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Analysis of a Compact Multi-Band Textile Antenna for WBAN and WLAN Applications

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Abstract—**A dual-band wearable antenna is designed on a textile material. The design operates at ISM bands available for Wireless Body Area Network (WBAN) and Wireless Local Area Network (WLAN) with an input match better than -15 dB. The antenna is designed by using Computational Electromagnetic Software (CEMS) based on Finite-Difference Time-Domain (FDTD) method. A three-layer phantom model including skin, fat and muscle has been considered to compute the specific absorption rate (SAR). The maximum value of SAR averaged over 1g and 10g of tissue is less than 1.6 W/Kg and 2 W/Kg, respectively, when the maximum incident power of the antenna is 63 mW. These values are incompliance with the international electromagnetic safety standards.**

Index Terms— **Antennas on textile, multi-band antennas, Specific Absorption Rate (SAR), wearable antennas, wireless Body Area Network (WBAN), 802.15.6, 802.11n.**

I. INTRODUCTION

THE ADVANCEMENT of wireless networks and Complementary Metal Oxide Semiconductor (CMOS) low power integrated circuit technology introduced the usage of wireless sensor nodes in many applications ranging from comfort enhancing consumer products to therapeutic medical devices.

In the last two decades, several standards have been developed for such use. Wireless Personal Area Network (WPAN), Medical Implant Communication Service (MICS) and WBAN are examples of these standards. Some outdoor applications also utilize 802.11n bands.

The allocation of 402-405MHz band for MICS for the use of devices in diagnostic and therapeutic purposes enabled numerous application opportunities [1]. Many implantable, in-vitro and body worn medical devices from cardiac defibrillators to wireless capsule endoscopic devices which utilizes this band are being developed [2]. The communication shift from inductive coupling to wireless telemetry put more emphasis on the antennas used in such systems. Many different varieties of antennas have been developed for such applications. The remote-control units utilized helical or dipole antennas whereas planar antennas such as meandered inverted-F type is preferred for body implants [3], [4].

Although the MICS frequencies were close to optimum in terms of balancing the size of antennas and losses due to human tissue and flesh, the applications suffered from the low data rates. The allocation of only 300 kHz bandwidth allowed the maximum achievable data rate up to around 450 kbit/s for the MICS applications [4]. This greatly reduce use cases as many modern wireless links involve the fusion of many sensor nodes requiring much higher data rates and smaller device sizes. In 2012, Federal Communications Commission (FCC) allocated 40 MHz of spectrum at 2360-2400 MHz band to Medical Body Area Network (MBAN) as a secondary basis user of the band for short range indoor low power wireless links. The short range is defined as wireless communications in the vicinity of, or inside, a human body. IEEE 802.15.6 communication standard is established for these MBAN devices which can operate with data rates up to 10 Mbps. The standard also considers effects on portable antennas due to human presence. It covers radiation pattern shaping to minimize SAR into the body [5].

With the standardization of WBAN, many wearable medical and consumer products have been released to market. Although the sensors and electronics differ depending on the applications, these devices all utilize some sort of antennas for wireless communications. Many different topologies, materials and forms are investigated to be used as antennas. In addition to wireless medical applications [6], the wearables found applications in many areas such as mobile communications [7] and military [8]. Printing the antenna on textile materials, which is mostly jeans, has become a preferred method for most of the wearable electronics. These antennas must be flexible, low cost, lightweight, and easy to implement on clothes. The antennas are usually placed in proximity of human body which is the

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antenna's reactive near-field region namely Rayleigh region. The performance of the antennas is significantly affected by the presence of the human tissues due to their lossy behavior.

In addition to the degradation of antenna performance, prior studies [9] show that electromagnetic radiations from the antennas may produce a detrimental effect on the human body. As defined in the 802.15.6 standard, the power rating of WBAN device antenna is limited to keep the SAR below a certain level. However, as more wearable applications with complex features are introduced to our daily life, some features require WLAN connection in addition to WBAN operations. Therefore, it is important to consider the rate of electromagnetic energy absorbed by the human tissues at both bands and keep the SAR below the internationally accepted levels.

