Real-time qualitative and quantitative analysis of Saccharides using CSRR based RF sensor

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***Abstract*—This paper demonstrates radio frequency (RF) sensing of saccharides such as glucose, fructose and sucrose based on Complementary Split Ring Resonator (CSRR). The CSRR based planar sensor is designed and fabricated over FR4 substrate of thickness 1.6 mm and with copper on both sides of thickness 0.035 mm. The fabricated sensor is connected to the Vector Network Analyzer (VNA) to study the electromagnetic interactions behavior between the designed sensor and saccharides. The quantitative and qualitative analysis is conducted by changing the concentration of saccharides in aqueous solution from 10 mg/ml to 50 mg/ml in steps of 10 mg/ml and then by changing the overall sample volume from 1 μl to 100 μl in variable step sizes. The resonant frequency property is utilized for detecting small changes in saccharides concentration of up to 10 mg/ml and overall sample volume change of 1 μl. The proposed RF sensor is highly robust, reliable, cost-effective and easy to use over other existing methodologies.**

***Index Terms*—Radio Frequency, Microwave sensor, CSRR, Glucose, Fructose, Sucrose, Saccharides**

I. Introduction

Saccharides, also known as carbohydrates are polyhydroxylated aldehydes or ketones with the chemical formula $C_nH_{2m}O_m$ where n and m can be different [1]. Saccharides and their derivatives are essential ingredients in various life processes and play crucial role in metabolism and various cell processes for energy production in both humans and plants [2]. The above processes take place in presence of water which is chosen as the solvent in this work. Glucose is monosaccharide and an essential component of blood, whose levels, if not controlled, can lead to diabetes mellitus and other cardiovascular diseases [3]. Sucrose is disaccharide containing one molecule of glucose and one molecule of fructose, also known as table sugar is an important ingredient in various foods and beverages [4]. Whereas, fructose is another monosaccharide used as a cheap alternative to sucrose used for sweetening [5]. The above mentioned saccharides are significant samples for quality control in various foods, drinks processing, medical and pharmaceutical industries. Therefore, real-time monitoring of such saccharides is of great significance.

The current methods for analysis of saccharides are chromatography, spectroscopy, chemical and enzyme-based biosensing methods [2], [6]–[8]. These techniques are cumbersome, requiring skilled technicians and controlled laboratory environment. Whereas, RF sensing is highly desirable due to the ease of sample preparation and enabling real time monitoring of saccharides.

RF sensing can be broadly classified into resonant and non-resonant categories. Resonant methods have gained much more attention recently over their counterparts as they offer higher accuracy and sensitivity due to operation in narrow frequency bands. Amongst all resonant techniques, planar microwave sensors are preferred due to their ease of fabrication and design simplicity, making them compatible with other RF components. Planar resonant sensors such as Complementary Split Ring Resonator (CSRR) [9], [10] and Split Ring Resonator (SRR) [11], [12] are widely chosen for sensing and characterization of bio-samples because of their high quality factors. CSRR is preferable over SRR due to its larger electric field area useful for sensing larger sample volumes. In this work, the focus is mainly on the sensing of monosaccharides such as glucose and fructose and disaccharide sucrose. Our major goal is to provide a robust, highly sensitive and low cost alternative for studying the qualitative and quantitative behavior of saccharides.

II. Materials and methods

A. Design of Sensor

The designed sensor consists of a microstrip line coupled to the CSRR etched out of the ground plane as shown in Fig. 1. Where, 'l_s' is the length and 'w' is the width of the microstrip line. 'g' is the width of the conductor connecting the center copper plate of CSRR and the ground plane. 'l' is the length and 'x' is the width of the etched portion of CSRR. The designed sensor is fabricated over a FR-4 substrate of relative permittivity of 4.3 and loss tangent of 0.025. The yellow portion in Fig.1. shows the conductor area, whereas the grey portion depicts the etched-out area. The electromagnetic wave (EM) travels across the microstrip line in quasi transverse electro-magnetic (TEM) mode where the magnetic field circulates and the electric field directs from the microstrip plane towards the ground plane [13]. The excitation of EM wave leads to coupling in microstrip line and CSRR [5]. The electric field distribution of the sensor is shown in Fig. 2 (a). The E-field is maximum in the lower and side edges of the CSRR suitable for sample placement. The designed sensor is such that it resonates at 1.51GHz frequency ideal for sensing aqueous solutions [14].

