Multi-Layered Low-Profile Monopole Antenna using Metamaterial for Wireless Body Area Networks

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***Abstract*— This article presents a low profile MTM enabled antenna operating at 2.18-2.43 GHz for Wireless Body Area Network (WBAN) application. The integrated antenna comprises of 2x2 H-shaped unit elements underneath the monopole antenna. The integration of ground plane with monopole greatly reduces the surface waves and enhance radiation performance. The integrated MTM antenna lowers the average 1-g SAR to 0.187 W/kg at the designated band when antenna is 1 mm apart from body-tissues. Compare to the reference patch antenna and the planar monopole, the proposed antenna exhibits efficient impedance performance, improved gain and front-to-back (FB) radiation ratio.**

Keywords*— *Metamaterial (MTM), Specific Absorption Rate (SAR), Unit Element.

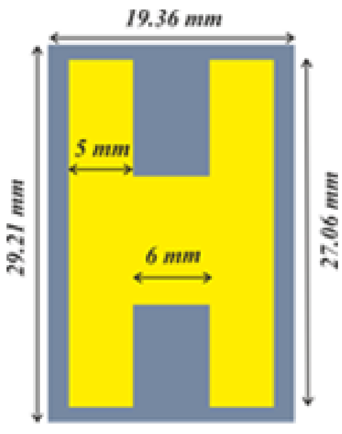
I. Introduction

The low-profile wearable antennas are of growing interest in modern wireless communication systems. The devices are now used for on-body and off-body communication to examine several features for wearable applications[1]. Different planar antennas are designed to operate in wireless body area network (WBAN) applications [2-5]. The existence of the ground plane initiates isolation and reduces the coupling between the human body and the wearable antenna which results in lower SAR values. Wireless implantable sensors have a crucial part in the fields of medical, personal health maintenance, safety, and security. To provide a wireless and low-cost communication connection between the human tissues and surrounding environment across wearable and implantable devices, implantable radio-frequency identification (RFID) technology devices contributes an important role [6-7]. Body-mounted wireless communication devices are contemplated a vital role in fourth-generation (4G) mobile communications systems. Therefore it is assumed to be associate of the upcoming convergency and systematization of personal area network (PAN) and body-area network (BAN) applications. To examine the wearable performance of different human body parts, a rectangular microstrip antenna has been designed at 2.4 GHz industrial, scientific, and medical (ISM) band [8]. Now-a-days as use of wearable devices become too familiar, health issues arising from electro-magnetic radiations become an important issue. AMC structures can behave as a perfect magnetic conductor (PMC) and govern the radiation mechanism of the antennas. Therefore, AMC based antenna structures are efficient for blocking dangerous electro- magnetic radiations being emitted towards direction of the body.

In this article we propose a multi-layered, low-profile MTM enabled antenna for reducing SAR in the respective band. The paper shows the design methodology and performance of unit element and MTM layer and analyses the reflection properties. The antenna is placed above the MTM layer substrate composed of two dielectric layers parted by gap of air. The MTM enabled antenna offers effective impedance performance compare to that of microstrip patch and monopole antenna. To increase the gain further, we use multi-layered substrate with same dielectric material to reduce surface waves. The simulated results show that the MTM enabled antenna exhibits efficient impedance matching with S_{11} minima of -30.71 dB, gain of 2.45 dBi and FB ratio of 13.74 dB. It is also exhibit that the insertion of the MTM greatly minimizes back lobe radiation. The low values of SAR further signifies the usability of the MTM antenna for body-centric applications.

II. Design of Unit Cell & MTM

The unit-element configuration of metamaterial (MTM) antenna is presented in Fig.1 (a). In this article, FR4 Epoxy substrate with ε_r of 4.4, tan δ of 0.0009 is used for the structures. The MTM unit-element is verified by its reflection phase features. Therefore two master-slave boundary conditions are applied for infinite repetitions in Ansys HFSS. A 2x2 unit-element array is selected depending on the overall size of the antenna and shown in Fig. 1(b). The separation between the two adjacent unit-elements towards x and y axes are g_1=5.73mm and g_2=6.64mm. Fig. 1(c) shows that the zero phase reflection ranges between ±180° and crosses zero near 2.5 GHz. Fig. 1(d) shows that the magnetic field of the H-shaped element attains its peak value around 2.5 GHz corresponding to zero reflection phase.



