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REAL-TIME SENSING THE GLUCOSE CONCENTRATION BY QUADRATIC-SHAPED MICROWAVE SENSOR

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In this study we present a microwave sensor based on the quadratic-shape and designed for detecting glucose concentration in aqueous solutions by using a microwave near-field electromagnetic interaction technique. We found a linear relationship between the microwave S_{11} reflection coefficient of the suggested system and the concentration of glucose in solution. Due to this linear relationship we were able to determine the glucose concentration in the range of 0–250 mg/dL at an operating frequency near 3.6 GHz. The measured minimum detectable signal was 0.0044 $dB/(mg/dL)$ and the measured minimum detectable concentration was 6.8 mg/dL. These results suggest that the system we offer has a high enough accuracy for non-contact glucose monitoring and provides a promising basis for developing a non-invasive glucometer.

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***Keywords*:** quadratic resonator, microwave sensor, glucose concentration.

Introduction. In the 21 century there is a tendency for medical devices to become more comfortable and safe. Microwave sensing technology plays a prominent role in these developments. Especially many research groups try to find more reasonable solutions for diabetics [1]. In some cases diabetics need to test their glucose level every day several times (6–7 times) by pricking their fingers [2]. This technique has precise indices, but is not comfortable, and there is a probability of infection of patients. There are several types of techniques for glucose detection such as fluorescence spectroscopy, optical, ultrasonic, infrared spectroscopy, electrochemical [3–7]. However, some of these techniques are invasive, low precise, not sensitive and have expensive preparation methods.

Microwave resonant structures are used to develop noninvasive detection techniques. Due to their high Q-factor, the microwave resonators can serve as non-invasive sensors with high sensitivity at specific frequencies [8, 9]. In present study a

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resonator of a quadratic shape is presented. We propose a microwave sensor based on this resonator for determination of the D-glucose ($C_6H_{12}O_6$) concentration. The suggested system could measure the microwave reflection coefficient S_{11} at resonant frequency of about 3.6 GHz. The changes of glucose concentration lead to shifts of reflection coefficient S_{11} due to the electromagnetic interaction between the microwave sensor and the sample. In our study we have measured the reflection coefficient of system varying the glucose concentration from 50 to 250 mg/dL, which corresponds to the range of glucose concentration in human blood of both normal and diabetic patients [10].

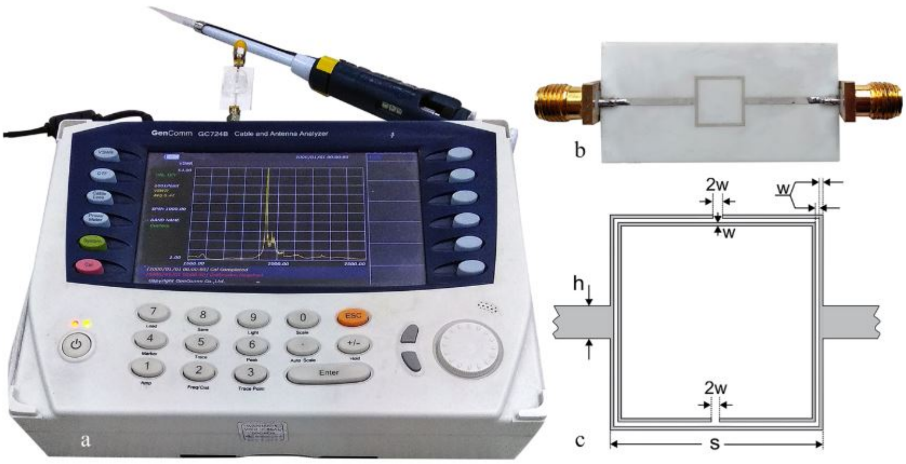

Fig. 1. Experimental setup and sensor (a); optical (b) and structural (c) configuration.

