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by Yusnita Rahayu

Submission date: 23-Jan-2023 09:24AM (UTC+0800)
Submission ID: 1997262748
File name: piers_-revisi_Figure.docx (910.83K)
Word count: 4355
Character count: 24301

Experimental Based Blood Glucose Monitoring with a Non-Invasive Cylindrical Biosensor Antenna

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Abstract— In this work, we have designed and fabricated a non-invasive flexible biosensor antenna with a simple and printable structure for blood glucose monitoring. The antenna has been experimentally proven to monitor blood sugar levels through frequency shifts. A cylindrical design with a coplanar waveguide (CPW) feeding technique has been proposed. A targeted frequency of 2.4 GHz with the best S11 at -22.623 dB and a bandwidth of 323 MHz was obtained. However, after propagating through the finger phantom, the signal is sensitive to the blood glucose levels with a significant frequency shift. The antenna worked well at 1.55-1.88 GHz, representing a finger, without a phantom in the ISM band of 2.4 GHz. There is a bit of shifted frequency during the antenna measurement with less than a 1.41% error with a sensitivity of 0.3 1/(mg/dL). The overall size of the antenna is 50.66 mm x 60.31 mm. The antenna uses a flexible Dupont Pyralux substrate; thus, the index finger is easy to insert. The 25 volunteers were involved in this experimental blood glucose. For this, we use an invasive device to measure the volunteers' blood glucose levels. The invasive measurement results obtained are used as a reference for the blood sugar levels of each sample. The test results using a cylindrical antenna show a frequency shift at 7.5 MHz for every mg/dl of blood sugar levels, with a sensitivity of 0.43 1/(mg/dL). This frequency shift can be used to observe changes in the concentration of sugar levels in the blood. This flexible antenna is a good alternative biosensor for measuring blood glucose levels due to its low cost and printable structure.

1. INTRODUCTION

Diabetes is a rapidly growing global problem that affects many people. According to the International Diabetes Federation (IDF) 2021 data, the number of diabetic patients in Indonesia will reach 19.47 million in 2021, putting the country in fifth place as the country with the highest number of diabetic patients [1]. This increases the risk of other diseases, such as heart attack, stroke, blindness, and kidney failure, and can even result in paralysis and death. Diabetes affects 537 million adults between the ages of 20 and 79. This figure is expected to rise to 643 million by 2030 and 783 million by 2045 [2]. Blood glucose monitoring is a must as an early action to prevent diabetes from getting worse. The finger-pricking process to measure blood glucose is a popular invasive method today. However, this causes pain to the patient. Another alternative is to use a painless, non-invasive method.

A healthy individual's blood glucose level should be within the normal range, or between 70 and 100 mg/dL in the fasting state and 70 and 140 mg/dL after eating. Both high blood sugar (hyperglycemia) and low blood sugar (hypoglycemia) are harmful. Hypoglycemia might result in weakness or even unconsciousness. On the other hand, hyperglycemia in the blood can potentially constitute a medical emergency or lead to diabetes-related issues [16].

Electromagnetic wave (EM-wave) technology is the most suitable for developing non-invasive sensors. This is because of its penetration depth to biological tissue [3]. Numerous nonresonant (wide band) [27-29] and resonant (narrow band)[30-31] techniques for evaluating EM characteristics based on microwave and millimeter waves have been developed. Resonant technologies have grown in popularity, particularly for applications requiring great speed, precision, and sensitivity. One way to improve the accuracy of EM parameter detection by microwave resonant sensors is to increase the number of sensor resonances because a broader frequency range can be used to measure the EM parameters of the materials and obtain more detailed information about the EM properties of the sample under test (SUT) [16]. Recently, many researchers have worked on non-invasive antenna design as a sensor for blood glucose monitoring [3-20], [23],[25-31].

