Development of a passive wireless sensor for fluidic detection and characterization utilizing the PCB-based coplanar electrode (PCE) configuration

Do Quang Loc[1*], Hoang Bao Anh[2]

[1]Faculty of Physics, VNU University of Science, 334 Nguyen Trai, Thanh Xuan, Hanoi, Vietnam;
[2]Center for Electronics and Telecommunications Research, VNU University of Engineering and Technology, 144 Xuan Thuy, Cau Giay, Hanoi, Vietnam.
[*]Corresponding author: locdq@hus.edu.vn

Received 13 Apr. 2024; Revised 29 May 2024; Accepted 12 Jun. 2024; Published 25 Jun. 2024.
DOI: https://doi.org/10.54939/1859-1043.j.mst.96.2024.116-123

ABSTRACT

During the global economic development, there's a growing focus on healthcare, especially in the advancement of medical diagnostic technologies, with a significant emphasis on glucose level evaluation. Glucose biosensors, predominantly electrochemical, have evolved over four generations, with the first three being enzyme-based and known for sensitivity and cost-effectiveness, albeit with limitations due to environmental susceptibility and reliance on enzyme activity. Recent advancements in non-invasive blood glucose monitoring, utilizing optical, microwave, and electrochemical techniques, offer diverse benefits without tissue penetration. Among these, impedance sensing stands out due to its flexibility and integration capability in handheld devices. This study proposes a wireless passive impedance method leveraging the inductor-capacitor (LC) sensing technique and PCB (Printed Circuit Board)-based coplanar electrode (PCE) configuration for fluidic sample detection. The proposed system integrates a two-coplanar-electrode layout with a square spiral inductor to assess fluidic conductivity and characterize various fluid types within samples. The effectiveness of this configuration was validated through experiments with NaCl and glucose solutions, confirming the feasibility of integrating PCB-based coplanar electrodes into conventional LC passive wireless sensing designs for fluidic detection and characterization.

Keywords: Fluidic detection; LC passive wireless sensing; Printed circuit board; Glucose biosensors.

1. INTRODUCTION

Amidst ongoing economic development, there is a growing societal focus on healthcare, leading to the advancement of various medical diagnostic technologies. Of particular importance is the evaluation of glucose levels as a key diagnostic indicator. Currently, the predominant glucose biosensors belong to the category of electrochemical sensors, which have evolved into four generations over time. The first three generations are enzyme-based biosensors known for their sensitivity, reproducibility, and cost-effectiveness [1, 2]. However, these biosensors have limitations, including susceptibility to environmental conditions and reliance on enzyme activity, restricting their applicability and reliability. Recently, non-invasive blood glucose monitoring has transformed glucose level measurement by avoiding invasive procedures and tissue harm. This technology includes optical, microwave, and electrochemical techniques, each offering distinct benefits for glucose measurement without tissue penetration. Optical methods, such as near-infrared reflectance spectroscopy, polarized optical rotation, Raman spectroscopy, fluorescence, and optical coherence tomography, utilize light properties to detect glucose concentrations, providing diverse monitoring options with reduced discomfort and complications [3-6]. Various approaches and advancements have been made to enhance glucose detection, particularly in exploring enzyme-free detection methods, resulting in the emergence of the fourth generation of glucose biosensors—nonenzymatic glucose (NEG) sensors [7, 8]. Among the physical techniques for NEG sensor development, the impedance sensing approach stands out due to its flexibility, integration capability in handheld wearable devices, and elimination of bulky optical equipment and operational staff training. Additionally, with the ability to wirelessly connect to the sensing part by utilizing the RF power transmission, this method enables miniaturization for the integration of implantable devices, which holds promise as a solution for patient monitoring and diagnosis in today's healthcare system, especially for point-of-care applications and wearable devices [9-12].