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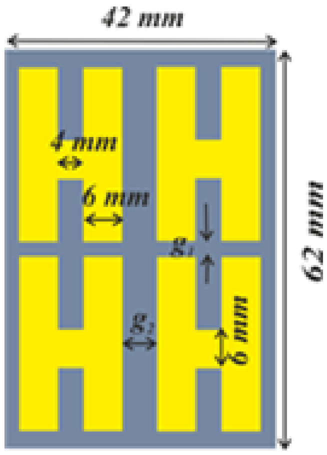

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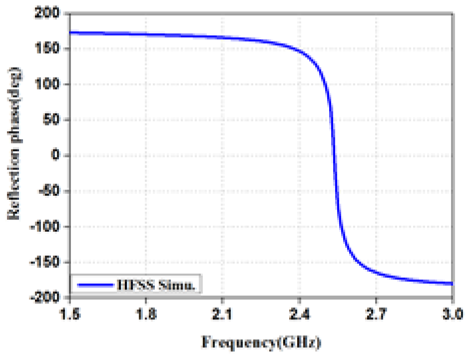

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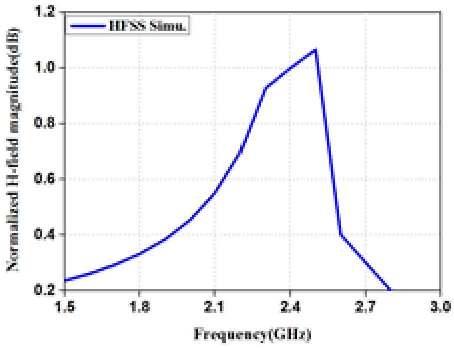

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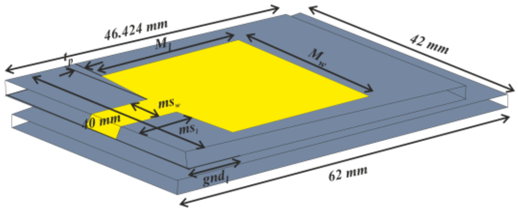
Fig.1 (a) Design of single unit-element (b) Design of 2x2 unit- element array (c) Simulated Reflection phase and (d) Normalized H-field magnitude of single unit-element.

III. Monopole Design

The arrangement of proposed antenna layers is shown in Fig. 2(a) and dimensions are M_w=38 mm, M_l=29.424 mm, ms_w=8 mm, ms_l=12 mm, gnd_l=10 mm and t_p=1.15 mm. FR4 Epoxy material is utilized to design and fabricate the 50Ω feed antenna. The antenna is situated on top of ground surface at a height of 2.4 mm. The antenna substrate is consisted of three layers. The height of the two substrates are 0.4 mm. The two dielectric materials are separated by a layer of air with 1.6 mm height. The monopole is designed to increases gain, FB radiation ratio and impedance performance while integrated with the MTM. Fig. 2(b) presents the multi-layered structure of MTM antenna.



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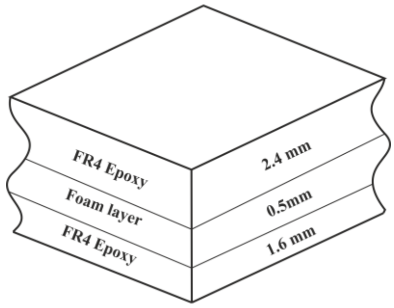


(b)

Fig. 2 (a) Layout of proposed antenna and (b) multi-layered arrangements.

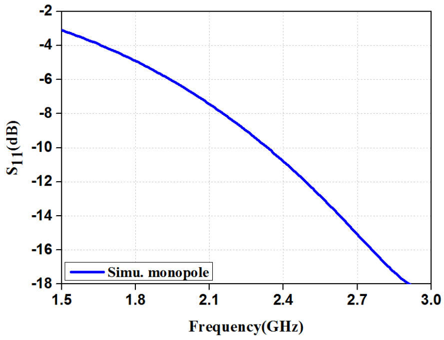
IV. Integrated Antenna Design

The proposed antenna is consisted of three substrates. It consist of monopole, foam and a 2x2 MTM array. Integrated antenna is consisted of two elements parted by a foam substrate of 0.5 mm. The antenna is situated collateral to the x- axis of the periodic construction for a coherent excitation. The position of the antenna relative to the metamaterial (MTM), which governs the coupling between the monopole and the metamaterial (MTM). The numerical dimensions of the antenna were optimized so that this attains the impedance matching, higher gain and higher FB ratio at the designated frequency band.