The feasibility study on monopole antenna for blood glucose monitoring was reported in [3]. In [4,], two mm-wave antennas operating at 37 GHz were proposed, with absorbers strategically placed around the antenna sensors. As a result, the sensing system's sensitivity to changes in glucose is increased. [5] designed a patch resonator with a two-port structure operating at 2.40 - 2.48 GHz, and the energy is capacitively coupled to the patch via two feeding lines. SMA connectors are used to feed the feeding lines. A sensor inspired by metamaterials was created for non-invasive blood glucose monitoring [6]. The sensor integrates three resonant cells of single split rings with a microstrip line and operates at 3-4 GHz. The authors [7] also proposed an antenna design for non-invasive glucose concentration measurement in blood plasma, which included a complementary split-ring resonator (CSRR) loaded truncated patch and electromagnetic band gap structure etching on the ground plane. [8] also reported another CSRR antenna using a different technique. [9] investigated a small flexible ultra-wideband (UWB) monopole antenna fed by a coplanar waveguide (CPW) that operates from 4 to 10 GHz. The commercial Kapton substrate was used as antenna material. Another planar UWB antenna was also developed for this system [10]. A narrowband antenna consisting of four spiral arms fed by a coaxial line through the substrate was discussed in [11]. [12] investigated a flexible slot antenna that can be integrated inside a wearable glove to allow enough electromagnetic wave penetration to monitor blood glucose variations wirelessly. [13] describes the use of spoof surface plasmon polariton (SSPP) end-fire sensor-based structures (meta-materials antennas) for measuring glucose concentrations in aqueous glucose solutions as well as on-body measurements. The textile material adopted as the dielectric substrate for the antenna sensor was developed in [14]. Authors [15-16] proposed planar sensors with substrate-integrated waveguide (SIW) technology for blood glucose monitoring using volunteers' fingertips. Finger placement and the influence of fingerprints affect the sensor sensitivity [15]. However, most researchers employed rigid substrates (FR4, RT/Duroid, Roger 3210, Arlon) for their antenna substrate material [3-8][10-11][13][15-16]. A limited number of studies employed flexible/textile substrates in their antenna design [9][12][14]. The microstrip line and coaxial probe are the mostly feeding techniques applied in many works of literature.

[8] summarized several microwave/RF transmission and/or reflection techniques, such as transmission lines, free-space, resonant, and so on. Method selection is influenced by the operating frequency, physical state (solid or liquid) of the material under test (MUT), losses, and volume [8]. [17] described a microstrip line (MLIN)-based glucose sensor with a T-shaped pattern for blood glucose monitoring using the fingers as the object. This technology bridges the gap between transdermal and microwave/RF techniques. This is due to the fact that blood glucose concentrations can change the dielectric properties of the blood [18-20]. By constructing the MLIN around the subject under sensing, such as a finger, the main field of an MLIN can be used for glucose sensing. Because of the high intensity of the main field, the sensitivity is significantly higher than when the fringing field is used [17]. The fingertip is a common measuring site because a good amount of fresh blood is stored there [3]. Based on this idea, we propose a cylindrical antenna with Dupont Pyralux as the flexible substrate to measure the blood glucose concentration by detecting the variation of the dielectric changes of the different blood glucose concentrations. We employed the CPW feeding technique to optimize the structure. This method will not harm the patient's body. It only simply inserts the finger into the antenna rather than presses onto it [26].

This paper is organized as follows. First, section 2 presents the materials and methods used in the proposed system. Next, measurement and simulation results are discussed in Section 3. Finally, Section 4 concludes the paper.

2. MATERIALS AND METHOD

2.1. Antenna Design Structure

The purposes of the non-invasive biosensor antenna design are as follows. 1) A fingertip must be easily placed on the sensor sensing area. 2) It should be compact and flexible. 3) It must have easy and cost-effective fabrication. To achieve these purposes, a cylindrical antenna with a CPW feed line has been selected with Dupont Pyralux material used as a sensor to measure glucose levels in this paper. An antenna can both transmit and receive electromagnetic waves. Fig. 1(a)-(c) presents the cylindrical antenna with Dupont Pyralux as the substrate with the size (Table 1). Table 1 lists the antenna with the cylindrical phantom dimension. For the housing, the thickness of the wall is 0.2 mm, and the total height is 60.31 mm with $\varepsilon_r \approx 3.5$.

