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Design and Dimensional Measurement of Interdigital Sensor for Blood Glucose Measurement through Non-Invasive Method

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Abstract: Diabetes has shown to be a chronic disease world over, mainly caused due to reduced physical activity and increased obesity. World health organization statistics show diabetes as a leading cause of disability universally. To avoid extreme medical conditions of subjects, regular monitoring of their glucose levels has been suggested. The most common method that has been in use is the pinprick method for glucose monitoring which carries the risk of contamination as well as irritation. One possible approach called noninvasive technique can be adopted to avoid this major concern. This paper presents designing Inter-Digital-Sensor (IDS) for non-invasive sensing of the glucose level. The sensor-based chip once mounted onto the upper arm or pinkie finger of diabetes subject, is able to sense different glucose levels concentration as impedance plots. A set of several simulation results has been obtained using COMSOL for getting optimized dimensions of the sensor digits. This research has presented the generation of an electric field and intensity by using electrode of known length with element spacing varying from 250µm to 600µm developed over 15mm x 20mm sensor area. An ID of 475µm width spacing with ten (10) digits producing 2.33 pF of capacitance value with impedance resonating at 13 GHz of frequency is reported in this paper.

Keywords: Blood glucose, COMSOL, Inter digital, Non-invasive

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I. INTRODUCTION

Diabetes is a medical condition which occurring in cases when the body is unable to regulate blood sugar levels. It has been showing to be as one of the world's leading healthcare challenges mainly due to reduced physical activity and increased obesity, even in the US, 1-out-3 Americans is with diabetes. According to the World Health Organization (WHO), diabetes mellitus will affect approximately about 220 million patients by 2025, which is more than 30% of the world population including. This number is going to shoot up to 366 million by 2030, and 642 million by 2040 [8]. Diabetes has been becoming an alarming situation in Malaysia as well, as 7 million of diagnosed and undiagnosed adults are projected to be affected by diabetes by 2025, which makes it 31.3% of the total population. It is called lifestyle disease with excessive body weight and physical inactivity as the main reasons [1]. Type 1 diabetes, which is known as Insulin Dependent Diabetes Mellitus (IDDM), has been characterized by patients whose pancreas is producing minimal or no insulin at all. Type 2 diabetes, which is also called Non-Insulin Dependent Diabetes Mellitus (NIDDM), is characterized by insulin resistance and contribute about 90% of the cases, found mostly affecting children or young adults. Diabetes relates to rise in blood of the glucose levels which are the main source of energy extracted from food by human cells. Blood glucose is measured in milligram per deciliter (mg/dL). Hypoglycemia is a condition where the blood glucose is below 72mg/dL or Hyperglycemia is a condition where the blood glucose is above 200 mg/dL.

Regular monitoring of blood glucose levels is certainly sure to prove controlling diabetes. As irregular monitoring may end up having excessive levels of diabetes which may lead to causing ultimately health complications such as damage to blood vessels, nervous system diseases, cardiovascular diseases, blindness, stroke, and even amputation of the foot due to ulceration in extreme cases [2]–[5]. Regular and self-monitoring of glucose levels are thus highly important, as studies have shown them helping to keep the glucose levels within the normal physiological range by regulating insulin and nutrition levels of patients. Therefore, maintaining glucose at a healthy level is essential and should be included in one's life.

Numerous techniques of blood glucose monitoring have been explored and studied. Among the famous and conventional technique is the finger pricking method. The patient needs to extract a blood sample of about 50ul for placing on an enzyme coated test strip, called lancet. The lancet is then placed in the measurement device for Electro chemical estimation of glucose levels. This routine way of glucose checking is invasive, as it is triggering pain to patients, damaging the nerve, carrying the risk of contamination, exposing infection and interfering patient
Daily life of those requiring repeated daily testing. Everyday testing is also limited by the potentially high cost of the one-time-use test strips [6]. Optical estimation in the form of light in the eye is one such non-invasive approach reported in [7], measuring optical dispersion graphs for glucose for two temperatures and three pH combinations are obtained. As reported in [8-10], it is basically a near-infrared transmission spectroscopy-based glucose monitoring system to measure glucose concentration, and can be used in vitro as well as in vivo experiments.

Another continuous-time glucose level estimation is reported in [10]. In [11] a micro fluidic device for clinical diagnostics on human physiological fluids of blood, serum, plasma, urine, saliva, sweat and tears is presented while an RF-based sensitive and passive biosensor chip is presented in [12]. Non-invasive techniques are reported in [13]–[17] while in [18] is used an electrochemical biosensor.

