A V-Band Highly Directive Circularly Polarized Antenna Array for Wireless and Contactless Continuous Glucose Monitoring

***Abstract*—In this work, we present an aperture-coupled, series-fed, multilayer structure array antenna for contactless continuous non-invasive glucose monitoring. The proposed miniaturized, highly directive and circularly polarized V-Band antenna array continuously and non-invasively monitors blood glucose variations. Experiments executed on fetal bovine serum (FBS) solutions and in-vivo experiments on animal models demonstrate high accuracy in the ability of the proposed wireless system to continuously track glucose variations across the diabetic range [30mg/dl - 500mg/dl]. Furthermore, clinical studies executed reveal an acceptable clinical ability of the proposed system in continuously detecting glucose variations. The antenna array system integrated into an earring is able to transmit its radiated beam across the veins of the neck to be received by a second antenna array integrated into a second earring on the other side of the neck. To our knowledge, this is the first wearable system that is capable of continuously monitoring glucose variations in a fully contactless manner.**

I. Introduction

Monitoring glucose variations using electromagnetic waves has resulted in systems, operating in the microwave range of the spectrum, that are wearable [1] for continuous non-invasive monitoring. On the other hand, other researchers resorted to millimeter wave frequencies to analyze blood glucose properties in the lab [2] or to develop a wireless glucometer such as the one discussed in [3].

In this work, we present a mm-wave, highly-directive antenna array that can be integrated in an earring for wireless and contactless continuous non-invasive glucose monitoring as shown in Fig. 1(A). The proposed antenna array exhibits circular polarization and is capable of targeting both jugular veins and carotid arteries in the neck to measure glucose level. This is validated by experiments on fetal bovine serum (FBS) solutions, in-vivo experiments on animal models, and clinical studies. In section II of this paper, the antenna array design concept and configuration are exhibited. Section III presents the results achieved during different experimental setups. The paper is concluded in section IV.

II. Concept and Design of the Sensing System

A. 4x4 Antenna Array Design

The stack-up structure of the proposed multilayer antenna consists of two laminates (Rogers5880 and Rogers4003C), stacked 3 times as shown in Fig. 1(B) with four metal layers. The cross aperture proves to represent the best approach used to retain the symmetry in the radiation pattern. The aperture is fed using a single series-fed technique with sequential rotation. The square patch has also a cross aperture and an edge-based microstrip fractures to better enforce a circularly

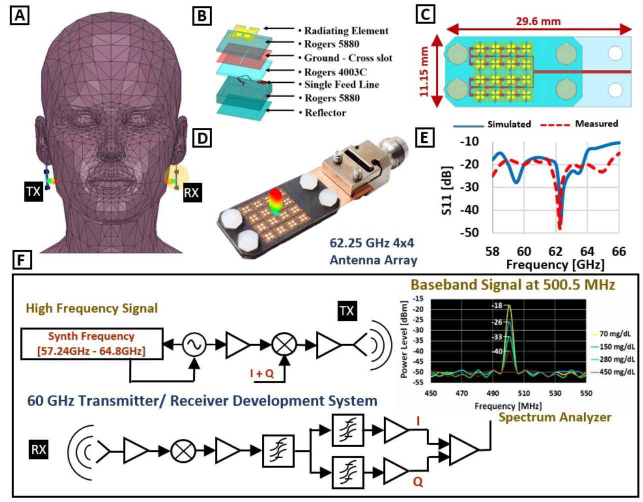

Fig. 1. Visual Summary of the novel V-band Wireless System for Blood Glucose Level Monitoring.

polarized radiation beam for V-band antenna arrays. Based on the optimized radiating element design introduced, a 55-65 GHz extremely miniaturized 4x4 antenna array is modeled as shown in Fig. 1(C), and fabricated as depicted in Fig. 1(D), with total dimensions of 29.6×11.15×1.246 mm^3. In Fig. 1(E), the simulated and measured S11 plots are perfectly overlapped with resonance at 62.25 GHz and a high realized gain of 14 dB.

B. Proposed Wireless V-Band BGL Monitoring System

Two extremely miniaturized circularly polarized V-band 4x4 multilayer structure antenna arrays are fabricated and implemented as two wearable earrings. One antenna is connected to a transmitter and the other one is connected to the receiver end as shown in Fig. 1F. The signal from the transmitter antenna array propagates through the jugular and carotid arteries in the neck and completes its journey until it is well received by the array at the receiver side. Once this signal is received it propagates through the receiver chain and is down-converted to 500.5 MHz at baseband. Variations in glucose in the bloodstream result in variations of the power received at 500.5MHz, which is visualized on a spectrum analyzer. The resulting data is then treated with data analytics and machine learning algorithms that correlate the changes in the power received with the blood glucose variations.

