Simulation of a non-invasive glucometer based on a microwave resonator sensor

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Abstract. In this paper a simulation of a microwave resonator sensor for constructing a non-invasive blood glucose meter is presented. A relationship between changes of the dielectric permittivity of the blood and the frequency response of S parameters of the sensor is observed. This can lead to a measuring procedure in which the glucose level present has a correlation with the value of the frequency resonance of the sensor. The test bank consists of a planar spiral microwave resonator over which the individual under test places his/her finger. This modifies the initial frequency resonance of the resonator because of the change produced in the measuring procedure over the dielectric permittivity of the resonator. Simulations show a correlation between dielectric permittivity blood changes, and changes in the value of the frequency resonance, in the frequency response of S parameters of the resonator.

1. Introduction

Diabetes mellitus [1] is a common disease that causes significant levels of mortality and morbidity. It is a serious disease that has now reached epidemic proportions and the prevalence rates are expected to go even higher in the future [2]. In 1995 the number of people suffering this disease was estimated to be 135 million, rising to be 154 million in 2000. It is expected that in 2025 this number will be 300 million, with a higher increasing rate in developed countries [4]. In general terms we can identify two types of diabetes. Type 1 diabetes [3] is the most serious type and affects $5 - 10\%$ of the diabetic population. It is a disease that develops during childhood or adolescence and is characterized by a severe deficiency of insulin secretion, resulting from atrophy of the islets of Langerhans, and causes hyperglycemia and eventually ketoacidosis [11], [13].

Type 2 diabetes, also known as diabetes mellitus [14], affects $80 - 95\%$ of the diabetic population, and it is present mostly in adults and more frequently obese people. The disease generally deals with an inefficient use of insulin. A lack of proper treatment increases the rate of mortality due to diabetes mellitus. Type 1 diabetics have to provide themselves with insulin by injection or pumps, whereas most of type 2 diabetics can control their blood glucose levels by a proper diet, exercise, loss of weight and oral medication. Type 1 diabetics usually test their blood glucose levels once or twice a day, but a proper treatment of this condition would require around

6 to 7 tests a day. This is however quite bothering due to the puncturing of fingers for obtaining the blood sample of classic glucometers. This is why a non invasive glucometer would be of great help to these people, to have a better control of their insulin and glucose levels. A sensor based on a microwave resonator is selected here as the main part of a non invasive glucometer. This leads to an introduction of important parameters of a given microwave resonator like microwaves, dielectric permittivity, S parameters, blood characterization, and mainly what is understood as a sensor.

This paper is organized as follows. Section 2 describes the basis of measuring blood glucose levels by using a microwave resonator sensor. Section 3 depicts the designed scheme for simulations. Section 4 presents results of simulations. Finally section 5 is devoted to conclusions and further work.

2. Measurement of glucose in blood

In a recent paper [5], Hofmann et. al. analyses the behaviour of microwave based non-invasive measurements in glucose concentrations in blood using in-vitro samples, for 40 cases of study. They found a clear correlation between microwave measurements of dielectric properties and a concentration in solutions and emulsions. They also identify a high sensitivity of the proposed techniques that is also sensitive to errors. In a previous work of the authors [6], They also use open electromagnetic waveguides for non-invasive glucose monitoring, finding also a correlation between the glucose concentration variation and the phase of the measured parameter.

Based on this evidence, but considering that the above results were obtained over in-vitro samples, the present paper approaches by simulation, the behaviour of a microwave resonator sensor, that takes into account the additional complications that appear in a non-invasive measure of glucose concentrations in blood. This is done by considering the effect of the different tissues associated to a measurement done over of a human finger.

In order to provide an introduction of the technique that is studied, some of the related concepts are briefly described below.

Microwaves are electromagnetic waves that are characterized for being in the frequency range between $300MHz$ to $300GHz$. The corresponding wavelengths are between $1m$ to $1mm$. Microwaves are utilized because their wavelengths are such that the signal can easily penetrate most of the materials [7].

Materials can be characterized in terms of their electrical properties by constants, one of which is the so called dielectric permittivity, a number that measures the capacity of the material to polarize its particles in the presence of an external Electric Field.