People adhering to noninvasive will take blood glucose values directly by without pulling out the blood, this type of procedure makes the patient relaxed and encouraged to monitor the blood glucose at regular intervals, and even many times a day. According to the latest developments, an inter digital sensor has been used in applications using noninvasive procedures for characterization of liquids in terms examining conductivity and blood permittivity variations as a function of glucose concentration [20]. Such sensors have recently received an intensive attention in healthcare applications for continuous and real-time monitoring of physiological parameters and personal health of patients and non-patients.

This paper presents an analysis of the electrical properties for capacitance estimation of an inter digital sensor (IDS) in terms of its dimensions. The IDS along electrode is specially designed to analyses the distribution the inter-digital electrical field. The electrical field distribution, its intensity, and hence its capacitance value in are assessed in consequential analysis through modeling function that is embedded in COMSOL simulation software. By fixing the appropriate dimensions of the electrode, the electrical intensity generated from IDS is enough for depth penetration through blood vessels. Therefore, the design of the IDS is important to obtain an optimized electric field for estimating the concentration of blood glucose.

Section 2 explains the theoretical framework and design of the IDS configuration. Section 3 describes the modeling and optimization of the IDS simulated using Finite Element Method software, COMSOL Multi physics 5.3. This is followed by Section 4 with a discussion of the simulation results in terms of resonance frequency, and electric field strength of the studies, while Conclusions are presented in Section 5.

II. DESIGN AND THEORY

The variables ‘l’ is for length, ‘w’ is for width ‘d’ is for gap spacing between electrodes and ‘t’ is for the thickness of electrodes. Due to the current design, the ratio of w/d is kept as a standard ratio of 1:1 inter digitized electrode configuration. Electrode length is fixed and uniform at 15mm and thickness is set is 16uM [10]. The number of electrode fingers (N) is optimized based on the sensor dimension given as 15mm x 20mm. In order to avoid air gap formation, the sensor dimension shall be followed strictly otherwise, it can obstruct with the result. In this paper, Polyethylene terephthalate (PET) is identified as the most suitable material to be printed out with a pattern of the inter digital sensor. The PET is chosen because its flexibility may decrease the error caused by the patient’s movement. This is to show the concept of PET as a flexible substrate used to gain confidence as a novel IDS capacitive device.

Fig. 1 The Proposed IDS Configuration for Blood Glucose Estimation

III. MATHEMATICAL EXPRESSION FOR CAPACITANCE ESTIMATION

The capacitance of Interdigital Sensor can be calculated using the following equation.

$$C = \frac{\varepsilon_r + 1}{W'} \times l[(N-3)A_1 + A_2] \quad (1)$$

Here, A_1 and A_2 for an infinite number of elements. The value of A_1 and A_2 can be calculated by using the general expression.

$$A_1 = 4.409\, tanh\, tanh \left[0.55\left(\frac{h}{W'}\right)^{0.45}\right] \times 10^{-6}\, p\, F/\mu m \quad (2)$$

$$A_2 = 9.92\, tanh\, tanh \left[0.55\left(\frac{h}{W'}\right)^{0.45}\right] \times 10^{-6}\, p\, F/\mu m \quad (3)$$

Now for the estimation of capacitance by using 10 electrodes; PET uses as dielectric material which is ε_r =3.3 in value and the length of electrode (l) 15mm along 20mm of width. The values of A_1=0.089 and A_2=0.10 respectively, the expression can be written as:

$$C = \frac{3.3+1}{2} \times 1.5[((10-3) \times 0.089) + 0.10] \quad (4)$$

$$C = 2.33pF$$

IV. MODELLING TECHNIQUE AND SIMULATION

The structure of an interdigital sensor can be examined by an ordinary driving circuit, which can be able to control the planar and monotonous nature of the capacitive configuration of the sensor. Based on the complexity of the interdigital sensor structure it has been necessary to construct a 3D model of the sensor. The capacitance values of the interdigital sensor design have been simulated through an AC/DC module of the COMSOL Multi physics®. The overall electrode structure of the sensor model is highly conductive so any involvements of magnetically induced current generated within the electrode are supposed to be negligible. At the same time, the field generated within the electrode structure has been observed in this paper.

