A Radio-Frequency Planar Resonant Loop for Noninvasive Monitoring of Water Content

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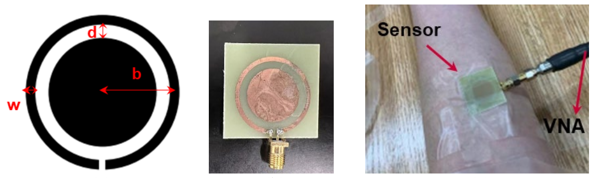
***Abstract*— In this work, a planar radio-frequency sensor is developed to noninvasively monitor the water content variations in tissues. The sensor is based on the detection of electromagnetic resonance which is dependent on effective permittivity. The planar loop resonator tuned with a metal pad features improved resonance, compact size, and the ability to conform to a surface. Experiments to monitor human hydration processes have been demonstrated. Discrete and continuous measurements match well with the simulations conducted by using documented, generalized human skin permittivity properties. The recorded data shows distinct trends when a person gets hydrated from a dehydrated state. With the advantages of a small and planar form factor, it can be integrated into wearable on the human forearm. Additionally, the sensor has been used to demonstrate its ability to detect water content changes in produce such as fruits and meats. These promising results show great potential in sensing applications for healthcare, agriculture, and food industries.**

Keywords—hydration; noninvasive; planar sensors; water sensing.

I. INTRODUCTION

Water plays a vital role in the human and animal bodies, such as transporting nutrients and waste across cells as a carrier and maintaining a stable body temperature in different environments [1]. Significant loss of body water causes dehydration and severe health problems. Physiologically, dehydration contributes to a higher risk of musculoskeletal injury due to impaired anaerobic muscular power [2] and decreased cardiac outputs with reduced blood volumes [3]. Mentally, dehydration exacerbates cognitive performance and mood [4], making it hard to concentrate with feelings of fatigue and nervousness [5]–[10]. Generally, the urinary system primely balances the regulation of hydration. Excess body water is excreted by the urinary system, and urine volume is reduced when the body gets dehydrated [11]. The thirsty feeling is activated to remind the person to take in fluid [12]. However, such feedback mechanisms may be impaired for specific populations and scenarios, including infants, the elderly, soldiers, and athletes [13]–[15]. It is critically essential to continuously, noninvasively, and efficiently monitor the hydration level of those who may be at risk.

Microwave sensors have been utilized for water sensing owing to the distinctive dielectric properties of water at high frequencies for remote sensing applications [16]. Three main types of microwave measurement methods are used: resonance, transmission, and reflection. Resonance cavities can accurately measure the dielectric properties of a medium, obtaining frequency characteristics owing to the interference in the medium. However, measurement is limited for medium with high dielectric losses [17]. The physical constructures of resonators have constraints to be used on the human body. The transmission measurements require both transmitter and receiver antennas, by which electric fields pass through and interact with the medium. Garrett *et al.* developed a transmission sensor to monitor human hydration levels by evaluating the effective permittivity in the forearm with microwave signals passing the tissues [18]. Such a system can be bulky, and the high electric fields may have safety concerns. Reflection type has simpler physical structures and can be potentially designed as a wearable for long-term continuous monitoring. However, near-field characteristics, sizes, and wave scattering for planar antennas face design challenges. The radiation powers also affect the interference effects at different depths inside tissues.



(a) (b) (c)

Fig.1 (a) The sensor configuration. (b) Photograph of the assembled sensor. (c) Setup of human hydration experiment with the sensor placed on the forearm and connected to the vector network analyzer.

In this work, we developed a near-field planar resonant loop as a wearable for noninvasive water content monitoring. The structure is based on a planar loop [19], with a metal pad embedded as a tuning element, as shown in Fig. 1(a). The center pad provides distributed reactance to match the impedance of the loop at the desired resonant frequency. We chose the ISM band around 912 MHz for our designs. Similar designs for improving power-transfer performance in subcutaneous implants have been investigated in our previous work [20], [21]. The results

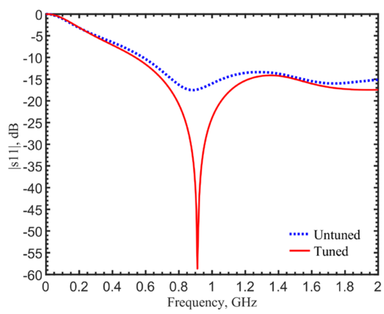


Fig. 2 Simulation results of the sensor with (tuned) and without the center pad (untuned).