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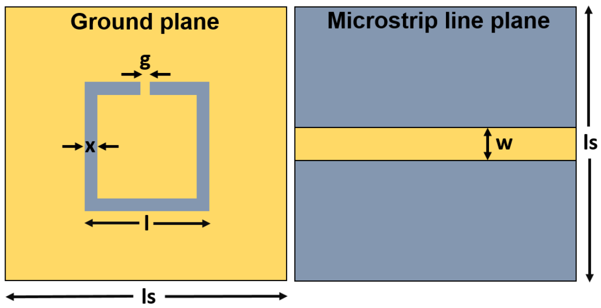

Fig. 1. Front and back view of CSRR based sensor

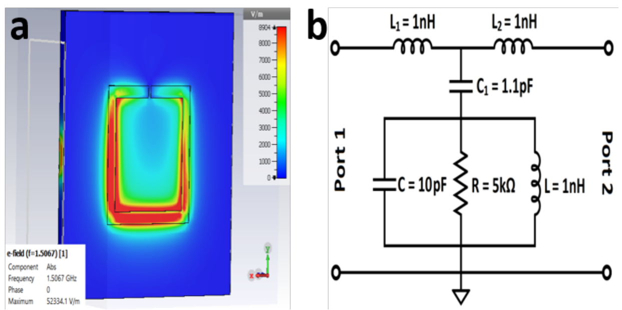

Fig. 2. (a) Electric Field distribution of the sensor. (b) Equivalent lumped model of the sensor.

CSRR usually behaves as a band reject filter, the rejected frequency is known as the resonant frequency of the sensor (also known as transmission notch). The equivalent lumped circuit model [15] is shown in Fig. 2 (b), which resonates at 1.51 GHz frequency. Where, R represents the loss due to the conductor in the CSRR, L represents the inductance due to the conductor of width 'g'and C represents the capacitance contributed due to gap 'x'. L_1, L_2 and C_1 represents the inductances and capacitance of the microstrip line, respectively. The resonance condition is achieved when the electrical energy in C and C_1 is equal to the magnetic energy stored in L. Hence, when the sample under test (SUT) is placed in this region, the change in permittivity of the sample leads to capacitance change in the CSRR and therefore it affects sensors resonant frequency behavior. The resonant frequency of the sensor is given by [16]

$$f_r = \left(\frac{1}{2\pi\sqrt{L(C_1 + C)}} \right) \tag{1}$$

B. Simulation results

The sensor is designed and simulated using CST Microwave Studio. Fig. 3 shows the simulated and measured resonant frequency at 1.51 GHz and 1.413 GHz of the empty sensor. Considering the limitations in the fabrication process, environmental effects around the experimental setup, and the uncertainty in the substrate's dielectric constant, the sensor's simulated and experimental resonant frequencies do not match exactly.

C. Fabrication of sensor

The sensor is fabricated on FR-4 substrate of thickness 1.6 mm, with copper of thickness 0.035 mm on both sides. The

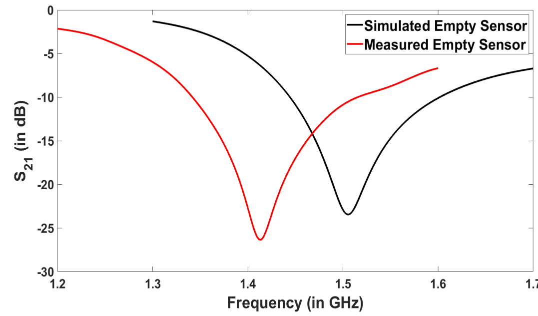

Fig. 3. S_{21} versus resonant frequency for simulated empty sensor and measured empty sensor

fabricated sensor is of size 38 x 32 mm^2 with dimensions: l_s = 32 mm, l = 15.5 mm, w = 3.13 mm, c = 1.4 mm and g = 0.4 mm. A layer of green mask of thickness 0.035 mm with dimensions 28 $\times$ 32 mm^2 is deposited over the copper ground plane in order to prevent oxidation. On each side 2 mm of copper is exposed to solder the SMA connectors that connects the fabricated sensor to the VNA.

