Bandage compatible chipless RFID pH sensor for chronic wound monitoring using chitosan in the ISM frequency band

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ABSTRACT

We propose a chipless RFID pH sensor which can be easily integrated into a bandage for wound monitoring. The sensor can detect the pH level from 4 to 7 of the wounded area through frequency shift owing to the pH sensitive dielectric parameter of chitosan hydrogel, embedded into the substrate of the sensor. The substrate is composed of fabric material which makes it a strong candidate for non-invasive wound monitoring application. The frequency shift can be wirelessly detected by RFID reader to get the status of the wounded area.

Keywords: Chipless RFID tag, pH sensor, Wearable sensor, Remote monitoring.

1. INTRODUCTION

There is a growing need for affordable, intelligent wound monitoring solutions. Generally, there are two types of wounds. (chronic & acute). By examining variables like pH, temperature, infections, and moisture, the damaged region may be followed to monitor the healing process. The pH range changes toward alkali (above 6.5) for chronic wounds [1] and a healthy new tissue has a pH between 4 and 6 [2]. In order to monitor the progress of wound healing, pH might be a useful and accurate indication. In recent years, more research has been conducted in this area to create technologies like smart bandages [1-4]. Many of the solutions now in existence rely on electrochemical sensors with integrated chips. Here the levels of different indicators in the wound are sensed electrochemically and the data is delivered via an integrated electronic system. These kinds of systems typically require batteries for power [2, 3]. Despite being small, these technologies are expensive and complicated to be simply integrated into a bandage. A chipless RFID sensor tag is a potential solution to this challenge. Reports were made on wireless pH sensors based on integrated chip [5], electrode system [6], inductive coupling [7], and color-change RFID tag [8]. However, these designs are not appropriate for a wearable platform or wound monitoring. Hence a smart pH sensitive material that changes its dielectric property with respect to different pH levels can address the need for a simple and compact chipless RFID pH sensor. Different polymer materials were explored for their pH sensitivity [9]. Recently, a pH sensitive coating was reported called Polyvinyl alcohol (PVA)-S100 [10]. It was reported that a pH sensitive RFID tag coated with PVA-S100 that dissolves after a threshold pH level triggers a frequency shift. However, this material doesn’t show the sensitivity for different pH levels rather than a threshold pH level. On the other hand, chitosan turned out to be a pH sensitive material which also has a sensitive pH range (4-7) applicable to the wound monitoring system [11-13]. On the on the hand, using small and compact chipless RFID tag for wound monitoring is challenging since its RCS signal is typically very weak compared to the RCS signal from the human body. De-polarizing or cross-polarizing tag structures are used to overcome this issue [14, 15].These structures can generate an extra RCS signal which is polarized in the perpendicular direction with respect to the incident signal and this allows it to be detected by a RFID reader polarized in the same direction. In our previous study we designed a cross polarized chipless RFID tag for wound monitoring using pH sensing where chitosan was used as the sensing material [16]. However, the substrate used in that design was FR4 which is hard and not compatible with regular bandage. In this paper we proposed a new bandage compatible pH sensitive RFID tag working in the pH range from 4 to 7 where we used a fabric like substrate. We also report the characterization method for the dielectric property of the chitosan hydrogel under different pH conditions.

2. CHIPLESS RFID TAG DESIGN

2.1 Cross polarized tag structure

Designing a chipless RFID tag small in size and generating a large RCS signal is not trivial. In addition to the smaller RCS signal created by the tag the RCS from the surrounding large objects suppress the RCS signal of the RFID tag. This becomes an even bigger challenge when the RFID tag is placed on a human body. To compensate for this issue depolarizing

Smart Biomedical and Physiological Sensor Technology XX, edited by Brian M. Cullum,
Douglas Kiehl, Eric S. McLamore, Proc. of SPIE Vol. 12548, 125480B

or cross-polarization technique is used. This way the RFID structure can generate an RCS signal which is polarized in the perpendicular direction with respect to the polarization of the impinged E-field. Taking this effect into account we designed an Asymmetric Circular Split Ring Resonator (ACiSRR) [12] structure for the RFID tag. The ACiSRR consists of a solid conductive surface with a non-conductive circular split-ring portion etched from out of the material. The split in the ring, which bridges the outer conductive portion to the inner portion, is rotated 45° counterclockwise from the horizontal position. The split ring is rotated to 45° so that it can generate a cross polarized RCS as well. The circular ring structure contributed to the smaller size of the RFID Tag. A detailed analysis of this structure was done is [16]. Initially the structure was built on a FR4 (dielectric constant = 4.4) substrate. For the top and the ground material copper was used. A top and cross section view of the tag is shown in Fig. 1 (a) and (d), respectively.