In this paper, a dual-band wearable microstrip antenna on textile which is operating in both WBAN and WLAN bands is designed, fabricated, and measured. Although a separate piece of jeans fabric material and copper woven conductive fabric are used to build the prototype, it can be printed/painted by using conductive paints on a t-shirt made of jeans fabric, as shown in Fig. 1. The antenna design is carried out by using Computational Electromagnetic Software (CEMS) [10] based on the finite-difference time-domain (FDTD) method [11]. The antenna operates in the WBAN and WLAN ISM bands (2.45 GHz and 5.7 GHz). A three-layer phantom consisting of skin, fat, and muscle is used to imitate the human model. The effects of phantom on the radiation patterns and input reflection coefficient of the antenna are investigated. The SAR distributions over 1g (SAR_{1g}) and 10g (SAR_{10g}) of tissues on the model are computed at 2.45 GHz and 5.7 GHz using ANSYS HFSS [12] with an incident power of 63mW. Numerical results show that the performance of the antenna is affected by the presence of the phantom and maximum SAR_{1g} and SAR_{10g} values for the tissues are less than the internationally accepted standards of 1.6 W/kg set by FCC in the United States [13] and 2 W/kg set by CENELEC in the EU [14], respectively.

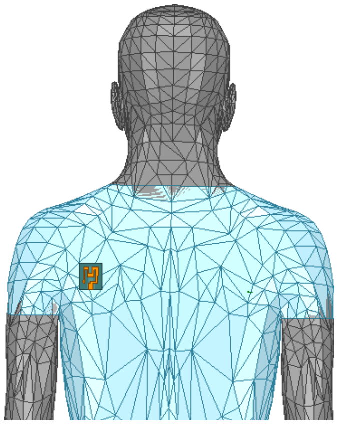

Fig.1. Antenna printed on the back of dress shirt worn by a human.

II. ANTENNA DESIGN AND PERFORMANCE

The top and bottom views of the proposed antenna along with its dimensions in mm are shown in Fig. 2. The wearable microstrip antenna is backed by a partial ground on the bottom of the substrate with a slot. The design is compact with an area of 40mm x 35mm. The antenna is designed on a 2 mm thick jeans substrate of dielectric constant 1.54 with negligible loss. It operates in the industrial, scientific, and medical (ISM) band at 2.45 GHz and 5.7 GHz. The input reflection coefficient (S_{11}) of the antenna is below -15 dB as seen from Fig. 3. Here, the dashed curve shows the simulated performance with phantom where there is 15mm separation between antenna and phantom. The radiation pattern and gain plots of the antenna are shown in Fig. 4.A-C which are similar to that of a monopole antenna, except that it is transformed due to the partial ground plane and the slot.

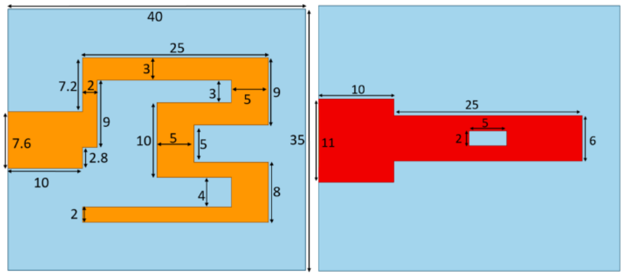

Fig.2. Proposed wearable microtrip antenna, all dimensions in mm. (*left*) Top view of the antenna, (*right*) bottom view with a slotted partial ground.

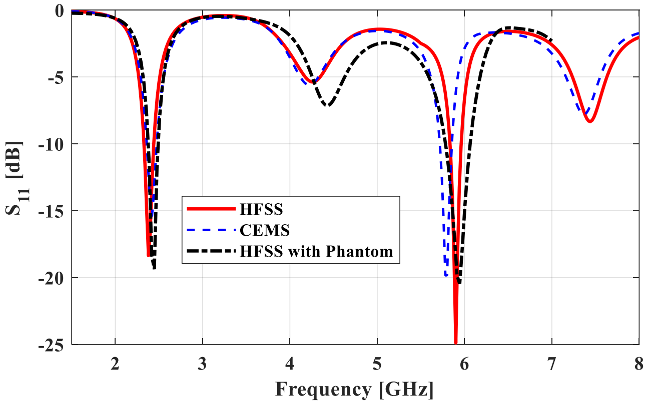

Fig.3. Simulated S_{11} of the antenna.

III. PROPOSED ANTENNA WITH PHANTOM

After the satisfactory performance of the antenna, it was placed in the proximity of a phantom, as shown in Fig. 4. The phantom shown in Fig. 5 consists of a three-layered tissue, namely, skin, fat, and muscle. The electrical properties of the tissues, at the two resonant frequencies, are provided in Table 1. In the table, ε_r and σ represent the relative permittivity and the electrical conductivity of the tissues, respectively.

