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Utilization of a Novel High-Permittivity Flexible Substrate for the Design of a Wearable Antenna for In-Body Communications

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***Abstract*—This paper involves the design and analysis of a coplanar waveguide-fed loop antenna produced on a novel high-permittivity flexible substrate (HPFS). The fabricated HPFS with the dielectric constant of 10 provides the authors with not only desired durable flexibility but also facilitates outstanding antenna miniaturization. The proposed antenna has an overall size of 53 mm x 68.5 mm x 2 mm and operates at 403 MHz centred MICS band. It is designed to be directly placed on the human body without any separation. The input parameters of the antenna are analyzed for different bending scenarios. The in-body transmission performance is analyzed in a back-to-back scenario where two antennas are located on the anterior and posterior torso. It has been shown that the antenna is operational at the intended frequency band with more than 30 dB return loss and approximately -46 dB simulated transmission coefficient for 21 cm in-body propagation length.**

***Index Terms*—Body sensor networks, wearable sensors, loop antenna, dielectric constant, coplanar waveguide, flexible, in-body communication**

I. Introduction

Today, it is clear that there is a requirement for comprehensive healthcare services with the growing population around the world. The report published by World Health Organization (WHO) and World Bank in December 2017 showed that half of the world's population lacks fundamental healthcare services [1]. In addition, the COVID-19 pandemic demonstrated that remote, noninvasive, and easily accessible telehealth applications should be further improved. Therefore, on-body sensing systems have been drawing attention [2].

On-body antennas can be used as wearable sensors for certain applications where the in-body link between wearable antennas is affected by the parameter to be sensed. While a direct mapping between the transmission coefficient and the parameter to be sensed might be possible, it can be challenging for poor transmission scenarios. The sensitivity can be improved by the meticulous design of the wearable antenna. So, there are lots of constraints and challenges in the design of wearable antennas. While the propagation into the human body should be maximized, specific absorption rate (SAR) restrictions and biocompatibility should be taken into account [3].

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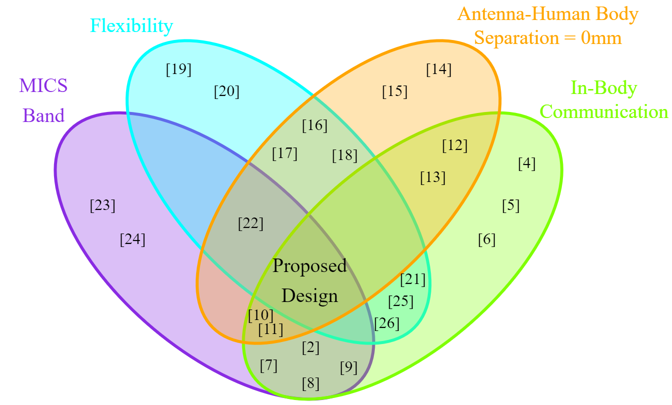

Fig. 1: The comparison between the proposed antenna and the related antennas in the literature.

There are numerous on-body antenna designs in the literature [4]–[26]. These on-body antennas are designed to operate for various standards such as the medical implant communication system (MICS) band ($402 - 405$ MHz), industrial, scientific and medical (ISM) bands ($2.4 - 2.5$ GHz) and ($5.725 - 5.875$ GHz), and ultra-wideband (UWB). One common concern among all these antenna designs is the user acceptability issue which can be overcome by utilization of flexible substrates [16]–[21]. The flexible substrates discussed in the literature include RF substrates with thin profile [20], standard wearable materials such as jean or wool fabric [17], [18] or foam [16], [19], [21]. For all cases, miniaturization using substrate loading is not possible. The wearable materials have low permittivity due to their nature while the thin substrates fail to load the antennas due to their low filling factor. Here we are utilizing a novel flexible material which has high permittivity to achieve both flexibility and miniaturization simultaneously. Increasing the permittivity is achieved by doping polymer substrates with high permittivity ceramic materials [27]. The most commonly used polymer is PDMS while common doping ceramics include Al_2O_3 [25], $BaTiO_3$ [27], and $SrTiO_3$ [28]. Here we achieved a relative permittivity value of 10 by doping RTV silicone with graphite which has never been proposed for the development of HPFSs before.