V. Result and Discussion

A. Analysis of the Proposed MTM

The performance of the MTM antenna has been examined in terms of S_{11}. If the antenna is positioned on top of the continuous metallic ground, it shows an immensely bad impedance performance throughout the whole band around 2.4 GHz as shown in Fig. 3(a). After verifying the dimensions of MTM, the antenna is situated at a height of 4 mm and incorporated with the MTM. Thus an impedance matching (S_{11}<-10 dB) is achieved from 2.18 GHz to 2.43 GHz. The measured results also agrees well with the simulations. It is observed that the integrated monopole antenna provides S_{11} minima of -30.71 dB at 2.38 GHz and offers 10.41% bandwidth. It is also seen from Fig.3b that the integrated antenna offers enhanced impedance characteristics in comparison to that of the reference patch antenna. The integrated MTM enabled antenna lowers S_{11} minima by -26 dB as compared to reference patch antenna. Almost all of the previously demonstrated integrated body-centric antennas which consist of a PEC artificial magnetic conductor ground plane, have an operational frequency band same as zero reflection phase frequency of the PEC backed metamaterial (MTM) substrate. However, it behave as an inductive surface because the operating frequency band of the integrated antenna is near the same frequency range where the zero-phase-reflection is approximately ±90°. Because the monopole antenna is operating at 2.38 GHz frequency band which is lower than 2.4GHz and therefore the input impedance value is capacitive. The inductive impedance surface which accumulates enough magnetic energy and hence a better impedance match is achieved by reducing the reactance of the metamaterial (MTM) integrated antenna. This too validates an antecedent hypothetical research on this matter. These analysis revealed that an appropriately designed PEC backed metamaterial (MTM), too with a significantly shorten area in the horizontal plane, can provide increase to substantial enhancement in the impedance matching for miniaturized low-profile antenna. These type of conception can also be appeal to different varieties of planar antennas.



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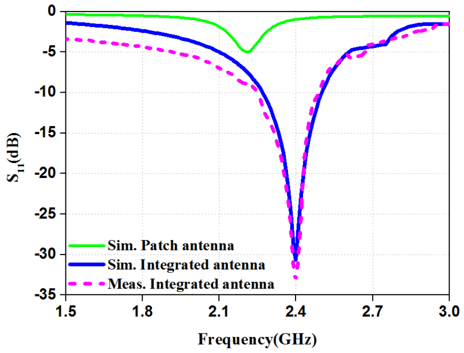
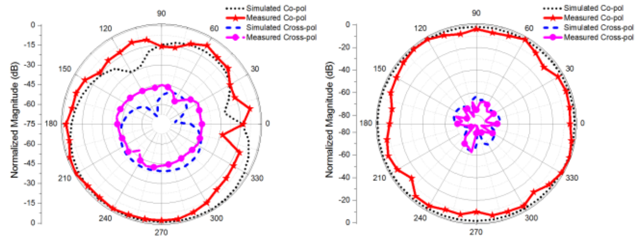


(b)

Fig. 3 Simulated S_{11} of (a) Patch antenna, and simulated and measured S_{11} of (b) MTM Integrated antenna.

B. Radiation pattern,Gain and FB ratio

The simulated and measured field patterns are shown in Fig. 4 to explain polarization. A dipole type criterion is noticed in E-field and an omni-directional criterion is noticed in H-field. Comparing with monopole, the MTM antenna has lowered backward radiations which indicates less EM energy transmission. The low backward energy transmission property supports to decrease the peak specific absorption rate. This also helps to construct the antenna further robust to loading effects of the human body. These two are the sensible features of implantable antenna applications. It should also be prominent that specific absorption rate and front-to-back radiation ratio properties are owned to other radiating areas. But these properties are interconnected to a certain level, because the back radiation and specific absorption rate of integrated antenna are both produces diffracted wave at the ground plane edges.



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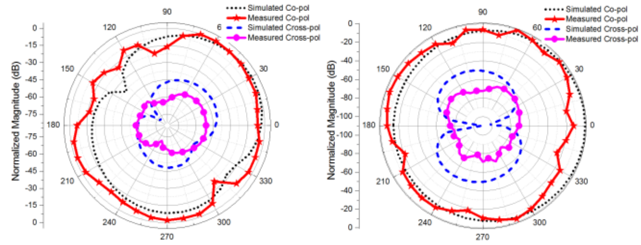
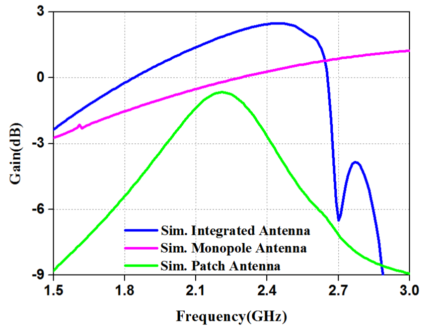


(b)

Fig. 4 Simulated and measured E-field and H-field of (a) Monopole alone and (b) MTM antenna.



