Hydrogel Based Implant Resonator for Wireless pH Sensing

Ipek Hilal Kacar[(1)], Burak Ferhat Ozcan[(1)], Zeliha Cansu Canbek Ozdil[(2)], and Sema Dumanli[(1)]

[(1)] Bogazici University, Istanbul, Turkey, sema.dumanli@bogazici.edu.tr
[(2)] Yeditepe University, Istanbul, Turkey, cansu.canbek@yeditepe.edu.tr

Abstract—This study introduces a pH-sensitive hydrogel-based implant resonator for real time, in-body sensing. The hydrogel's pH dependent dielectric and conductive properties enable its use as a passive microwave resonator, wirelessly interrogated via a wideband on-body reader antenna. The system, designed for chipless RFID-based communication, eliminates the need for active power sources in-body. It demonstrates high sensitivity to physiological pH changes, particularly relevant for postoperative infection detection, where wound pH shifts from 4.5–6 to 6.5–8 for healthy and infected respectively. Experimental results confirm that the dielectric properties of the hydrogel change with pH consistently with no hysteresis behavior, underscoring its potential for next-generation biomedical sensors in continuous health monitoring. It has been shown that the pH of the immediate surrounding of the hydrogel based sensor can be tracked with minimum of 5 MHz shifts for every 2-units of pH change.

I. INTRODUCTION

The rapidly advancing field of body-centric sensing systems is reshaping the landscape of healthcare and biomonitoring by enabling precise, real-time insights into human health. Among these innovations, in-body sensing technologies stand out as transformative solutions for monitoring physiological parameters, addressing critical challenges such as miniaturization [1], biocompatibility [2], and power efficiency [3]. These technologies integrated with chipless RFID systems and wireless communication methods can eliminate the need for bulky batteries or active power sources [4].

They also simplify sensor deployment within the body, reduce risks associated with invasive procedures [5], and enable real-time monitoring of surgical site infections (SSIs), where pH levels serve as critical indicators of wound health. While a healthy wound typically exhibits a pH range of 4.5 to 6 [6], infections increase the pH to 6.5–8.5 [7], signalling bacterial activity and inflammation. This pH shift provides a reliable metric for timely intervention, revolutionizing infection management and improving patient outcomes.

Traditional glass electrode pH sensors are accurate but fragile and require frequent calibration, limiting their use in dynamic biological environments. To overcome these limitations, alternative approaches such as optical, electrochemical, and transistor-based sensors have been developed, offering enhanced sensitivity, durability, and adaptability [8], [9].

Recent studies show that fiber optic pH sensors provide high sensitivity and minimal temperature interference, making them ideal for biomedical applications [10], while all solid state potentiometric sensors enable robust and miniaturized in situ monitoring [11]. Hydrogel-based sensors, with their tunable properties, have also shown promise for pH-responsive applications like drug delivery [12]. Although these advances highlight the potential of wireless pH detection, real-time wireless infection monitoring is currently absent in the literature, making our project novel in this field.

In this work, a novel approach utilizing hydrogels as pH-sensitive resonators for passive wireless in-body sensing is proposed. Functionalized polymer materials, such as hydrogels with high water content and tunable structural and physicochemical properties, have great potential to be used as next-generation implantable bioelectronics, adaptability to physiological conditions, and the ability to dissolve after their functional lifespan, eliminating the need for secondary surgeries and expanding their potential for diverse biomedical applications [13].

The physical permittivity, and conductivity of the hydrogel vary with pH [14], making it suitable for hosting an embedded resonator. The embedded resonator interacts with the hydrogel, where pH-induced changes in the hydrogel's dielectric properties cause shifts in the resonator's resonance frequency. An on-body wideband reader antenna detects these frequency shifts in real time, enabling continuous health monitoring. This passive, battery-free system offers a compact and sustainable platform for in-vivo pH sensing, providing transformative potential for real-time diagnostics and advanced healthcare management.

The paper first introduces the synthesis and the electrical properties of the pH sensitive hydrogel in Section II. Section III details the design of the hydrogel based implant resonator and the mock setup simulations to evaluate system performance under realistic conditions. Finally, the conclusions and future prospects are discussed in Section IV.

