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A Comparative Study of a Novel Shape Dual-band Wearable Antenna on Different Types of Artificial Ground Planes

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Abstract. This article describes design of four types of wearable dual band (2.444 and 5.4 GHz) planar patch antennas. The first one is designed on a traditional ground plane. The other three are designed on three different types of two-dimensional artificial ground planes. The traditional ground plane based antenna has a bandwidth of 81.6 and 161.8 MHz at 2.444 and 5.4 GHz respectively. An improvement of 8.6 and 41.7 MHz in bandwidth for the 2.444 and 5.4 GHz frequency bands, respectively, has been achieved by employing electromagnetic bandgap (EBG) with hexagon-shaped conducting patches. Directivity, gain, efficiency and other parameters are improved by a ponderable amount using EBG ground planes. As the considered antennas are wearable therefore the performance of all the four types of antennas has been investigated with different bending radii. It was observed that the performance of all the considered antennas remain stable in terms of reflection coefficient and radiation characteristics. Bending has negligible effects on the performance of the considered four types of antennas. The proposed antennas can be used for the industrial, scientific, and medical (ISM)and wireless local area network (WLAN) band applications.Computer simulation technology(CST) has been used as a designing and simulating software for all the proposed antennas.

Keywords: EBG, wearable antennas, dual band, WLAN, Felt

1 Introduction

Textile antennas present a raising field for researchers with new developments and inventions in the last decade. Depending on the type of material, the electronic system can be integrated into the garments in a comfortable manner. Wearable antennas are part of a wearable system and continuously oversee activity, such as body temperature or heartbeat and so on. Wearable antennas play primary role in body area network (BAN) and therefore they have received tremendous attention[14]. Compactness and flexibility are the primary features in systems that should be installed into wearable apparels. Therefore, wearable electronics should be whippy, durable, and lighter than the non-wearable electronic systems. For wearable systems, microstrip patch antenna (MPA) is of special interest due to its peculiar properties (lightweight, flexibility, conformability,and ease of manufacturing). The full ground plane which is a part of the MPA, helps in isolation of the fields of antenna from the wearer's body[18, 26, 30]. However, the field's concentration of the antennas with full ground plane is much higher in the substrate and thereby degrades the efficiency of the antenna[10]. But also, the efficiency of antenna is a function of the loss factor (loss tangent) of the substrate material, as the loss factor increases; the antenna efficiency decreases[16].Therefore in practical applications, designing of wearable antenna still faces many disputes. Apart from the advantages mentioned above, microstrip patch antennas (MPAs) have also some disadvantages, such as low gain, reduced efficiency, spurious feed radiations, narrow bandwidth,

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and so on[7]. The reason for this is that, although MPAs are compact (low profile) but when employed on traditional metal or perfect electric conductor (PEC) ground plane, they do not radiate efficiently. The fact is that the currents reflected by the ground plane towards the radiating element interfere destructively with the antenna currents[1]. This dramatically drops different parameters such as gain, return loss, and efficiency of the proposed antenna. By employing a metamaterial surface as a ground plane, some of these disfavors can be palliated. Metamaterials or EBG are artificial materials and they are usually employed as ground planes.

EBG performs two primary functions[3]. The first one is the in-phase reflection for certain bands of frequencies called the reflection phase bandwidth. Since EBG does not revert the phase of the waves reflected by it, so the image currents are in-phase with the antenna currents[20]. The in-phase reflection is useful for designing of compact antennas that can be used in portable systems[4]. The second one is the suppression of transverse magnetic and transverse electric (TM and TE) surface waves in some bands of frequencies called the bandgap of the EBG structure. The suppression of the wavesincreases gain and radiation efficiency[2, 5]. The most common type of EBG is the mushroom-like. It is compact, planar and required low cost of manufacturing[24].

