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Design and Analysis of a 2.4 GHz Antenna using Metamaterial Ground Planes for Body Worn Wireless Applications

Usman Ali, Sadiq Ullah and Haroon

***Abstract* — In this paper a 2.4 GHz wearable patch antenna is designed on different types of Metamaterial based artificial ground planes. Wearable substrate (butyl rubber) is used in the design of the ground planes which are characterized in terms of surface wave suppression. The slotted Electromagnetic Bandgap (EBG) ground possesses surface wave Bandgap centered at the 2.4 GHz. The EBG-based antenna performance is compared with traditional patch antenna on the breast and muscles of human body. As a proof of concept flat section of human body is considered for the analysis of the antenna.**

The proposed antenna gives a 2.1 dB enhancement in gain, 8.5 dB and 6.0 dB reduction in back and side lobe levels respectively at 2.4 GHz. The 2.4 GHz band is unlicensed ISM (Industrial Scientific and Medical) band which is used in a variety of applications such as Wi-Fi, Body Area Networks (BANs) and medical diagnostics.

The antenna and the EBG surfaces are analyzed using the Finite Integration Technique (FIT) employed in CST-MWS. The proposed antenna is compact, low-profile and light weight, therefore can be used for portable wearable applications.

***Index Terms* — Electromagnetic Bandgap; surface wave suppression, wearable antenna**

I. INTRODUCTION

Portable electronic devices are an integral part of people's life, i.e. use of mobile phones for voice and video calls, internet access, multimedia, video streaming, and video conferencing has exponentially increased during the last decade [1]. A body-worn communication system consisting of portable wireless devices and sensors is the demand of future wearable electronics. The communication devices within the system must have the ability of consistent communication with each other and the outside world under all operating conditions (both fixed and mobile). These goals are achieved using wearable antennas which can guarantee to maintain the wireless link being enabled under these conditions. These antennas are of great interest towards personal communication technology employed in smart clothing, which incorporates a variety of electronic devices, including wireless transmitters, receivers and sensors. In personal electronics, antenna is the key to wearable or hand-held units for communication. Wearable antennas [2-5] are used in portable applications (such as patient monitoring and identification, rescue works, telemedicine and recreation), therefore, are designed and optimized for increase range, longer battery life, lowest cost and compact size (i.e. low profile).

The radiation pattern of the wearable antennas should be away from human body, if used in body-worn applications (such as smart garments). In other words, the radiation pattern must have minimized side and back lobe levels in order to direct maximum power along bore sight direction. In typical microstrip antennas, surface waves [6] are excited in the substrate, causing unwanted side and back lobe radiations which adversely affect gain and efficiency of the antenna. The unwanted radiations from the antennas are absorbed in the human body causing an increase in Specific Absorption Rate (SAR) [7, 8]. To solve this problem various methods, such as designing the patch antenna on low dielectric and externally perforated high dielectric substrates were proposed [9, 10], but at a cost of size and reduction in bandwidth of the antenna. Single layered antennas [11] were analyzed at various heights (or distance) from human body in order to achieve free-space gain but at the cost of size (high-profile) proving it unsuitable for wearable applications.

The EBG structures have the ability to reduce the size (profile) of the antenna due to in-phase reflection. These structures also suppress the surface waves [12, 13] within the required Bandgap to improve the performance of antenna in terms of gain, directivity and efficiency. Hence an artificial ground plane (EBG) can be used to enhance the radiation characteristics of the wearable antennas by minimizing the unwanted side and back lobes.

In this paper an inset feed wearable patch antenna employing an EBG ground plane is designed and analyzed in close proximity of human body. The proposed antenna performance is analyzed and compared with traditional patch antenna on breast and muscles of human body.

The rest of the paper is organized as follows: Section II explains the design methodology of the wearable patch antenna and its performance on breast and muscles of human body. Section III characterizes the two types of EBG surfaces which are used as a ground planes for the proposed antenna. The effects of parts of human body with high water content (i.e. muscles) and breast on the performance of the Metamaterial-based antenna are discussed in this section. Section IV concludes the paper and gives directions for future work.

