Transmission Characterization of Glucose Solutions at Ku-band for Non-Invasive Glucose Monitoring

Yijun Zhou, Xianming Qing, Terence Shie Ping See, Francois Chin and Muhammad Faeyz Karim
Institute for Infocomm Research, A*STAR, Singapore
1 Fusionopolis Way, #21-01 Connexis, Singapore 138632
{yjzhou, qingxm, spsee, chinfrancois}@i2r.a-star.edu.sg, faeyz@hotmail.com

***Abstract*— The transmission characteristics including the amplitude and phase responses of the glucose solutions with different concentrations are studied for non-invasive glucose monitoring. Two glucose solutions using saline and distilled water are investigated at Ku-band of 17 GHz with simulation and measurement. It is found that the transmission phase of the glucose solutions exhibits linear response to the glucose concentration from hypoglycemia to hyperglycemia, which shows high potential in developing non-invasive glucose monitoring system using microwave technology at Ku-band.**

Keywords*— *Glucose; glucose solution; glucose concentration; microwave; transmission; hypoglycemia; hyperglycemia

I. INTRODUCTION

Diabetes mellitus is a very serious chronic disorder. According to the World Health Organization (WHO), one person dies of diabetes in every six seconds. The number of patients affected by diabetes mellitus worldwide stands as high as 415 million in 2015 and will increase by 55% to 642 million patients by 2040 as estimated, i.e. 10% of adults globally will be suffering from the diabetes mellitus.

Diabetes mellitus is characterized by an abnormal regulation of glucose levels in the blood. The failure of controlling glucose levels will lead to disastrous complications such as kidney disease, blindness, lower limbs amputation, stroke heart attack. The treatment of diabetes mellitus requires the consistent monitoring of the blood glucose level for proper and safe titration of the anti-diabetes medication. Currently, the glucometers available for blood glucose level monitoring are invasive, operationally cumbersome, and costly, which prohibits them from wide adoption in the daily diabetes self-monitoring. In order to provide the diabetes mellitus patients more convenience for glucose self-monitoring, there is a great need to develop the non-invasive and cost-effective glucose monitoring system with acceptable accuracy.

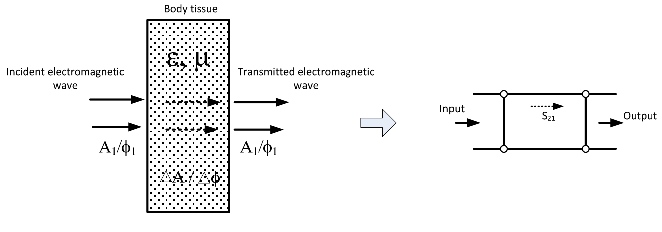
The quantity of glucose in the blood of a healthy adult male of 75 kg is about 5g, and the normal fasting blood glucose level varies in the range of 70 to 110 milligrams per deciliter (mg/dl) only. Thus, it is a great challenge to detect the blood glucose level non-invasively and accurately, although studies in this area have been conducted since the 1980s. Over the last 30 years, the full spectrum from direct current (DC) to light has been exhaustively explored and a number of non-invasive glucose monitoring systems have been developed by using electrical impedance, electromagnetic, and infrared technologies. However, the accuracy is not satisfactory for practical applications [1–5].

The use of microwave and millimeter wave technologies for non-invasive glucose monitoring have attracted more attention in recent years [2–4]. The electromagnetic wave with centimeter or millimeter wavelength provides sufficient penetration capability through human body tissues and offers the desired resolution to characterize the transmission response of with different glucose concentrations. Some works have been reported but they only show the capability to detect glucose concentrations which are far above the normal range [3, 4].

In this paper, the transmission characteristics of the glucose solutions with different concentrations at Ku-band of 17 GHz will be investigated. The amplitude and phase responses of the glucose solutions with saline and distilled water are studied by simulation and experimental validation.

II. TRANSMISSION CHARACTERISTICS OF THE GLUCOSE SOLUTIONS

As shown in Fig. 1(a), when the electromagnetic wave passes through a material such as human body tissue with permittivity of ε and permeability of μ, it will result in the transmission loss (ΔA) and phase delay (Δϕ). Moreover, based on microwave network analysis, the electromagnetic wave transmission can be described using an equivalent two-port network, and the transmission response can be analyzed by using the scattering parameter of S_{21} and measured by using a vector network analyzer.



(a) (b)

Fig. 1 (a) Schematic view of electromagnetic wave transmission through human body tissue and (b) equivalent two-port network.

The permittivity of a material can be described as:

$$\varepsilon(\omega) = \varepsilon_0(\omega)\varepsilon_r(\omega) = \varepsilon_0(\omega)(\varepsilon_r'(\omega) - j\varepsilon_r''(\omega)) \quad (1)$$

where ε_r is the relative permittivity of the material, and $\varepsilon_0 = 8.854\times10^{-12}$ F/m is the vacuum permittivity, ω is the angular frequency. In general, the ε_r' and ε_r'' will lead to the larger transmission phase delay and higher transmission loss, respectively.

