Experimental Parametric Study of Dual-Layer Planar Wearable Magnetoinductive Waveguides

Connor Jenkins and Asimina Kiourti
ElectroScience Laboratory, Department of Electrical and Computer Engineering, The Ohio State University, Columbus, OH 43212 USA (e-mail: jenkins.1124@osu.edu)

***Abstract*—Magnetoinductive waveguides have been shown to have strong potential in wearable applications due to their extremely low loss and unobtrusive design, among other factors. Previously, we reported a limited experimental study of a wearable e-textile-based dual-layer planar MIW. In this work, we expand the experiment considerably by accounting for two dimensions of clothing misalignment. Results show a strong agreement between simulation and experiment in terms of performance and robustness to change. A clear passband is maintained across the misalignments, experimentally confirming the robustness to clothing transitions of the dual-layer planar design.**

Keywords— Body area networks; magnetoinductive; wearables.

I. INTRODUCTION

A magnetoinductive waveguide (MIW) is constructed by placing electrically small resonant loops near one another. When the transmit loop is excited, current is induced on the neighboring loops which leads to a traveling wave phenomenon through careful design [1]. MIWs outperform the state-of-the-art in wireless body area network (WBAN) applications through the extremely low loss, simple channel modeling, reliability, and unobtrusive design [2].

Recently, we have reported a new class of wearable MIWs for WBAN applications that utilizes a dual-layer planar design to overcome limitations in the state-of-the-art MIW technology in terms of anatomical independence and robustness to mechanical failures [3]. Initial experimental results confirmed the expected transmission performance based on simulation data, and a partial experimental clothing transition study confirmed robustness to clothing transitions that cause a transverse shift between two MIWs [3].

As full MIW-based WBAN systems are realized, rigorous human subject testing is needed to fully characterize MIW behavior over a wide variety of circumstances that can occur due to the dynamic nature of the human body. This work expands the previous experimental clothing transition characterization to include vertical and longitudinal clothing transitions. Validation takes place on a human subject.

The rest of the paper is organized as follows. Section II showcases the MIW under test and the overall experimental setup. Section III follows with the results of the vertical and longitudinal clothing transition results. Section IV concludes the work.

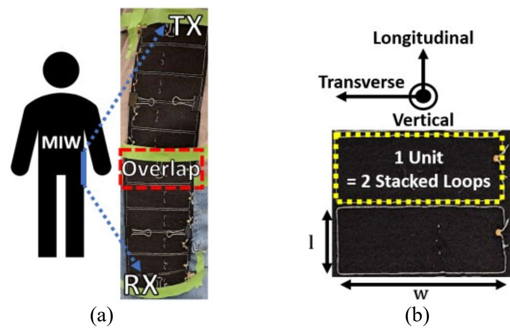


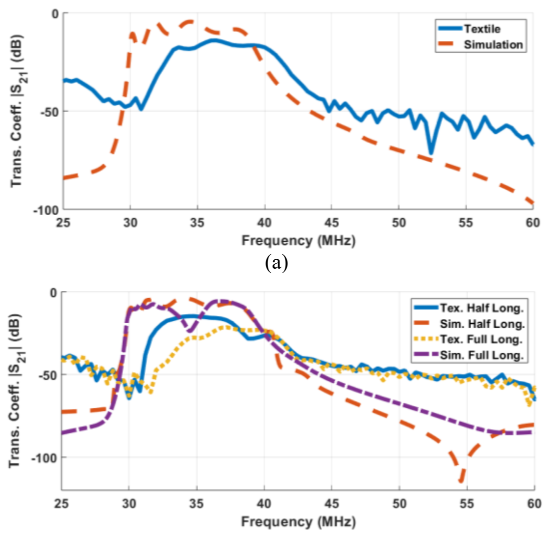
Fig. 1 Dual-layer planar MIW fabricated on e-textiles: (a) clothing transition on the hip of a human subject, and (b) physical parameters.

II. EXPERIMENTAL SETUP

Two 6-unit dual-layer planar MIWs were constructed using a Brother Duetta 4500D embroidery machine and Liberator-40 e-thread. The constructed MIW is shown in Fig. 1(a). Aligning with Fig. 1(b), each loop has the following dimensions: $l = 3.5$ cm, $w = 9.1$ cm, $g = 0.25$ cm, and $C = 56$ pF. The two layers are separated by 0.1 cm of fabric. Clips are used to maintain the alignment of the layers. The inclusion of these clips had minimal impact on performance.

As shown in Fig. 1(a), the MIWs are placed on the side of a human subject such that the MIW overlap is placed along the shirt-pant overlap to mimic the real-life multi-garment transmission scenario under test. This study is conducted under Institutional Review Board approval from The Ohio State University (#2020H0548). The ideal overlap for the MIW, and therefore the initial position, is a single unit overlap which is labeled in Fig. 1(a) along with the two misalignments of interest. In this case, vertical misalignment is represented by moving the bottom MIW away from the subject and longitudinal misalignment is represented by shifting the bottom MIW towards the top MIW. This test setup is identical to the previously reported experiment [3]. The novelty lies in the new directions of misalignment.

