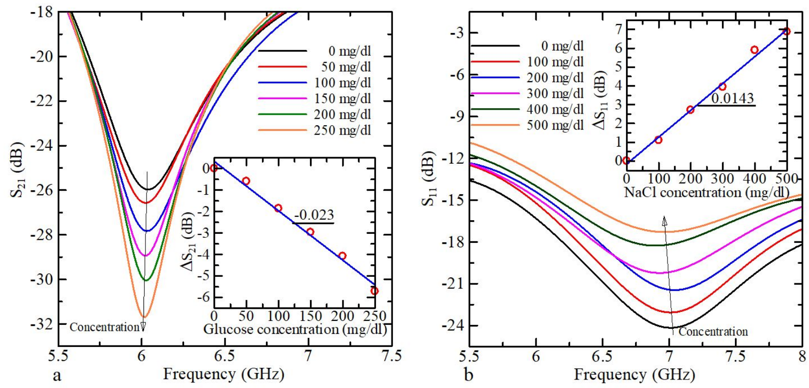

Fig. 4. The simulated results of (a) microwave transmission coefficient S_{21}(single rectangular resonator) profiles for DI water and for D-glucose aqueous solution with glucose concentrations of 50–250 mg/dL; (b) microwave reflection coefficient S_{11} (double rectangular resonator) profiles for DI water and for NaCl aqueous solution with sodium chloride concentrations of 100–500 mg/dL. Inset plots show dependence of (a) S_{21} (single rectangular resonator) parameter on the glucose concentration of the solution at 6 *GHz*; (b) S_{11} (double rectangular resonator) parameter on the NaCl concentration of the solution at 7 *GHz*.

In the simulation the rectangular shaped resonator had been loaded with glucose aqueous solution with various D-glucose concentration (0–250 mg/dL) and the double rectangular shaped sensor had been loaded with sodium chloride aqueous solutions with various NaCl concentrations (0–500 mg/dL) in increments of 50 mg/dL and 100 mg/dL, respectively (Fig. 4)

When loading the resonators with MUT the resonance frequencies were shifted due to change of total impedances of the system. Simulated S_{21}-parameter had a resonant minimum at around 6 *GHz* for the single rectangular shaped resonator and simulated S_{11}-parameter had a resonant minimum at around 7 GHz for the double rectangular shaped resonator loaded with MUT. The loading of resonators by MUT caused the changes of total impedance of the system and S-parameter due to change in complex dielectric permittivity of MUT depending on the concentration of D-glucose or NaCl in an aqueous solution.

Conclusion. Single and double rectangular shaped microwave resonators were designed and prepared as non-invasive sensors. D-glucose and NaCl aqueous solutions were chosen as sensing samples. Simulation were done for single rectangular shaped resonator to monitor concentrations of glucose and NaCl. The linear relationship were found at about 6 GHz with a slope of -0.023 $dB/(mg/dL)$ between simulated S_{21}-parameter and concentrations of D-glucose for single rectangular resonator, and at about 7 GHz with a slope of 0.0143 $dB/(mg/dL)$ between simulated S_{11}-parameter and concentrations of NaCl for double rectangular resonator. The obtained results indicate the feasibility of using the designed microwave stripline resonators for real-time non-invasive sensing in biophysical applications.

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