The frequency dependent complex permittivity of the blood can be described as below based on the modified Cole-Cole model [6].

$$\varepsilon(\omega) = Re\left[\varepsilon_\infty + \sum_{m=1}^{2}\frac{\Delta\varepsilon_m}{1+(j\omega\tau_m)^{1-\propto_m}}\right].[(-0.001445)g + 1.145882] + Im\left[\varepsilon_\infty + \sum_{m=1}^{2}\frac{\Delta\varepsilon_m}{1+(j\omega\tau_m)^{1-\propto_m}} + \frac{\sigma_s}{j\omega\varepsilon_0}\right] \quad (2)$$

where $\varepsilon_\infty = 2.8$ is the permittivity at infinite frequency, τ_m is the relaxation time ($\tau_1 = 8.377e^{-12}, \tau_2 = 132.629e^{-9}$), $\sigma_s = 0.5$ is the static conductance, α_m is the exponent parameter ($\alpha_1 = 0.057, \alpha_2 = 0.1$), $\Delta\varepsilon_1 = 56.5, \Delta\varepsilon_2 = 5500$, g is the glucose concentration.

The varying glucose level in the blood changes the ε_r of the human body tissue from time to time and therefore offers the possibility to monitor the glucose level non-invasively by characterizing the transmission response of the human body tissue.

A. Simulation Model

The simulation is conducted using the electromagnetic simulation software – CST Microwave Studio. The blood plasma is modelled as a 2 mm thick dielectric substrate with varying permittivity at different glucose levels. Using the unit cell with open boundary conditions and plane wave excitation, the RF transmission characteristics can be obtained and analyzed.

B. Measurement Set-up

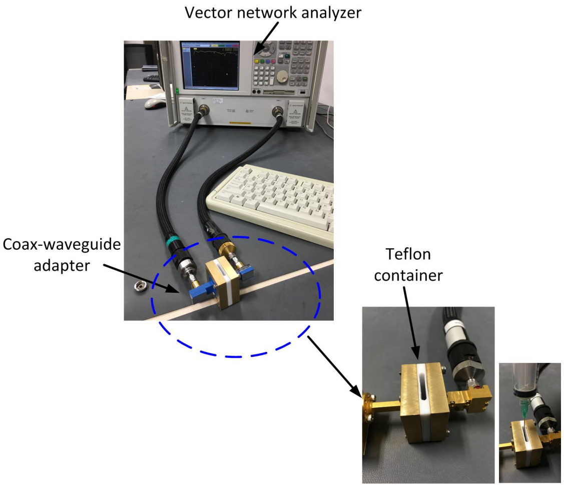


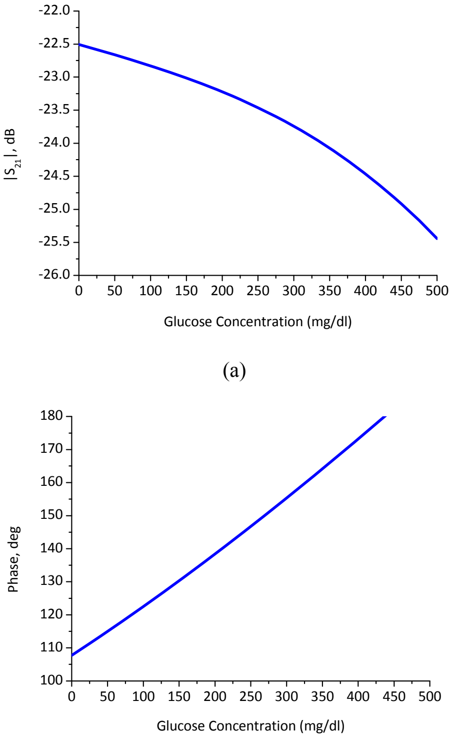
Fig. 2 Measurement set-up.

The measurement set-up is shown in Fig. 2. A pair of coaxial line to waveguide adapters are connected to the two ports of a vector network analyzer (VNA) separately and used to transmit and receive electromagnetic waves at Ku-band of 17 GHz. A Teflon container with a 2-mm cavity is positioned in between the waveguide outputs of the adapters. The glucose solutions are injected and sucked out using an injector. The amplitude and phase changes of the transmission scattering parameter S_{21} can then be characterized.. Two types of glucose solutions, one with saline and the other with distilled water with are used in the measurements..

III. RESULTS

A. Simulation Results

With the Cole-Cole model for the complex permittivity of blood, the forward scattering parameter, S_{21}, of the blood plasma sample with different glucose concentrations is simulated using CST Microwave Studio. Figs. 3(a) and (b) show the amplitude and phase of the simulated S_{21} with different glucose concentrations at 17 GHz. The results clearly exhibit the linear amplitude and phase responses with varying glucose concentrations. Generally, the higher glucose concentration results in the larger transmission loss and phase lag.