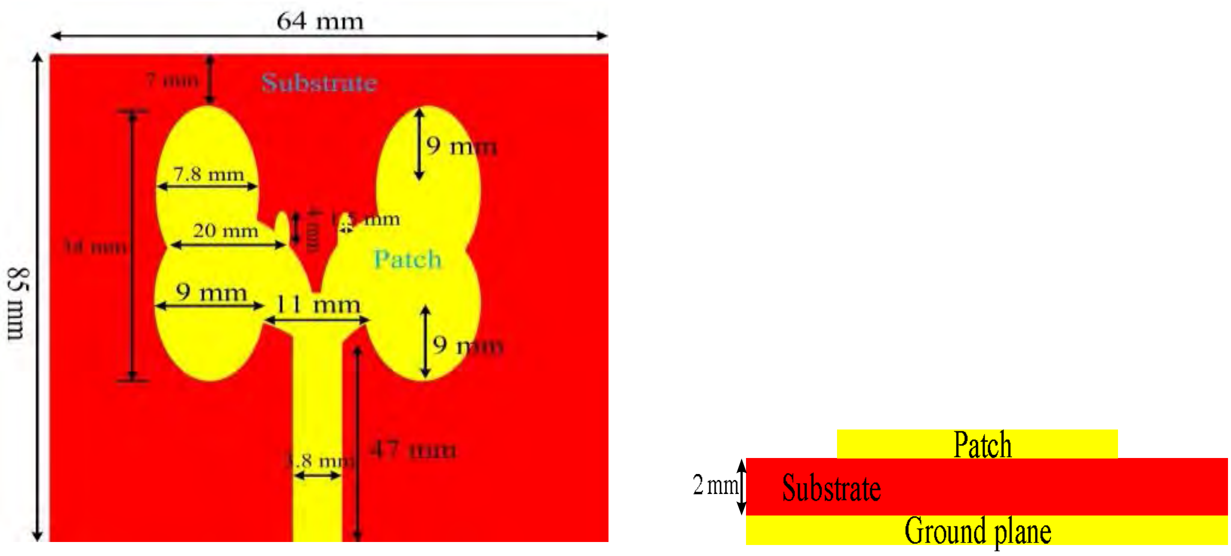
EBG can also be used for reduction of, mutual coupling[21], specific absorption rate (SAR)[15] and conversion of linear polarization to circular polarization. In [29], two different EBG structures have been used for reduction of mutual coupling within elements of multiple-input multiple-output (MIMO) arrays. The first one structure is comprised of S-shape conducting patches with via inserted in center and the second structure was based on a multilayer structure that was based on the formation of the S-shape. A reduction of 13.5 and 20.5 dB in mutual coupling was observed for the first and second configurations respectively. In [9], the interaction of the antenna with the human body is belittled by using EBG. The radiation pattern of the traditional antenna is dipole-like which provides significant radiations towards the human body. By employing EBG as ground plane, the back radiations have been shifted in the forward directions, which minimize the interaction of the antenna with the human body. Along with minimizing interaction, improvement in gain has been achieved. In [22], EBG has been used as a ground plane to a wide band antenna to convert its linear polarized radiation pattern to a circular polarized radiation pattern. Also, the proposed configuration allows polarization switching capability between left hand circular polarization (LHCP) and right hand circular polarization (RHCP). The proposed design is applicable for GLONASS, Galileo, IRNSS, and satellite navigation.

As wearable antennas are usually installed into garments, therefore bending of these antennas may occur. Bending mismatches the impedance bandwidth [12] of the antenna which produces, increase/decrease in the reflection coefficient or a shift in the operating frequency[28] or variation in the radiation pattern[8]. So, one must be concerned to evaluate different parameters of the wearable antenna in various bending conditions.

In this work, a novel shaped dual-band textile patch antenna is designed. The considered antenna operates at 2.444 and 5.5 GHz and has a compact size of $85 \times 64 \times 2$ mm. A multi or dual band antenna is most attractive in commercial applications due to having single radiator that has an ability to receive and transmit multiple frequencies[23]. For performance improvement, three different types of artificial ground planes have been designed for the traditional antenna. In the design of both traditional and EBG based antennas, a wearable material felt is used as a substrate. As the proposed antennas are wearable and it is impossible for them to sustain its flat condition over the wearer's body all the time. Hence the performance of all the four considered antennas has been investigated in different bending conditions. The rest of this work is organized in the following manner. First the traditional antenna design and its results are presented in section 2. Section 3, describes the results and discussion. In section 4, designs and characterization of the three different EBG unit cells and its array versions along with performance comparison of traditional and EBG based antennas are presented. Section 5, describes the effect of bending on the proposed four different types of antennas. Section 6, summarizes general conclusions.