In this study, a wireless passive impedance method for detecting and characterizing the fluidic sample leverages the inductor-capacitor (LC) sensing technique is proposed, designed, fabricated and experimented in conjunction with the PCB (Printed Circuit Board)-based coplanar electrode (PCE) configuration (figure 1). This fusion, known as passive wireless PCE configuration, offers distinct advantages, particularly its compatibility with biochips and chemical analysis structures that are easy fabrication and low-cost. The concept of PCE has resurfaced as a prominent trend in a growing number of research studies reported in recent years [13]. The dimensions and configuration of the electrodes are readily adaptable to enhance efficiency and fulfill the precise demands of the sensor's intended use. In contrast to conventional electrode fabrication techniques like lithography, employing printed circuit board (PCB) technology substantially diminishes manufacturing expenses. Furthermore, the sensor design proposed herein, leveraging PCB circuits, enables label-free detection in biomedical contexts. This obviates the necessity for incorporating specific markers for sensing, as the test substance can be directly deposited onto the sensor's detection region. This streamlines and enhances the detection process [13]. By utilizing this configuration, the antenna for transmitting/receiving RF power, capacitive sensors, and electronics can be swiftly and affordably integrated onto the same PCB platform, thanks to the widespread availability of PCB technologies [14-17]. The proposed passive wireless PCE sensor system integrates a two-coplanar-electrode layout with a square spiral inductor to evaluate fluidic conductivity and characterize various fluid types within samples. By detecting subtle changes in fluid conductivity and other electrical properties, variations in impedance between sensing electrodes impact the resonance frequency of the LC resonator. These frequency shifts are identified using a network analyzer and analyzed using customized software, enabling a comprehensive understanding of fluidic behavior and composition for use in biotechnology, environmental monitoring, and industrial processes. In this study, the fabricated sensing structure underwent examination, and the effectiveness of the proposed configuration was validated through implementation with NaCl and glucose solutions ranging in concentration from 10 mM to 100 mM. This research indirectly confirms the efficacy and feasibility of integrating PCB-based coplanar electrodes into conventional LC passive wireless sensing designs for fluidic detection and characterization.

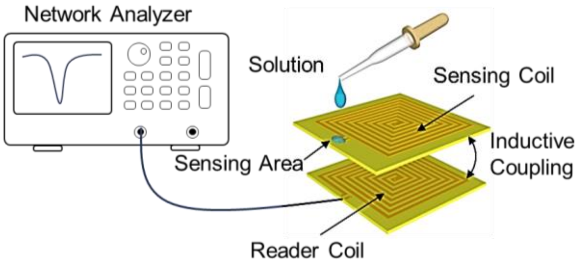


Figure 1. *Conceptualization of LC passive wireless sensor with PCE configuration.*

2. THEORY AND DESIGN

2.1. Theoretical foundations

The suggested configuration integrates capacitively coupled contactless detection with the LC passive sensing approach. LC passive wireless sensing relies on the mutual inductance coupling between two inductors, as depicted in figure 2 (a). The reading inductor L_R, serving as the transmitting antenna, is magnetically linked to the sensing inductor L_S. L_R performs dual roles, compromising to act as the energy transmitter, provide power to L_S, and as the signal receiver, reflecting the resonance frequency of the LC sensing circuit comprising L_S and sensing capacitor C_F. The parasitic resistances of the sensing inductor are identified R_S. The resonance frequency (f_{res}) can theoretically be defined as Eq. 1 while C_F serves as the fluidic sensing capacitance [18]. Variations in the dielectric material between electrodes can cause fluctuations in the capacitance of C_F, leading to changes in the resonance frequency of the LC circuit. These frequency shifts can be easily detected by analyzing the reflection coefficient S_{11} on L_R. The sensing capacitor is formed by capacitively coupling contactless electrode structures, allowing for the utilization of their inherent advantages.

$$f_{res} = \frac{1}{2\pi\sqrt{L_S C_F}} \tag{1}$$

2.2. Experiment preparation

2.2.1. Sample preparation

An LC sensor is built by combining a square spiral inductor with a sensing capacitor, creating a resonance LC tank. Figure 2(b) illustrates the proposed experimental setup of LC passive wireless sensing designed for detecting the fluidic presenting at the capacitive sensing area. The sensing system comprises a capacitor formed by two copper coplanar electrodes encircling the capacitive sensing region, along with two inductors serving as transmitters and receivers of radiation. These inductors are positioned apart from each other in the air, with a defined distance between them. In this study, the primary and secondary inductors were fabricated using the Printed Circuit Board (PCB) etching technique on a single-sided copper FR4 PCB. The parameters of the implemented antennas, which are constructed from coplanar spiral-shaped inductors, are detailed in table 1. In this study, solutions of NaCl and glucose with varying concentrations spanning from 10 mM to 100 mM were employed to evaluate the efficacy of the proposed system and structure. NaCl and glucose were diluted in deionized (DI) water to achieve the desired concentrations for the experiments.