Design, Fabrication and Operating Principle. The experimental configuration of measurement setup is shown in Fig. 1 (a). The Figure shows optical image (b) and structural scheme (c) of the prepared quadratic-shaped sensor. Ceramics with dielectric permittivity of about 9 as a substrate of sensor was chosen. Two sides of substrate were coated by silver paste with thickness of about 50 μm. The sensor was dried out and one side of sensor was patterned by laser patterning technique. Finally, the sensor was annealed and soldered to the conductors. The ceramic substrate had dimensions of $20 \times 40 \times 1 (mm)$. The geometry of the quadratic shape sensor is shown in Fig. 1 (c). The designed parameters of the sensor were, $mm: \ h = 1, \ w = 0.1, \ s = 8$. The sensor with the material under test (MUT) was connected to a network analyzer (GenComm GC724B) to analyze the S_{11} reflection coefficient of the system. The entire system was placed on a mechanical vibration isolated table and the experiments were conducted at a temperature of $24 \pm 1°C$ under a relative humidity of $43 \pm 10\%$.

The glucose-water solution with various concentrations (0–250 mg/dL) was injected into the glass $(\varepsilon = 4.2)$ vial and the response of the MUT was measured by vector network analyzer (VNA). The height and thickness of the vial was 8 and 1 mm, respectively, and the outer and inner radius were 7.5 and 6.5 mm, respectively. The glass vial was fixed in the center of the sensor for fully interaction and the volume of aqueous solution was maintained at 500 μL during all experiments. The resonator was calibrated with de-ionized (DI) water giving an S_{11} minimum of -25.7 dB. After each test, the glass vial was washed and dried for the next test. The reflection coefficient S_{11} of the sensor was shifted when replacing the MUT as a load. Measuring the reflection coefficient for each concentration we indirectly measured the dielectric permittivity for each concentration. Thus, the system served as a glucose sensor.

Theoretical Background. The operational principle of sensor-MUT system is based on the variation in the microwave transmission coefficient S_{11}. The change of concentration of solution leads to change of dielectric permittivity ε, as a result of which the microwave transmission coefficient S_{11} changes. The frequency-dependent relative permittivity of material has complex form: $\varepsilon(\omega) = \varepsilon'(\omega) + \varepsilon''(\omega)$, where $\varepsilon'(\omega)$ and $\varepsilon''(\omega)$ are the real and imaginary parts of complex permittivity, respectively. In the presence of electromagnetic field, the storage and loss of energy in the MUT are induced by real $\varepsilon'(\omega)$ and imaginary $\varepsilon''(\omega)$ parts of complex dielectric permittivity, respectively [11].

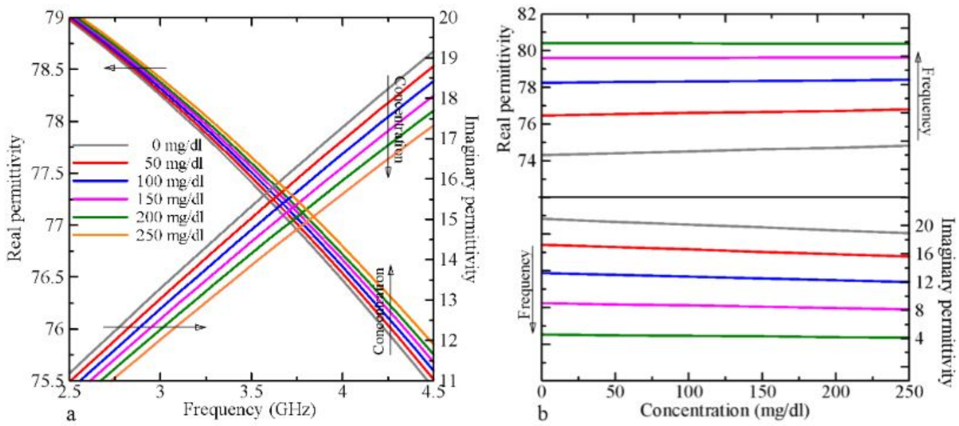

Fig. 2. Estimated real and imaginary parts of the complex relative dielectric permittivity of the glucose aqueous solution in the frequency range of 2.5–4.5 GHz (a) and for the D-glucose concentration up to 250 mg/dL (b).