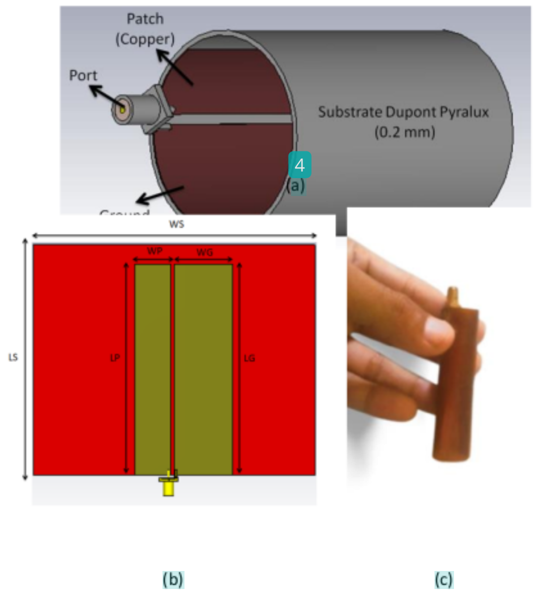

Figure 1. Configuration and prototype of the proposed antenna: (a) 3D View; (b) antenna geometry; (c) antenna prototype.

Table 1. Dimension of Proposed Cylindrical Antenna and Cylindrical Phantom

Parameter	Value (mm)
WS	50.66
LS	60.31
WP	15.35
LP	38.82
WG	20.56
LG	39.32
D	20
DS	20
DF	17.5
DBL	5.2
DBO	13.8

Dupont Pyralux is a double-sided copper-coated polyimide laminate made in sheets and rolls with global availability that is ideal for medical and automotive applications and compatible with conventional flexible circuit fabrication processes. It has good physical, chemical, and electrical balance over a wide frequency range, with a low loss factor. Furthermore, Dupont Pyralux has a very low dimension profile (50.66 x 60.31 mm) but is very strong, with a tensile strength of 165 MPa at 73 F and a dielectric strength of 3500-7000 V/mil, as well as a Glass Transition Temperature rating of 280 [19]. The biosensor is fabricated using the Brother DCP-T310 printer with ink (Durabrite). Fabrication begins by entering the antenna design into Corel draw software and then printing with Dupont Pyralux substrate. The next stage is Etching, a metal dissolving process using strong acid on the unprotected part of the metal surface to make the planned design using ferric chloride ($FeCl_3$). Then connect the

SMA connector using soldering tin. The final fabrication process is folding the antenna into a cylinder with insulating tape.

2.2 Finger Phantom Design

The dielectric quantity in the body tissue used to analyze glucose levels changes at a specific frequency. The characteristics of these changes in several body tissues have been studied and modeled using the Cole-Cole equation [16]. In addition, variations in permittivity caused by changes in glucose concentration can impact an antenna's near-field coupling and electromagnetic wave transmission [21].

Blood glucose level detection will be carried out on cylindrical phantom modeling, as a finger will be used as a medium for testing the penetration depth of the antenna. The phantom modeling is made up of finger elements such as skin (DS), fat (DF), blood (DBL), and bone (DBO). Because it contains sufficient blood, the fingertip model is frequently used to measure invasive sugar levels. The fingertip, however, is attached to the sensor's surface in its non-invasive measurement application. As a result, a finger model with a length of 60 mm and a diameter of 20 mm was created for this study.