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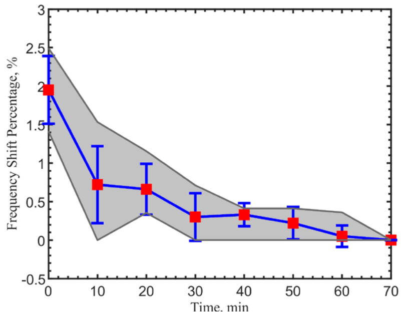

Fig. 3 Seven human hydration experiments. Reflection coefficients are recorded every 10 minutes. When the intake of water starts, a gradually and monotonically descending trend of resonant frequencies appears. The shaded area shows the overall ranges of resonant frequency shifts from the baseline frequency when achieved fully-hydrated. The red point shows average values while the error bars are calculated from the seven datasets.

indicated that the planar tuned structure can be made in a compact size, yet with an excellent performance on resonance. Both are great features for wearable devices. Experiments and simulations were conducted to investigate the feasibility of monitoring human hydration. Additionally, general water content measurements for produce, like meat or fruit, were conducted to demonstrate wider applications of the sensor.

II. Human Hydration Experiments

A. Hydration Monitoring Experiment

The sensor operates at around 912 MHz. It has a loop radius b = 12 mm and a metal width w = 1.6 mm. The spacing between the loop and pad is d = 2.2 mm. The sensors are fabricated on a single-layer FR4 substrate with a dielectric constant of 4.4 and a thickness of 1.5 mm, as shown in Fig. 1(b). Finite-element simulations are conducted with and without the metal center pad for comparison. The result is shown in Fig. 2. It clearly indicates a significant enhancement in resonance with the reflection coefficient $|s_{11}|$ improved from −17.5 to −58.7 dB. The resonant frequency shifts from 882 to 912 MHz, which is acceptable. The material permittivities for human skins in simulations are obtained from the database in [20]. It should be noted that this database is generalized, and variations are expected for individuals. In the measurements, the sensor is placed on the person's forearm touching the skin. A 50-Ω SMA adaptor connects the resonator to a vector network analyzer (Keysight PNA N5227B), as shown in Fig. 1(c). Medical-grade tapes are used to fix the device in order to avoid movements. The participant stops taking in water or liquid after 10 PM on the night before the experiment. At 9 AM the next day, the participant completes jogging for 45 minutes on a treadmill prior to the measurements. After the sweat is wiped dry and the body temperature cools down to the one before jogging, the participant starts to continuously and slowly sip water. Reflection coefficients are recorded every 10 minutes up to 70 minutes. The final resonant frequency is considered as the fully hydrated state and is used as the baseline to calculate the frequency shift in percentage for other time points. The frequency in the beginning is treated as the initial dehydrated level, which depends on body conditions

Fig.4 (a) The sensor design and (b) a photograph of the sensor connected with an SMA connector.

and is different on different days, even for the same participant who follows the same protocol. A total of seven datasets are collected in this study.

Figure 3 shows the results of monitoring hydration progresses. Each dataset has a different initial dehydrated level, ranging from 1.4% to 2.4% at the start of the experiments, as expected. After the intake of water, gradual and monotonical descending trends are observed. The resonant frequencies stop shifting after 60 minutes, indicating the persons are fully hydrated.

The experiments indicate the feasibility of utilizing a planar resonator for water content measurements in tissues. However, the connectors and soldering parts make it uncomfortable for the person and difficult to make a constantly firm contact with the forearm during the entire experiment period. Consequently, there are deviations in measurements, clearly due to the tension from the coaxial cable, which causes gaps to appear between the device and skin. To overcome this issue, an improved sensor is built.

B. Continuous Hydration Sensing Experiment

The sensor is modified with two extending legs from the loop gap in order to mount the SMA connector vertically. This configuration alleviates the cable tension. The loop is redesigned with a radius of loop b = 13.6 mm, a metal width w of 1.6 mm, and a spacing between the metal loop and tuning pad d of 3.4 mm. The leg length L is 6 mm. Fig. 4 shows its dimensions and photo. Simulations are conducted using the documented dry and wet skin permittivities in [22]. The results, including measurements on the forearm, are shown in Fig. 5. In simulations, the sensor is tuned for the dry skin data, assuming as the dehydrated level at the resonant frequency of 915 MHz with $|s_{11}|$ better than −47.8 dB. The resonant frequency shifts to 876 MHz for the case using the wet skin data, assuming to be the fully hydrated level, which is a 4.26 % shift from 915 MHz. There are deviations in measurements due to the physiological condition of the person, the exact

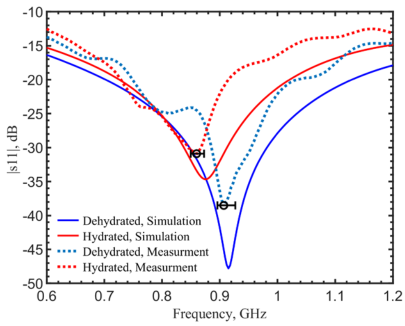

Fig. 5 Simulation (solid line) and measurement (dash line) results of the sensor.