The on-body antenna design requirements differ depending on the application they are used for. For example, on-body antennas forming in-body links should be optimized to propagate into the human body [2], [4]–[13], [21], [25], [26]. While the requirements vary, the user acceptability aspect still holds. However, most of the studies in the literature prefer performance over flexibility since in-body links often are used for medical applications rather than consumer usage. Among these studies, only [25] and [26] use flexible substrates. An antenna array printed on a flexible polymer-ceramic composite comprising RTV silicon and Al_2O_3 is proposed in [25]. The antenna elements are utilized in the frequency range of $0.9 - 2.5$ GHz for head imaging. Similarly, reference [26] presents another antenna array system operating at around 1 GHz printed on a custom flexible substrate for head imaging. Moreover, both designs include a flexible matching layer between the head and the antennas for better impedance matching. Distinctly, we designed an antenna on a flexible HPFS at 403 MHz MICS band and placed it directly on the human body without any matching layer.

In this article, an on-body flexible antenna operating in the MICS band for in-body communications is introduced. A comparison between the proposed antenna and the other closely related antennas is given in Fig. 1. The structure we propose is a coplanar waveguide-fed loop antenna. The novelty in this paper lies in the fact that we utilize a novel high permittivity substrate and achieve a reasonably sized flexible on-body antenna although our frequency of operating is 403 MHz. The high permittivity value of the fabricated substrate is used for miniaturization and hence a reasonable antenna size as well as satisfying the user's convenience with high flexibility.

This paper is organized as follows: the introduction is followed by section II, where the antenna design and the production of the HPFS are presented. In section III, simulation and measurement results are discussed. Finally, the work is concluded in section IV.

II. HPFS & Antenna Design

A. HPFS Production

The constituent materials of the novel HPFS are RTV-2 silicone as the polymer matrix and microscale graphite powder as the filler. To create the substrate, the RTV-2 silicone base and graphite powder were mixed in a mass ratio of 15:6 to achieve the intended relative permittivity level of 10. After achieving a uniform mixture, a curing agent was added to the mixture in a mass ratio of 15:0.2 (RTV-2 silicone base:curing agent) and mixed vigorously for more than 4 minutes. The prepared silicone-graphite mixture was then poured into a mold of the desired shape. Following the curing step, the relative permittivity and loss tangent of the HPFS were measured at room temperature using Speag's DAKS 3.5 dielectric measurement kit. The measured data is presented in Fig. 2.

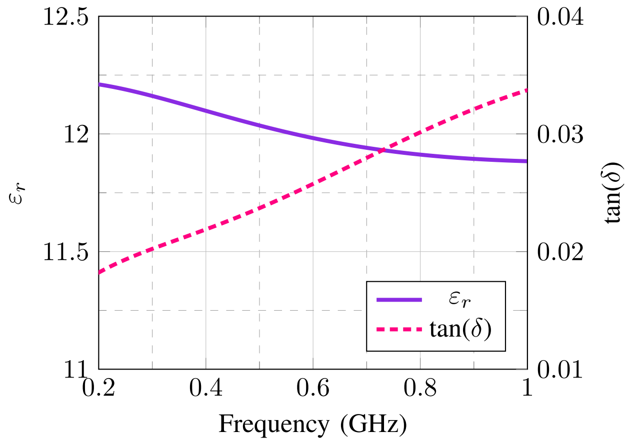

Fig. 2: Relative permittivity and loss tangent values versus frequency for the fabricated HPFS.

B. Antenna Design

In this work, an antenna on HPFS is designed to be placed directly on the anterior and posterior torso. The antenna is expected to operate under a high dielectric load due to the body tissues. Therefore, the loop antenna structure that can perform sufficiently at high dielectric load is preferred. Fig. 3a shows the coplanar waveguide-fed loop antenna that is designed. Parametrized dimensions are indicated in Fig. 3a and the optimized values are listed in Table I. With these values the antenna operates at the MICS band. The prototyped antenna can be seen in Fig. 3b.

The antenna is going to be located on the human body which on average has high permittivity and high conductivity. However, these values are going to change depending on the position of the antenna on the human body and from person to person depending on the body fat index [3]. Our aim here is to minimize the effect of this change on the antenna performance as much as possible. That's why, we are trying to trap the near-field of the antenna in a controlled medium. To achieve this, the loop is sandwiched between 1 mm thick HPFSs. The relative permittivity of the substrate is estimated to be 10 with a dielectric loss tangent (tanδ) of 0.03. The sandwiching results in not only the near-field trapping that we target but also provides miniaturization. The overall size of the proposed antenna is 5.3 cm by 6.85 cm, which is quite acceptable considering the operating frequency and flexibility property.