To investigate the effects of blood density, a voxel-based finger phantom with varying numbers of cylinder-shaped blood slots is used. Each slot of the blood cylinder represents 30 mg/dl of blood density. It makes the blood slot easier to model the blood vessel on the finger phantom. Assuming that each blood slot is 30mg/dl, it is easier to perform a simulation to see the shift in the frequency resonance to the increase in blood sugar levels. There are 8 blood slots in this finger phantom with a total of 240 mg/dl, as presented in Fig. 2. This is based on a predetermined blood glucose setting; diabetes is diagnosed at a blood sugar of greater than or equal to 200 mg/dl [20].

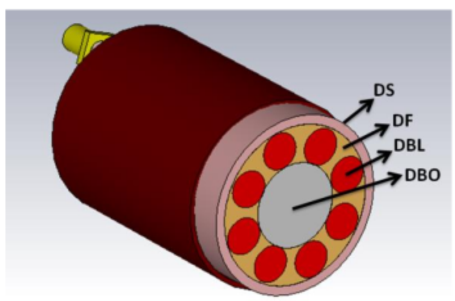

Figure 2. Finger phantom design

From the literature [3-16], the diagnostic method using a non-invasive antenna is through reflection coefficient, input impedance, and resonance frequency. These two diagnostic methods are used in this paper, reflection coefficient and resonance frequency. The cylindrical antenna works well at a frequency of 2.4 GHz without phantom and shifts to 1.5 – 1.8 GHz with phantom at different blood glucose concentrations.

2.3 Experimental Setup

Fig. 3 shows an illustration of the experimental setup. The SMA connector was connected to Port 1 of a pocket vector network analyzer (VNA). The measurements were conducted 20x for each volunteer so that the real test for all samples was 500 times. The results were averaged for further analyses. These 25 volunteers were involved in this research.

The process begins with measuring blood sugar levels from 25 volunteers using an Invasive Device. The measurement results obtained are used as a reference for the blood sugar levels of each sample. The antenna requirements for biological measurement applications differ from those for free space antennas in a number of ways. The inhomogeneity of the antenna environment and significant variation depending on the humidity of the patient's skin and the measurement point are the most difficult [21][23].

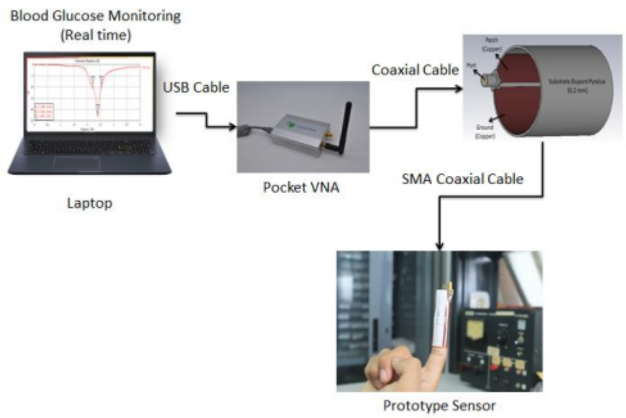

Figure 3. Experimental Setup

3. RESULT AND DISCUSSIONS

Fig. 4 shows the cylindrical antenna's simulated and measured S11 using Dupont Pyralux. From the results, the simulated bandwidth is 323 MHz in the frequency range of 2.210 GHz to 2.533 GHz, while in the frequency range of 2.264 GHz to 2.541 GHz, the measured bandwidth resulting is 277 MHz. The error of 1.41% is obtained during the antenna measurement and calculated using equation 1.

$$Error(f) = \left|\frac{fm - fs}{fs}\right| \times 100 \ (\%) \quad (1)$$

where f is the error obtained in the measurement and fm and fs for the measurement and simulation resonant frequency, respectively.