II. TRADITIONAL PATCH ANTENNA DESIGN AND ON-BODY ANALYSIS

A. *Design of traditional wearable antenna*

The geometry of an inset-feed 2.4 GHz microstrip patch antenna is shown in Figure 1. The dimensions of the patch,

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inset feed and ground plane are found using the well-known patch antenna theory in [14].

The length (L), width (W) and thickness of the radiating patch are 39.22, 47.55 and 0.04 mm respectively. A 1.6 mm thick butyl rubber (ε_r=2.35) is used as a substrate which is backed by a finite (120 mm x 90 mm x 0.04 mm) copper ground plane. The antenna is fed via a 50 ohm inset feed microstrip line of width (w_0=*5.543 mm*) and depth (y_0=*17.5 mm*).

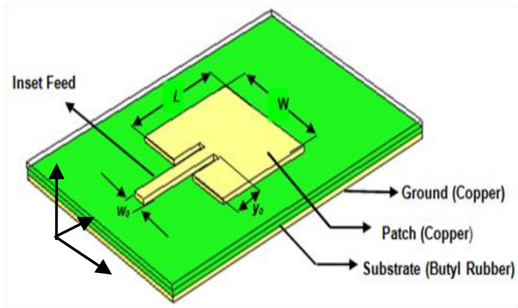

Fig. 1 Geometry of traditional patch antenna on wearable substrate

B. On-body analysis of traditional patch antenna

The traditional antenna is worn on the flat section Figure 2 of human body to study its radiation characteristics by taking into account the dielectric properties of breast fat (εr =5.1563, conductivity=0.13344 [s/m], penetration depth=0.090761 m) and muscles of high water content (εr =52, conductivity=1.74 [s/m], penetration depth=0.022785 m).

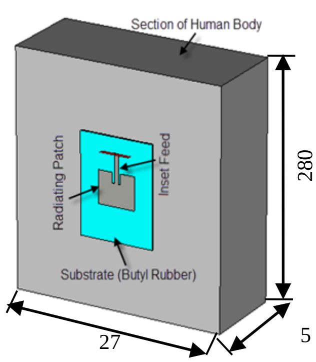

Fig. 2 Patch antenna worn on the flat section of human body= {breast fat or muscle}

The return loss of the antenna is compared in Figure 3, which shows a noticeable reduction (of -7 dB @ 2.4 GHz) on muscles due to its higher dielectric constant and conductivity.

The E-plane radiation patterns of the traditional patch antenna alone and when worn on body are compared in Figure 4. It is worth noting that the back lobe level is increased by 2.6 dB when the antenna is worn on breast fats. The total efficiency of traditional patch alone, worn on breast fat and muscles is 79, 75 and 72% respectively. The degradation in the efficiency for the latter is due to its higher conductivity and permittivity.

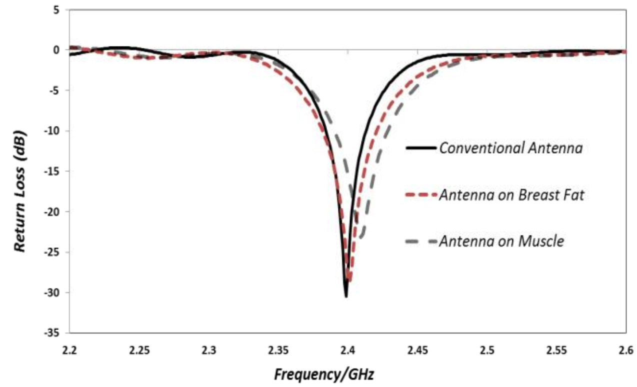

Fig. 3 Return loss of microstrip patch antenna on different parts of body

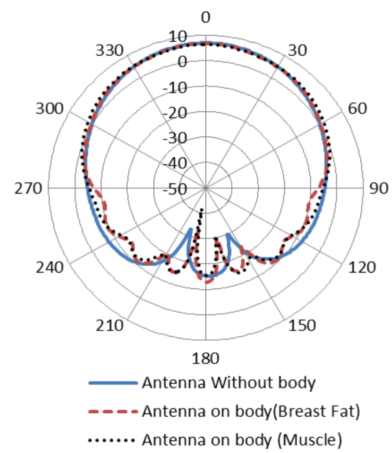

Fig. 4 Comparison of far field gain pattern of antenna alone and antenna worn on the body

