An Improved Design of Wearable Strain Sensor Based on Knitted RFID Technology

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***Abstract*—In this study, we built a lumped component model for knit tag antennas. Comfortable, seamless, and wireless antennas were manufactured using conductive yarns and RFID technology. Knitting fabrication enabled rapid prototyping of these wearable antennas. Using the lumped component model, we optimized the geometry and knit structure of the antenna, resulting in improved radiation efficiency, reading range, and sensitivity.**

I. Introduction And Related Work

Passive UHF (Ultra High Frequency) RFID technology, coupled with real-time signal processing, can provides the capability to design wireless and battery-free sensors equipped with real time signal processing technology. Researchers have recently been exploring wearable applications of tag strain sensors [1][2]. In our work, we have been integrating the tag antenna into a smart garment device using industrial knit fabrication as opposed to embroidery.

A simple and versatile laboratory-fabrication method of embroidered tag antennas is demonstrated in paper [1]. The calculated realized gain and theoretical read range of the tag at 910 MHz is -5 dBi and 4 m, respectively. However, the authors did not quantify how stretching the tag can be used to implement sensing. Hasani et al. [2] presented a novel embroidered RFID strain sensor tag, utilizing both reading range extraction and variation of the tag Radar Cross Section (RCS). However, the change of RCS within the UHF RFID band is less than 1dB when the length of the tag varies by 20 mm. This variation in RCS due to physical deformation is insufficient to detect the deformations present with many biological processes such as respiration or uterine contraction [3]. Moreover, the embroidered bands have limitations, including bulkiness and connection issues between the tag chip and the fabric.

Patron et al[4] addresses these drawbacks by integrating the tag antenna into a smart garment device using knitting fabrication. This mechanical strain gauge device works by embedding an RFID chip into a knit antenna fabricated on an industrial knitting machine. Because the whole design is inspired by the application of fetal monitoring, the integrated tag antenna is called the “Bellyband Antenna”. Properties of the Received Signal Strength Indicator (RSSI) are continuously monitored as the output of sensor tag antenna, as shown in Fig. 1. Inductively coupled RFID technology was used, avoiding the need to physically solder the RFID chip to the antenna arms. However, the coupling technology proved to be difficult to control during fabrication and required less than 10 μm spacing between the chip pads and antenna arms.

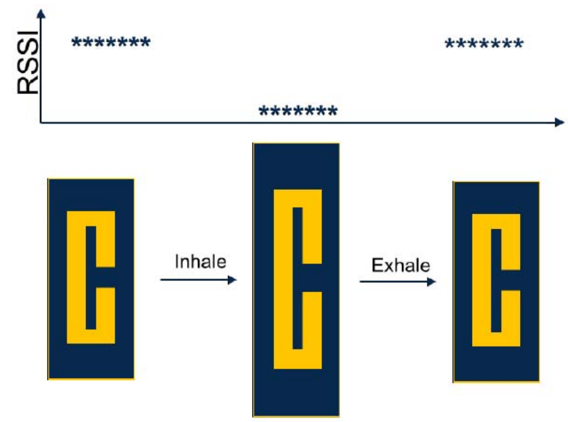

Fig. 1. Mechanical strain gauge sensor (Bellyband Antenna) utilizing the mechanical motion of the fabric antenna and corresponding changes in RSSI.

In this paper, we look at knit RFID strain sensor design and fabrication. In Section II, we will discuss the wearable RFID tag antenna model using lumped components, showing the HFSS simulation model of the improved antenna. Section III describes the manufacturing process and the simulated and experimental results in terms of the antenna return loss, reading range and radiation pattern. We will also discuss human body proximity effects on RFID sensor performance. Lastly, Section IV will summarize our findings and propose future research.

II. Lumped Component Model and Simulation Model of the Tag Antenna

Our new design solves the coupling problem faced by previous versions of the Bellyband antenna by soldering the tag chip onto a small and thin Printed Circuit Board (PCB) or Flexible Printed Circuitry (FPC) (10x10 mm^2). Copper pads have been wrapped around the sides of the PCB or FPC to improve coupling. The PCB or FPC is then inserted into an integrated pocket within the knit antenna. Conductive yarns are knitted into the pocket using tuck stitches, stitches produced when a knitting needle holds an original loop while receiving a new one, to improve the connection between the antenna arms and the RFID chip. The Bellyband is designed such that during the stretching of the antenna, the transmission coefficient and radiation efficiency significantly increases or decreases simultaneously. By studying the lumped component model of the tag antenna, the antenna's reading range, which starts from the reader antenna to the the tag, was improved up to 13 feet and the tags sensitivity was also improved with an RSSI change of about 0.5 dB/mm.