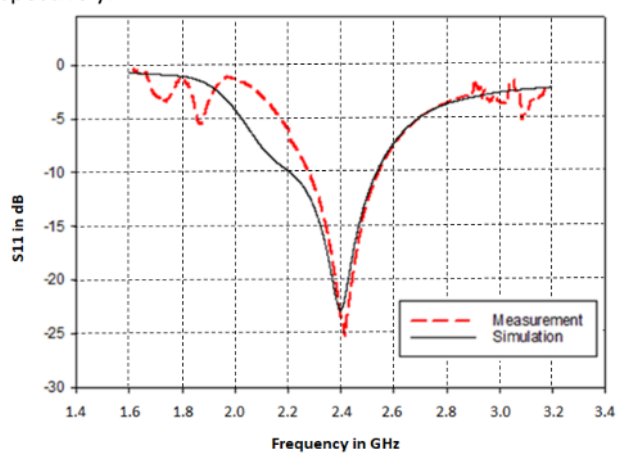

Figure 4. Measured and simulated S-parameters of the proposed antenna

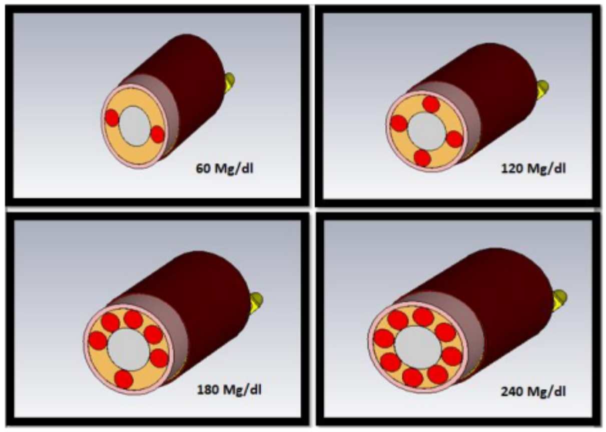

Figure 5. Cylindrical antenna with finger phantom

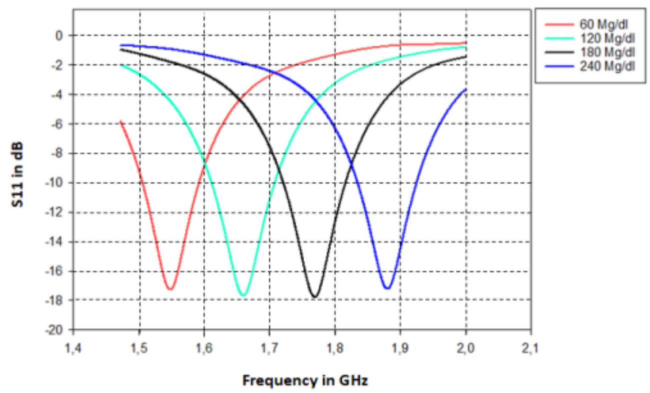

Figure 6. Simulated S11 of a cylindrical antenna tested with finger phantom

The signal is sensitive to blood glucose levels after passing through the finger phantom with a significant frequency shift. The simulated S11 of a cylindrical antenna tested with the finger phantom is presented in Fig. 6. The simulated results obtained a change in frequency according to the addition of phantom blood slots, as shown in Fig. 5. As illustrated in Fig. 6, combining two simulated phantom blood slots provides a frequency of 1.552 GHz with a bandwidth of 86.3 MHz. In comparison, a combination of 4 phantom blood slots gets a frequency of 1.663 GHz with a bandwidth of 91.2 MHz. A combination of 6 blood slots shows a change in S11 at a frequency of 1.772 GHz with a bandwidth of 94.5 MHz. Last, a combination of 8 phantom blood slots results from 1.879 GHz, a bandwidth of 89.4 MHz. Examining the findings for different blood glucose concentrations reveals that the suggested sensor's resonant frequency alters with each increase in glucose concentration. Due to the inherent conductivity of biological tissues, low frequencies penetrate deeper into the tissues than higher frequencies. Consequently, when the fingertip is in contact with the sensing area, electromagnetic waves penetrate the fingertip and disrupt the electromagnetic fields. In addition, the change in the effective permittivity at the detecting area induces noticeable changes in the sensor transmission response [16].