Table. 6 Summary of Skin-Electrode Geometry Setting, Permittivity and Conductivity [14] For Electrostatic Solver in AC/DC Simulation

Layer	x(μm)	y(μm)	z(μm)	Permittivity	Conductivity (S/m)
Substrate (PET)	20000	15000	1000	3.3	0.004
Metal electrode, Silver	500	10000	500	1	61×10^{6}
Skin Tissue	20000 22000	15000 17000	1500 10000	1133 1085	2×10^{-4} 2×10^{-2}
Blood vessel	1600	-	-	(25-75)	0.7
Air	22000	17000	10000	1	0

The electrostatic solver of AC/DC module calculates the capacitance using the following equation:

$$Q = C(V_1 - V_2) \qquad (5)$$

Where Q is the charge on the electrode, C is capacitance between the two adjacent electrodes, and V_1-V_2 is the voltage potential between two electrodes. A series of simulations is performed for various permittivity values on top of the dielectric material. The 3D geometry of the simulation model is shown as in Figure. 2 below

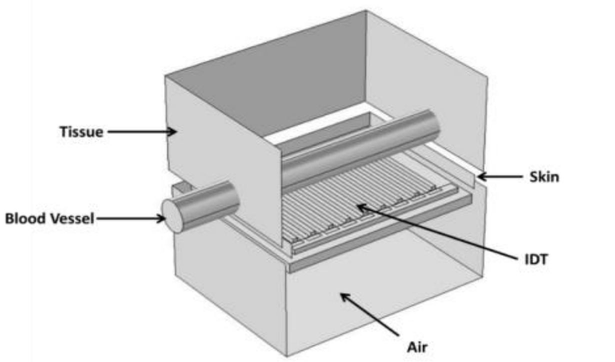


Fig. 2 3D Model for IDT Capacitive Sensor in Electrode-Skin Interface

V. SIMULATION RESULTS

Electric Field

The first simulation has an impact on the penetration of the electric field into the blood vessel. As discussed, the coverage of the electric field must be sufficient to penetrate the main blood vessel to precisely estimate the changes of capacitance due to variation in glucose concentration. Figure 3 shows the electric field distribution for two designs, the minimum width (250μm) and the maximum width (600μm).

Wide coverage of electric field prevails in the vicinity in both dimensions, suggesting that the penetration of the electric field is not a major concern in this study. However, a higher intensity of the electric field is desired to achieve the best accuracy possible. The simulation results are extracted to obtain the average normalized electric field generated on device concentration and inside the blood vessel. Figure 3 shows the plotted of electric field magnitude under both conditions. It suggested that the electric field signal is able to penetrate the blood vessel for capacitive-glucose sensing.

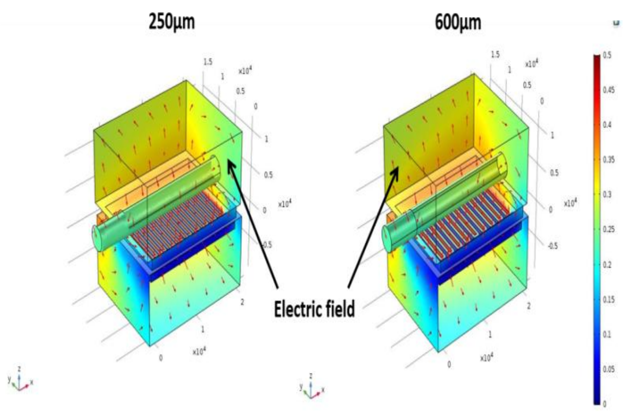
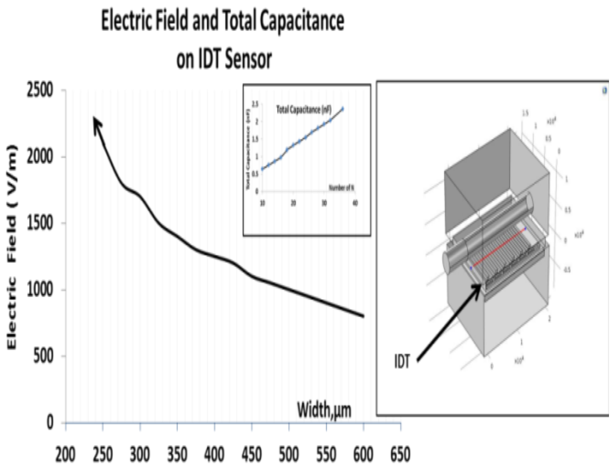
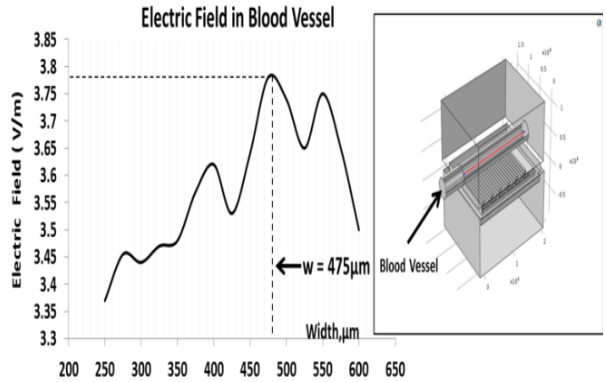