The antenna is composed of a knit textile folded dipole antenna, equipped with an RFID tag microchip. An image of a Bellyband antenna is shown in Fig. 2.

Fig. 2. Knit Bellyband Antenna with a folded dipole antenna shape. Silver part of the antenna is knitted using conductive yarns.

A knit textile is created through consecutive rows of interlocking loops. The resulting structure when using conductive yarns is dissimilar to a solid sheet of copper. Therefore, designing the textile folded dipole deviates from the antenna impedance equation typically used when designing a copper folded dipole antenna. Additionally, we must match the input impedance of the tag chip. The HFSS (High Frequency Structure Simulator) calculated the current density (J) and electric field (E) distribution across the antenna, as shown in Fig. 3 and 4.

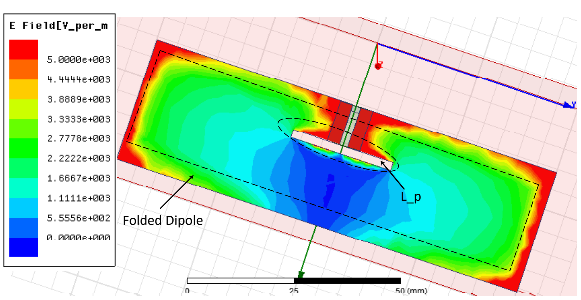

Fig. 3. HFSS simulation of current density on the surface of the textile folded dipole antenna.

The electric field mainly distributes near the edge of the antenna, forming the outer loop, as well as around the rectangular slot near the center of the antenna, forming the inner loop. The outer loop acts like a folded dipole antenna with a serial resistance determined by the conductive yarns. The inner loop does not radiate effectively, but has a strong current going around the loop. Thus, the inner loop can be considered as a loop inductor L_p in parallel with the folded dipole antenna, as shown in Fig. 4. The current is so strong within the inner loop inductor that most of the loss is from the serial resistance Rs of the inductor due to the resistivity of the yarn. The analysis above yields the lumped component model of the textile folded dipole antenna, see Fig. 5. Longer and wider dimensions of the outer loop folded dipole antenna increase the radiation efficiency or gain G_{tag} of the antenna. Increasing the length of the inner slot will increase the input impedance of the antenna, yielding lower reflection coefficient Γ. By designing an antenna with higher efficiency and good matching while it is being stretched and lower efficiency and poor matching while at rest, the RSSI value will change according to the following equation[5]:

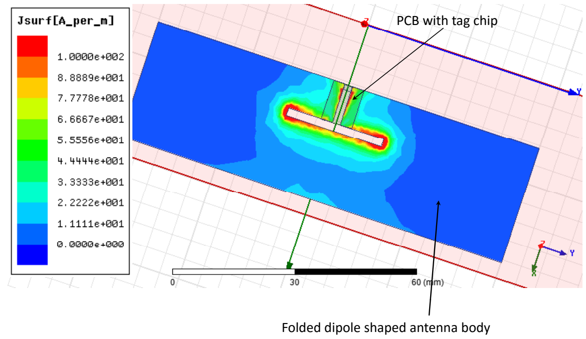

Fig. 4. HFSS simulation of current density on the surface of the textile folded dipole antenna.

$$RSSI = f(P_t, d)G_{tag}(1 - \Gamma^2) \quad (1)$$

P_t is the transmitted power from the reader antenna, and d is the distance from the reader antenna to the tag.