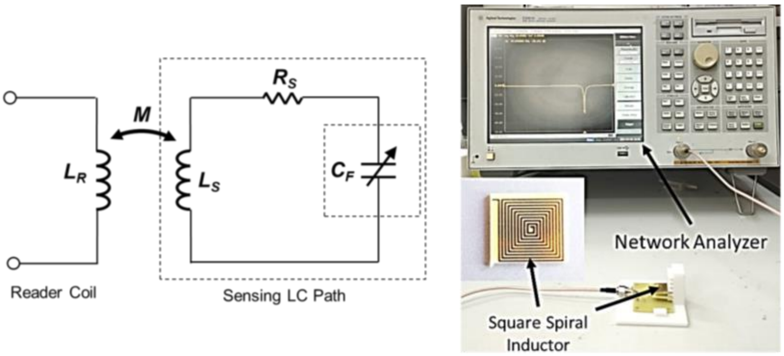
Table 1. *PCE integrated passive wireless sensor parameters.*

Parameter	Value	Unit
Inductor’s outermost length	12.3	mm
Number of turn	10	
Line width	0.3	mm
FR4 substrate’s thickness	1	mm
Electrode gap	0.3	mm
Electrodes length	5	mm

2.2.2. Experimental setup

In the experimental setup, instruments and software are utilized for precise data acquisition and analysis. The Agilent E5061A ENA Series network analyzer measures the reflection coefficient S_{11} within a specific frequency range to determine the passive sensor's resonance frequency. A custom Visual Basic program monitors resonance frequency shifts corresponding to different solution dropped, streamlining data analysis. Additionally, the sensing electrodes are serially connected to the sensor inductor to enhance sensitivity in a series resonance configuration.

To verify the effectiveness of the proposed measurement system, a series of experiments were undertaken to assess the variation in resonance frequency upon the manual deposition of a 10 µL droplet of the target fluidic sample onto the sensing region of the capacitive sensing electrode structure. The experiments further investigated the relationship between the resonance frequency change and the type of fluidic sample deposited, as well as the alterations in the reflection coefficient across different excitation sweeping frequency ranges as the distance between the two inductors was adjusted. The data collected from these experiments were meticulously recorded and subjected to thorough analysis.



(a) (b)

Figure 2. *(a) Simplified equivalent circuit of LC passive wireless sensing structure; (b) Experimental setup.*

3. RESULTS AND DISCUSSIONS

3.1. Reflection coefficient change with different NaCl concentration

Figure 3 demonstrates the reflection coefficient measurements within the frequency range of 150 MHz to 280 MHz corresponding to NaCl solution droplets deposited on the capacitive sensing area, with concentrations ranging from 10 mM to 100 mM. The resonance frequency of the LC sensor is determined from the frequency at which the minimum reflection coefficient value occurs. The impact of NaCl concentration on the resonance frequency is visually depicted by the minimum peaks in figure 3.

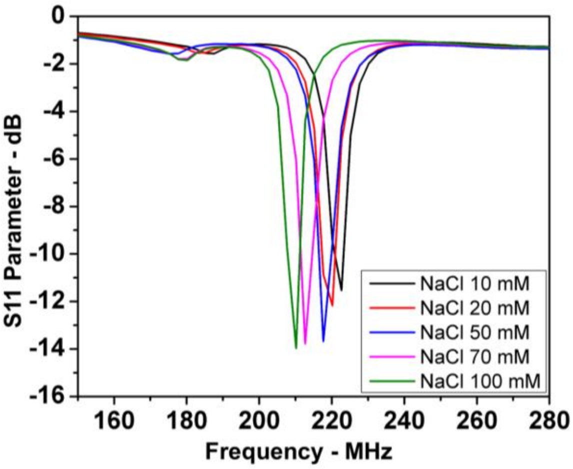


Figure 3. *Dependence of reflection coefficient S_{11} on the concentration of NaCl solution.*

Experimental findings reveal that with a NaCl concentration of 10 mM, the resonance frequency of the sensing LC path is approximately 225 MHz. Subsequently, as the NaCl concentration increases, the resonance frequency progressively shifts towards lower frequencies. For instance, at NaCl concentrations of 20 mM, 50 mM, 70 mM, and 100 mM, the resonance frequencies are observed to be about 221 MHz, 219 MHz, 213 MHz, and 209 MHz, respectively. The resolution of the sweeping frequency range was fixed at 1 MHz, enabling distinct differentiation in resonance frequency among varying concentrations of the solution. Notably, the reflection coefficient at these minimum peaks, i.e., resonance frequency, experiences slight variations with increasing NaCl concentration. These observations suggest that changes in NaCl concentration primarily affect the electrical properties of the fluidic droplet, leading to alterations in the sensing capacitance without significant modifications in the sensing resistance within the sensing LC path. In addition to the direct influence of the fluidic's electrical properties on the resonance frequency, several other factors also contribute to the acquired resonance frequency, such as the distance between the inductors and the geometric angle between them. Throughout this study, these parameters remained constant across all experiments.