2 Designing methodology of traditional wearable antenna

The considered antenna is a dual-band textile or wearable MPA. The operating frequencies of proposed antenna are 2.444 and 5.4 GHz. Geometrical model of designed dual-band wearable antenna is shown in Figure 1. The designed antenna consists of three layers. The upper radiating patch and a substrate backed by a conducting or PEC full ground plane. The upper radiating patch is composed of two identical branches that is the left and right one. Each branch is basically obtained from combination of three elliptical shapes arranged in a proper geometrical manner. A 50 ohm microstrip feed line is used for excitation purpose and to combine the two branches. The proposed antenna has a compact size of $85 \times 64 \times 2$ mm which is viable for wearable diligence.



(a) 2.444 GHz (b) 5.4 GHz

Fig. 1: Wearable antenna geometry

A wearable material called felt with a standard thickness of 2 mm, relative permittivity of 1.38 and loss tangent of 0.02 is used for the substrate. The results of the traditional antenna (without EBG) are described below.

3 Results and discussion

Fig. 2 presents the return loss of the traditional dual-band antenna. The -10 dB bandwidth corresponding to 2.444 GHz is 81.6 MHz and that corresponding to 5.4 GHz is 161.8 MHz which is feasible for a reliable communication.

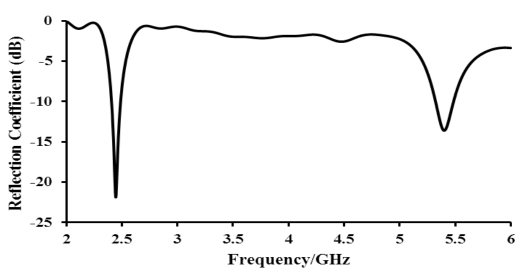


Fig. 2: Reflection coefficient of traditional dual-band wearable antenna

The voltage standing wave ratio (VSWR) at desired resonance frequencies is shown in Fig. 3. The VSWR at both resonance frequencies is lower than 2, which confirms good impedance matching of the proposed traditional antenna.

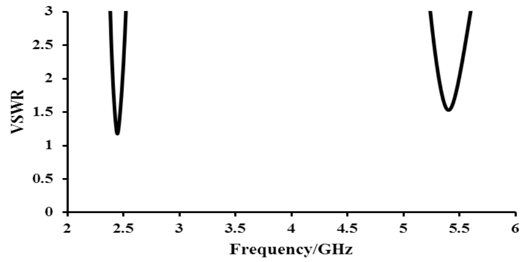


Fig. 3: VSWR of traditional dual-band wearable antenna

The 2D directivity and gain polar patterns of the traditional dual-band antenna at 2.444 and 5.4 GHz are depicted in Fig. 4 and 5 respectively. Maximum values of 8.08 and 8.55 dB were achieved for directivity at 2.444 and 5.4 GHz respectively. The maximum achieved gain value at 2.444 GHz is 4.26 dBi while that at 5.4 GHz is 6.96 dBi.

(a) 2.444 GHz (b) 5.4 GHz.

Fig. 4: 2D directivity polar patterns of traditional antenna

At 2.444 GHz, the 3dB angular width is 59.6owhere 49.2o for 5.4 GHz. A small disturbance occurs in the radiation patterns at the upper resonance frequency (5.4 GHz). But this disturbance is always observed as the resonance frequency increases. The same disturbance has been noted in the radiation patterns with increase in frequency in [11, 17].