Due to the complex nature of knit smart textiles, the sheet impedance of the antenna is determined through a series of parametric simulations and compared with a measured prototype. The optimal sheet impedance value is $Z_s = 0.8 + j1.8$ ohm/sq. Based on the estimated sheet impedance and lumped component model, the dimension of the antenna is tuned for matching with the complex microchip impedance Z_c = 25 - j200 ohm, while considering the radiation efficiency. Fig. 6 shows the 3D antenna HFSS model for numerical simulations. In the stretching condition with good impedance matching and radiation efficiency, the outer dimension of the optimized antenna is W = 30 mm and L = 100 mm, while the internal slot dimension is W_{slot} = 2mm and L_{slot} = 25mm, as shown

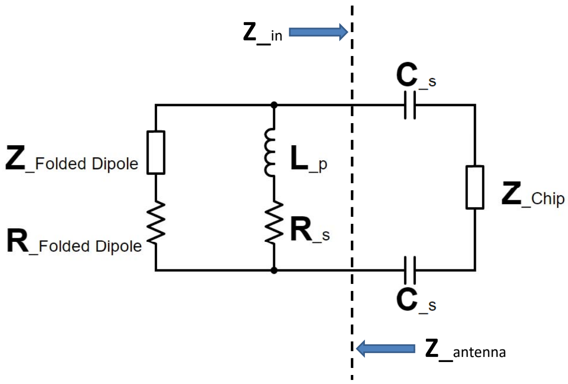

Fig. 5. Lumped component model for textile folded dipole antenna.

in Fig 6. When the antenna is at rest, the outer dimension is W = 30 mm and L = 80 mm, while the internal slot dimension is W_{slot} = 2mm and L_{slot} = 20 mm. This results in larger return loss, lower radiation efficiency, and lower gain.

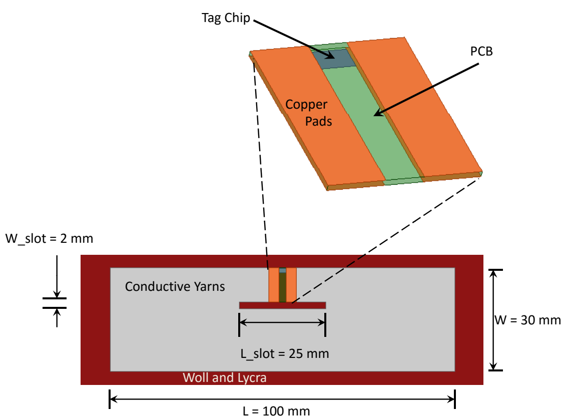

Fig. 6. Knitted antenna dimension when stretching with PCB in the pocket.

III. Antenna Manufacturing and Experimental Results

A. Antenna Manufacturing

The Bellyband is programmed on Shima Seiki's SDS-ONE APEX3 proprietary design system and knitted on a Shima Seiki SSG-122SV knitting machine. The antenna is knitted with both conductive and non-conductive yarns and integrated into the host garment. Silver-coated nylon was chosen as the conductive yarn. The non-conductive yarns include a viscose and polyamide blend, providing the necessary comfort and elasticity. The RFID PCB or FPC is inserted into a pocket within the Bellyband during the knitting process.

To match the geometry of the manufactured antenna to the simulated antenna, the dimensions in millimeters of the band at rest are converted to numbers of stitches. The conversion value is adjusted depending on the tightness of the knitted loops. The knit structure was revised to improve the elasticity of the antenna relative to previous versions of the Bellyband. Antennas were knitted using every other needle on the needle bed to reduce the number of stitches per inch, commonly referred to as half gauge knitting. Additionally, elastane was added to the antenna to increase the contact between conductive yarns.

B. Experimental Results

The antenna is first knitted with a PCB alone (without an RFID chip) to measure the reflection coefficient and radiation pattern using a vector network analyzer. Fig. 7 demonstrates both the simulated reflection coefficient and measured results. While the antenna is being stretched, simulated and measured results match very well. Both show the return loss is lower than -8dB within the RFID band. At rest, we observe the frequency shift of the return loss curves, resulting in lower RSSI. However, simulated and measured results do not match as well because the sheet impedance of the knitted yarns is also a function of frequency and antenna size. Fig. 8 demonstrates the radiation pattern of the antenna. The gain G_{tag} is about 3dB greater in stretching condition than in the rest condition. The HFSS simulation shows the radiation efficiencies are 54.96% in the stretching condition and 27.11% at rest.