3.2. Reflection coefficient change with different glucose concentration

In the parallel investigation into glucose droplet concentrations spanning from 10 mM to 100 mM, following a methodology akin to the NaCl study, intriguing results were unveiled. Figure 4 presents the reflection coefficient measurements across a broad frequency spectrum of 150 MHz to 280 MHz, providing insight into the capacitive sensing area's response to varying glucose concentrations. Similar to the NaCl analysis, the resonance frequency of the LC sensor is identified by locating the frequency at which the minimum reflection coefficient occurs. Notably, a consistent trend was observed wherein elevating glucose concentration correlates with a gradual shift in resonance frequency towards lower values. For instance, at a glucose concentration of 10 mM, the resonance frequency of the sensing LC path registers at approximately 183 MHz. With increasing glucose concentrations, resonance frequencies of 180 MHz, 178 MHz, 175 MHz, and 173 MHz are sequentially recorded for concentrations of 20 mM, 50 mM, 70 mM, and 100 mM, respectively.

Echoing the NaCl study, minor fluctuations in the reflection coefficient at the minimum peaks, indicative of resonance frequency, are noted with changing glucose concentrations. This underscores the resonance frequency's efficacy as a robust analytical parameter for detecting and analyzing glucose concentration in the fluidic sample. These findings not only underscore the system's capability to detect glucose concentration in fluidic samples but also highlight its potential for characterizing the composition of various fluidic compounds by leveraging their distinct electrical properties.

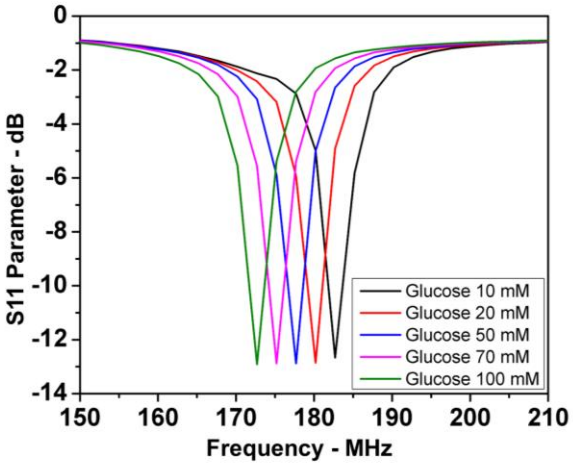


Figure 4. *Dependence of reflection coefficient S_{11} on the concentration of glucose solution.*

3.3. Characterization of Glucose solution and NaCl solution with different concentrations

The proposed passive wireless sensing approach utilizing the PCE configuration showcases exceptional performance in characterizing and distinguishing between various types and concentrations of solutes within fluidic samples. Figure 5 provides a comprehensive overview of the dependence of acquired resonance frequency on the concentration of both glucose and NaCl solutions, ranging from 10 mM to 100 mM. By closely monitoring resonance frequency shifts through experimental observation, this method elucidates intricate details about the electrical properties of solutes, facilitating precise analysis and differentiation between different fluidic substances.

The systematic decrease in resonance frequencies as solute concentrations increase serves as a robust indicator of the system's sensitivity to changes in the fluidic environment. For instance, as the concentration of glucose solution increases from 10 mM to 100 mM, the system's response demonstrates a corresponding decrease in resonance frequency from 225 MHz to 209 MHz. Similarly, for NaCl solutions, the resonance frequency decreases from 183 MHz to 173 MHz over the same concentration range. This consistent trend reaffirms the system's capability to detect alterations in solute concentration with remarkable sensitivity, underscoring its potential for precise quantitative analysis.