II. FABRICATION AND PROPERTIES OF HYDROGEL

A. pH Sensitive P(AAm-co-AAc-co-PEGDA) Hydrogel

The pH-sensitive Acrylamide/ Acrylic Acid/ Polyethyleneglycol diacrylate (P(AAm-co-AAc-co-PEGDA)) hydrogel is synthesized via copolymerization of acrylamide and acrylic acid with PEGDA using free radical copolymerization. In a typical hydrogel synthesis, 0.8 g of AAm and 0.2 g of AAc are dissolved in 9 mL of DI water followed by the addition of 0.19 g PEGDA as the crosslinking agent. As the homogenous solution is obtained, 50 uL of N,N,N,N',N'-tetramethylethylenediamine (TEMED) is added and the mixture is cooled to +4 °C in an ice–water bath under an inert atmosphere for 30 minutes. The polymerization reaction is initiated with the addition of 0.016 g ammonium persulfate

(APS) and the reaction is conducted at 25 °C. The pH-sensitive nature of the hydrogel is governed by the ionization of AAc groups within the polymer network. The hydrogel's pKa value is carefully formulated to align with the pH range of infection zones (pH 6.5-8.0) [15]. In this pH range, the carboxylic acid groups (-COOH) begin to deprotonate into carboxylate ions (-COO$^-$), initiating electrostatic repulsion within the polymer matrix. This repulsion causes the hydrogel to swell as it absorbs water to stabilize the increased charge density causing a drastic volume increase. In contrast, under neutral or slightly basic conditions, the hydrogel remains in a less swollen state due to reduced ionization and weaker electrostatic interactions. As the hydrogel swells the increase of water content causes an increase in the overall permittivity of the material [16].

B. Electrical Properties of the Hydrogel Across Varying pH Levels

The hydrogel sample, with dimensions of 27 mm in diameter and 15 mm in height, was synthesized for electrical characterization across varying pH levels. It was sequentially immersed in solutions with pH values of 4, 6 and 8 for 2 days each, allowing sufficient time for the hydrogel to reach equilibrium with the medium. The pH solutions used for hydrogel measurements were prepared using hydrochloric acid (HCl) for acidic mediums and sodium hydroxide (NaOH) for basic mediums. After 2 days of immersion in each solution, the hydrogel's relative permittivity and conductivity were measured over the frequency range of 1 GHz to 4 GHz using Speag's DAK 3.5 dielectric measurement kit. Before each measurement, the surface water on the hydrogel was blotted. Measurements were taken at three different points on the sample, and the average values along with the standard deviations of relative permittivity and conductivity are shown in Fig. 1 (a) and (b), respectively. As the pH of the medium increases, the hydrogel sample swells, increasing its water content. Consequently, the permittivity of the sample also increases, as shown in Fig. 1 (a).

III. HYDROGEL BASED IMPLANT RESONATOR

A. Implant Resonator Design

The implant design, based on a nested split-ring resonator (NSRR), is presented in Fig. 2. The NSRR is a modified version of the split-ring resonator (SRR), incorporating additional capacitive fingers to miniaturize the resonator structure. Polyamide serves as the base substrate, while gold is used as the conductive material of the resonator. The NSRR is encapsulated in 5.3 × 5.3 × 2 mm^3 pH-sensitive hydrogel. As the pH level of the medium increases, the hydrogel's relative permittivity also increases, resulting in a resonant frequency shift of the NSRR. This enables a chipless RFID-based wireless pH monitoring through an on-body antenna.

The resonant frequency of the NSRR can be calculated analytically using the equivalent circuit model as described in [17]. The NSRR can be modeled as an LC resonator, as illustrated in Fig. 3. Inductance L_s consists of two components: the self-inductance of each strip and the average mutual
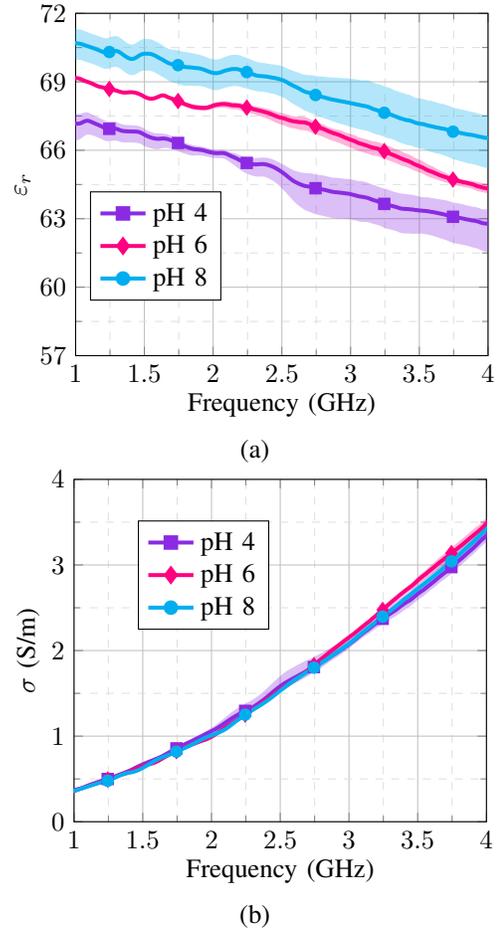

(a)

(b)

Fig. 1: (a) Relative permittivity and (b) conductivity of the hydrogel at varying pH levels.

inductance between a strip and all other strips. Capacitance is also divided into two forms: 1) Gap capacitance C_{gap} between a strip and its opposing strip. 2) Capacitance C_s between two parallel strips. The overall capacitance increases proportionally with the number of fingers in the NSRR, resulting in a decrease in the resonance frequency ($f_{\text{res}} = 1/\sqrt{L_{\text{eff}}C_{\text{eff}}}$), where L_{eff} and C_{eff} are the effective inductance and capacitance of the NSRR, respectively.