Table 1. Comparative Study of Different Types of Flexible Antennas

Characteristic	Proposed cylindrical antenna	Flexible polyester antenna [9]	Wearable antenna [14]	MLIN[17]
Size (mm)	50.66 x 60.31	19.2 x 17.8	4 X 4	11 x 20
Thickness (mm)	0.02	3	0.01	1.5
Band /F_0 (GHz)	Single/2.4	Dual/ 5.76 and 10.1	Single/2.4	Dual/ 0.95 and 2.99
Substrate	Pyralux εr = 3.5	flexible polyester εr = 2.8	Denim Material εr = 1.6	NaCl εr = 4.4
Tensile Strength (MPA)	High 165	High 860	-	-
Flexural strength (p.s.i)	High 50000	High 11117		-
Deformability	Low	Low	Low	Low
Thermal Stability	High	low	High	High
Fabrication Complexity	Simple/ Printable	Complex/Non-printable	Complex/Non-printable	Complex/Non-printable

Given the applications envisioned in this paper, this paper compared various flexible antennas reported in [9][14][17]. Compactness (size and thickness), electrical properties, and robustness are all compared in the study. The term "robustness" refers to the mechanical properties of flexible/conformal electronic devices, such as tensile strength, flexural strength, deformability, and thermal stability. This comparative study takes into account the fabrication complexity criteria as well. Table 1 demonstrates that the proposed antenna provides extremely robust and flexible designs. This antenna is also printable and offers low-cost, roll-to-roll production.

Table 2. Experiment Results with Invasive and Non-Invasive Devices

No	Blood Glucose (mg/dl) (Invasive)	Non-Invasive (proposed sensor)			
		Blood Glucose (mg/dl)	$\bar{f}$ (GHz)	S11 (dB)	Bandwidth (MHz)
1	73	73	1.5343	-26.32	93.61
2	86	86	1.6045	-26.05	98.65
3	90	90	1.6301	-26.12	95.65
4	103	103	1.7031	-26.04	96.72
5	112	112	1.7478	-25.71	98.32
6	129	129	1.7857	-25.92	100.1
7	151	151	1.8320	-26.34	97.29
8	163	163	1.8605	-26.71	99.54
9	190	190	1.8921	-25.92	96.48
10	213	213	1.9712	-25.90	97.54

Table 2 represents the 10 experimental results of the blood glucose test for volunteers. The test is performed for invasive and non-invasive devices. For a non-invasive device, measurements were made using a VNA operating at 1-4 GHz. Before testing with a cylindrical antenna, calibrate the VNA with a frequency setting of 1-4 GHz, then insert a finger on the antenna and measure it using VNA. Fig. 7 shows the experimental blood glucose detection using the cylindrical antenna. The test results using a cylinder antenna show that the S11 values range from -25.62 dB to -26.32 dB, while the bandwidth obtained ranges from 92.47 MHz - 100.1 MHz. Therefore, the testing for blood sugar levels of 73 mg/dl - 98 mg/dl or belonging to the non-diabetic category, carried out with a cylindrical antenna, will display results at a frequency of 1.5343 GHz - 1.6712 GHz, for 100 mg/dl - 123 mg/dl or pre-diabetes category will display test results in the frequency range 1.7031 GHz - 1.7857 GHz, and 129 mg/dl - 213 mg/dl or diabetes category the test results obtained at a frequency of 1.7857 GHz - 1.9712 GHz.
The tests using a cylindrical antenna showed a significant change, where an increase in blood sugar levels made a frequency shift towards a larger one. The test results using a cylindrical antenna obtained

a frequency shift of 7.5 MHz for every mg/dl blood sugar level. Glucose is present in the interstitial fluid (ISF) and blood vessels. Changes in glucose levels in these two regions and their interaction with EM waves penetrating the skin vary the sensor's resonance frequency, allowing us to manage the user's blood glucose levels [16]. Figure 8 depicts the distribution of frequency shifts.