The dependence dielectric permittivity on the concentration of solute glucose is expressed by the molar increment δ and is given by

$$\varepsilon_g(\omega) = [\varepsilon_0'(\omega) + c\delta'] - j[\varepsilon_0''(\omega) + c\delta''],$$

where $\varepsilon_o(\omega)$ is the complex permittivity of DI water ($\varepsilon'(\omega) = 77.23$ and $\varepsilon_0''(\omega) = 15.72$ at 3.6 GHz, 25°C), c is the concentration of glucose, $\delta = \delta' - j\delta''$ is the increase in permittivity when the glucose concentration is raised by 1 unit ($\delta' = 0.00577$ $(mg/dL)^{-1}$ and $\delta'' = 0.00015$ $(mg/dL)^{-1}$) [12,13]. Here the complex dielectric permittivity of DI water is given by the Havriliak–Negami relaxation model:

$$\varepsilon_0(\omega) = \varepsilon_\infty + \frac{\Delta\varepsilon}{(1+(j\omega\tau)^\alpha)^\beta}, \quad (1)$$

where $0 \leq \alpha,\ \beta \leq 1,\ \varepsilon_\infty = 4$ is the permittivity in the high frequency limit, $\varepsilon_s = 72$ is the static, low frequency permittivity ($\Delta\varepsilon = \varepsilon_s - \varepsilon_\infty$), and $\tau = 10^{-12}\ s$ is the characteristic relaxation time of DI water at 3.6 *GHz*. Exponents α and β describe the asymmetry and broadness of the corresponding spectra, respectively. In special cases when $\alpha = 1,\ \beta = 1;\ \alpha \neq 1,\ \beta = 1$ and $\alpha = 1,\ \beta \neq 1$ the Eq. (1) describes the Debye, Cole–Cole and Cole–Davidson relaxation models, respectively. The main relaxation process in water occurs in microwave frequency region and complex dielectric permittivity can be described by relaxation models mentioned above [14, 15]. Fig. 2 shows estimated behavior water real and imaginary dielectric permittivities as function of frequency (a) (for various glucose concentrations) and concentration (b) (at various operating frequency).

Results and Discussion. The measured responses of the S_{11} microwave reflection coefficient at different glucose-water solutions concentrations (0–250 mg/dL) are shown in Fig. 3 (a). As was expected, S_{11} parameter depended on the variation of the glucose concentration in the aqueous solution. The largest change in S_{11} was observed at 3.6 *GHz* resonant frequency. The linear relationship between measured S_{11} parameter and glucose concentration is shown in Fig. 3 (b). The measured S_{11} parameter decreased with increasing the concentration of glucose at resonant frequency of 3.6 *GHz* from $-25.7\ dB$ for DI water to $-26.7\ dB$ for 250 mg/dL glucose concentration. The S_{11} parameter varied linearly with a change in glucose concentration with a slope of 0.0044 $dB/(mg/dL)$. The measured resolution of the system was 0.03 *dB* and the minimum detectable concentration $c_{\min}$ of designed sensor was found to be 6.8 mg/dL.