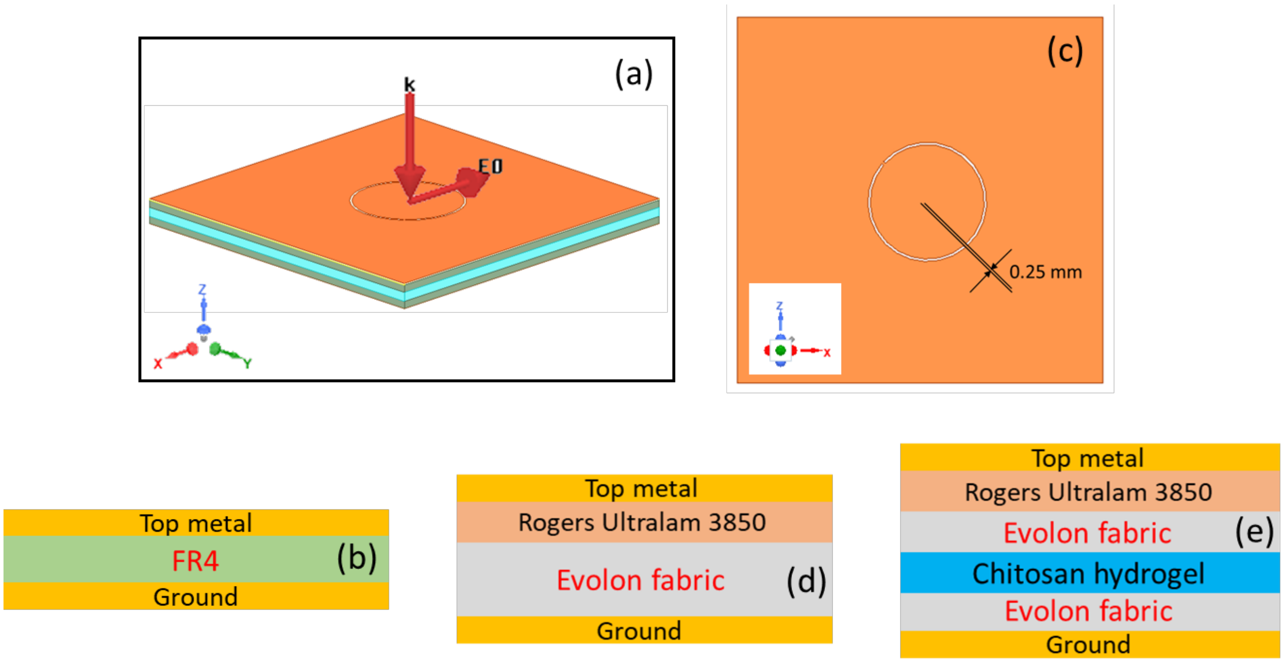

Figure 1. (a) View of the simulation set-up. (b) Cross section view of the FR4 based tag. (c) Top view of the FR4 and Evolon fabric-based tag. Cross section view of the Evolon fabric-based tag: (d) excluding chitosan layer (f) including chitosan layer.

2.2 Bandage compatible RFID tag

The whole RFID tag structure was simulated using Ansys HFSS 2021 R1 where the structure was excited with a plane wave with x-polarized E-field as shown in Fig. 1 (a). The initial model was designed with a thick and rigid FR4 substrate (shown in Fig. 1 (b)) which is difficult to integrate into bandage. In the new design we used a fabric type material known as Evolon (dielectric constant = 1.7) [17] instead of FR4. The new tag is consisted of etched copper on Rogers Ultralam 3850 (dielectric constant = 2.9) adhered with a heat pressed thermoplastic polyurethane (TPU) [17] film to the Evolon fabric carrier substrate. The top layer of Evolon has the same ACiSRR structure previously introduced in the initial model. A top and cross-sectional view of the new RFID tag are shown in Fig. 1 (c) and (d). TPU was used to attach the Rogers Ultralam 3850 layer and the bottom conducting layer to the to the middle layer of Evolon fabric. Evolon is soft, flexible, and thin allowing it to be easily integrated with any kind of usual bandage. Moreover, the substrate (Rogers Ultralam 3850) used in the top copper layer is thin enough to construct a layer with sufficient flexibility for use on a human body. For the final design the chitosan hydrogel is sandwiched between two Evolon layers as shown in the cross-section view in Fig. 1 (e). While the ground layer is modeled using copper tape, it may also be realized by using a conductive thread, which may add more flexibility to the structure. As the substrates of the new design are changed so is the effective dielectric property of the combined substrate. To tune the new tag to the industrial, scientific, and medical (ISM) frequency band the dimensions of the structure were also altered. The new tag has the parameters listed in Table 1.