III. EBG-BASED WEARABLE ANTENNA

Artificial ground planes are engineered two-dimensional metamaterial surfaces used in compact and efficient modern antenna designs. These surfaces behave as an Electromagnetic Bandgap (EBG) structure [15, 16] or as an Artificial Magnetic Conductor (AMC) [17, 18] within a specific frequency band. In this section, two types of 2.4 GHz artificial surfaces are designed and characterized. Both are used as a ground planes to investigate and compare the performance of the proposed antenna in OFF and ON-body conditions.

A. Design and characterization of wearable EBG surfaces

A Sievenpiper's [19, 20] square-shape model is used to design the mushroom and slotted type wearable EBG surfaces as shown in Figure 5. The resonant frequency of the EBG surface is given by:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \qquad (1)$$

Where, C is the capacitance due to fringing between the neighboring unit cells, given by [20]:

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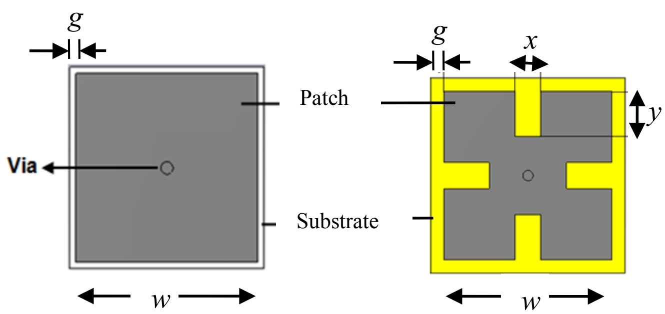
$$C = \frac{w\varepsilon_{0(1+\varepsilon_r)}}{\pi} cosh^{-1}\left(\frac{w+g}{g}\right) \quad (2)$$

Where, ε_0 is permittivity of vacuum, w, width of the unit cell and g, gap between neighboring unit cells. The inductance L is directly dependent on length of metal via (or thickness t of the substrate):

$$L = \mu_0\mu_r t \quad (3)$$

At 2.4 GHz the optimized dimensions of unit-cells in Figure 5 are:

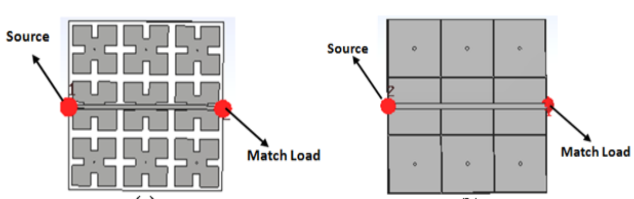
Mushroom EBG: w=0.24$\lambda_{2.4GHz}$, g=0.012$\lambda_{2.4GHz}$, ε_r=2.35, t=1.58mm, where $\lambda_{2.4GHz}$ is free space wavelength at 2.4 GHz, via (radius) = 0.004$\lambda_{2.4GHz}$.
Slotted EBG: w=0.26$\lambda_{2.4GHz}$, g=0.04$\lambda_{2.4GHz}$, ε_r==2.35, t=1.58 mm, x=0.04$\lambda_{2.4GHz}$, y=0.14$\lambda_{2.4GHz}$, via (radius) = 0.004$\lambda_{2.4GHz}$.



(a) (b)

Fig. 5 EBG unit cells (a) Mushroom (b) Slotted

The two surfaces were characterized in terms of surface wave suppression [20] within the resonant bandwidth, using the two port arrangement of Figure 6. I.e. a 50 ohms microstrip line is fixed on EBG surface to transmit the surface waves. The line is excited at both ends using discrete ports, one port acts as a source and the other as a matched load. The scattering parameters for the slotted EBG and mushroom surfaces are obtained from this setup are depicted in Figure 7 and 8 respectively.