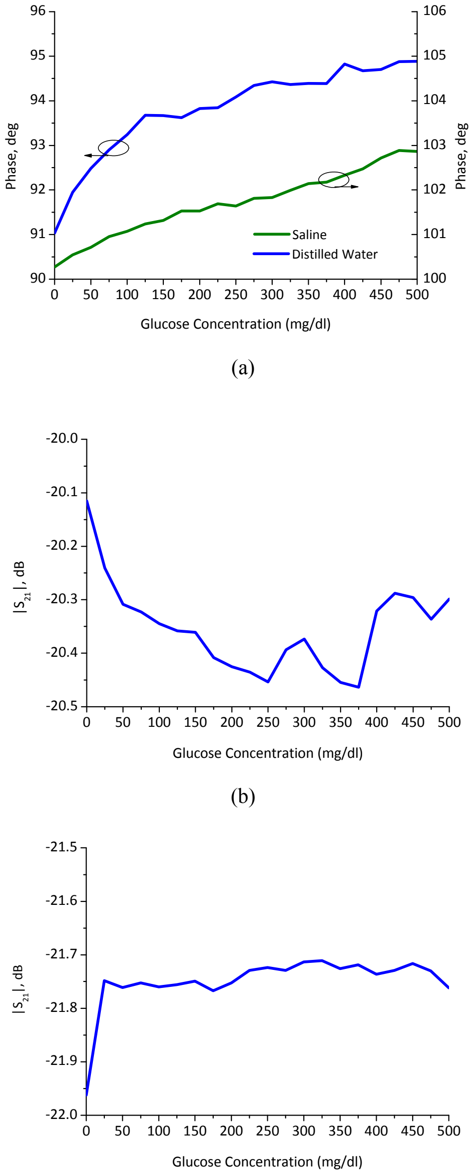
(a)

(b)

Fig. 3 Simulated S_{21}: (a) amplitude and (b) phase responses

B. Measurement Results

With the set-up as shown in Fig. 2, the glucose solutions using saline and distilled water are measured at 17 GHz. From the measured S_{21}, the transmission phase and loss characteristics for the different glucose concentrations are obtained and shown in Fig. 4.



(a)

(b)

(c)

Fig . 4 Measured results: (a) phase responses of the glucose solutions with saline/distilled water, (b) $|S_{21}|$ of the glucose solution with distilled water, and (c) $|S_{21}|$ of the glucose solution with saline.

The measured transmission phase delay is shown in Fig. 4(a). It can be observed that the phase delay increases with the glucose concentration for both solutions, and the one with saline exhibits the more linear response, which is consistent with the the simulation trend. However, the measured transmission losses exhibit very little variation of less than 0.5 dB over the glucose concentration level of 0 mg/dl to 500 mg/dl, which does not match the simulation well. The discrepancy between the measured and simulated results is mainly attributed to the difference in the samples used in the simulation and measurement. In the simulation, the permittivity derived from equation (2) is considered for the blood sample. On the other hand, for the measurement, the samples used are solutions comprising saline or distilled water with dissolved glucose powder.

CONCLUSION

The simulation and experimental validation of two glucose solutions using saline and distilled water at Ku band has demonstrated the high potential of using microwave technology for developing a new type of non-invasive glucose monitoring system. Moreover, as compared with the transmission amplitude, the transmission phase delay is more adequate to be used for monitoring the glucose concentration more accurately since it is more sensitive to the changes in the glucose concentration.

ACKNOWLEDGEMENT

The authors would like to thank Dr Khoo Chin Meng from the National University Health Cluster, Singapore, for his valuable suggestions.

REFERENCES

[1] S. K. Dhar, P. Biswas, S. Chakraborty, “DC impedance of human blood using EIS: An appraoch to non-invasive blood glucose measurement,” *2013 International Conference on Informatics, Electronics & Vision (ICIEV)*, May 17–18 2013.

[2] M. Hofmann, G. Fischer, R. Weigel, D. Kissinger, “Microwave-based noninvasive concentration measurements for biomedical applications,” *IEEE Trans. Microw. Theory Tech.*, vol. 61, no. 5, pp. 2195–2204, May 2013.

[3] H. Cano-Garcia, P. Kosmas, C. Parini, I. Papadopulos-Kelidis, I. Sotiriou, G. Palikaras, and E. Kallos, "Glucose sensing in saline solutions using V-band waveguides," *4th International Conference on Wireless Mobile Communication and Healthcare , MobiHealth 2014*, 2014.

[4] P. H. Siegel, A. Tang, G. Virbila, K. Yanghyo, M. C. F. Chang, V. Pikov, “Compact Non-Invasive Millimeter-Wave Glucose Sensor,” *40th International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz)*, pp. 1–3, 2015.

[5] K. Song *et al.*, “An impedance and multi-wavelength near-infrared spectroscopy IC for non-invasive blood glucose estimation,” *IEEE J. Solid-State Circuits*, vol. 50, no. 4, pp. 1025–1037, April 2015.

[6] B. Freer, “Feasibility of a non-invasive wireless blood glucose Monitor,” 2011 MS thesis, Rochester Institute of Technology.