Table 1. Dimensions of different parameters of the proposed tag.

Parameters	Dimension (mm)
Edge length of the patch	44
Slot width	0.25
Split width	0.25
Thickness of substrate (Evolon)	1.6
Thickness of Rogers Ultralam 3850	0.18
Thickness of metal	0.035
Ring radius (outer)	6.15

3. SENSING MATERIAL SYNTHESIZE AND MICROWAVE CHARACTERIZATION

3.1 Material preparation

The Chitosan hydrogel was synthesized using four ingredients (DI water, acetic acid, chitosan, and polyethylene glycol 3350 (PEG)). The varying concentrations and ratios between the Chitosan and PEG will result in different hydrogel characteristics. Using a 1:1 ratio between chitosan and PEG allows for a hydrogel that has enough structure and malleability to be used as a testable hydrogel. Also, it was reported that this ratio has the highest swelling ratio under different pH solutions [11]. The primary solution is prepared by 1M acetic acid which is then heated up to 70° C and maintained around this temperature using a hot plate. As the primary solution began to warm up chitosan and PEG were added into the solution. Initially the chitosan powder appeared to be clumped together, but the solution was stirred well until all the chitosan and PEG were thoroughly mixed and became a clear solution. Moreover, the solution was continuously stirred to increase the reaction process using a magnetic stirrer. The mixture was heated until the solution turned into a gel like formation. The solution was taken off the hot plate before completely drying up the mixture so that the gel can be shaped into preferred structure suitable for the RFID device. While the hot newly formed hydrogel is highly malleable, we poured it into a molding/casting tray for the hydrogel to take form. Once set into the molding tray the hydrogel was left to cool down and was dried under the fume hood till it turned into a gel-rubbery form. Different stages of the chitosan hydrogel preparing process are shown in Fig. 2 (a)-(d).

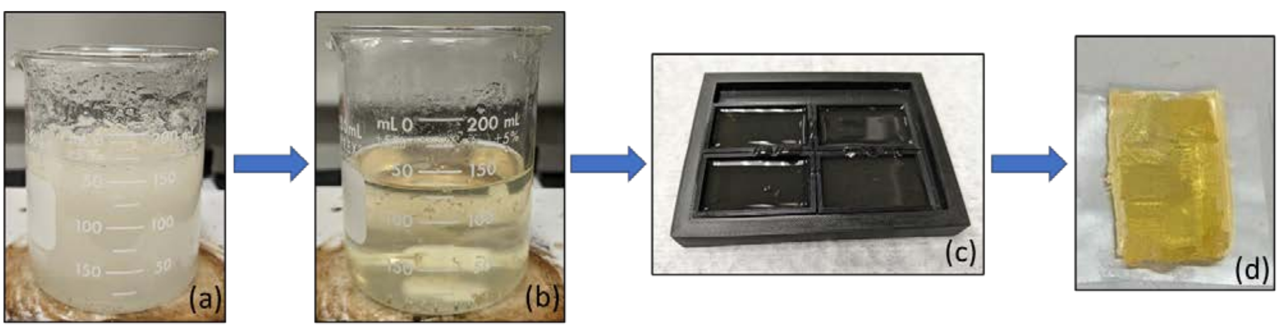

Figure 2. Different stages of chitosan hydrogel synthetizations: (a) primary solution mixed with chitosan and PEG (cloudy) (b) thoroughly mixed solution with chitosan and PEG (clear view) (c) gel formation in preferred shape (b) after cooling down and dried under fume hood.

3.2 Microwave characterization

Though solid chitosan tends to swell and de-swell under acidic and alkaline medium, respectively, its dielectric property change is similar in both mediums. However, the dielectric property of the smart sensing material under different pH levels is needed for the chipless RFID pH sensor tag. We prepared a measurement setup to characterize the dielectric property of the hydrogel in the target frequency (2.45 GHz) for different pH conditions. A simple patch antenna was designed at 2.45 GHz frequency. A rectangular slab of chitosan hydrogel was used as a superstate for the patch antenna. Vector network analyzer ENA E5071C was used to record the S11 parameter of the patch antenna. The measurement setup is shown in Fig. 3.