However, the equation should be modified considering the high effective permittivity of the mediums in which the NSRR is merged. Here, an empirical approach is taken where the implant is located inside a rectangular waveguide, as shown in Fig. 4. The implant is sandwiched between a muscle phantom and a variable pH medium. The resonant frequency of the NSRR is then observed through the transmission coefficient between the two wave ports. During this analysis, the conductivity values of all materials inside the waveguide are set to zero since loss is not of concern.

To validate the pH-sensing capability of the implant, the measured relative permittivity data presented in Fig. 1 were fed into the waveguide simulations. The resonant frequency shift resulting from the pH changes can be clearly seen
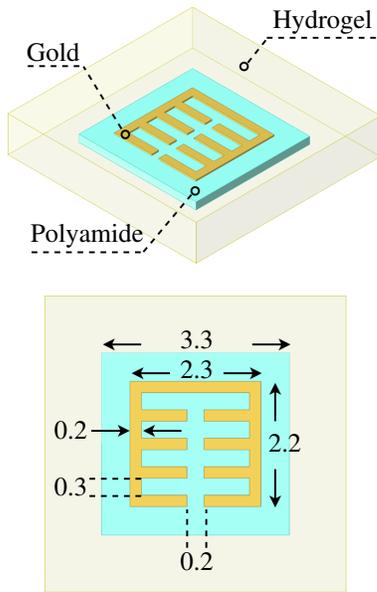
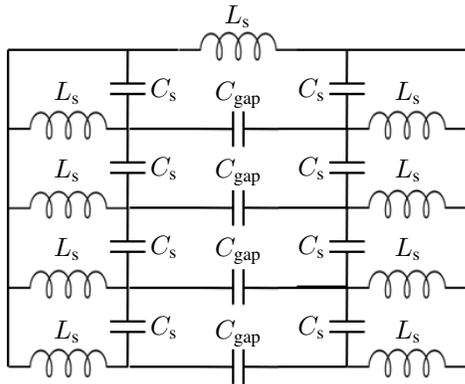Fig. 2: The geometry of the hydrogel implant (in mm).

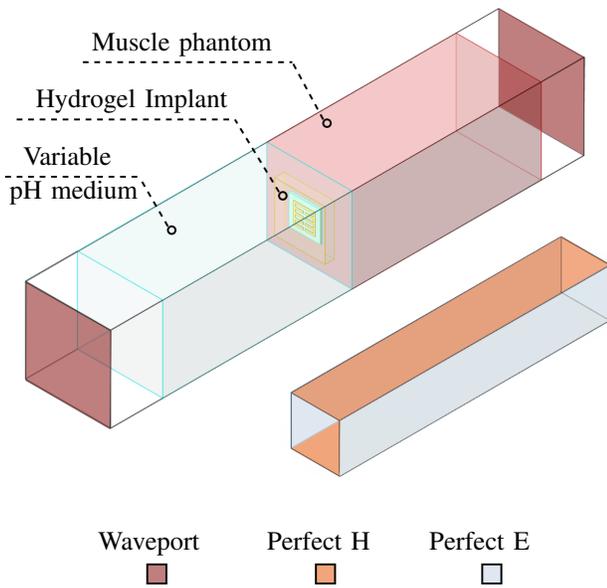Fig. 3: The equivalent circuit model of the NSRR [17].

Fig. 4: The waveguide simulation setup.

in the transmission coefficients between the two waveports of the waveguide, as presented in Fig. 5. Each pH change corresponds to a resonant frequency shift of at least 20 MHz.
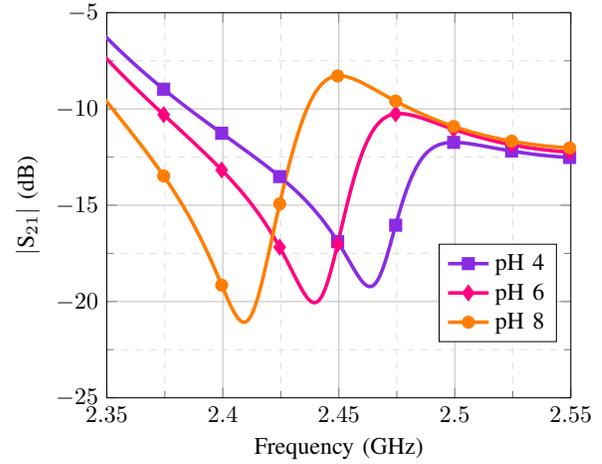

Fig. 5: The transmission coefficient of the waveguide for pH levels.