Furthermore, the distinct resonance frequency signatures exhibited by NaCl and glucose solutions highlight the system's ability to differentiate between solute types based on their unique electrical characteristics. This capability is invaluable for applications requiring the identification and characterization of specific solutes within complex mixtures. Leveraging the precise responses of the PCE configuration to different solutes, the system offers a reliable means of discriminating between various substances present in fluidic samples, thus enhancing its utility across a broad spectrum of applications in biomedical diagnostics, environmental monitoring, and industrial process control.

Furthermore, the utilization of PCB copper coplanar electrodes enhances the system's performance by providing a stable and reproducible sensing platform. The precise fabrication techniques employed in creating these electrodes ensure uniformity and consistency, resulting in reliable and repeatable measurements. This stability is essential for accurate and reliable analysis, especially in applications where precise quantification and detection of solutes are paramount.

In essence, the proposed passive wireless sensing approach offers a comprehensive solution for analyzing fluidic samples, providing detailed insights into solute properties and concentrations. Its ability to effectively differentiate between solute types and concentrations, coupled with the stability and reliability afforded by PCB copper coplanar electrodes, positions it as a valuable tool in various fields such as biomedical diagnostics, environmental monitoring, and industrial process control.

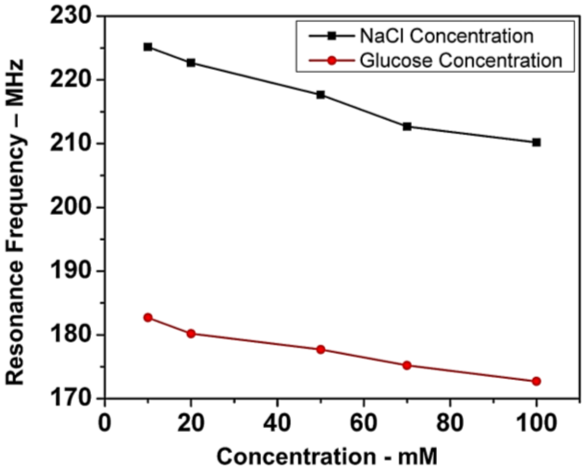


Figure 5. *Dependence of resonance frequency of the LC sensing path on the concentration of NaCl and Glucose solution.*

This study broadens the application scope of LC passive wireless sensing and sets the stage for future miniaturization and integration of the proposed passive wireless PCE sensors. Moving forward, the integration of advanced electrode materials such as copper oxide, copper sulfide, and various metal oxides into PCB-based glucose sensors can significantly enhance their performance [19, 20]. These materials, chosen for their superior electrochemical properties and cost-effectiveness, improve not only the detection capabilities but also the immediacy of non-enzymatic glucose sensors, offering a more stable and economical alternative to traditional enzymatic sensors. This advancement highlights the potential for further innovation in sensor technology, particularly in medical and environmental applications.

4. CONCLUSIONS

Along with global economic growth, healthcare and medical diagnostics, especially in assessing glucose levels, have gained increased attention. Glucose biosensors, predominantly electrochemical, have evolved over four generations, initially enzyme-based and later focusing on nonenzymatic methods like impedance sensing. This study introduces a wireless passive impedance method using LC sensing and a PCB-based coplanar electrode (PCE) configuration for fluidic sample detection and characterization. The innovative approach combines a two-coplanar-electrode layout with a square spiral inductor to comprehensively evaluate fluidic conductivity and identify various fluid types within samples. The proposed sensing structure was designed, fabricated, and experimentally examined using NaCl and glucose solutions ranging from 10 mM to 100 mM. This research broadens the application scope of LC passive wireless sensing and sets the stage for the future miniaturization and integration of the proposed passive wireless PCE sensors.

Acknowledgement: *This work was funded by the Vietnam Ministry of Science and Technology under Grant ĐTĐL.CN-40/23.*

REFERENCES

[1]. Weibel M K and H J Bright, *"The glucose oxidase mechanism. Interpretation of the pH dependence"* The Journal of biological chemistry, vol. 246, no. 9, pp. 2734–44, (1971), [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/4324339

[2]. Yoo Eun-Hyung and Soo-Youn Lee, *"Glucose Biosensors: An Overview of Use in Clinical Practice,"* Sensors, vol. 10, no. 5, pp. 4558–4576, (2010), doi: 10.3390/s100504558.

[3]. Balas Costas, *"Review of biomedical optical imaging—a powerful, non-invasive, non-ionizing technology for improving in vivo diagnosis,"* Measurement Science and Technology, vol. 20, no. 10, p. 104020, (2009), doi: 10.1088/0957-0233/20/10/104020.

