Flexible Electromagnetic Phantom with Electrotextile Backing for 60 GHz Wearables and Remote Monitoring

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INTRODUCTION

Over the years wireless sensors have replaced wired devices in several medical applications [1], especially for on-body or near-body monitoring of physiological activities. The millimeter-wave (mmW) range around 60 GHz [2] is a promising solution for short-range high-resolution radar sensing and monitoring of physiological parameters. To evaluate the wireless performance of such devices, it is essential to test them under controlled real-life scenarios, considering posture variations and body movements. To this purpose and to avoid testing the devices directly on human beings, experimental tissue-equivalent phantoms with electromagnetic (EM) properties similar to those of the body tissues have been proposed over the years. Phantoms can be categorized as liquid, semi-solid, and solid based on their physical properties. Water-based liquid phantoms are suitable for in-phantom measurements, including assessing specific absorption rate (SAR) and testing of wearable devices [3]-[5]. Semisolid phantoms have similar mechanical properties to human tissues [6] and find application in wearable technology and body area network (BAN) testing [7], [8]. For instance, agar-based phantoms have been effectively used in the 55–65 GHz range for body-centric propagation and on-body antenna characterization [9]. Solid phantoms can maintain their biomimicking properties for an extended period (due to the absence of water) and offer the possibility of creating complex shapes [10]. These phantoms are suitable for evaluating the impact of human body proximity on wearable devices' performance or characterizing on-body propagation channels [11]-[14].

This paper introduces the first electrotextile-based flexible solid mmW phantom designed to realistically emulate the reflection coefficient of human skin at frequencies around 60 GHz. The phantom is thin, lightweight, and maintains its dielectric and mechanical properties over time. Thanks to its characteristics it may be used to model curved body parts as well as to reproduce macro and micro-movements of the body surface (for instance for heartbeat or respiration monitoring).

PHANTOM DESIGN

The reflection coefficient at the air/skin interface is roughly 60% at 60 GHz at the normal incidence [15]. It strongly depends on the polarization and the incidence angle [16], varying from 20% to 100% for transverse magnetic (TM) mode and from 60% to 100% for transverse electric (TE) mode. To emulate the skin's reflection coefficient, using solid phantoms, conductive and high-permittivity additives are usually incorporated into a lower-permittivity base material during the curing process. The proposed phantom is composed of silicone mixed with 40% (in weight) of carbon powder and backed with an electrotextile ($\sigma = 1.96\, x\, 10^5\, S/m$). The electrotextile acts as a ground plane, also shielding from the presence of an object behind the phantom. The chosen weight ratio of carbon to silicone is a compromise between the necessity to increase the complex permittivity and the need to maintain its elastic properties. The complex permittivity of the silicone-carbon mixture is measured using the DAK TL-2 system within the 5-65 GHz range. At 60 GHz, the measured relative complex permittivity is $13.3 \cdot (1 - j \cdot 0.28)$.

Optimization:

An analytical transmission line model was developed and implemented in MATLAB to expedite the investigation of the EM behavior of the phantom. The model considers two interfaces: air/silicone-carbon and silicone-carbon/electrotextile. Characteristic impedances are calculated for both TM and TE polarizations, and the reflection coefficient is then calculated at the air/phantom interface. This coefficient depends on the thickness of the silicone-carbon layer. The phantom thickness is optimized to minimize the relative deviation between the reflection coefficients at the air/phantom and air/skin interfaces. The relative permittivity of dry skin is taken from Gabriel et al. [17] ($7.98 \cdot (1 - j \cdot 1.37)$). During optimization, the silicone-carbon layer's thickness is varied from 1 mm to 3 mm and the incidence angle from 0° to 60°. The analysis indicates that thicknesses from 2 mm to 2.2 mm yield the best fit with the scattering properties of skin, considering the magnitude and the phase of the reflection coefficient. The thickness of 2.1 mm is selected for the phantom, as this value falls in the midpoint of the optimal range of thicknesses. This makes the phantom more robust to the thickness uncertainty of the fabricated phantom (typical uncertainty is within 5%). Figure 1 (a) and (b) show, respectively, the magnitude and phase of the reflection coefficient at the air/skin and the air/phantom interfaces at 60 GHz. Comparing the coefficients of the phantom and the skin models the average relative error for the amplitude is 2.7% for TM polarization and 1.7% for TE polarization. The phase average errors are 8% and 4.6% respectively, with a maximum relative error of 16.2% for TM mode at 60°. Note that these variations are within natural physiological variations, such as age or skin moisture [18]. The chosen phantom thickness demonstrates reliable performance in emulating skin behavior in the frequency range around 60 GHz.