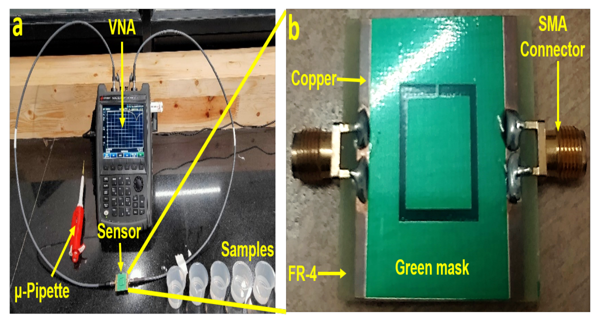

Fig. 4. (a) Experimental setup. (b) Fabricated sensor.

D. Procedure

The samples used in this work were lab-grade extra-pure dextrose (glucose), D-fructose and sucrose. Aqueous solutions of each sample with concentrations varying from 10 mg/ml to 50 mg/ml with a step size of 10 mg/ml were prepared by adding samples to deionized (DI) water by stirring thoroughly. The fabricated sensor is connected to Keysight VNA with the help of 50 ohm impedance coaxial cables, as seen in Fig. 4 (a). SMA connector is used to connect the fabricated sensor to the cable, as seen in Fig. 4 (b). S_{21} is chosen as a parameter to identify and quantify the change in the RF characteristics of the sensor when the sample is placed. Firstly, S_{21} is measured for the empty sensor in the presence of DI water. Next, S_{21} is measured and recorded for concentrations varying from 10 mg/ml to 50 mg/ml in step sizes of 10 mg/ml for all 3 samples in the frequency range 0.8 to 0.95 GHz. Sample with 30 μl of each aqueous solution is dropped with the help of micro-pipette on the high sensitivity region of the sensor i.e. the lower edge of the CSRR. Furthermore, the volume of a particular sample is varied from 1 μl to 100 μl in step sizes while the overall sample concentration is kept constant at 30 mg/ml. The experiments are performed at room temperature and at normal ambient conditions. The same experiment is conducted several times in order to check the repeatability of the measured results and to eliminate any human error occurred while dropping the sample using micro-pipette.

III. Experimental results and discussion

For DI water, the resonant frequency is observed at 861.1 MHz. For glucose aqueous solution, the resonant frequency is at 864.8 MHz, 870.8 MHz, 876.2 MHz, 882 MHz and 886.7 MHz for 10 mg/ml, 20 mg/ml, 30 mg/ml, 40 mg/ml and 50 mg/ml respectively, as seen in Fig. 5 (a). Similarly, in case of fructose aqueous solution, the resonant frequency is observed at 866.8 MHz, 871.1 MHz, 876.1 MHz, 882.4 MHz and 886 MHz for 10 mg/ml, 20 mg/ml, 30 mg/ml, 40 mg/ml and 50 mg/ml respectively, as shown in Fig. 5 (b). Lastly, for sucrose aqueous solution, we observe resonant frequency at 872.8 MHz, 878.1 MHz, 882.2 MHz, 887.7 MHz and 891.8 MHz for 10 mg/ml, 20 mg/ml, 30 mg/ml, 40 mg/ml and 50 mg/ml respectively, as shown in Fig. 5 (c). The shift in the resonant frequency with change in concentration of the saccharides is due to the electromagnetic interaction between the components of the CSRR and saccharides. The shift in the resonant frequency (Δf) is given by

$$\Delta f = f_{ref} - f \tag{2}$$

where, f_{ref} and f are the resonant frequency of the empty sensor and with varying concentrations of saccharides. We observed that the resonant frequency increases along with concentration of saccharides in the aqueous solution resulting in increase in the relaxation time [17], thus reducing the dielectric constant of the overall solution. The shift in the resonant frequency Δf with respect to the change in the concentration of the saccharides is also analyzed, as shown in Fig. 6. Furthermore, Δf is closer for isomers glucose and fructose for all concentration levels as they have very close dielectric constant for the same concentration levels [18]. Whereas, sucrose has a higher molecular weight and lower dielectric constant so it offers less Δf for a particular concentration when compared to glucose and fructose [19].