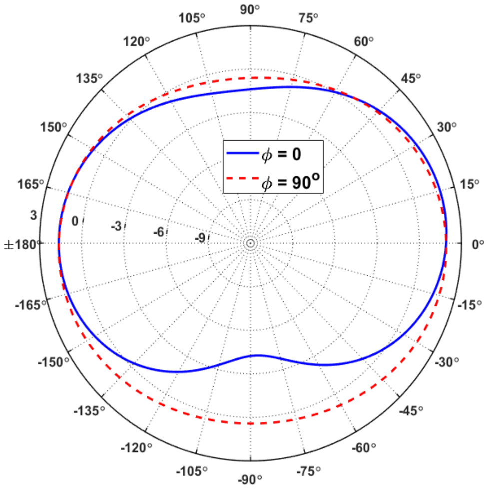

Fig.4.A. Radiation pattern of the antenna.

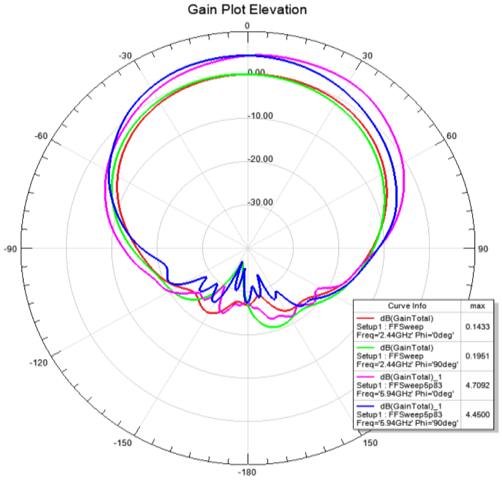

Fig.4.B. Gain plot vs. elevation angles.

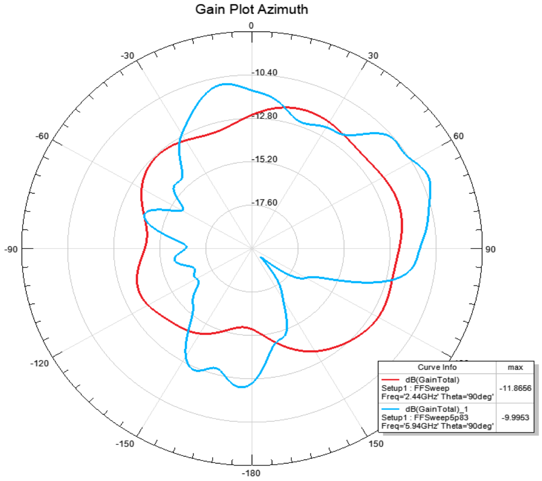

Fig.4.C. Gain plot vs. azimuth angles.

TABLE I
ELECTRICAL PROPERTIES OF TISSUES AT THE TWO RESONANT FREQUENCIES [14].

Tissue	**Thickness**	**2.45 GHz**		**5.7 GHz**	
	(mm)	ε_r	σ (S/m)	ε_r	σ (S/m)
Skin	5	38	1.46	35.2	3.63
Fat	7	5.3	0.11	9.88	0.81
Muscle	30	52.7	1.77	48.6	4.84

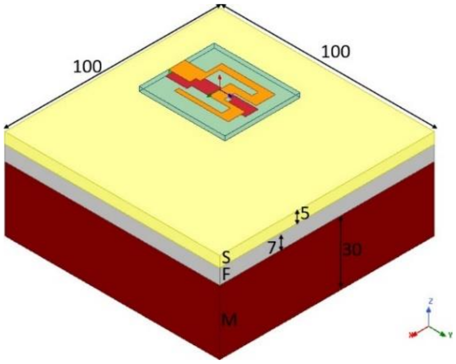

Fig.5. Proposed antenna placed on a three-layered phantom consisting of skin (S), fat (F) and muscle (M) tissue. Dimensions are in mm.