III. Results & Discussion

A. Simulation & Measurement Setup

It is envisaged that the proposed antenna is going to be placed on the anterior and posterior torso. Therefore, the

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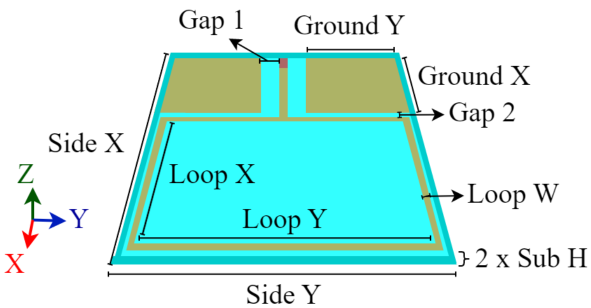


(a)

(b)

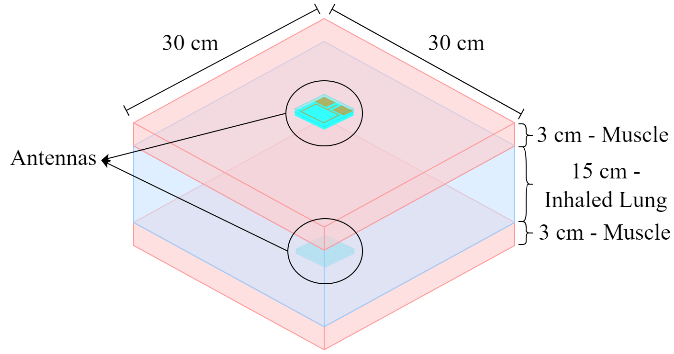
Fig. 3: (a) Oblique view of the proposed coplanar waveguide-fed loop antenna and its parametrized dimensions. (b) Prototyped antenna.

TABLE I: Dimensions of the proposed antenna.

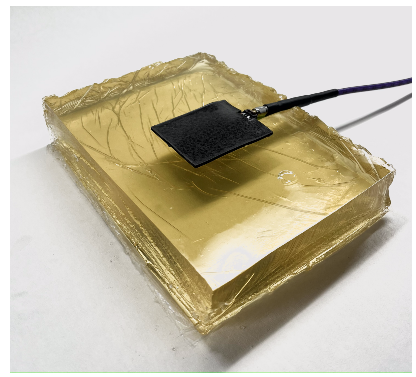
Parameter	**Dim. (mm)**	**Parameter**	**Dim. (mm)**
Sub H	1	Loop W	1
Side X	68.5	Gap 1	1.5
Side Y	53	Gap 2	3.5
Loop X	50	Ground X	12
Loop Y	49	Gound Y	24.8

simulation setup shown in Fig. 4a is prepared in HFSS. 15 cm of inhaled lung tissue block is sandwiched between 3 cm of muscle tissue blocks for the numerical phantom. The measurements are taken on both the realistic phantom and the back of the first author. The relative permittivity and the conductivity of the realistic phantom shown in Fig. 4b were measured at room temperature using Speag's DAKS 3.5 dielectric measurement kit and the values are 59.43 and 0.34 S/m at 405 MHz respectively.

Frequency-dependent muscle tissue which is available in the HFSS library is used for muscle blocks whereas dielectric properties of the inhaled lung are assigned manually according to the data provided by IT'IS foundation [29]. The dielectric constant of 23.8 and the conductivity of 0.375 S/m are used for the simulations at 403 MHz.



(a)



(b)

Fig. 4: (a) The simulation model. (b) The realistic measurement setup.

B. Simulation and Measurement Results

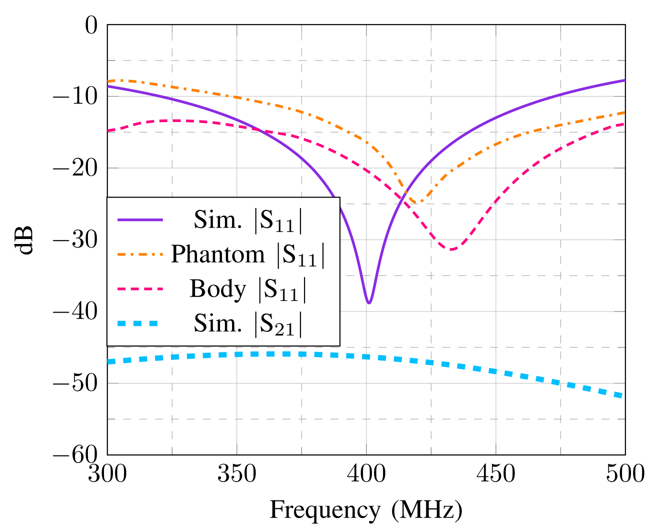


Fig. 5: The simulated and measured return loss, and back-to-back transmission for 21 cm propagation length. Measurements on realistic phantom and human body are shown separately.