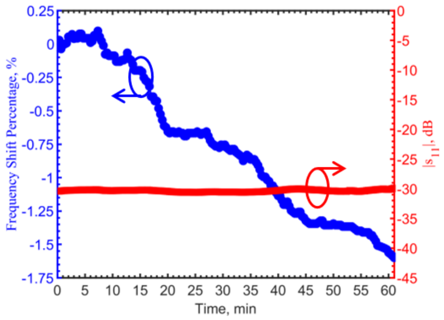

Fig.6 Results of the continuous hydration monitoring. The blue curve indicates the resonant frequency shift while the red one indicates the magnitude of the reflection coefficient.

sensor location on the forearm, and the initial dehydrated levels in different experiments. The results show a dehydrated range of 849.7–872.7 MHz and a hydrated range of 896–927 MHz. The distinguishable frequency ranges indicate a robust performance.

The sensor is inserted into an adjustable compressing foam and then connected to the vector network analyzer. The forearm is comfortably confined by a layer of elastic foam to ensure a firm contact of the sensor on the skin. The data is recorded every 20 seconds to provide more details on the hydration process. The reflection coefficient magnitudes are recorded as an indicator to monitor sensor movements. When its contact with skin changes, the reflection coefficient changes abruptly. The data are then filtered as body artifacts.

Figure 6 shows the results from the higher sampling rate measurements and improved data processing method. Measurements are recorded every 20 seconds after the dehydrated person starts to continuously and slowly sip water every several minutes. The experiment lasts one hour. The baseline used is the resonant frequency at the beginning. As the person gets hydrated the frequency shifts a lower one, and the shift percentage is calculated. The stable magnitudes of reflection coefficients indicate the frequency data without significant body artifacts. The declining trend in the resonant frequency shifts indicates the body is gradually getting hydrated during continuous water intake. The results suggest that the sensor can detect the hydrating process in the human body continuously with a high temporal resolution.

III. WATER CONTENT MONITORING FOR PRODUCE

The sensor also lends its features of being planar, noninvasive, and sensitive to water content to other applications, such as monitoring the water concentrations in produces like fruits or meats. Fresh orange and moist ground pork are used to demonstrate such an application.

A slice of fresh orange is covered with a layer of plastic

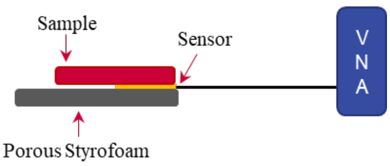

Fig. 7 Setup of continuous and long-term water content monitoring of produce.

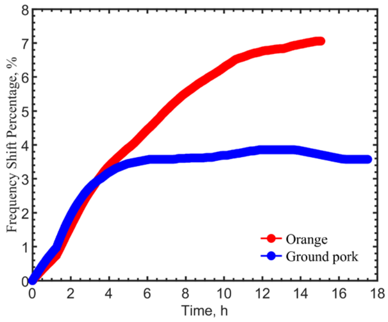

Fig.8 Continuous and long-term water content monitoring experiments for orange and ground pork patty.

wrap. The wrap is open at the top of the slice to allow water to evaporate. The sensor is placed underneath the orange slice, as shown in Fig. 7. The experiment is designed this way because it is challenging to measure time-lapped water concentration changes with the skin remaining on the orange as it takes a long time for water to evaporate, even inside a dehydrator. Reflection coefficients are recorded every 3 minutes, and the total recording time is 15 hours. The start resonant frequency is served as the baseline to calculate the frequency-shift percentage. Fig. 8 (red curve) shows increasing frequency shifts as orange loses water. At the end of the experiment, there is a 7% frequency shift.

Similarly, another experiment is conducted using moist ground pork with the same setup in Fig. 7. The ground pork is also sealed with a layer of plastic wrap with the top open for water to evaporate. The sensor is placed underneath the patty, and measurements are taken every 3 minutes for 17.5 hours. A similar trend with the increasing resonant frequency is shown in Fig. 8 (blue curve). The increasing trend slows down after 6 hours when the exposed surface of the tissues becomes tough and prevents water from going out. At the end of the experiment, there is a 3.5% frequency shift. Both experiments show that the sensor is sensitive to water content changes.

IV. CONCLUSION

We have demonstrated a radio-frequency planar resonant loop for noninvasive water content monitoring. The sensor is susceptible to dielectric property changes due to water content variations. Human hydration experiments have been successfully conducted with discrete and continuous monitoring on the hydration processes. Both statistical experiments show distinct trends when a person gets hydrated from a dehydrated state. And it can be potentially made into a wearable with the advantages of being planar, compact, and with high sensitivity. Moreover, the sensor also has been used to identify water contents in produce. The demonstrations show great potential for a variety of noninvasive sensing applications in agriculture, the food industry, and diagnostic tools.

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