Fig. 5 (d), 5 (e) and 5 (f) shows the variation of S_{21} vs. frequency for change in the sample volume of 30 mg/ml glucose, fructose and sucrose aqueous solutions respectively. It is observed that as the sample volume is increased, the resonant frequency of the sensor decreases; hence Δf increases. This increase is observed due to an increase in the area occupied by the sample above the sensing region leading to higher capacitance offered by the sensor, hence reduced resonant frequency.

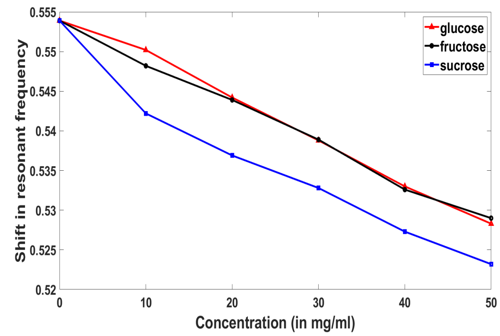

Fig. 6. Shift in resonant frequency (Δf) vs concentration (in mg/ml) varying from 10 mg/ml to 50 mg/ml for all samples.

IV. Conclusion

The qualitative and quantitative analysis of saccharides such as glucose, fructose and sucrose has been conducted in this work using CSRR-based RF sensor by observing the resonant frequency shift. Thus, the proposed RF sensing technique offers low-cost and easy-to-fabricate sensor, a portable and quick measuring system for on-field real-time monitoring of saccharides suitable for numerous applications.

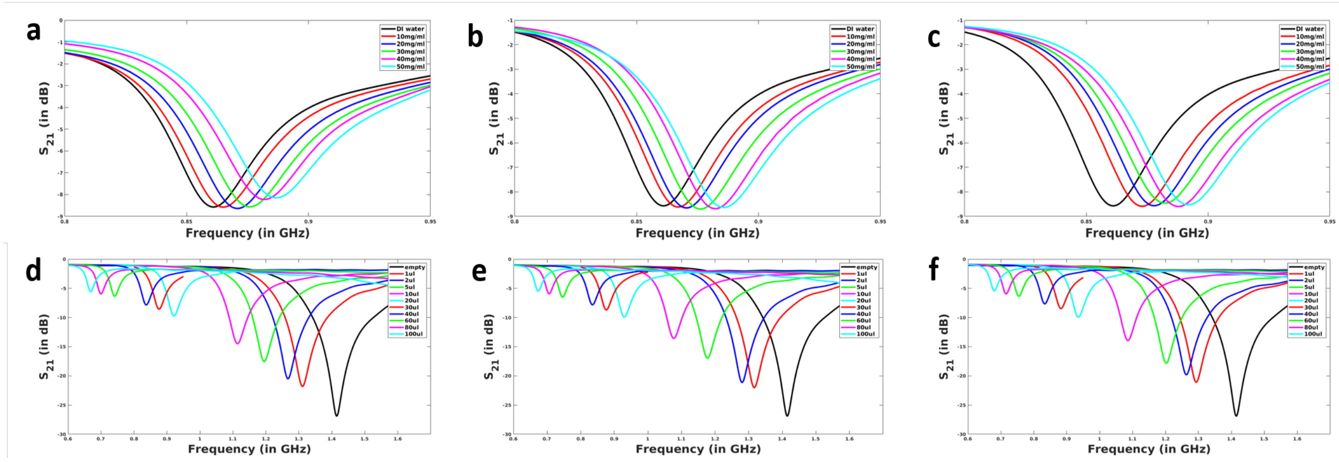

Fig. 5. S_{21} vs frequency for concentrations from 10 mg/ml to 50 mg/ml of (a) glucose (b) fructose (c) sucrose. S_{21} vs frequency for volume of sample varying from 1 μl to 100 μl for 30 mg/ml concentration of (d) glucose (e) fructose (f) sucrose.

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