(a) (b)

Fig. 6 Arrangement for surface wave suppression (a) Slotted- EBG and (b) Mushroom- EBG ground planes (height of microstrip line above EBG surface=0.02 λ)

The transmission coefficient (S_{21}) is minimum (below -40 dB) within a specific band of frequencies centered at 2.4 GHz for the slotted EBG. This means that within this band the transmission of surface waves is kept to the minimum level. The band of frequencies within which the surface acts as a high impedance surface to suppress the surface waves, is called its Bandgap. The mushroom type EBG lacks the ability to suppress surface waves at the design frequency (2.4 GHz), but rather shows a minute Bandgap at higher frequencies (2.8 and 3.2 GHz) as shown in Figure 8. The mushroom type surface gives in-phase reflection at 2.4 GHz and can be used in low profile antenna designs.

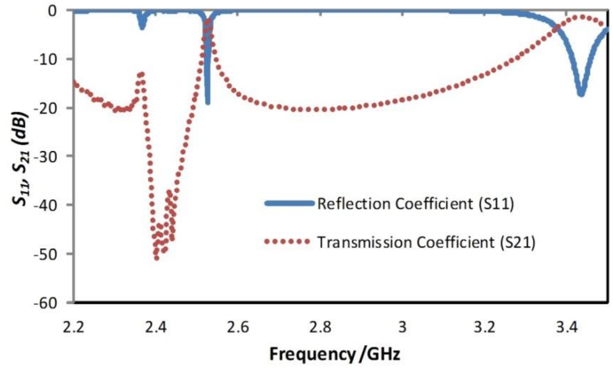


Fig. 7 Scattering (S)-parameters of microstrip line over the slotted-EBG

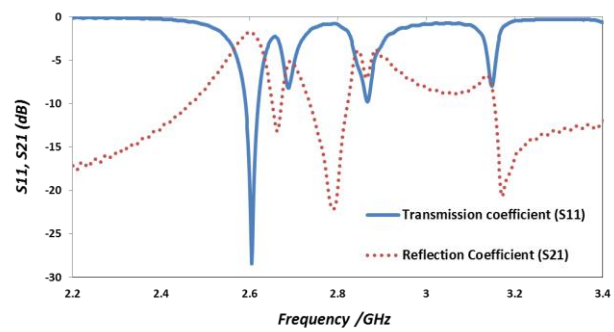


Fig. 8 Scattering (S)-parameters of microstrip line over the mushroom-EBG

B. EBG based antenna-OFF body analysis

The patch antenna is mounted on a 7 x7 EBG ground plane as shown in Figure 9. The return loss of the patch antenna is improved by -5 dB, when mounted on a slotted EBG ground plane. It is worth mentioning that due to fringing, an increase in the effective capacitance of the mushroom type EBG surface reduces the resonant frequency. Figure 10 shows the return loss comparison of the OFF-body traditional patch antenna with and without EBG surfaces.

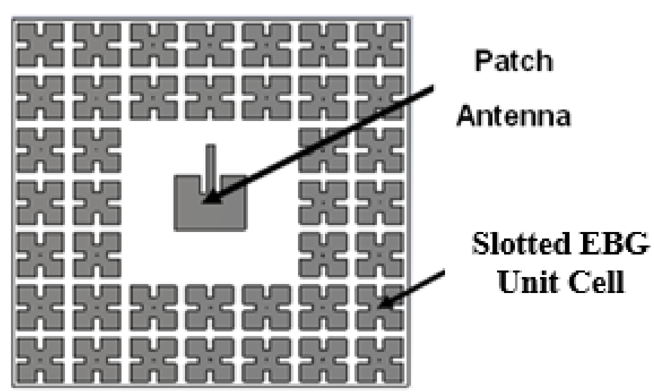


Fig. 9 Microstrip patch antenna mounted on the 7×7 slotted-EBG surface

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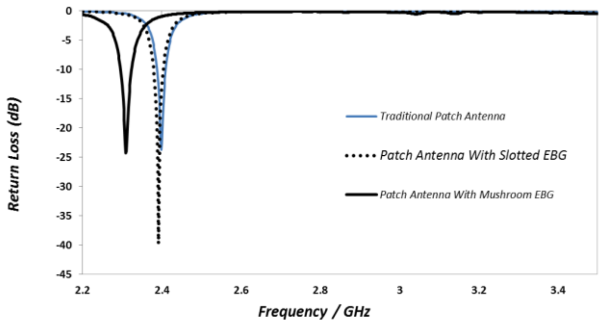