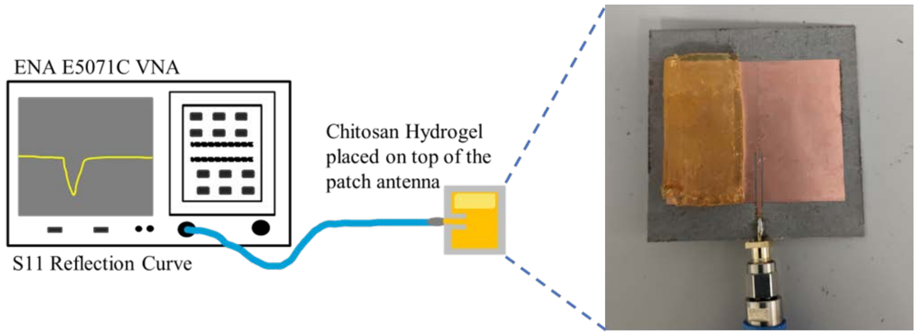

Figure 3. Measurement setup to characterize the chitosan hydrogel using patch antenna.

After putting the chitosan hydrogel on top of the antenna the shift of the resonance in the S11 parameter was captured to get the baseline for the initial condition. Drops of different levels of pH solutions from 4 to 7 were put on the hydrogel, sequentially. The hydrogel slab absorbed the drops of pH solution and showed different resonances in the S11 parameter for different pH levels which indicates the change in its dielectric property. We also noticed a similar dielectric property change like as the resonance frequency shifted in the same direction. Later, we replicated this measurement structure in the simulation environment using Ansys HFSS 2021 R1 where we tried different dielectric constant of the chitosan hydrogel to match the S11 parameters of the patch antenna for different pH levels found from the measurements. Our best matched simulation results of S11 parameter for each of the pH levels from 4 to 7 are shown in Fig. 4 (a). We found a dielectric change of our synthesized hydrogel from 6 to 10.5 for pH level from 4 to 7 as shown in Fig. 4 (b). These pH sensitive characteristics of chitosan hydrogel can be used on the pH sensing RFID tag to monitor the healing process of a wound where the pH level is between 5.5 and 6.5. The resonance frequency shifted towards the lower frequency and the amplitude of the peaks reduced as the pH moved to a more acidic medium which is like what was reported in [11].

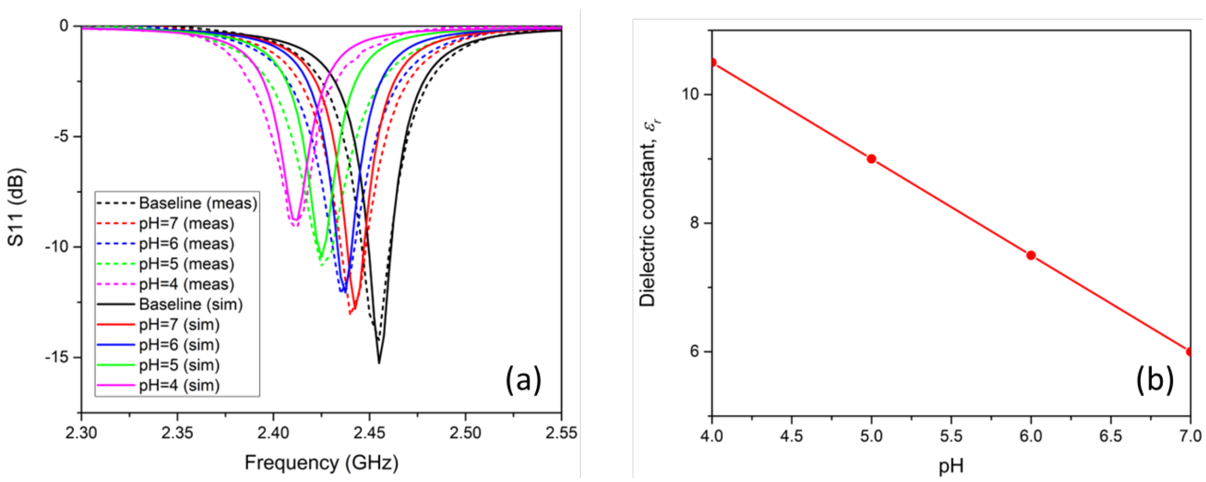

Figure 4. (a) Measurement and simulation results of S11 curves of the patch antenna for baseline and different pH levels. (b) Change of dielectric constant of the synthesized hydrogel with respect to pH values (4 to 7).

