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Flexible Electromagnetic Phantom with Electrotextile Backing

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Abstract

This paper introduces the first flexible skin-equivalent phantom operating in the millimeter-wave (mmW) range. Its thin and flexible structure makes it suitable for the performance testing of human-centered wireless devices, where mechanical reconfigurability of a planar or conformal surface representing the human body is needed. It consists of a homogeneous layer of carbon powder mixed with silicone, backed by an electrotextile on one side. The thickness and composition of the dielectric layer are optimized to reproduce the reflection coefficient at the air/skin interface around 60 GHz. The maximum relative error between the reflection coefficient of the phantom and the one of human skin is within 3.5% in magnitude and 16.2% in phase.

1 Introduction

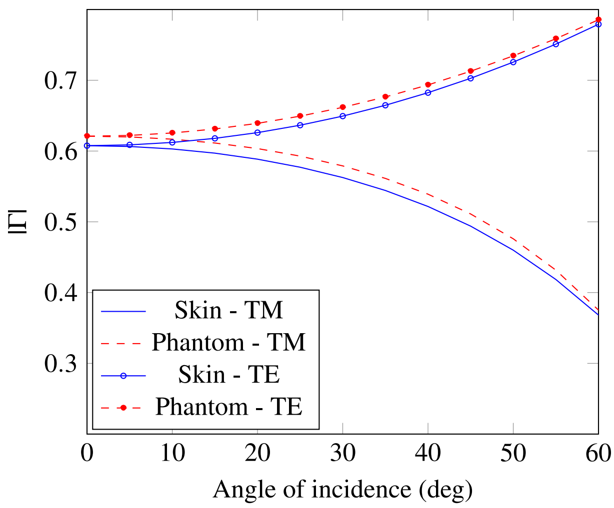
Wireless on-body and near-body sensors are gaining prominence as adds on to conventional wired networks in medical applications [1]. The millimeter-wave (mmW) band and in particular the band around 60 GHz have been identified as promising for such applications due to low interference, high resolution, high data rates, and compact size [2]. To assess the electromagnetic (EM) performance of these wireless devices, controlled testing in real-case scenarios is necessary, including accounting for posture variations and body movements. Experimental tissue-equivalent phantoms are employed for simulating the EM properties of body tissues. Liquid, semi-solid, and solid phantoms have been proposed over the years for this purpose. Liquid phantoms are suitable for in-phantom measurements, such as assessing specific absorption rate (SAR) [3] and testing the performance of wearable devices [4]. However, they require the presence of an external shell that significantly impacts the phantom properties at mmW. Semisolid phantoms approach the mechanical properties of human tissues [5] and they are commonly used for wearable technology and body area network (BAN) testing [6]. Solid water-free phantoms may reproduce complex shapes and have extended lifetimes [7–9]. They are suitable for evaluating the performance of wearable devices or external EM sources [10–12]. However, to the author's knowledge, none of the solutions proposed in the literature so far allows to locally reconfigure, in real-time, the phantom surface.

In this paper, an electrotextile-based skin-equivalent solid mmW phantom is introduced. Its flexibility and thin profile enable it to reproduce conformal non-planar surfaces and to emulate micro-movements of the body surface, such as those caused by heartbeat or breathing.