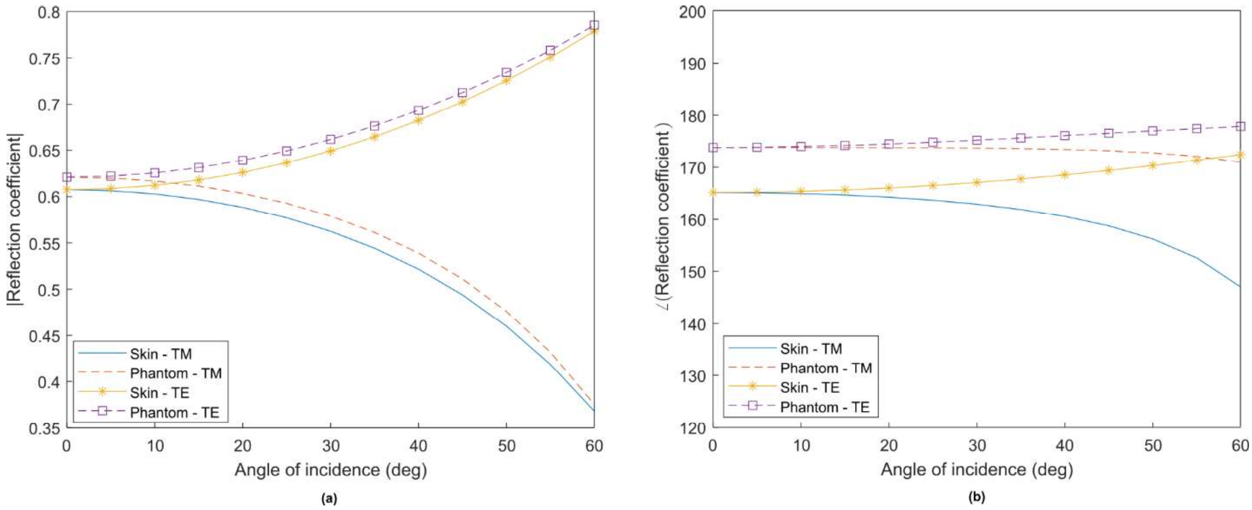

Figure 1: (a) Magnitude and (b) phase of the reflection coefficient for the skin and the phantom at 60 GHz.

REALIZATION AND VALIDATION

The phantom was then fabricated using SYLGARD 184 Silicone Elastomer base and curing agent [19], and Sigma-Aldrich 484164 Carbon powder [20]. The process begins by mixing one part of the curing agent with ten parts of the base, followed by adding carbon to achieve the 40% concentration in the composite's total weight. Thorough mixing ensures homogeneity while vacuum degassing removes air bubbles introduced during the preparation process. The mold was then placed in an oven at 110°C for two hours, to solidify the liquid composite. For optimal electrotextile stretching without folds, the silicone-carbon layer was placed flat, and the textile was stretched while silicone was poured to glue it. After curing the silicone in the oven for an hour, we obtained the flexible phantom shown in Figure 2 (a) and (b).

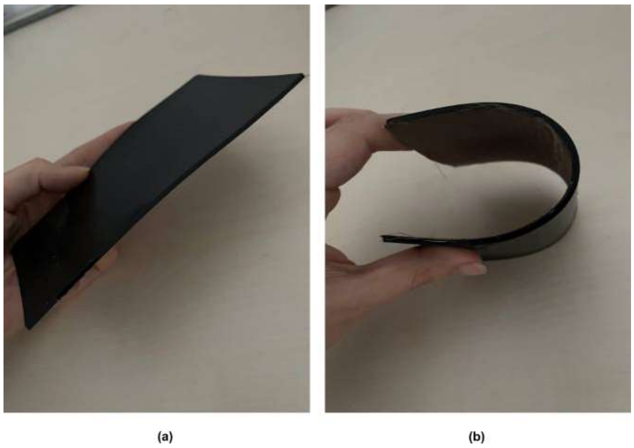

Figure 2: Realized flexible phantom for (a) planar and (b) conformal configurations.