The simulated and measured return loss ($|S_{11}|$) plots and the simulated transmission response ($|S_{21}|$) are plotted in

Fig. 5. The proposed design has an acceptable reflection performance in a relatively larger interval than the MICS band, and it is matched at 403 MHz. It can be seen that the measurements agree with the simulations. The large bandwidth guarantees immunity to detuning effects. Note that the antenna is conformable and the performance should also be immune to various wrapping conditions. Hence, conformability analysis is conducted.

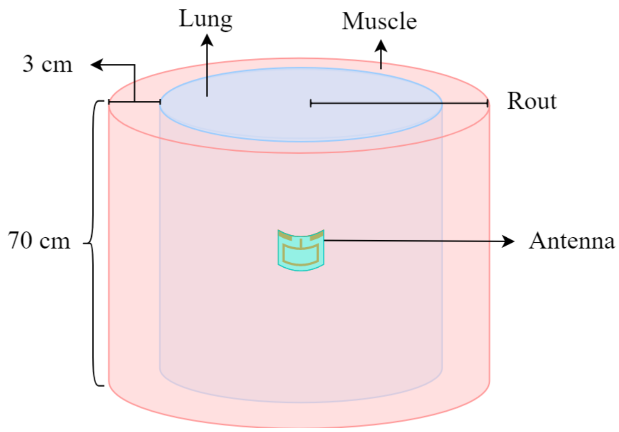


Fig. 6: The simulation model prepared for the conformability analysis.

The setup for the conformability analysis of the proposed antenna is given in Fig. 6. In order to mimic real-life applications, the antenna is wrapped around a cylinder representing the human torso. In a similar fashion to our previous simulation setup, a two-layer numerical phantom is used as seen in Fig. 4. To inspect the effect of bending, the radius (Rout) of the numerical phantom is altered gradually. As seen in Fig. 7, the proposed antenna has a stable $|S_{11}|$ performance with less than 3.5% detuning. It should be noted that the reflection performance in the MICS band is still acceptable. Moreover, the simulated 1 g average SAR value at the resonant frequency for an incident power of 10 mW is 0.3442 W/kg abiding by the limit of 2 W/kg set in the European Standards.

IV. Conclusion

This article presents an on-body loop antenna designed to operate in the MICS band. The presented antenna is produced utilizing a novel HPFS with a relative permittivity value of more than 10. The HPFS provides flexibility, miniaturization, and immunity to near-field effects. The input parameters of the antenna are shown to be suitable for the intended application of in-body communications through both simulations and measurements. Moreover, a conformability analysis is conducted and the antenna is shown to be performing well under various wrapping conditions. In the future, the proposed design can be used to track smart implants and on-body sensors, and diagnose different medical conditions.

Acknowledgement

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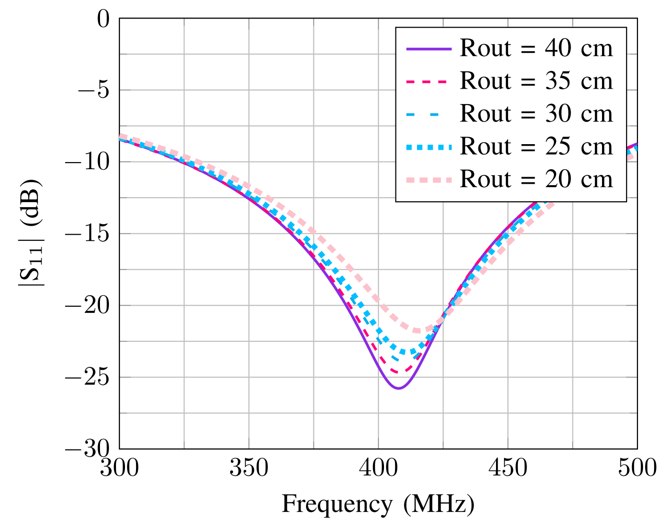

Fig. 7: The conformability analysis, the return loss for different Rout values.

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