Fig. 3 Electric-Field Distribution on 250μm and 600μm width of IDT Electrodes



(a)



(b)

Fig. 4 Electric Field and Total Capacitance Electric-Field Intensity in Blood Vessel

Figure 4(a) shows a plot of the changes of the electric field as a function of digit width, varying from 250µm to 600µm on the surface of the sensor. From the graph, an inversely proportional relationship of the electric field to width is seen. A smaller width of the electrode can produce a higher electric field. This is as expected from (1), a distance between two electrodes can affect the total electric field in the system. A smaller width can fit a higher number of electrodes (N) on the specific sensor total area, therefore increasing the total electric field on the sensor. Similarly, the capacitance will also increase with the increasing of N as shown in the inset of Figure 4(a). The electric field intensity as a function is the digit width shows consistency as well as shown in Figure 4(b) and it also shows the average electric field generated inside the blood vessel. The highest electric field was seen for the 475µm width, which indicates this width is the optimum dimension compared to the others. In addition, a lower electric field is generated on the sensor but a higher electric field inside a blood vessel at 475µm wide suggests a more confined electric field inside blood vessel for higher accuracy of glucose monitoring with less interference from the surrounding biomaterials.

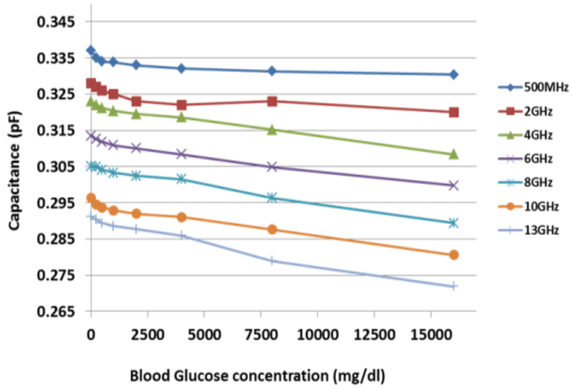


Fig. 5 Effect of Different Frequencies on the Capacitance of Blood Glucose Concentration

The simulation results of Figure 4 here are completely consistent with the analytical results of [11]. Figure 5 shows the graph for the range of capacitance for several high-frequency dispersions on 475µm wide IDS. Higher capacitance can be seen at 500 MHz frequency, but a wider range of capacitance change can be seen at 13 GHz, which indicates it is a better frequency for monitoring subtle changes in glucose concentration. Subsequently, 13 GHz is chosen for the next simulation. Figure 5 shows the plot of capacitance values of the device with different permittivity values. Range of permittivity values is taken from [19] where the values reflect the range of normal glucose concentration in the human body. As expected, the device capacitance is increased as the relative dielectric constant (permittivity) of material is increased. Therefore, an increase in blood glucose concentration can be proportioned to the increase of the capacitance. Capacitance changes are expected to be in the range of 2.33pF by using (1) and Figure 5 by simulation for this design at 13GHz.

VI. CONCLUSION

In this paper, a critical review of the non-invasive techniques of optical, RF, including some sensor design is presented. Additionally, the proposed Interdigital sensor design is presented in much detail. The IDS design is simulated using COMSOL for optimization of the width and spacing of the digits, using which capacitance of a given set of digits of known length, width and thickness. It is observed that 476 um spacing of 10 mm length of IDS produces 2.33pF of capacitance. On top of it, the impedance plots for glucose levels resonating at different frequency have been obtained which proving the simulation results are completely consistent with the analytical results. The future research includes fabrication of the sensors using screen-printing techniques and testing on patients with real-time monitoring of non-invasive glucose monitoring is proposed. The proposed measurement system should be portable and easy to be used for different measurement approaches like a heartbeat, ECG, blood pressure, skin impedance for cancer detection, etc. This measurement system will offer new approaches and opportunities to noninvasive biomedical systems in the field of medicine and other useful areas.

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