4. RESULTS AND DISCUSSION

4.1 RCS of FR4 and Evolon based tags without chitosan

We used two horn antennas connected to the vector network analyzer (ENA E5071C) to measure the RCS of both RFID tags. To determine co- and cross-polarized RCS from the target RFID tags one of the horn antennas was aligned horizontally and another one was aligned vertically. The transmission parameter (S21) from the VNA was measured which is the RCS of the RFID tags. We recorded the RCS signal of the tags in normal condition as well as when put on human body. For this measurement we used the FR4 based tag and the new bandage compatible Evolon based tag without chitosan hydrogel layer. The cross-section view of the tag without the chitosan layer is shown in Fig. 1 (d). The RCS measurement setup is demonstrated in Fig. 5. The new tag was also simulated to check the cross polarized RCS signal and to tune the resonance frequency to the ISM band (2.4-2.5 GHz).

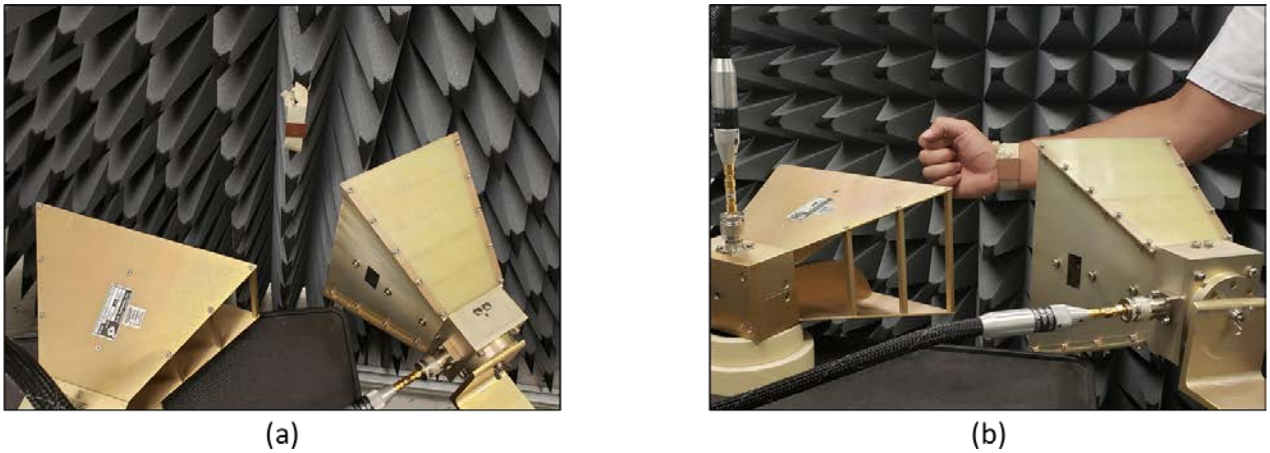

Figure 5. RCS measurement setup for the RFID tags (a) in normal environment, and (b) on human hand.

We observed the desired resonance peaks in the ISM frequency band in the cross/vertically polarized RCS signal from the FR4 based tag for both conditions: in normal environment and on human hand as shown in Fig. 6 (a). Though the signal amplitude was lower than the co-polarized signal, the cross-polarized signal was able to retain the resonance peaks generated by the RFID tag in the targeted frequency band. On the other hand, co-polarized signal did not show the resonance peak as it was suppressed by the larger RCS signals coming from the surrounding objects. In a similar manner the newly proposed Evolon fabric-based tag was also tested on human hand using the same RCS measurement setup. The cross-polarized RCS plots revealed resonance peak at 2.43 GHz for the proposed tag where the amplitude of the peak was around -36 dB as shown in Fig. 6 (b). The simulation result also corroborated the resonance peaks at 2.42 GHz which is close to the measurement result. However, the amplitude of the simulation result was higher than the measurement which could be due to the fact of unbale to perfectly mimic the measurement environment in the simulation.