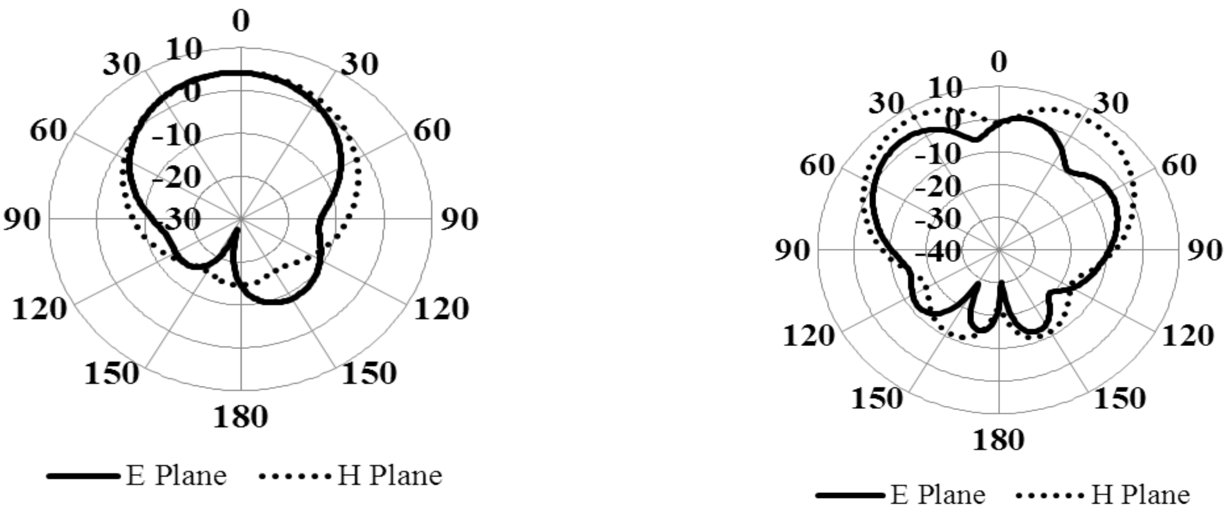
Fig. 6 depicts radiations of surface electric fields (E-fields) by the traditional antenna at 2.444 and 5.4 GHz which clearly highlights the lengths resonating at the desired frequencies. At the lower frequency (2.444 GHz), about the whole patch is responsible for radiations. At 5.4 GHz, the main radiation is from the centered portion and the two bumps at the inner boundary of each branch.

4 Artificial ground planes (EBG)

EBG are engineered materials which are employed as a ground plane to enhance the performance of an antenna. EBG enhances performance of an antenna by performing two primary functions[13, 25], the in-phase reflection and surface waves suppression[19, 31].

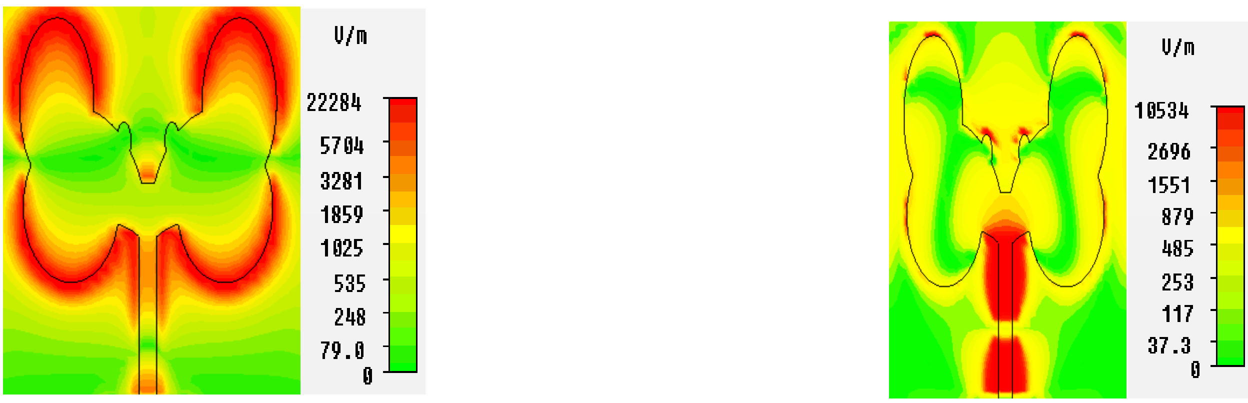
4.1 Designing methodology of dual-band ebg

The geometrical models of all the three EBG unit cells are shown in Fig. 7. Same material (felt) with thickness of 2 mm has been used as a substrate in the design of all the three unit cells. In Fig. 7, the unit cell with hexagon-shape conducting patch is more compact than the unit cell with circular-shape conducting patch



(a) 2.444 GHz (b) 5.4 GHz.