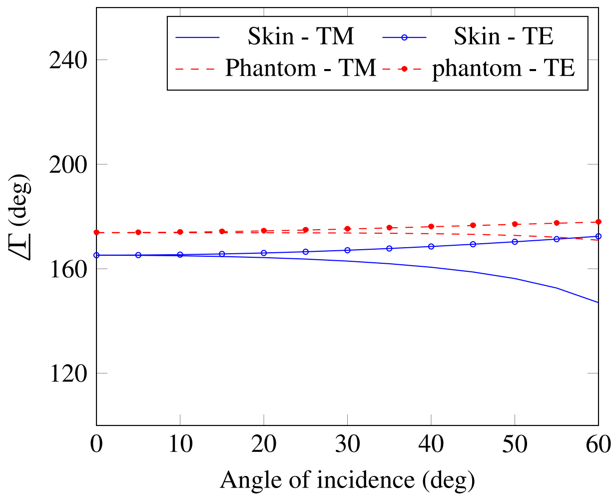
2 Phantom design

At 60 GHz and under normal incidence, the reflection coefficient at the air/skin interface is approximately 60%, with variations based on polarization and angle of incidence [13]. Specifically, it ranges from 20% to 100% for transvers magnetic (TM) mode and from 60% to 100% for transvers electric (TE) mode.To artificially reproduce the reflection coefficient at the air/skin interface, we designed a phantom composed of silicone material mixed with carbon powder and backed with an electrotextile. The electrotextile acts as a ground plane and it shields the phantom from nearby objects positioned behind it. Samples with 40% of carbon were selected to enhance the permittivity and losses, while preserving its elastic properties. Dielectric properties measurements are performed in the 5–65 GHz range using the DAK TL-2. The obtained relative permittivity at 60 GHz is $\varepsilon_r = 13.3{\cdot}(1-j{\cdot}0.28)$.

The phantom thickness is optimized to minimize the deviation between the reflection coefficient at the air/phantom interface and the one at the air/skin interface, considering the relative permittivity of dry skin equal to $7.98 - j \cdot 10.93$ at 60 GHz [14]. The reflection coefficient is computed for angles of incidence ranging from 0° to 60°. A thickness of 2.1 mm is selected for the phantom, as it shows the lowest deviation in terms of magnitude and phase of the reflection coefficient. Figure 1a and 1b show, respectively, the magnitude and phase of the reflection coefficient calculated for the skin and the phantom. Comparing the two results, the average relative error for the amplitude is 2.7% in TM polarization and 1.7% in TE polarization. In terms of the phase, the average relative error is 8% for TM polarization and 4.6% for TE polarization. The maximum relative error pertains to the phase of the reflection coefficient, reaching 16.2% and occurring in the TM mode at 60°.



(a)



(b)

Figure 1. (a) Magnitude and (b) phase of the reflection coefficient for a homogenous skin model and the phantom for TM and TE modes at 60 GHz.

3 Realization

To fabricate the phantom, we used SYLGARD 184 Silicone Elastomer base and curing agent [15], and Sigma-Aldrich 484164 Carbon powder [16]. The process begins by preparing the silicone, where one part of the curing agent is added for every ten parts of the base, followed by thorough mixing. Carbon is then incorporated into the mixture to achieve a 40% concentration of the total weight of the composite, with careful mixing until homogeneity is achieved. The air bubbles introduced during this process, are removed in a vacuum chamber. The mold is then oven-cured at 110 °C for two hours, allowing the liquid composite to solidify. To ensure the maximum stretching of the electrotextile without folds, the solid silicone-carbon layer is placed on a flat surface, and the textile is draped over it, stretched, and hold in place while silicone is poured on it as a glue. The silicone is then solidified in the oven at 110 °C for an hour. Fig. 2 shows the flexible phantom realized through this process.

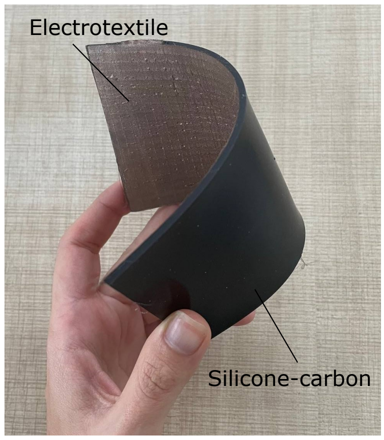


Figure 2. Realized silicone-carbon phantom.

4 Conclusions

The study aims to design, fabricate and characterize the first flexible solid skin mmW phantom. It is composed of a silicone-carbon mixture, to emulate the scattering properties of human skin around 60 GHz. To maintain flexibility and introduce adequate losses, a 40% carbon concentration was chosen. The proposed phantom remains stable over time without requiring special care, and its flexibility makes it suitable for applications requiring non-planar and/or moving surfaces. For example, a planar phantom can replicate the micro-movements of the body surface, simulating the chest displacements associated with heartbeats and breathing activity.

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