The mass densities of skin, fat, and muscle are assigned as 1020 kg/m^3, 909.4 kg/m^3, and 1060 kg/m^3, respectively. The volume of the phantom was (100 x 100 x 42) mm^3. The antenna was placed 15 mm above the phantom in order to compute the SAR$_{1g}$ and SAR$_{10g}$ distribution over the phantom. The input reflection coefficient of the antenna was not drastically affected by the phantom. It was noticed that the resonance at 7 GHz was further enhanced. The manufactured prototype is shown in Fig. 6.A. Figure 6.B shows the simulated S$_{11}$ of antenna with and without phantom. The measured S$_{11}$ of the antenna being placed at three different locations, chest, back, and shoulder are shown in Fig. 6.C. The SAR$_{1g}$ and SAR$_{10g}$ distributions are calculated for two different frequencies. Since the tissues are dispersive, their electromagnetic properties change with frequency [15]. Therefore, we must use the electrical properties of the tissues at the specific frequency as given in Table 1.

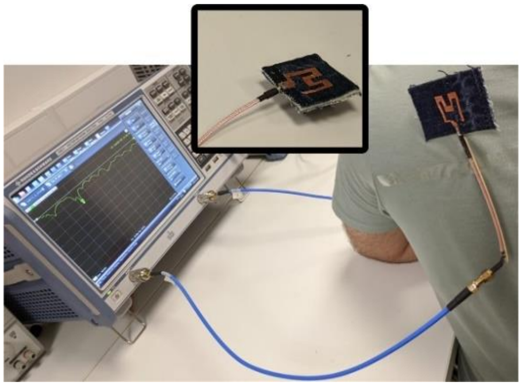

Fig.6. A. Measurement of the proposed antenna.

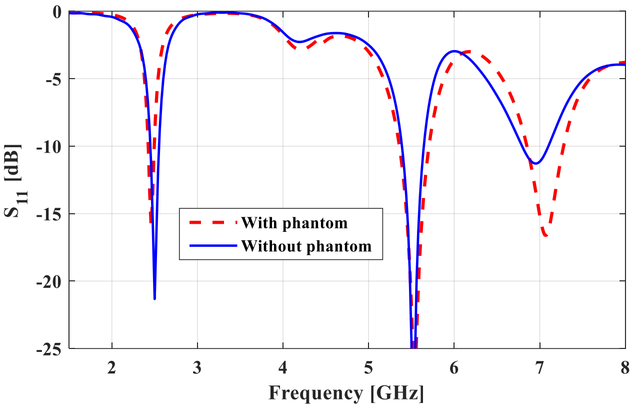

Fig.6. B. Simulated S_{11} of the antenna with and without the phantom.

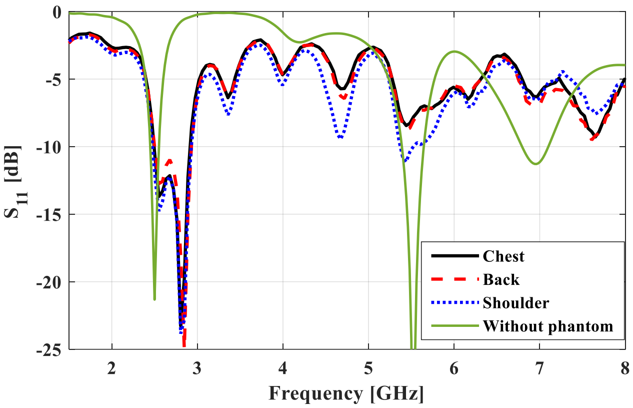

Fig.6. C. Measured S_{11} of the antenna placed on different body parts.

The obtained SAR_{1g} and SAR_{10g} distributions on the phantom due to the proposed antenna are shown at each frequency of interest in Fig. 7 and 8, respectively. The simulation was performed using ANSYS HFSS with an incident power of the antenna set to 63 mW. It can be realized that the maximum SAR_{1g} and SAR_{10g} values are less than 1.6 W/kg and 2 W/Kg, respectively.

Figure 9 shows the radiation pattern of the proposed antenna when it is placed above the phantom. The phantom behaves as a reflector which results in the pattern being directive, unlike the one shown in Fig. 3.

The gain has increased from 2 dB to 6.5 dB. The directivity allows more efficient communication with less power. Similar pattern is observed at 5.7 GHz. Comparison of the results for the proposed antenna with previously published results are presented in Table 2. An ideal antenna for a WBAN device should have maximum gain with minimum dimensions and it should have minimal SAR.