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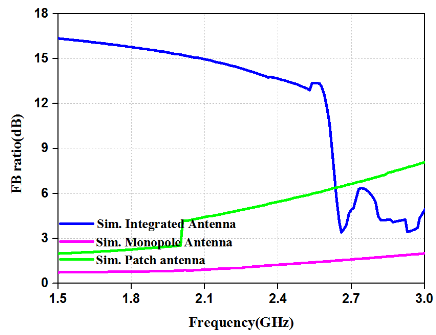


(b)

Fig. 5 (a) Gain and (b) FB ratio of monopole, reference patch and integrated antenna.

Fig. 5(a) presents that the monopole possess a gain of 0.4325 dBi and the MTM antenna offers a gain of 2.45 dBi at the respective frequency band. A conventional reference antenna has been designed at 2.4 GHz and contrast with MTM antenna. The patch antenna is showing lower gain in the whole band as compared to the MTM antenna due to backward energy transmission. Fig.5 (b) presents the front-to-back radiation ratio of monopole, patch and MTM antenna. The MTM antenna offers a FB radiation ratio of 13.74 dB while the monopole antenna shows 1.22 dB. Compare to MTM antenna the patch antenna also offers lower gain in the whole region. Therefore, it is proved that incorporation of MTM has reduced the backward radiation and increases FB ratio and gain significantly.

The radiation efficiency of metamaterial antenna is presented in Fig. 6. The MTM antenna gives a value of 0.963 at 2.38 GHz when it is situated at 4 mm apart from the MTM. Fig.7 presents the E-field and surface current distributions of the MTM antenna at the respective frequency band. To verify the different propagating modes of the antenna, we have considered vector electric-field variation (VEFV) through the vertical faces of the substrate.

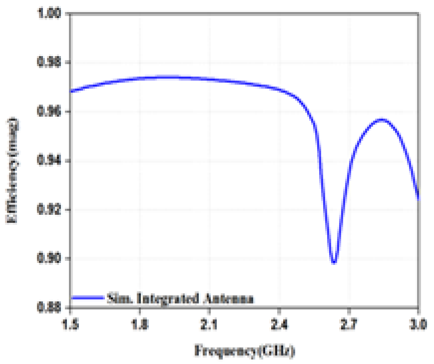
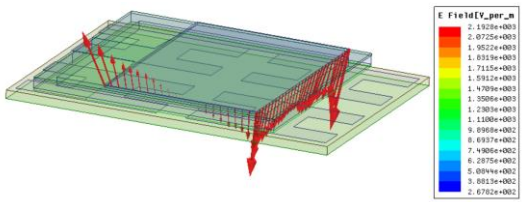


Fig. 6 Simulated radiation efficiency of MTM antenna.



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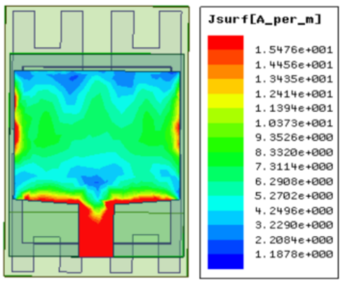


(b)

Fig. 7 Simulated (a) E-field distribution and (b) surface current distribution of integrated antenna.

To indicate the propagation modes of radiating element and understandable anticipation, the substrate dimensions have been shortened to the width and length of the radiating element and electric-field vector has plotted for the vertical sides of monopole, as depicted in Fig. 7(a). It is noticed in Fig. 7(a) that at 2.38 GHz, we got one half wave cycle (HWC) along the monopole length, therefore gives the TM_{10} mode. The high current distributions of antenna is shown in Fig. 7(b).

VI. HUMAN TISSUE MODEL ANALYSIS

In this section, we have analysed the human tissues effect for metamaterial(MTM)-antenna. A human phantom model for body-centric application is designed as presented in Fig. 8. The phantom model consists of skin, fat, muscle and bone. The gap between MTM and tissue layers was differed to see the loading effect of the human body reduced by MTM. The properties of different material for phantom model is listed in Table 1.