Fig. 10 Return loss analysis for the OFF-body traditional patch antenna

The far-field gain characteristics at 2.4 GHz are compared in Figure 11, which shows a noticeable reduction in back lobe (up to 10 dBi) and side lobe level (up to 8 dBi) for the slotted EBG based antenna. This is due to the fact that surface waves are blocked to propagate by this high impedance ground plane. Similar reduction in back lobe level (about 6.5 dBi) occurs for mushroom type EBG. The peak gain of the slotted-EBG based antenna is improved by 1.461 dBi as compared to the conventional patch.

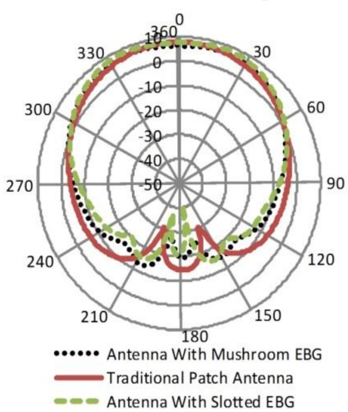

Fig. 11 Gain of 2.4 GHz traditional patch antenna with and without EBG (OFF body condition)

C. ON body antenna performance on EBG surfaces

In this section the proposed wearable patch antenna backed by finite mushroom and slotted EBG ground plane as shown in Figure 12, is positioned and analyzed on a flat section of human body (i.e. breast fat and muscles).

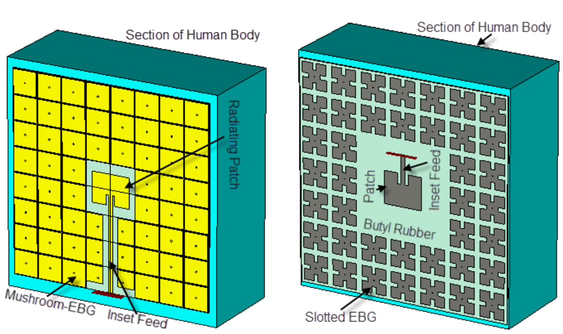

Fig. 12 ON-body antenna arrangement with (a) mushroom EBG and (b) slotted EBG on section of human body = {breast fat or muscle}

The on-body analysis shows that the resonance frequency for both the traditional antenna and mushroom-type EBG based antenna each fitted on breast occurs at the 2.4 GHz shown in Figure 13.The resonant frequency is slightly shifted to 2.41 GHz for the traditional antenna on muscle, due to its higher water content. The slotted-EBG based antenna retains its resonant frequency (2.4 GHz) irrespective of the fact if worn on breast fat or muscles.

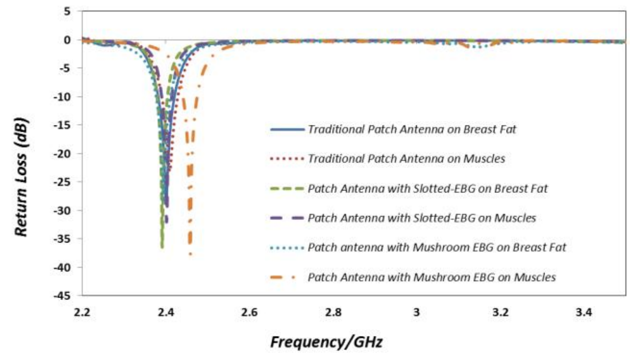

Fig. 13 Return loss analysis for the on-body wearable antenna

The E-plane gain patterns of antenna with mushroom type and slotted EBG on different parts of the body are compared in Figure 14 and 15 respectively. It is apparent from Figure 14 that for the patch with mushroom type EBG worn on breast, the peak gain is increased (by 0.3 dBi), while the back lobe level is significantly reduced (by 5.4 dBi).