[4]. Walther Julia, Maria Gaertner, Peter Cimalla, Anke Burkhardt, Lars Kirsten, Sven Meissner, and Edmund Koch, *"Optical coherence tomography in biomedical research,"* Analytical and Bioanalytical Chemistry, vol. 400, no. 9, pp. 2721–2743, (2011), doi: 10.1007/s00216-011-5052-x.

[5]. Boppart Stephen A., Amy L. Oldenburg, Chenyang Xu, and Daniel L. Marks, *"Optical probes and techniques for molecular contrast enhancement in coherence imaging,"* Journal of Biomedical Optics, vol. 10, no. 4, p. 041208, (2005), doi: 10.1117/1.2008974.

[6]. Kollias Nikiforos and Georgios N. Stamatas, *"Optical Non-Invasive Approaches to Diagnosis of Skin Diseases,"* Journal of Investigative Dermatology Symposium Proceedings, vol. 7, no. 1, pp. 64–75, (2002), doi: 10.1046/j.1523-1747.2002.19635.x.

[7]. Naikoo Gowhar A., Hiba Salim, Israr U. Hassan, Tasbiha Awan, Fareeha Arshad, Mona Z. Pedram, Waqar Ahmed, and Ahsanulhaq Qurashi, *"Recent Advances in Non-Enzymatic Glucose Sensors Based on Metal and Metal Oxide Nanostructures for Diabetes Management- A Review,"* Frontiers in Chemistry, vol. 9, (2021), doi: 10.3389/fchem.2021.748957.

[8]. Li Hong, Haibo Xu, Shiru Lin, and Yi Jia, *"A Wireless Resonant LC Sensor for Glucose Detection,"* in The 9th International Electronic Conference on Sensors and Applications, (2022), p. 29. doi: 10.3390/ecsa-9-13365.

[9]. Jang Chorom, Hee-Jo Lee, and Jong-Gwan Yook, *"Radio-Frequency Biosensors for Real-Time and Continuous Glucose Detection,"* Sensors, vol. 21, no. 5, p. 1843, (2021), doi: 10.3390/s21051843.

[10]. Li Yang, Zhao Yao, Wenjing Yue, Chunwei Zhang, Song Gao, and Cong Wang, *"Reusable, Non-Invasive, and Ultrafast Radio Frequency Biosensor Based on Optimized Integrated Passive Device Fabrication Process for Quantitative Detection of Glucose Levels,"* Sensors, vol. 20, no. 6, p. 1565, (2020), doi: 10.3390/s20061565.

[11]. Zafar Hima, Asma Channa, Varun Jeoti, and Goran M. Stojanović, *"Comprehensive Review on Wearable Sweat-Glucose Sensors for Continuous Glucose Monitoring,"* Sensors, vol. 22, no. 2, p. 638, (2022), doi: 10.3390/s22020638.

[12]. Dautta Manik, Muhannad Alshetaiwi, Jens Escobar, and Peter Tseng, *"Passive and wireless, implantable glucose sensing with phenylboronic acid hydrogel-interlayer RF resonators,"* Biosensors and Bioelectronics, vol. 151, p. 112004, (2020), doi: 10.1016/j.bios.2020.112004.

[13]. Moschou Despina and Angeliki Tserepi, *"The lab-on-PCB approach: tackling the μTAS commercial upscaling bottleneck,"* Lab on a Chip, vol. 17, no. 8, pp. 1388–1405, (2017), doi: 10.1039/c7lc00121e.

[14]. Kontakis Konstatinos, Anastasios Petropoulos, Grigoris Kaltsas, Thanassis Speliotis, and Evangelos Gogolides, *"A novel microfluidic integration technology for PCB-based devices: Application to microflow sensing,"* Microelectronic Engineering, vol. 86, no. 4–6, pp. 1382–1384, (2009), doi: 10.1016/j.mee.2009.01.088.

[15]. Liu Robin Hui, Piotr Grodzinski, Jianing Yang, and Ralf Lenigk, *"Self-Contained, Fully Integrated Biochips for Sample Preparation, PCR Amplification and DNA Microarray Analysis,"* Integrated Biochips for DNA Analysis, vol. 76, no. 7, pp. 46–67, (2008), doi: 10.1007/978-0-387-76759-8_4.