Fig. 5: 2D gain polar patterns of traditional antenna



(a) 2.444 GHz (b) 5.4 GHz.

Fig. 6: E-fields radiated by traditional antenna

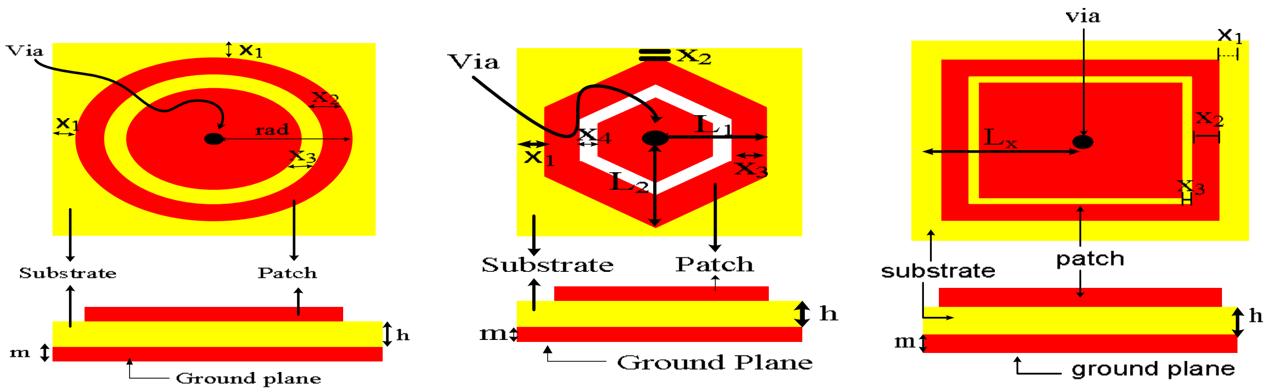
while the mushroom-like (dual band concentric square) unit cell is more compact than the unit cell with the hexagon-shape conducting patch. The three unit cells are designed according to theory of the uniplanar EBG surfaces[27]. The effective inductance (L) and capacitance (C), are the factors on which the resonant frequency (f_r) of the unit cell depends, i.e.

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

$$C = \frac{w\varepsilon_0(1+\varepsilon_r)}{\pi} cosh^{-1}\frac{\alpha}{g} \tag{2}$$

$$L = \mu_0 h \tag{3}$$

Where,$_0$ presents the free space permeability and ϵ_0 denotes the free space permittivity. In each unit cell, there is a via of radius 1 mm that connects the metallic patch with the metallic ground plane. In the case of the EBG unit cells with circular-shaped and square-shaped radiating patches, the gap $(*1)$ between conducting patch and substrate outer boundary is 2 mm.In Fig. 7(b), x_1 is 3 mm and x_2 is 2 mm. The values of all the parameters mentioned in Fig. 7 are summarized in Tab. 1