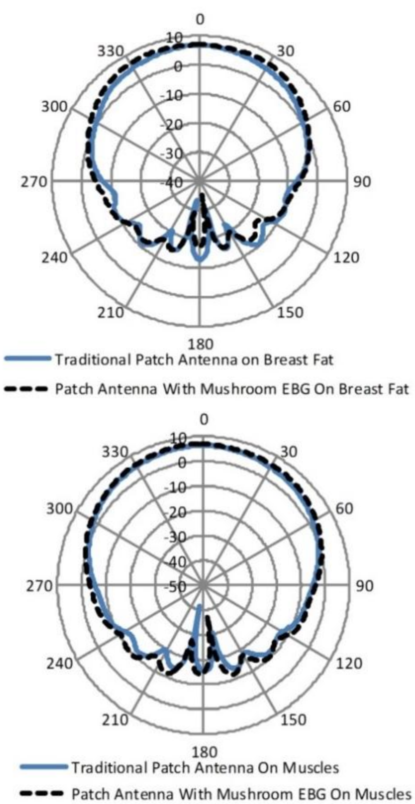

Fig. 14 E-plane gain pattern of 2.4 GHz patch antenna with mushroom EBG on human body

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If the antenna backed by the slotted EBG ground plane is worn on body, a significant improvement in peak gain, reduction in back lobe and side lobe levels is observed in Figure 15. I.e. the peak gain level is enhanced by 1.6 and 2.1 dBi for this antenna if worn on breast and muscles respectively.

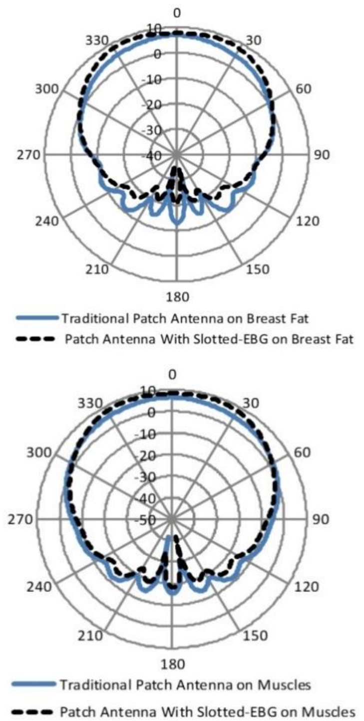

Fig. 15 E-plane gain pattern of 2.4 GHz patch antenna with slotted EBG, on human body

The summary of improvement in performance of the EBG based antennas worn on human body as compared to the traditional antenna is outlined in Table I

Table. 1 Gain, Back Lobe Level (BLL) and Side Lobe Level (SLL) Of The EBG Based Antenna

Antenna\Parameter	Gain (dBi)	BLL (dBi)	SLL (dBi)
On Muscles with slotted EBG	2.1	3.15	4.9
On breast with slotted EBG	1.6	8.5	6.03
On Muscles with mushroom EBG	0.7	-1.3	-2.1
On breast with mushroom EBG	0.3	5.4	3.6

IV. CONCLUSION

In this paper a wearable antenna on two types of EBG ground plane has been analyzed on different parts of human body. The gain and return loss (S_{11}) of the antenna has been improved significantly when slotted EBG was used as a ground plane. In addition the slotted EBG minimized the surface wave propagation and reduced the level of side and back lobes by more than 6 and 8 dBi respectively on various parts of the body. Butyl rubber has been used as a wearable substrate to give flexibility and conformability to the proposed design. The proposed metamaterial based 2.4 GHz antenna can be used in wearable applications, such as smart clothing by combat, rescue and security agencies. The same antenna can be used to provide efficient wireless connectivity in Body Area Networks (BANs) and Personal Area Networks (PANs). The prototype of the proposed antenna and EBG structures will be fabricated in order to compare the simulated and measured results in an anechoic chamber. The SAR analysis of the proposed antenna can be conducted on different parts and sexes (male, female) of human beings. Similar analysis of the antenna by considering different human races (Asian, African, Europeans and Americans) can also be conducted. A multiple element array of the proposed 2.4 GHz antenna can be designed for high gain, Multiple Input Multiple Output (MIMO) applications.

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