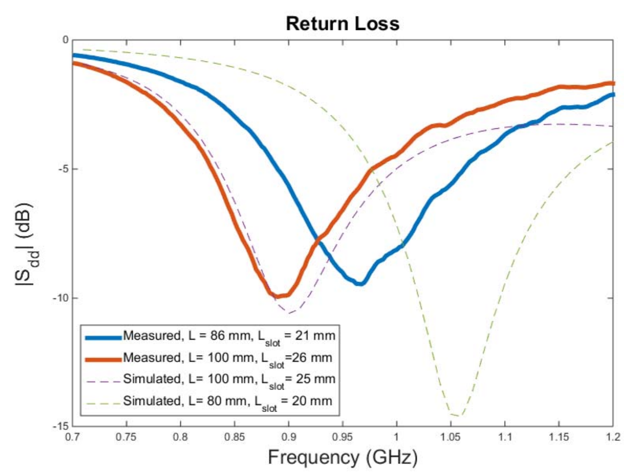

Fig. 7. Comparison of measured and simulated Reflection Coefficient v.s. Frequency when stretching and at rest.

The Bellyband Antenna is then knitted with an RFID chip soldered onto the PCB. By using an Impinj Speedway RAIN RFID Reader, the variation of maximum RSSI value is verified and the maximum reading range is measured. Reader antenna is placed 3 feet away from the tag antenna. Fig. 9 shows the measurement results of RSSI change vs. the change of antenna length L. Due to the contribution of both radiation efficiency (antenna gain) and impedance matching condition (reflection coefficient or return loss), RSSI changes from -58 dBm to -48

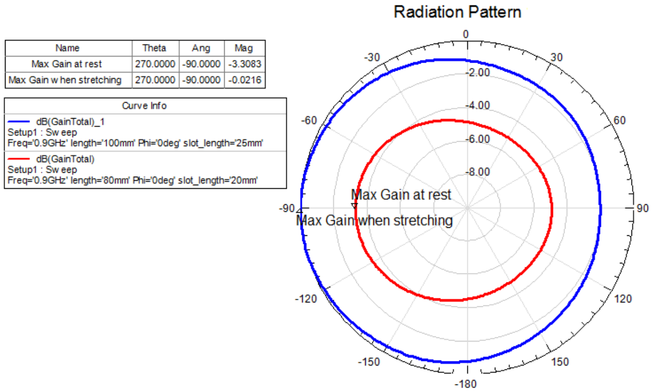

Fig. 8. Azimuthal radiation pattern of Bellyband Antenna showing the change of maximum gain while stretching at center frequency of 900MHz.

dBm when stretched. The tag sensitivity to length change is about 1 dB/mm. The maximum reading range is up to 13 feet in the Line of Sight (LOS) indoor environment.

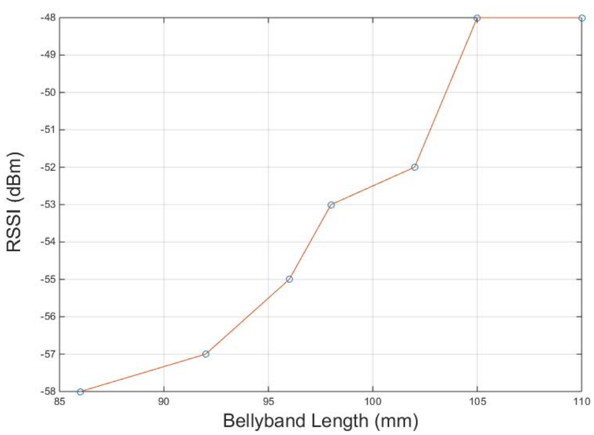

Fig. 9. RSSI v.s Antenna Length, Sensor's sensitivity is the slope of the curve.

Since the Bellyband is designed for medical applications, including respiration monitoring, human body effects need to be considered. When the Bellyband is placed close to the human body, as it would be when worn as a monitoring device, the efficiency of the antenna drops significantly due to lossy human tissues. The proximity of the human body also changes the matching condition for the antenna. Even so, we observe about 3dB RSSI change versus antenna length and a reading range of 4 feet. Planned future work includes refining the antenna design to account for the impedance characteristics of the human body.

IV. Conclusion

In this paper we discussed the modeling, design, and experimental results of a knitted RFID strain sensor. The lumped component model and HFSS model of the textile folded dipole antenna help to accelerate the analysis and design of the Bellyband. We discussed methods to improve the reading distance and enhance the RSSI dynamic range (sensor sensitivity). After designing and manufacturing the antenna with an RFID tag chip on a PCB in a knitted pocket, we tested and validated the strain sensing performance: the maximum reading range is measured to be up to 13 feet and sensor sensitivity is about 0.5dB/mm. In a future extended paper, we will discuss the design while considering human body effects.

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