[16]. Sánchez J. L.Acero, O. Y.F. Henry, H. Joda, B. Werne Solnestam, L. Kvastad, E. Johansson, P. Akan, J. Lundeberg, N. Lladach, D. Ramakrishnan, I. Riley, and C. K. O'Sullivan, *"Multiplex PCB-based electrochemical detection of cancer biomarkers using MLPA-barcode approach,"* Biosensors and Bioelectronics, vol. 82, pp. 224–232, (2016), doi: 10.1016/j.bios.2016.04.018.

[17]. M. Lewis A, L. L. Wu, S. Babikian, M. Bachman, J. G Santiago, *"SI: An Integrated Printed Circuit Board Device for Cell Lysis and Nucleic Acid Extraction S-1 S-4 Temperature-induced pressure S-2 S-3 Experimental Rayleigh num-,"* Analytical Chemistry, pp. 1–7, (2012).

[18]. Do Quang Loc, Tung Thanh Bui, Anh Bao Hoang, Pham Van Thanh, Chun Ping Jen, and Trinh Chu Duc, *"Development of a Passive Capacitively Coupled Contactless Conductivity Detection (PC4D) Sensor System for Fluidic Channel Analysis Toward Point-of-Care Applications,"* IEEE Sensors Journal, vol. 19, no. 15, pp. 6371–6380, (2019), doi: 10.1109/JSEN.2019.2908179.

[19]. Miao Fengjuan, Hao Wu, Bairui Tao, and Yu Zang, *"A passive-chipless LC carbon dioxide sensor with non-contact ZnO/CuO/RGO nanocomposites at room temperature,"* Vacuum, vol. 215, p. 112261, (2023), doi: 10.1016/j.vacuum.2023.112261.

[20]. He Denghui, Yuanhui Cui, Fangchao Ming, and Weiping Wu, *"Advancements in Passive Wireless Sensors, Materials, Devices, and Applications,"* Sensors, vol. 23, no. 19, p. 8200, (2023), doi: 10.3390/s23198200.

TÓM TẮT

Nghiên cứu phát triển cảm biến không dây thụ động nhằm phát hiện và phân tích chất lỏng sử dụng cấu trúc điện cực đồng phẳng PCB

Trong quá trình phát triển kinh tế toàn cầu hiện nay, lĩnh vực chăm sóc sức khỏe là một trong những lĩnh vực đang nhận được nhiều sự quan tâm của xã hội, đặc biệt là cùng với những tiến bộ của các công nghệ chẩn đoán y tế hiện nay. Các cảm biến glucose, chủ yếu là cảm biến điện hóa, đã phát triển qua bốn thế hệ, ba thế hệ đầu tiên dựa trên enzym với ưu điểm là độ nhạy và hiệu quả chi phí, mặc dù có nhược điểm do sự phụ thuộc vào hoạt động enzym và sự dễ bị ảnh hưởng của môi trường. Các tiến bộ gần đây cho phép theo dõi *glucose trong máu không xâm lấn, sử dụng các kỹ thuật quang học, sóng vô tuyến và điện hóa, cung cấp những lợi ích đa dạng mà không cần xâm nhập vào mô. Trong số đó, kỹ thuật cảm biến trở kháng là một phương án tiếp cận nổi bật với tính linh hoạt cao và khả năng tích hợp vào các thiết bị cầm tay. Nghiên cứu này đề xuất một phương pháp cảm biến trở kháng không dây thụ động sử dụng kỹ thuật cảm biến cuộn cảm – tụ điện (LC) và cấu hình điện cực đồng phẳng trên bảng mạch in (PCE) để phát hiện mẫu dung dịch. Hệ thống đề xuất tích hợp một cấu trúc hai điện cực đồng phẳng với một cuộn cảm có cấu trúc xoắn ốc dạng vuông để đánh giá tính chất điện của chất lỏng và phân loại các loại chất lỏng khác nhau trong mẫu. Hiệu quả của cấu trúc đề xuất này này đã được đánh giá thực nghiệm thông qua các thí nghiệm với dung dịch NaCl và glucose, xác nhận khả năng tích hợp các điện cực coplanar trên PCB vào các cấu trúc cảm biến không dây LC thông thường cho việc phát hiện và phân tích dung dịch.*

Từ khoá: Phát hiện dung dịch; Cảm biến không dây thụ động LC; Bảng mạch in; Cảm biến glucose.