Since all materials have always a dielectric constant that is equal or larger than that of the free space, we can make use of the so called relative dielectric constant [10], a number that indicates how many times larger is the dielectric constant of that material with respect to that of the free space. The dielectric constant is a parameter that can be experimentally measured. By measuring dielectric properties of a given material, we can indirectly measure other properties of that material related to their molecular structures. A given electric network of two ports ca be suitably characterized by its S parameters [9]. They are a measure of the relation between reflected and incident waves generated when the electric network is connected to a transmission line characterized by a given impedance, called the characteristic impedance of the transmission line.

Among the classic four S parameters of a two port electric network, parameters S_{11} (relation between the reflected and incident waves at the input port) and S_{21} (relation between the transmitted wave at the output port, and the incident wave at the input port) [11] were utilized. These two parameters contain valuable information to characterize a given microwave resonator.

Microwave sensors [12] are suitable for measuring blood characteristics because they operate at high frequencies (small wavelengths) and can easily pass trough skin and fat layers of the

human body. Resonance techniques have been widely used because their capacity of providing a measure with precision. In our case, we have used a planar resonator that can easily be placed on the human body surface in contact with the skin. A resonator sensor acts when electric fields interact with the dielectric that is part of the sensor, and energy is coupled to it. This coupled energy generates a peak response at the resonating frequency of the sensor, where the peak depends on the relative permittivity of the material under study [13]. Changes in the dielectric permittivity of the material modifies the frequency response generating peaks or valleys in it.

Since blood is a complex substance in which cells, proteins, hormones, glucose and other particles are dissolved in water, its permittivity depends on the frequency, and is also influenced by the other parameters. Bloods permittivity is influenced by each of its constituents. A microwave sensor that has a frequency response at multiple frequencies can potentially aisle the response of one of the parameters in spite of the change in the other parameters [15].

Dielectric permittivity of the different layers of the body can have noticeable variations as a function of the frequency [16].
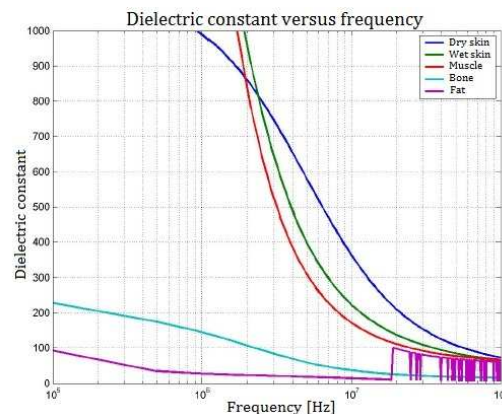

Figure 1. Relative Dielectric constant of different biologic tissues as a function of the frequency [17].

Since dielectric permittivity is a function of the frequency, the second order Debye Equation 1 is taken into account to model this behaviour [18].

$$\hat{\varepsilon(\omega)} = \varepsilon_\infty + \sum_n^2 \frac{\Delta\varepsilon_n}{1 + j\omega\tau n} \qquad (1)$$

Glucose sensor has to be placed on an area with the least amount of fat in order to maximize the transmission of waves th rough the different layers.

At a frequency of $1GHz$ a given wave passing through skin and fat layers is transmitted in a 50% of its intensity, whereas if the same wave passes trough skin and muscle layers it can be transmitted in a 93% of its intensity. Thus, the sensor would be in touch with more blood if it is placed on muscle than on fat tissues. The more blood is measured, the more accurate will be the measure. The sensor has to be able to properly detect changes in the dielectric permittivity. In our experiment, the individual places his/her finger on the surface of the planar resonator generating changes in its parameters, and this way the measuring procedure makes use of a body part with relative low content of fat and high content of blood that allows us to perform a measure with high level of the transmission of energy. With the use of this sort of sensors, diabetics, especially type 1 diabetics, could perform several measures a day in a non invasive way, making a better control of the glucose blood levels and improving the treatment and their life quality.