(a) Circular-shaped (b) Hexagon-shaped (c) Square-shaped

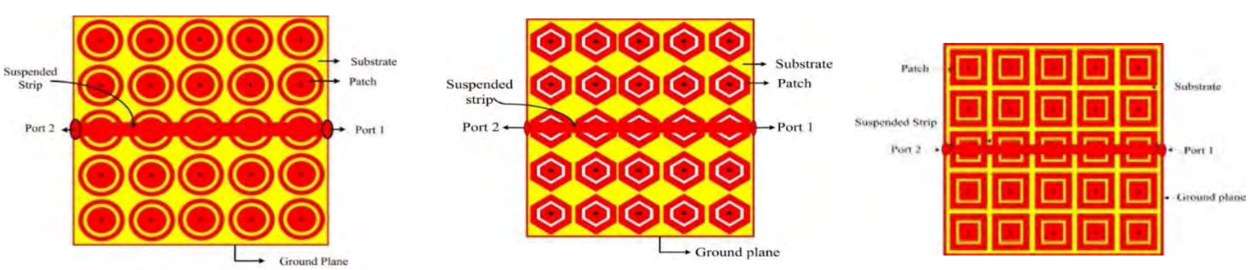
Fig. 7: EBG unit cells

Table 1: Summary of the three unit cells parameters

Parameters (mm)	Circular-shaped EBG unit cell	Hexagon-shaped EBG unit cell	Square-shaped EBG unit cell
x_1	2	3	2
x_2	7	2	1.5
x_3	5	1	1
x_4		2.5	
h	2	2	2
rad	20		
L_1		11	
L_2		18.5	
L_3			16.5

4.2 Dual-band EBG arrays

Suppression of unwanted waves (surface waves) within specific band gap is the important and crucial characteristic of the EBG ground planes. Due to this characteristic of EBG structures various parameters of an antenna such as efficiency, directivity, and gain can be enhanced. Fig. 8 portrays the setup for determination of the bandgap of the three EBG structures. For the purpose of simulation of the surface waves a microstrip line which is excited at two ports is used. In the case of all the three arrays, the port to the left-side is opined as source for excitation while the port to the right-side is considered as a matched load. From (a) to (c) in Fig. 8, the size of the array is, $212 \times 212 \times 2$ mm, $197.6 \times 127 \times 2$ mm, and $157 \times 157 \times 2$ mm respectively.

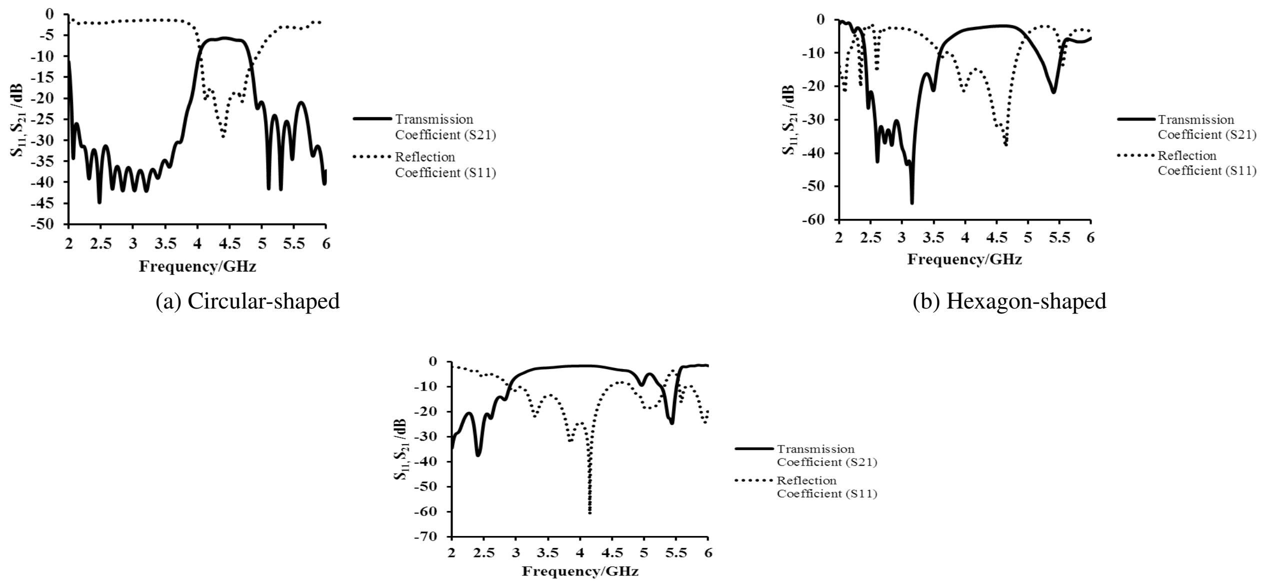


(a) Circular-shaped (b) Hexagon-shaped (c) Square-shaped

Fig. 8: 5×5 EBG arrays of the three EBG surfaces

The reflection (S_{11}) and transmission (S_{21}) coefficients of the three EBG surfaces are depicted in Fig. 9. Fig. 9 clearly demonstrates that for each array, the transmission coefficient at both the desired frequencies