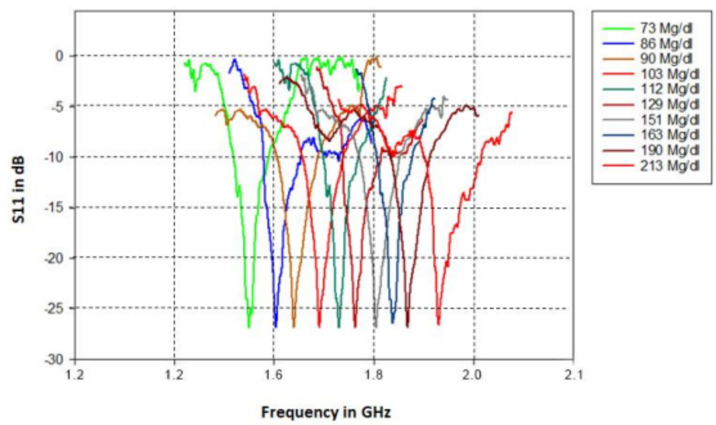

Figure 7. Result of blood sugar levels tested by the cylindrical antenna

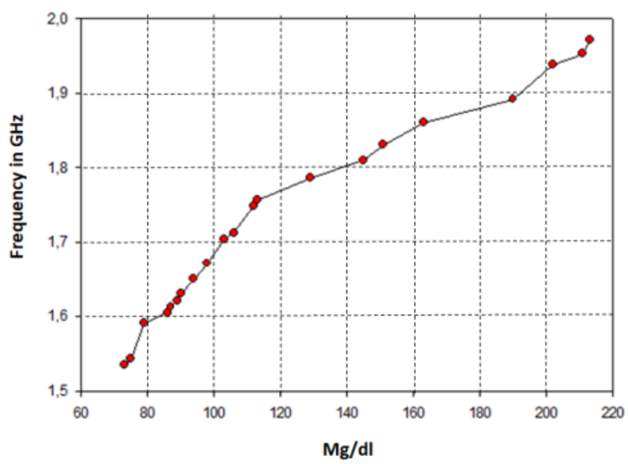

Figure 8. Blood glucose level versus frequency

The sensor's stability sensing indicates sensitivity. The sensors' sensitivity, which is stated in equation (2), is used to assess their accuracy. [16].

$$S = \frac{FDR}{f_{FL}}\ x\ 100\ (1/(mg/dL)) \quad (2)$$

Where the FDR is the frequency detection resolution (7.5 MHz/(mg/dL)) and is f_{FL} for freeload resonance frequency of the sensor(2.4 GHz). Thus, the sensitivity of the proposed sensor is 0.43 1/(mg/dL).

4. CONCLUSION

The cylindrical antenna uses a coplanar waveguide (CPW) feeding technique designed to work at a targeted frequency of 2.4 GHz with the best S11 at -22.623 dB with a bandwidth of 323 MHz. In comparison, the measurement results of the antenna prototype get an antenna S11 value of - 25.02 dB at a frequency of 2.411 with a bandwidth of 277 MHz. Changes in frequency occur when detection is carried out using a finger phantom ranging from 1.55 GHz to 1.88 GHz for each slot test.

The simulated gain of the cylindrical antenna obtained is 3.27 dBi with a directional pattern. Cylindrical antenna SAR simulation results show a value of 0.271 W/Kg and have met the ANSI/IEEE standard. The measurement results of each antenna (S11) show a significant difference in results, where the working frequency will shift towards the more dominant frequency, and when the measurement uses a fat finger phantom, the bandwidth is more than 83.5 MHz, and the S11 varies -10 dB. The sensitivity of the proposed sensor is 0.43 1/(mg/dL).

ACKNOWLEDGEMENT

The Directorate General of Higher Education Ministry of Education and Culture, the Republic of Indonesia, financially supports this work under the fundamental research grant project 2022. In addition, The authors would like to thank the National Research and Innovation Agency (BRIN) for providing the research facility, as well as the Research and Community Service Agency (LPPM) Universitas Riau for research management and motivation.

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