Reflection coefficient measurements:

To validate the prototype, we measured the phantom's reflection coefficient and compared it with the reflection coefficient of human skin. The measurements were performed with a transmission/reflection quasi-optical setup, using a focusing lens and a horn antenna. The reflection coefficient was derived over a frequency range from 55 GHz to 65 GHz and then compared to the reflection coefficient of human skin. The results (Figure 3) show good agreement between the two coefficients. The average relative error is below 3%, with a maximum relative error reaching 6.6%.

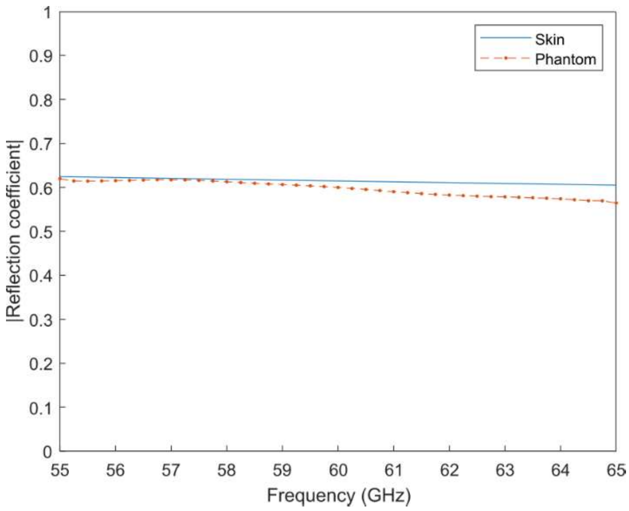

Figure 3: Magnitude of the reflection coefficient derived from the measurements compared to the coefficient of the skin in the 55-65 GHz range.

CONCLUSIONS

In this study, we developed and validated a novel flexible electrotextile-based phantom capable of replicating the scattering characteristics of human skin within the 55–65 GHz range. Unlike conventional rigid bulk phantoms, our design achieves flexibility through a thin structure and exhibits robustness to thickness uncertainty. The configuration is optimized to achieve scattering properties closely resembling human skin. The ideal configuration corresponds to a 40% carbon concentration in weight and 2.1 mm of thickness and exhibits relative deviation within 2.7% for the magnitude and 8% for the phase of the reflection coefficient at 60 GHz for 0°–60° angles. A proof-of-concept prototype displayed a reflection coefficient with a maximum relative error of 6.6% compared to human skin (for normal incidence) in the 55–65 GHz range.

This innovative phantom holds promise for diverse applications, including testing the performance of wireless wearables, radars for remote human-centered sensing and monitoring, and facilitating body-centric measurements where flexible, conformal, reconfigurable, or dynamic body models are essential. Its flexibility enables accurate reproduction of curved body parts, and its thin profile facilitates the emulation of micro-movements on the body surface, such as those caused by heartbeat or breathing.

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REFERENCES

[1] N. Rendevski and D. Cassioli, "UWB and mmWave communication techniques and systems for healthcare," *Ultra-wideband and 60 GHz communications for biomedical applications*, pp. 1–22, 2014, doi:10.1007/978-1-4614-8896-5_1.

[2] "ETSI EN 302 567 V2.1.1," tech. rep., ETSI, 07 2017. European Telecommunications Standards Institute, [Online], link: EN 302 567 - V2.2.1 - Multiple-Gigabit/s radio equipment operating in the 60 GHz band; Harmonised Standard for access to radio spectrum (etsi.org)

[3] K. Fukunaga, S. Watanabe, H. Asou, and K. Sato, "Dielectric properties of non-toxic tissue-equivalent liquids for radiowave safety tests," in *IEEE International Conference on Dielectric Liquids, 2005. ICDL 2005.*, (Coimbra, Portugal), pp. 419–422, IEEE, 2005, doi: 10.1109/ICDL.2005.1490116.

[4] G. Conway, W. Scanlon, C. Orlenius, and C. Walker, "In situ measurement of UHF wearable antenna radiation efficiency using a reverberation chamber," *Antennas Wirel. Propag. Lett.*, vol. 7, pp. 271–274, 2008, doi: 10.1109/LAWP.2008.920753.

[5] Z. Jian, H. Daigoro, and K. Takehiko, "Development of ultra-wideband electromagnetic phantoms for antennas and propagation studies," vol. 626, pp. 1–6, Dec. 2006, doi: 10.1109/EUCAP.2006.4584884.