3. Simulations

A first step in the development of a microwave resonator as the main part of a non invasive glucometer is to perform several simulation using software for electromagnetic simulation. The selected software is the CST Microwave Studio [20], which can accurately predict the behaviour of the microwave resonator. A simplified model of the different tissues of the body together with the second order Debye equation [18] was implemented using CST.
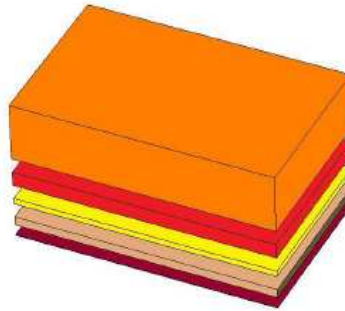

Figure 2. Layers model of a finger

The layer model seen in Fig. 2 is constituted of a dried skin layer of $0.015mm$, a wet skin layer of $0.3mm$, a fat layer of $0.2mm$, a blood layer of $0.5mm$ and a muscle layer of $0.2mm$. This simplified layer model models the finger of the individual placed on the planar resonator surface.
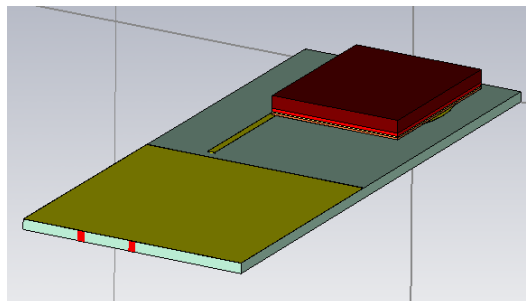

Figure 3. Layer model in contact with the resonator, as simulated using CST Microwave Studio.
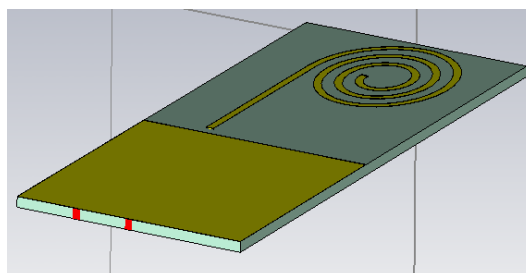

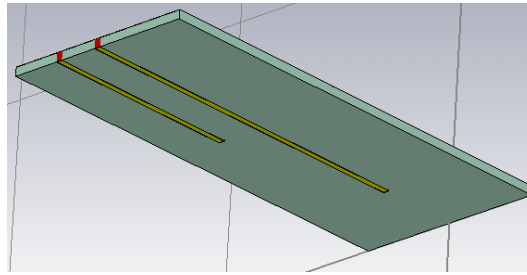**Figure 4.** Spiral sensor simulated using CST Microwave Studio.

Figure 5. Bottom view of the spiral sensor.

The board on which the resonator is constructed is of a material called Rogers3010 [19], known as RT/Duroid, whose relative dielectric constant is 10.2. This material has lower losses at microwave frequencies than other materials available like the so called FR4. The boards length is $83.067mm$, its width is $36.39mm$ and its thickness is $1.6mm$. Copper layer has a thickness of $0.035mm$, and the width of the microstrip is $1.1582mm$. This width and thickness of the microstrip makes its characteristic impedance be equal to 50Ω, so that the system is matched. The spiral form of the resonator aims to maximize the contact between the fingers surface and the resonator surface. The microstrip transmission line starts at the input port develops its spiral form and ends at the bottom of the board as the output port. This makes the structure be a resonator. Its behaviour can be understood as a wired antenna, thus behaving as an inductance, and copper at the top and bottom of the board separated by the dielectric material acts as a capacitance. Therefore at several given frequencies a resonance is observed, appearing as peaks or valleys of the frequency response of the S parameters of the resonator.

4. Obtained Results

The layer model is placed on the microwave sensor surface, a voltage pulse is applied at the input of the resonator, and the frequency response of parameters S_{11} and S_{21} is evaluated for different values of the bloods layer dielectric permittivity.

Transient solver tool of CST Microwave Studio [21] is set by using as boundary conditions the mode Open Add Space, and by defining a suitable resolution in dB in order to obtain a given precision in the frequency response of the S parameters under measure. The frequency range of the simulation is $0Hz$ to $3Ghz$.

Since the second order Debye model is used, blood permittivity frequency response is evaluated with three fixed values of the parameters $\varepsilon_\infty = 2, 5$, $\Delta\varepsilon_1 = 9$ and $\Delta\varepsilon_2 = 35$ [18]

Then these parameters are modified individually to determine their influence on the frequency response. Since variations over $\Delta\varepsilon_2$ and ε_∞ are no significant over the frequency response, then $\Delta\varepsilon_1$ changes are only evaluated.

Figures 6 and 7 show the influence on the frequency response of parameters and when the value of parameter $\Delta\varepsilon_1$ is varied.