The proposed hydrogel implant is tested in an experimental setup designed to mimic in-body conditions. The setup includes a muscle phantom measuring $16 \times 16 \times 8$ cm^3. Within this phantom, a variable pH medium measuring $2 \times 2 \times 4$ cm^3 is positioned, with the hydrogel implant placed at the base of the variable pH medium. A dual port on-body antenna, responsible for tracking the resonant frequency of the implant, is located at the bottom of the muscle phantom. The overall simulation set-up is illustrated in Fig. 6. The electrical properties of the muscle phantom were obtained from the IT'IS Foundation [18], while the electrical properties of the variable pH medium were measured using the SPEAG DAK 3.5. The conductivity and permittivity of the variable pH medium are set to 1.5 and 77 respectively for all pH levels.
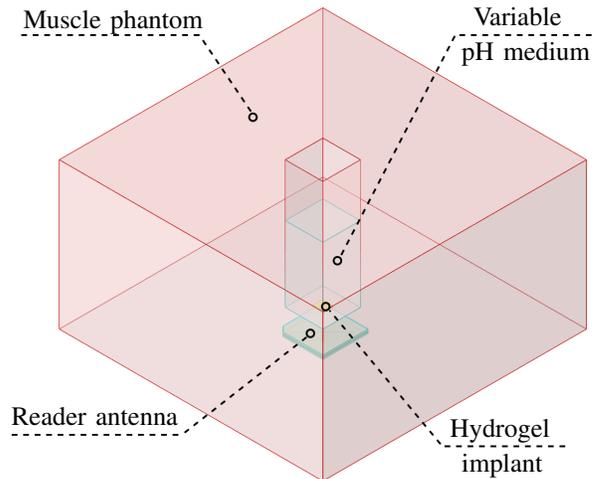

Fig. 6: The simulation model representing wireless pH sensing with an on-body antenna.

The transmission coefficient between the antenna ports is utilized to detect changes in the implant's resonance. To accurately track shifts in the resonant frequency within a lossy medium, such as human tissue, it is essential to minimize direct coupling between the two antenna ports. Furthermore, the on-body antenna must be broadband and operate reliably within the desired frequency range across various types of tissue with varying permittivity. So tracking is possible when the implant is located in various places inside the human body or to mitigate the variations between tissue variations over time or over different subjects. To meet these requirements, a wide-band dual-port cross-slot antenna which was previously designed [19] is used as the on-body antenna. The simulation results for the distance between implant and the on-body antenna is set to 1 cm are given in Fig. 7.
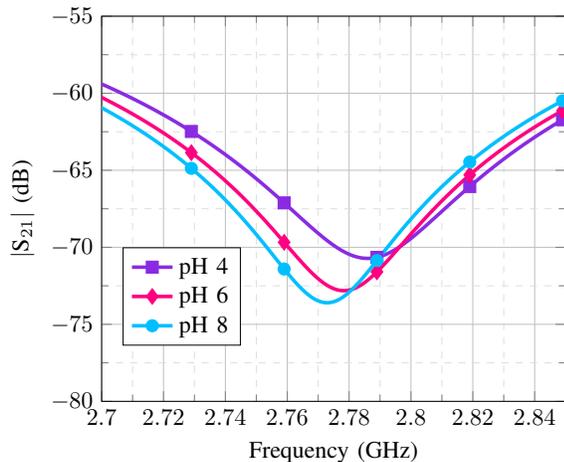

Fig. 7: Magnitude of the transmission coefficient between the two ports of the on-body antenna as the pH level changes.

CONCLUSION

In this study, we present a biocompatible, pH-sensitive hydrogel-based implant resonator for real-time, in-body sensing, utilizing the hydrogel's pH-dependent dielectric properties to induce resonant frequency shifts. The implant includes a nested split-ring resonator (NSRR) on a polyamide substrate with gold conductors, encapsulated in hydrogel. The system was tested in a muscle phantom with a variable pH medium and tracked using a dual-port on-body antenna positioned at the phantom's base. The EM simulations showed pH variations caused resonant frequency shifts of minimum 5 MHz, enabling detection of critical pH ranges for infection monitoring. Operating passively in the 2.4–2.5 GHz ISM band, this compact system offers reliable, continuous health monitoring for advanced biomedical applications.

Future work will focus on enhancing the accuracy of the system by developing a more sensitive design capable of detecting smaller pH variations. The proposed setup will be fabricated and tested under real-life conditions to validate its performance through experimental measurements. These improvements aim to optimize the system for practical biomedical use in dynamic physiological environments.

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