III. Detection of Glucose Levels: Experimental Setups and Results

A. Experiments on Fetal Bovine Serum Solutions

The initial testing of the transmit/receive system is executed over Fetal Bovine Serum (FBS) solutions that are diffused with glucose with varying concentrations. The purpose of this experiment is to test the capability of the proposed system to track glucose variations even in solutions with small increments of 15 mg/dL covering the hypo to hyperglycemic range from 30 mg/dL to 510 mg/dL.

B. Experiments on Animal Models

Experiments were performed on six anesthetized Sprague-dawley rats to assess the proposed sensing system's efficacy to detect blood glucose levels (BGL) in the jugular veins and carotid arteries of a living tissue of the animal models. The glucose variation is monitored every 10 min using the invasive glucometer and the proposed non-invasive technique for a total of two hours.

C. Clinical Studies

We evaluate the proposed V-band wireless system on 10 healthy volunteers to verify its ability to monitor the BGL in real-time settings during Oral Glucose Tolerance Tests (OGTTs). The 4x4 antenna array BGL sensor was installed in a helmet worn by the volunteers to ensure its stability and sturdiness during the testing as shown in Fig. 2(a). The helmet is designed in a way that both antennas can be easily aligned to target the neck of different volunteers using variable axes. The glucose variation is monitored every 15 min using the invasive conventional glucometer and our proposed contactless technique for a total of two hours.

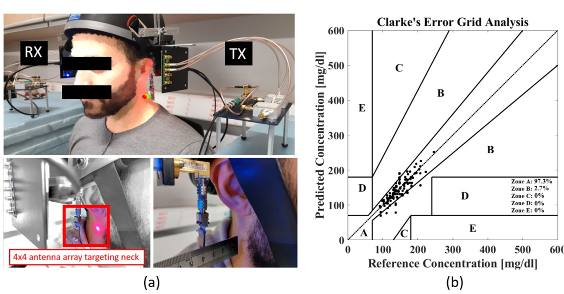

Fig. 2. Human Experiments Setup (a) and Results (b).

D. From Base-band Power Levels to Glucose Levels: Statistical Regression Model

To evaluate the performance of the proposed system when tested over FBS solutions, regression models were implemented that correlated the related received power to glucose variations through a Gaussian process (GP) regression model. To assess the accuracy of the proposed sensor, we compare the mean estimated Glucose Level (GL) with the reference GL. The correlation between the predicted glucose values and the actual glucose measurements from the conventional invasive glucometer is shown in Fig. 3 (a) and (b). On the other hand, the standard method of assessing clinical studies of glucose monitoring tools resorts to Clarke's error grid [4]. A Clarke's error grid evaluates the accuracy of a blood glucose monitoring system in estimating real glucose levels in blood. It is divided into 5 zones (A,B,C,D and E) where clinically acceptable results fall in Zones A and B. It is determined that all our results obtained from the 10 healthy volunteers fall in zones A and B. Hence, our proposed technique is proven to be clinically acceptable based on the data obtained from the sample of healthy volunteers that underwent the test.

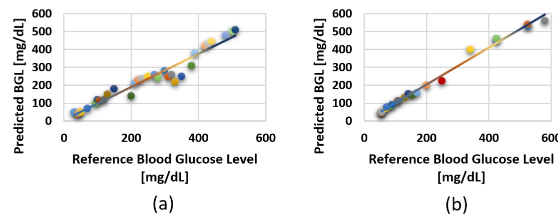

Fig. 3. Data Analysis Results: Predicted BGL versus Reference BGL (mg/dL) in [hypo/hyper]-glycemic range for (a) FBS-based experiments, and (b) in-vivo experiments.

IV. Conclusion

In this work, a V-band wireless highly directive, extremely miniaturized, 4x4 antenna array with circular polarization is proposed for continuous and wireless blood glucose monitoring. The sensor can be worn by a diabetic patient as an earring with its radiated beam targeting at a distance both the jugular veins and carotid arteries in the neck. From the interaction between electromagnetic wave propagation and the blood vessels, data analytic algorithms are implemented to extract glucose concentrations from the variations of received power levels at 500.5 MHz. The proposed sensing system achieves clinically acceptable results and is to our knowledge the first contactless system to evaluate blood glucose continuously in FBS solutions, animal models and clinical studies.

References

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