Based on these performance criteria, a Figure of Merit (FOM) which is given in Eq. (1) is defined to compare our antenna with prior work. The performance numbers are shown in Table 2.

$$\mathrm{FOM} = \frac{Gain\ (linear)}{1000(\mathrm{SAR}_{1g}\ \mathrm{x}\ DIM)}. \tag{1}$$

Here, *Gain* is the linear gain of the antenna and *DIM* is the area of the antenna normalized with respect to λ_0^2 at 2.45 GHz. The larger the FOM value is, the more suitable the antenna would be for the intended applications. As shown in the last column of Table II, the proposed antenna in this work has the best performance for such wearable WBAN applications when compared with prior work. Only simulation results are compared.

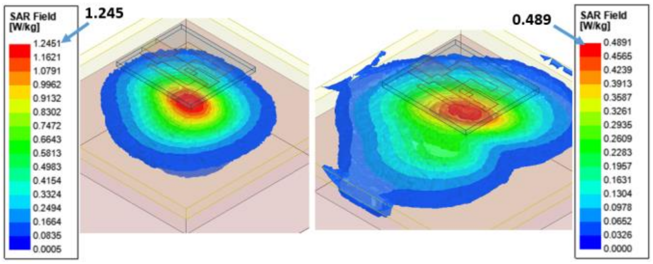

Fig.7. SAR_{1g} distribution in the phantom at (left) 2.45 and (right) 5.7 GHz.

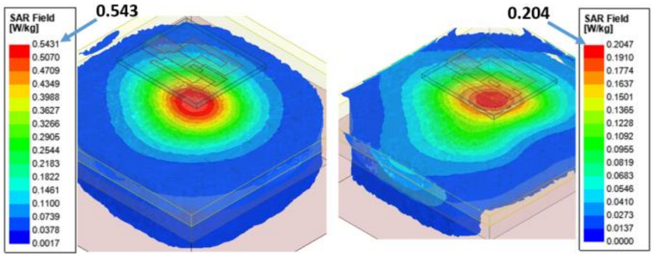

Fig.8. SAR_{10g} distributions in the phantom at (left) 2.45 and (right) 5.7 GHz.

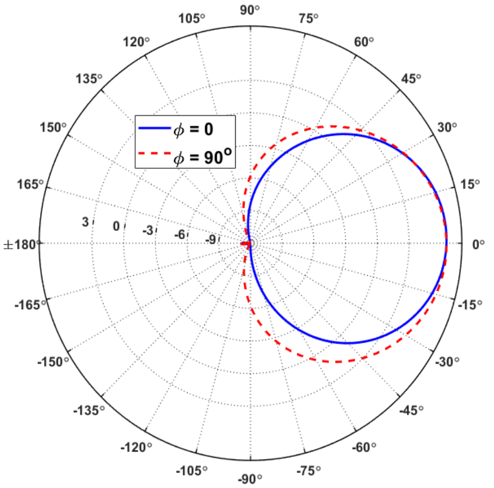

Fig.9. Radiation pattern of the antenna in the presence of the phantom.

TABLE II
COMPARISON OF THE PROPOSED WORK WITH PRIOR ART AT 2.45 GHZ.

Ref.	**Dimensions/λ_0^2**	**Gain (dBi)**	**SAR$_{1g}$ (W/Kg)**	**SAR$_{10g}$ (W/Kg)**	**FOM**
[16]	0.43×0.43	6.8	8.7	NA	378
[17]	0.37×0.30	5.0	32.5	133	2.8
[18]	0.50×0.46	6.8	53.6	11.2	53
[19]	0.50×0.30	6.2	16.8	NA	63
This Work	0.32×0.29	6.5	1.25	0.54	2917

IV. CONCLUSION

An M-shaped dual band wearable antenna on a textile material has been designed at 2.45 GHz and 5.7 GHz for wireless medical body area network and ISM applications. The performance of the wearable antenna is evaluated in the presence of human phantom which is a three-layered model reflecting the electrical properties of a human body. The antenna is built on a textile material and measured by attaching on different locations of a dressed t-shirt on a human torso. Besides verifying electrical performance of the proposed antenna, the specific absorption rate due to the proximity of the antenna is also investigated. The computed maximum SAR$_{1g}$ and SAR$_{10g}$ values at 2.45 GHz and 5.7 GHz are less than 1.6 W/Kg and 2 W/kg, respectively, for the antenna input power of 63 mW. A figure of merit is defined considering the antenna gain, compactness, and SAR values. It can be seen from the numerical results that the proposed antenna has the best FOM and superior performance than prior art and is a suitable candidate for wearable devices operating in the WBAN and WLAN dual-bands.

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