Simulation results are generated using CST Studio Suite [4]. The loops of the MIW are modeled as 30 AWG copper wire because Liberator-40 e-threads have not yet been characterized over frequency. Fortunately, e-threads and copper have been shown to behave similarly for MIW applications barring an increased loss due to the reduced conductivity of e-threads [3]. Fabric is excluded from the simulation as the electrical properties of most fabrics are similar to that of air due to the porous nature of the material



(a)

(b)

Fig. 2 Simulated and experimental transmission coefficient results for: (a) vertical misalignment of MIWs, and (b) longitudinal misalignment of MIWs (textile = Tex., simulation = Sim.)

[5]. The MIW is placed 0.1 cm above a flat torso model with electrical properties equal to 2/3rds of the electrical properties of human muscle.

III. Experimental Results

The MIW performance is examined through transmission coefficient ($|S_{21}|$) results and characterized via minimum loss and 10 dB absolute bandwidth. In simulation, with no misalignment between the two MIWs, a minimum loss of 4.9 dB and a 10 dB bandwidth of 7.9 MHz is achieved [3].

A. *Vertical Misalignment*

First, the second MIW was lifted away from the first MIW from 0.1 to 0.5 cm. Fig. 2(a) shows the transmission performance. The simulation achieves a minimum loss of 4.5 dB occurring at 34.5 MHz with a 10 dB bandwidth of 7.9 MHz. The experimental results show a minimum loss of 14.1 dB at 36.4 MHz with a 10 dB bandwidth of 8.4 MHz.

The increase in loss is anticipated due to the previously mentioned reduced conductivity of e-threads versus that of copper. The shift in frequency is likely due to experimental error in the manufacturing and setup processes vs. an ideal simulation. Finally, when accounting for the change in center frequency between the simulation and experiment, the fractional bandwidths are nearly identical at 23%. The experimental results agree very strongly with the simulation results after accounting for the changes between the models.

B. *Longitudinal Misalignment*

Fig. 2(b) shows the performance of the textile experiment and simulated models for longitudinal misalignment of half a loop length and full loop length (1.75 cm and 3.5 cm respectively). The simulation achieves minimum losses of 4.06 dB and 5.7 dB, with bandwidths of 8.2 MHz and 4.0 MHz while the textile MIW achieved minimum losses of 14.8 dB and 21.4 dB with bandwidths of 6.4 MHz and 7.6 MHz for the half and full-loop misalignments, respectively.

Accounting for the previously discussed frequency shift and reduced conductivity, there is good agreement between simulation and experiment. In particular, the robustness to increased longitudinal misalignment is present in both simulation and experiment as the performance is not reduced significantly, despite doubling the misalignment from half to full loop length. The gap between the simulation and experimental results may have resulted in the difference in curvature between the flat simulation model and the curved human subject which can have some effect on performance [6].

Overall, there is strong agreement between simulation and experiment, particularly when accounting for differences in modeling. Additionally, the performance under realistic clothing misalignments is only marginally reduced when compared to the ideal performance which experimentally confirms the outcomes of [3].

IV. Conclusion

This work is a significant step forward in characterizing the behavior of wearable MIWs in real-world environments. The MIW transitions showed strong agreement between experiment and simulation under vertical misalignment and good agreement under longitudinal misalignment. The discrepancy in longitudinal result is likely explained by the change in loop and tissue curvature experimentally versus the flat loops and tissue used in simulation. The dual-layer planar MIW design is confirmed to be robust to clothing transitions in the vertical and longitudinal directions following the previously reported validation for transverse misalignments. Future work will focus on full-garment based experiments and system-level implementation of textile-based MIWs. Ultimately, the goal is to create full MIW-based WBAN systems for a variety of applications that require both on- and in-body communication.

Acknowledgement

This work was supported by the National Science Foundation (NSF) under grant 20053318.

References

[1] E. Shamonina, V. A. Kalinin, K. H. Ringhofer, and L. Solymar, “Magnetoinductive waves in one, two, and three dimensions,” *Journal of Applied Physics*, vol. 92, no. 10, pp. 6252–6261, Nov. 2002, doi: 10.1063/1.1510945.

[2] V. Mishra and A. Kiourti, “Wearable Magnetoinductive Waveguide for Low-Loss Wireless Body Area Networks,” *IEEE Trans. Antennas Propagat.*, vol. 69, no. 5, pp. 2864–2876, May 2021, doi: 10.1109/TAP.2020.3030987.

[3] C. B. Jenkins and A. Kiourti, “Wearable Dual-Layer Planar Magnetoinductive Waveguide for Wireless Body Area Networks,” *IEEE Transactions on Antennas and Propagation*, vol. 71, no. 8, pp. 6893–6905, Aug. 2023, doi: 10.1109/TAP.2023.3286042.

[4] Dassault Systemes, “Electromagnetic Simulation Solvers | CST Studio Suite.” https://www.3ds.com/products-services/simulia/products/cst-studio-suite/solvers/ (accessed Sep. 07, 2023).

[5] R. Salvado, C. Loss, R. Gonçalves, and P. Pinho, “Textile Materials for the Design of Wearable Antennas: A Survey,” *Sensors*, vol. 12, no. 11, pp. 15841–15857, Nov. 2012, doi: 10.3390/s121115841.

[6] V. Mishra and A. Kiourti, “Wearable Planar Magnetoinductive Waveguide WBANs: Bending Around Anatomical Curvatures,” in *2021 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (APS/URSI)*, Singapore, Singapore: IEEE, Dec. 2021, pp. 1039–1040. doi: 10.1109/APS/URSI47566.2021.9704533.