[6] K. Guido, C. Matos, J. Ramsey, and A. Kiourti, "Tissue-emulating phantoms for in vitro experimentation at radio frequencies: exploring characteristics, fabrication, and testing methods," *IEEE Antennas Propag. Mag.*, vol. 63, pp. 29–39, Dec. 2021, 10.1109/MAP.2020.3003208.

[7] S. Castellò-Palacios, C. Garcia-Pardo, M. Alloza-Pascual, A. Fornes-Leal, N. Cardona, and A. Valles-Lluch, "Gel phantoms for body microwave propagation in the (2 to 26.5) GHz frequency band", *IEEE Trans. Antennas and Propag.*, vol. 67, no. 10, pp. 6564-6573, 2019, doi: 10.1109/TAP.2019.2920293.

[8] N. N. Graedel, J. R. Polimeni, B. Guerin, B. Gagoski, and L. L. Wald, "An anatomically realistic temperature phantom for radiofrequency heating measurements: realistic temperature phantom for radiofrequency heating measurements," *Magn. Reson. Med.*, vol. 73, pp. 442–450, Jan. 2015, doi: 10.1002/mrm.25123.

[9] N. Chahat, M. Zhadobov, and R. Sauleau, "Broadband tissue-equivalent phantom for BAN applications at millimeter waves," *IEEE Trans. Microwave Theory Techn.*, vol. 60, pp. 2259–2266, July 2012, doi: 10.1109/TMTT.2012.2195196.

[10] C. Gabriel, 'Tissue equivalent material for hand phantoms', *Phys. Med. Biol.*, vol. 52, no. 14, pp. 4205–4210, Jul. 2007, doi: 10.1088/0031-9155/52/14/012.

[11] H. Tamura, Y. Ishikawa, T. Kobayashi, and T. Nojima, “A dry phantom material composed of ceramic and graphite powder,” *IEEE Trans. Electromagn. Compat.*, vol. 39, no. 2, pp. 132–137, 1997, doi: 10.1109/15.584935.

[12] G. Fixter, A. S. Treen, I. J. Youngs, and S. Holden, "Design of Solid Broadband Human Tissue Simulant Materials", *IEE Proc. - Sci. Meas. Technol.*, vol. 149, no. 6, pp. 323-328, 2002, doi: 10.1049/ip-smt:20020647.

[13] R. Guraliuc, M. Zhadobov, O. De Sagazan, and R. Sauleau, “Solid phantom for body-centric propagation measurements at 60 GHz,” *IEEE Trans. Microwave Theory Techn.*, vol. 62, no. 6, pp. 1373–1380, June 2014, doi: 10.1109/TMTT.2014.2320691.

[14] J. Chang, M. Fanning, P. Meaney, and K. Paulsen, “A conductive plastic for simulating biological tissue at microwave frequencies,” *IEEE Trans. Electromagn. Compat.*, vol. 42, pp. 76–81, Feb. 2000, doi: 10.1109/15.831707.

[15] M. Zhadobov, N. Chahat, R. Sauleau, C. Le Quement, and Y. Le Drean, “Millimeter-wave interactions with the human body: state of knowledge and recent advances,” *Int. J. Microw. Wirel. Technol.*, vol. 3, pp. 237–247, Apr. 2011, doi: 10.1088/1361-6560/ab057a.

[16] K. Li, K. Sasaki, S. Watanabe, and H. Shirai, “Relationship between power density and surface temperature elevation for human skin exposure to electromagnetic waves with oblique incidence angle from 6 GHz to 1 THz,” *Phys. Med. Biol.*, vol. 64, no. 6, p. 065016, 2019.

[17] S. Gabriel, R. W. Lau, and C. Gabriel, “The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz,” *Phys. Med. Biol.*, vol. 41, p. 2251, Nov. 1996, doi: 10.1088/0031-9155/41/11/002.

[18] Sacco, Giulia, Stefano Pisa, and Maxim Zhadobov. "Age-dependence of electromagnetic power and heat deposition in near-surface tissues in emerging 5G bands." *Scientific Reports,* vol. 11, no. 1 p. 3983, 2021.

[19] Technical Data Sheet SYLGARD™ 184 Silicone Elastomer, *The Dow Chemical Company*, 2017, [Online], link: SYLGARD 184 Silicone Elastomer (dow.com)

[20] Safety Data Sheet Sigma-Aldrich 484164 Carbon powder, *Merck Life Science S.A.S*, 2023, [Online], link: 484164 (sigmaaldrich.com)