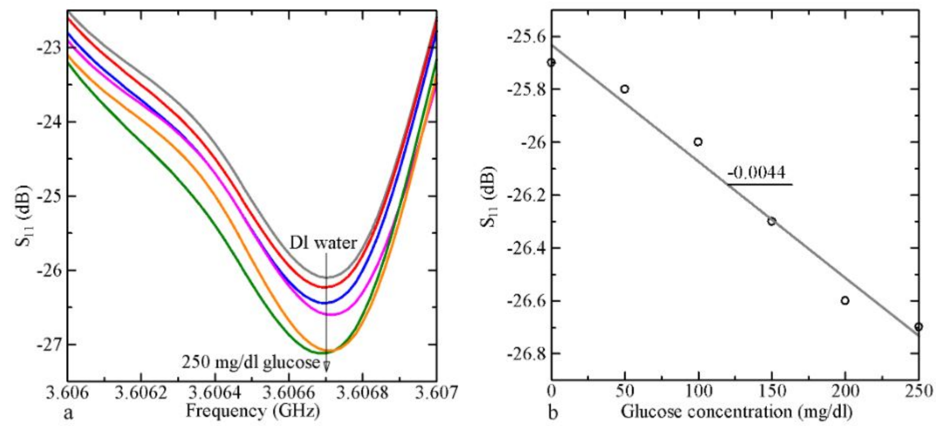

Fig. 3. Measured microwave reflection coefficient S_{11} profiles for DI water and for glucose aqueous solution with various D-glucose concentrations and with 500 μL MUT volume (a); the measured microwave response dependence on D-glucose concentration at the resonant frequency of about 3.6 *GHz* (b).

The reflection coefficient S_{11} of glucose solution also expressed the dependence on the volume of solution. When the volume of glucose-water solution increased the reflection coefficient increased and the resonance frequency decreased (data not shown here). The change of reflection coefficient S_{11} per volume was $\Delta S_{11}/\Delta V = 0.0183\ dB/\mu L$, which means that with a change of the solution volume by 1 μL the S_{11} increased by 0.0183 dB. The measurement sensitivity was the highest at 500 μL volume of the MUT, therefore, all measurements were done at this volume.

Conclusion. A quadratic-shaped microwave resonant sensor was designed and prepared for detection of D-glucose concentration in glucose aqueous solution by a non-invasive method. The slope of the linear relationship between response measured S_{11} and D-glucose concentrations at about 3.6 GHz was found to be 0.0044 $dB/(mg/dL)$. The minimum detectable resolution for glucose concentration was about 6.8 mg/dL for 500 μL MUT volume.

The obtained date characterize the proposed quadratic-shaped resonator as a promising tool and its future improvements can serve as a prototype for the development of a real-time non-invasive glucometer.

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ԻՐԱԿԱՆ ԺԱՄԱՆԱԿՈՒՄ ԳԼՅՈՒԿՈԶԻ ԽՏՈՒԹՅԱՆ ՉԱՓՈՒՄԸ ՔԱՌԱԿՈՒՍԱՅԻՆ ՁԵՎԻ ՄԻԿՐՈԱԼԻՔԱՅԻՆ ՍԵՆՍՈՐԻ ՄԻՋՈՑՈՎ

Աշխատանքում ներկայացված է քառակուսային ձևի միկրոալիքային սենսոր՝ նախատեսված ջրային լուծույթներում գլյուկոզի խտության չափման համար՝ հիմնված միկրոալիքային մոտակա դաշտի էլեկտրամագնիսական փոխազդեցության սկզբունքի վրա: Ստացվել է համակարգի միկրոալիքային անդրադարձման գործակցի և գլյուկոզի խտության միջև գծային կախվածություն, որի հիման վրա կարելի է որոշել գլյուկոզի խտությունը 0 – 250 *մգ/դԼ* փիրույթում, 3.6 Գ *Հց* աշխատանքային հաճախության դեպքում: Չափված փոքրագույն զգայունությունը՝ 0.0044 *մգ/դԼ* էր, իսկ փոքրագույն գնահատելի խտությունը՝ 6.8 *մգ/դԼ*: Ստացված արդյունքները վկայում են, որ առաջարկված համակարգը ցուցաբերում է մեծ ճշգրտություն ոչ հպումային չափումներում և կարող է հիմք ծառայել իրական ժամանակում աշխատող արյան գլյուկոմետրի մշակման համար: