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A centimeter-wave honey-cell CSRR sensor for non-invasive blood glucose level measurement

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Abstract: A frequent check of glucose level is necessary for diabetics to control their glycaemia and thus avoid undesirable complications such as kidney failure, lower limb amputation, stroke, heart attack. While most commercially-available devices are based on invasive or minimally invasive methods for glucose monitoring, other methods were also developed using optical techniques. However, these methods are sensitive to physiological changes and are costly to implement. In order to perform non-invasive and affordable measurements of blood glucose level for diabetics, a microstrip sensor operating in the centimeter-wave band (2.3GHz) has been developed. The proposed sensor is based on an array of hexagonal-shaped complementary split ring resonators (CSRRs) in a honey-cell configuration. It was fabricated on a low cost FR4 substrate and first tested *in vitro* with glucose aqueous solutions placed onto the sensor. To validate its detection capability for sensing glucose level variations and tracking diabetes, a human fingertip model has been developed. This paper presents 3D full-wave electromagnetic field simulations of the sensor loaded by various fingers and primarily experimental results by studying pressure effect on the sensor.

Keywords: Microwave sensor; complementary split-ring resonator; non-invasive glucose monitoring; dielectric characterization.

I. INTRODUCTION

In 2019, approximately 463 million adults (20-79 years) in the world were living with diabetes; by 2045, this will rise to 700 million. Diabetes is a chronic disease that occurs either when the pancreas does not produce enough insulin or when the body cannot effectively use the insulin it produces [1-2]. Insulin is a hormone that regulates blood sugar. Hyperglycemia, or raised blood sugar, is a common effect of uncontrolled diabetes and over time leads to serious damage to many of the body's systems, especially the nerves and blood vessels [3]. Type 2 diabetes is far more common than type 1 diabetes, accounting for about 90 percent of all cases. The frequency of type 2 diabetes varies greatly within and between countries and is increasing throughout the world. Most patients with type 2 diabetes are adults, often older adults, but it can also occur in

children and adolescents. Many people are unaware that they have diabetes. In 2018 for example, 34.2 million people of all ages in USA—or 10.5% of the US population—had diabetes and the percentage of adults with diabetes increased with age, reaching 26.8% among those aged 65 years or older [4].

Detecting diabetes remains difficult because finger-pricking procedures are painful and costly to the users. Therefore, a clear demand for a non-invasive pain-free biosensor for glucose monitoring is established [5]. Microwave sensing techniques are very interesting for non-invasive dielectric measurements because they can provide information data on biological tissues without contact (or very little) with the medium. The parameters measured are then the dielectric constant and the losses associated with the dissipation of electromagnetic energy in the tissues. In addition, microwaves can overcome structural obstacles and penetrate inside biological tissues without health risk and allow the design of integrated and communicating devices [6].

In this article, we propose a microwave sensor operating at 2.3GHz for measuring the glucose level non-invasively in a human fingertip. The sensor is realized using four similar hexagonal-shaped complementary split ring resonators (CSRRs) engraved in the ground plane of a microstrip structure with a honey-cell structure. Thanks to this configuration of honey-cell, the sensor sensitivity is improved to measure glucose samples at the levels of interest compared to conventional split ring resonator (SRR). Modeling and 3D electromagnetic simulations of the sensor with a human fingertip inserted in the sensing region are presented and compared to preliminary measurements. The effect of the finger pressure on the microwave sensor has been also investigated.

II. HONEY-CELL CSRR SENSOR BASED DESIGN

Among many RF/microwave dielectric characterization techniques, the resonant method is well suited for sensing applications which require a very high precision. The key

element is a microwave resonator whose electrical properties (resonant frequency, bandwidth and quality factor) will be modified when a dielectric material is applied on its surface, due to the interaction of the material with the electromagnetic field [7]. To obtain a small sensor, we focused on complementary split ring resonator (CSRR) which is one type of microwave resonators with high potential of integration compared to half wavelength conventional resonators. The CSRR has the same structure as the well-known split ring resonator (SRR), but is etched in a metal layer, and both of them have a band-stop filter behavior. Several shapes (square, circular...) could be used to design a CSRR resonator [8]. Instead of choosing a conventional shape like the ones above, we took a single hexagonal cell in order to easily perform an array of CSRRs. Indeed, those cells can be fitted together so a Honey-Cell shape can be arranged. The Honey-Cell CSRR's structure was chosen due to its capability of acquiring better sensor sensitivity.

The sensor consists of four similar hexagonal cells arranged in a Honey-Cell shape, as shown in Fig.1; two single CSRRs are placed horizontally along the transmission feed line with center-center distance $C=13\text{mm}$, the two other cells are placed vertically with the same center-center distance. The sensor is designed on a FR4 substrate (with dielectric constant $\epsilon_r=4.6$, loss tangent $\tan\delta=0.02$ and thickness $h=0.73\text{mm}$); the total dimensions of this piece of substrate are $L=40\text{mm}$ and $W=30\text{mm}$. The hexagonal unit-cell consists of two concentric split-rings engraved in the copper ground plane. The outer ring of the unit-cell is designed with a diagonal length $a=9.08\text{mm}$, a side width $s=0.4\text{mm}$ and a split gap $g=0.4\text{mm}$. The inner ring is designed with a similar side width and split gap to the outer one but with a diagonal length of $b=7.5\text{mm}$. The inter distance between the two rings which control the coupling is $t=0.4\text{mm}$. These dimensions have been optimized with the ANSYS HFSS software to obtain an unloaded resonance frequency f_0 around 2.3GHz . The geometrical parameters of the Honey-Cell CSRR sensor are listed in Table I. The feed-line of the structure consists in a 50Ω microstrip line whose width has been optimized to $W_L=1.42\text{mm}$. This copper line is realized on the upper face of the FR4 dielectric substrate with a length of $L=40\text{mm}$.

A proto-laser machine LPKF S4 was used to prototype the sensor with the former specifications controlled by the CircuitPro software. Both ends of the access-line on the upper surface of the structure are soldered to 50Ω SMA coaxial connectors to perform S-parameters measurements (Fig.2). A thin glass blade with a thickness $h_{\text{glass}}=0.15\text{mm}$ was added to avoid short-circuiting the slots of the CSRR and reducing damping effects while putting the finger on top of it.

Preliminary measurements of aqueous glucose solutions have already been performed with this type of Honey-Cell CSRR sensor [9]; these solutions are mimicking the blood at relevant diabetes Type 2 glucose concentrations ($70\text{--}120\text{mg/dL}$). Here, the CSRR's geometrical parameters are slightly different from the one proposed, in the sense that its

parameters are optimized to obtain a steep transmission resonance at 2.3GHz . These in-vitro tests were first performed to verify the continuous blood glucose sensing reliability of the sensor. The next step is the modeling of a human fingertip and its electromagnetic consequences on the CSRR sensing behavior to detect the blood glucose level.

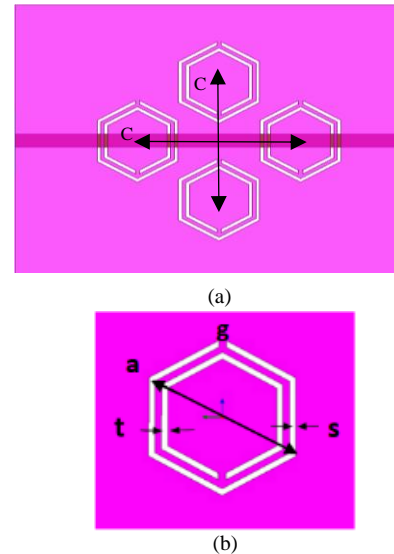


Figure 1. (a) Configuration of the Honey-Cell CSRR in the ground copper plane (top view) and (b) Topology of the hexagonal unit-cell

TABLE I. CSRR design parameters

Parameter	Value (mm)
a	9.08
g	0.4
t	0.4
s	0.4
C	13

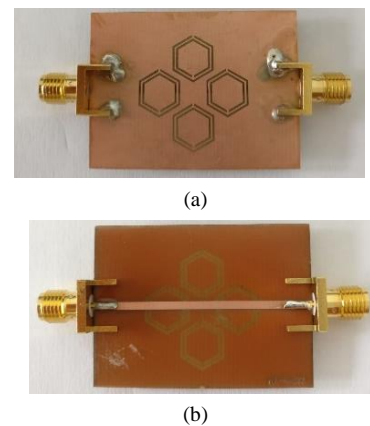


Figure 2. Prototype of the sensor (a) Ground, (b) Microstrip-Line

III. GLUCOSE SENSING APPROACH

To mimic a human index finger, a simplified model was implanted in HFSS taking into account the average thickness and permittivity of the layers composing the finger. The finger skin is composed of three layers: the epidermis, the dermis containing tough connective tissue, hair follicles and sweat gland and finally the hypodermis where subcutaneous fat is located [10]. Veins and arteries are found beneath the hypodermis [11]. Then the distal phalanx is a flat and rough bone which supports the finger pulp.

The dielectric parameters values of each tissue at 2.4GHz composing the finger model are detailed in Table II. The finger placement in the sensing region is illustrated in Fig.3a for blood glucose monitoring. The simplified model is shown in Fig.3b and the anatomy of the index in Fig.3c.

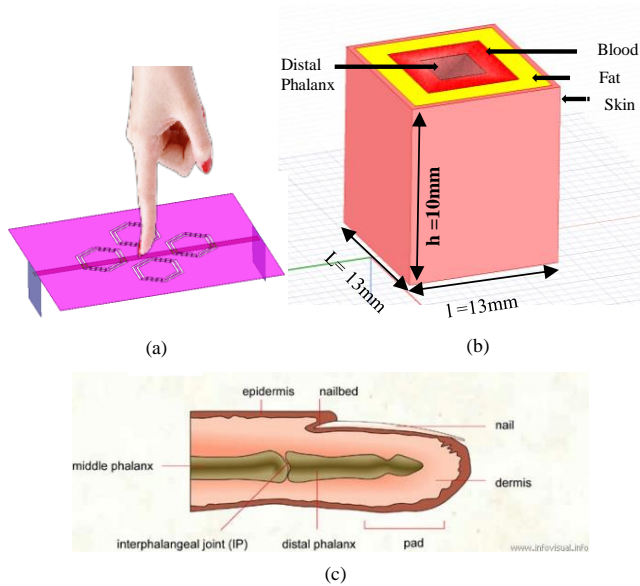


Figure 3. (a) The finger placement in the sensing region, (b) The simplified finger model, (c) The anatomy of the index finger.

TABLE II. DIELECTRIC PARAMETERS OF FINGER LAYERS

Tissue	Thickness (mm)	Relative permittivity
Skin	0.5	35
Fat	0.5	10.8
Trabecular blood	2.5	59
Bone	4	20

IV. SIMULATIONS AND MEASUREMENT RESULTS

The fabricated sensor is experimentally tested with a Rohde & Schwarz ZNB20 Vector Network Analyzer (VNA) in the frequency band (1–4 GHz). The VNA is calibrated by using the Short-Open-Load-Through (SOLT) standard to measure

S-parameters of the sensor. The same structure with identical specifications is numerically simulated when unloaded using ANSYS HFSS.

Fig.4 presents the magnitude of the measured and simulated transmission coefficient $|S_{21}|$ as a function of frequency for the unloaded Honey-Cell sensor compared to the single hexagonal CSRR. These results show good agreement between the measurements and the predicted numerical simulations. A tiny frequency shift Δf was observed between resonant frequency: $\Delta f=20\text{MHz}$ for the hexagonal-unit cell and $\Delta f=35\text{MHz}$ for the Honey-Cell. These differences are due to the etching precision while designing the sensor with the laser machine and some inaccuracy of the dielectric constant value of the low cost FR4 substrate in the cm-frequency band. The measurements and simulations also show a steepest resonant peak for the Honey-Cell than for the single hexagonal one. So, we expect better results while loading the Honey-Cell sensor.

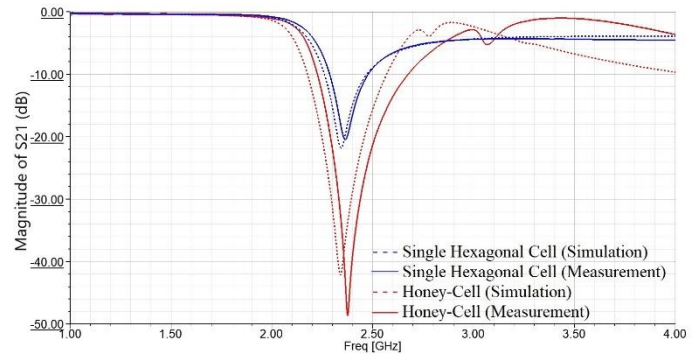
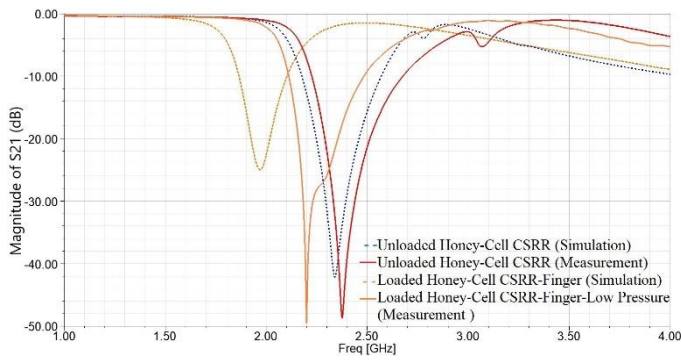


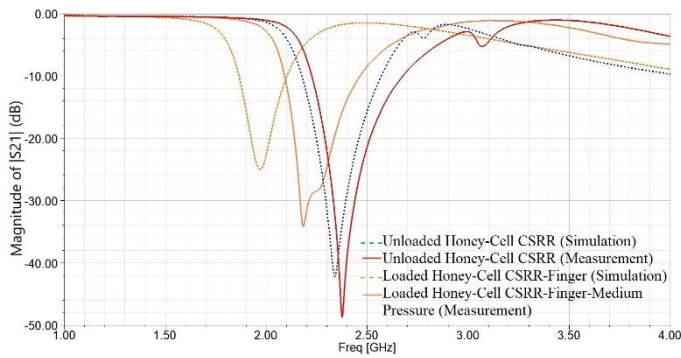
Figure 4. Measurements and simulations of the transmission coefficient S_{21} of the Honey-Cell and single hexagonal cell unloaded sensors.

Secondly, on the light of previous positive results, the Honey Cell has been tested in a simple in-vivo test which consists of putting the index finger perpendicularly on the top of the sensor. Tests were performed on a 23 years-old healthy woman before taking a meal so that the blood glucose level remains low. Two configurations were investigated with low and medium pressure applied such as to confirm the simplified finger model (Fig. 5). The configuration with the index perpendicularly on the top of the sensor applying a medium pressure was the most similar one to the simulations. A resonant frequency shift is observed between both measurement configurations: while applying a low pressure, the resonant frequency is shifted towards low frequencies by 220MHz and while applying a medium pressure, the frequency shift is equal to 213MHz. The pressure effect is also visible on the magnitude of the transmission coefficient which is lower for a low pressure of the fingertip.

The equivalent permittivity of the real finger is then lower than the modeled one.



(a)



(b)

Figure 5. Measurements and simulations of the transmission coefficient S_{21} of the Honey Cell sensor loaded with the finger on the top applying (a) Low pressure (b) Medium pressure

The results show that the finger as a superstrate can be very dynamic in comparison to the static simulated model. Many configurations could be possibly studied to quantify the effect of the applied pressure. The more the finger is applying a pressure, the more the resonance is shifted towards low frequencies with a decreasing magnitude. This could be due to the fact that skin tissue is thinner while compressed and/or even more capillary blood vessels appear nearer to the sensing region of the CSRR sensor. To take into account this fact, simulations lowering by 10% the thickness of the skin and the fat were performed. As these layers get thinner the effective permittivity of the simplified finger get lower resulting in a higher resonance frequency and lower magnitude. (Fig.6).

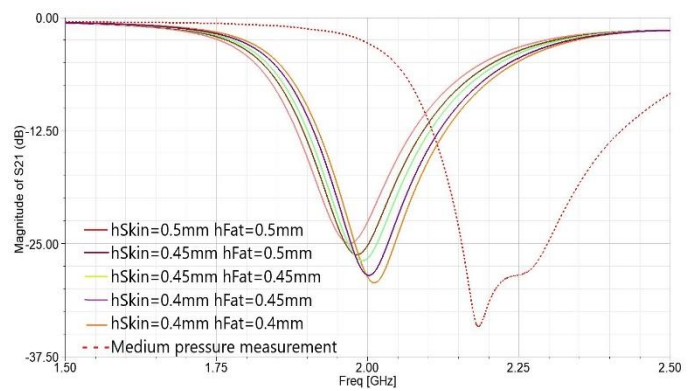


Figure 6. Simulated transmission coefficient S_{21} of the loaded Honey-Cell CSRR at different skin and fat thickness

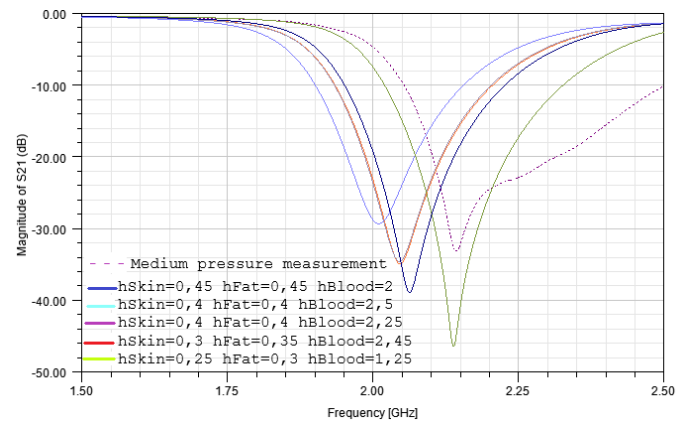


Figure 7. Simulations of the transmission coefficient S_{21} of the Honey Cell sensor loaded with the finger on the top while varying the thickness of the blood layer (hBlood)

Simulations of the transmission parameter taking into consideration the fact that the hypoderm containing capillary blood vessels is being flattened hence reducing its thickness, are shown in Fig.7.

There is a considerable shift in the resonance frequency and a steeper resonance depth while varying the thickness of the blood (hBlood).

By comparing simulated and measured results of the loaded sensor, the best suited configurations are the ones with relatively thin layers of skin and fat and thicker layer of blood. While decreasing the thickness of the skin, the fat and the blood by 40%, 30% and 2% respectively (hSkin=0.45mm hFat=0.45mm and hBlood=2mm configuration) a frequency shift of 100MHz is observed compared to the measured response, the magnitude remains nearly similar with a difference of 6dB.

Then while decreasing the thickness of these layers by 50%, 40% and 50% respectively (hSkin=0.45mm hFat=0.45mm and hBlood=2mm configuration) a considerable shift of 100MHz

towards low frequencies is noted compared to the other configuration while the magnitude gets lower reaching -46dB.

There are several physiological factors such as the variable composition of the blood, body temperature, humidity conditions [12] and methodological ones like the method of measurement that may have a significant influence on measured scattering parameters. But the results of this study can be considered as encouraging as this research is in progress, taking into account the different influencing parameters.

V. CONCLUSION AND PERSPECTIVES

This paper describes first simulations and experimental results on an optimized centimeter-wave sensor in order to detect non-invasively continuous glucose level changes of diabetic patients. This sensor consisting of a four honey-cell hexagonal-shaped CSRRs is applied on the extremity of the finger. Electromagnetic simulations using a simple model of the finger with the main tissue layers developed with HFSS are compared with measurements on a prototype of the sensor. These previous results show the influence of the applying pressure of the finger on the sensor. Further investigations are in progress to obtain a good reproducibility of experimental results.

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