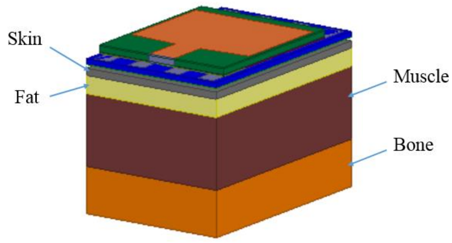


Fig. 8 Artificial body phantom integrated with MTM antenna.

TABLE 1. MATERIAL PROPERTIES OF HUMAN TISSUE PHANTOM.

Human body layers	Materials			
	ε_r	σ(S/m)	Density (kg/m^3)	Thickness (mm)
Skin	37.95	1.49	1001	2
Fat	5.27	0.11	900	5
Muscle	52.67	1.77	1006	20
Bone	18.49	0.82	1008	13

A. SAR Analysis

SAR is a variable to know the electro-magnetic absorption of human body when it is near RF devices. It is generally averaged either 1 g or 10 g of tissue. Specific absorption rate (SAR) values are deliberately counting on the size of the balancing volume. The differentiations between various measured values could not be produced in the absence of the statistics about the volume. Therefore, the European 10-g averaged categories shall be contrasted between themselves. But the American 1-g averaged categories should be compared between themselves only. According to the Federal Communication Commission (FCC) and IEEE C95.1-2005, the SAR value must not be more than 1.6 W/kg. According to specifications, a 100 mW power absorbed by the antenna is selected to examine and contrast the SAR implementation of the proposed integrated antenna. The input power accepted by the body tissues in the existence electro-magnetic field is given by

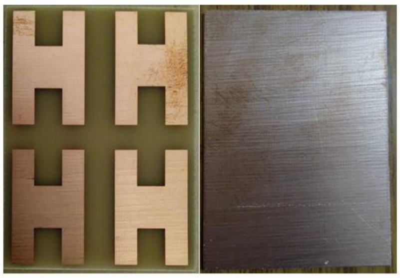
$$SAR = \frac{\sigma |E|^2}{\rho} \quad (1)$$

Where, σ= Conductivity of the human body, E = the electric field of the tissue, ρ= Mass density.

Equation (1) specifies that the input applied power is associated with the electric field. Table 2 describes the SAR values of flat phantom of MTM antenna. Variable d_a represents the air gap between the MTM antenna and body tissues. While MTM is incorporated with monopole, SAR reduces to 0.187 W/kg at 2.38 GHz while it is placed at 1 mm distance. Furthermore, it is seen that while the MTM antenna is positioned at 5 mm apart from the phantom, the average SAR reduces to 0.089 W/kg. The low SAR value specifies less electro-magnetic power absorption towards the human body.

TABLE 2. SAR PERFORMANCE OF MTM ANTENNA AT VARIOUS DISTANCES.

d_a(mm)	SAR(W/kg)
1 mm	0.187
2 mm	0.158
3 mm	0.135
5 mm	0.089



(a)

(b)

Fig. 9 Prototype of (a) metasurface and (b) proposed antenna.

The overall antenna achieves a superior impedance performance when monopole is loaded by inductive surface and reduced the integrated antenna reactance. The MTM and the monopole has been fabricated applying standard PCB board etching and shown Fig.9. A foam layer with the specified thickness has been attached in between the two components. The MTM antenna is measured using Vector Network Analyser. The -10 dB impedance bandwidth of integrated MTM is slightly narrower, but without noticeable frequency shifting. Altogether, the agreement between measured results and simulation results are found satisfactory.

VII. CONCLUSION

This article proposed a low profile, multi-layered MTM antenna for WBAN application. It utilizes 2x2 H-shaped unit-elements array for achieving better gain, better FB ratio, impedance bandwidth and low SAR. The proposed antenna provides 10.41% bandwidth at 2.38 GHz, gain of 2.45 dBi and FB radiation ratio of 13.74 dB at designated frequency band. The multi-layered antenna reduces backward lobe radiation and lower SAR value of 0.187 W/kg at the designated frequency band. The proposed MTM enabled antenna has lowered S_{11} minima significantly and widened the impedance bandwidth compare to that of microstrip patch antenna. The proposed MTM makes it an ideal prospective for gain and FB ratio enhancements, impedance bandwidth and low SAR.

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