Simulations show variations in discrete values of parameters $\Delta\varepsilon_1$ in the range of 9 to 90.

Figures 6 and 7 show that simulation of changes in the dielectric permittivity of blood results into changes of the frequency of resonance of the microwave resonator. Peaks and valleys become more abrupt, change in frequency or both. By means of a given algorithm, implemented using programmable electronics, we can take into account this behaviour in order to do a correlation between the observed changes in the resonance response of S parameters and a given value of the glucose present in blood, as one of the main factor that produce the change in its dielectric permittivity.
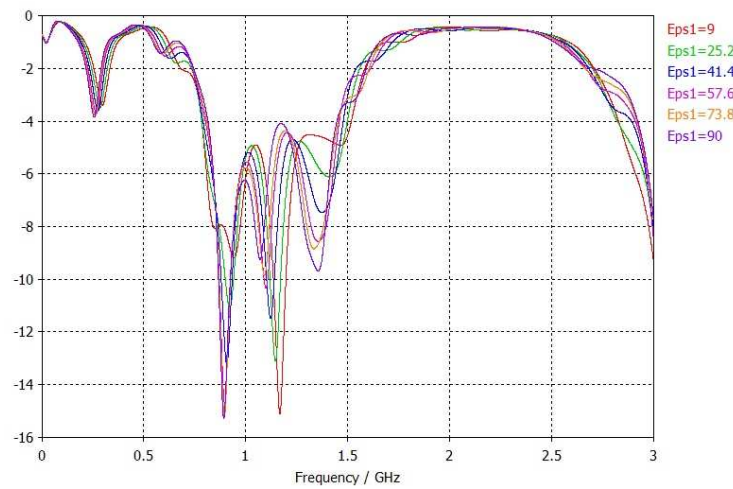
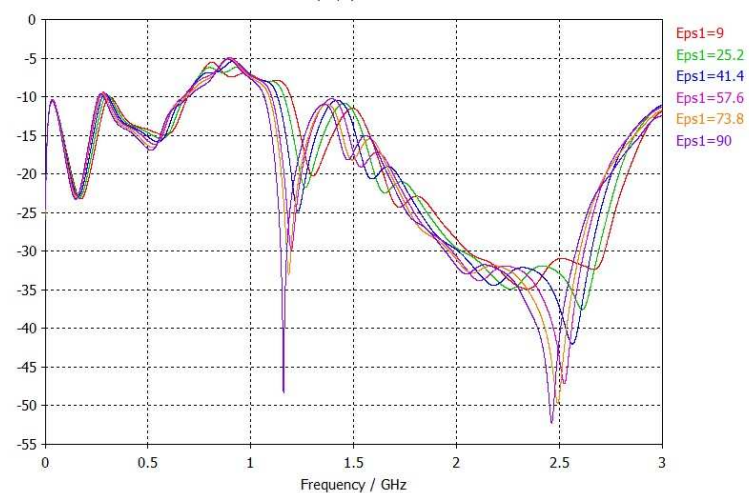**Figure 6.** Frequency response of S parameters as a function of variations of $\Delta\varepsilon_1$

Figure 7. Frequency response of S parameters as a function of variations of $\Delta\varepsilon_1$

5. Conclusions

A microwave resonator sensor constructed as a spiral microstrip line has been simulated to show significant changes in the frequency response of its S parameters due to changes in the permittivity of the material under test. These simulations show that is possible to measure physiological changes produced by changes in the glucose blood levels when the material under test interacts with a microwave resonator.

The correlation between the blood dielectric permittivity changes (produced by changes in glucose levels in blood) and changes in the frequency response of S parameters of the structure (as shifts in the value of the frequency for which the resonance is present before and after the measure) appears as further work.

Probable difficulties to make a suitable calibration of the measure with respect to the user profile could be expected. In order to avoid the dependence of the measure on the specific characteristics of the system with respect to the individual under test (that is to say, all the involved parameters apart from the blood layer in the proposed sensor can adopt different values depending on the individual under test) . A possible solution to this problem can be the

implementation of a prototype of the glucometer that can be used to take enough number of tests with individuals of known blood glucose levels in order to obtain statistical information, able to establish the correlation between blood glucose levels and frequency response changes or values.

Acknowledgment

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