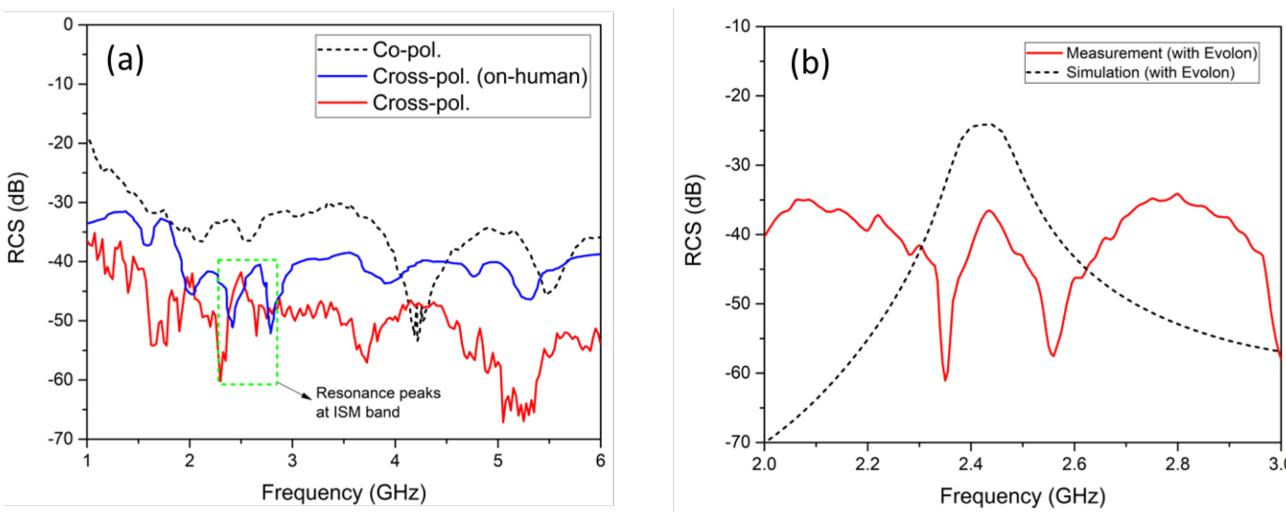

Figure 6. (a) RCS measurement results for FR4 based tag, and (b) Cross polarized RCS measurement and simulation results for Evolon based tag. (both cases without chitosan layer)

4.2 RCS simulation results for Evolon based tag with chitosan hydrogel

The Evolon based structure was simulated including a 1 mm thick pH sensitive hydrogel layer sandwiched between the two Evolon fabric layers as shown in the cross-section view in Fig. 1 (e). Different dielectric constant values found from the microwave characterization of the hydrogel was used for the chitosan layer used in the RFID tag structure to determine the resonance frequency shifts. The cross-polarized RCS signals were plotted for different pH levels in Fig. 7. The resonance peak of the tag is shifted towards lower frequency as the pH level increased from 4 to 7 which can be used to monitor the healing status of the wounds on human body. The resonance frequency shifts from 2.54 GHz to 2.4 GHz covering a total of 140 MHz shift for pH level from 4 to 7.

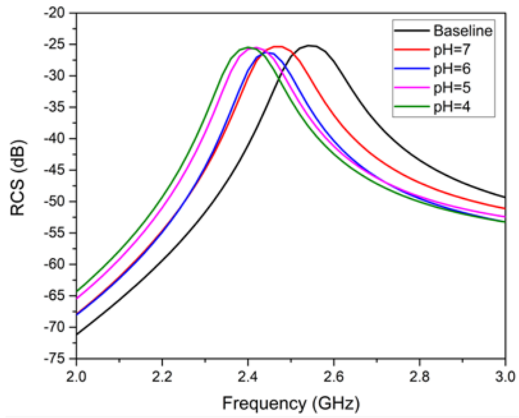

Figure 7. Cross-polarized RCS simulation results of the Evolon based RFID tag for pH level 4 to 7.

5. CONCLUSION

We demonstrated a bandage compatible chipless RFID tag structure which was able to show a clear resonance peak in the ISM band frequency in its cross-polarized RCS signal when tested on human hand. The synthesis of the sensing material chitosan hydrogel into preferred shape was demonstrated which will be helpful to integrate the hydrogel in the RFID tag. We characterized the dielectric property of the hydrogel in the ISM band for pH levels from 4 to 7. Our simulation results of the proposed tag showed resonance frequency shifts from 2.54 GHz to 2.4 GHz for pH 4 to 7 which can be used to monitor the healing progress of a wound. The demonstrated chipless RFID sensor with fabric substrate which is soft and flexible can be easily integrated into conventional bandages for touchless wound healing monitoring.

ACKNOWLEDGEMENTS

The work at FIU was supported by NSF REU Site: Preparing RF Engineers for Communication, Imaging and Sensing (PRECISE) (award # 1950788).

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