(2.444 and 5.4 GHz) is lower than −20 dB. Therefore, all the three EBG surfaces have a sufficient band gap and suppress surface waves at the two desired frequencies. But the hexagon-shaped array is about 44.163% more compact than circular-shaped array while square-shaped array is about 1.77% more compact than the hexagon-shaped array.



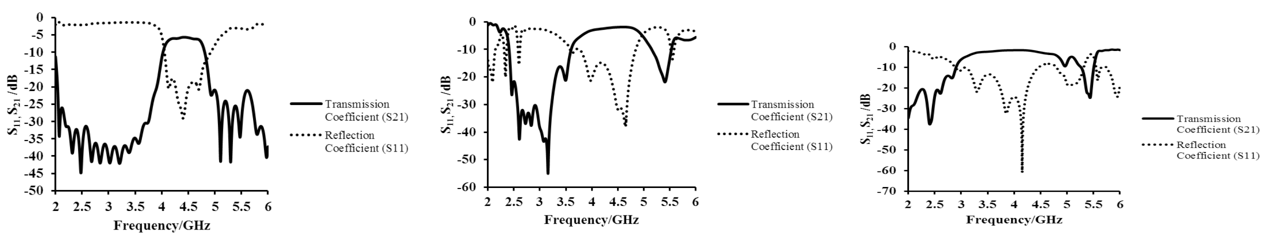
(a) Circular-shaped (b) Hexagon-shaped

(c) Square-shaped

Fig. 9: Transmission (S_{21}) and reflection (S_{11}) coefficients of 5×5 EBG arrays

4.3 EBG based antenna

In order to enhance the performance of the considered traditional dual band antenna, three different types of dual band EBGs have been designed as given in Fig. 8. After that the designed dual band wearable antenna is placed over the proposed artificial ground planes as depicted in Fig. 10. Hereafter the EBG based antenna with circular conducting patches will be referred as circular-shaped EBG based antenna while that with hexagon-shaped and square-shaped conducting patches will be referred as hexagon-shaped and square-shaped EBG based antennas. A performance comparison between the four antennas, that is traditional ground plane based antenna and the three artificial ground planes based antennas is carried out below.



(a) Circular-shaped (b) Hexagon-shaped (c) Square-shaped

Fig. 10: Antenna over artificial ground planes

Fig. 11 presents the return loss comparison of the considered four types of antennas which shows increase in return loss for both desired resonance frequencies by using EBG ground planes. In the same way, an increase of 50, 41.7, and 55.1 MHz in bandwidth for upper frequency band has been achieved by using Circular-shaped, hexagon-shaped and square-shaped EBG ground planes respectively. For the lower frequency band a decrease of 1 MHz has been occurred in the bandwidth for circular-shaped EBG ground plane while an increase of 8.6 and 3.3 MHz in bandwidth has been observed for the same frequency band by employing hexagon-shaped and square-shaped EBG ground planes. So in terms of bandwidth, the square-shaped EBG ground plane serves the best among the all. A small amount of shift towards the left side in the desired frequency bandsis observed for each of the three types of EBG. But this is common whenever an antenna is placed over EBG ground plane. The same shift in frequency bands has been observed in [3, 13]. Also, improvement in VSWR has been achieved for both resonance frequencies in the case of all the three EBG ground planes based antennas.

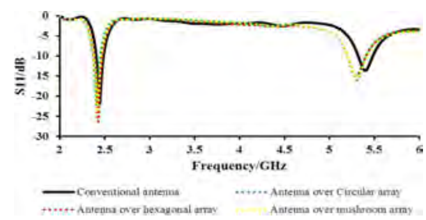
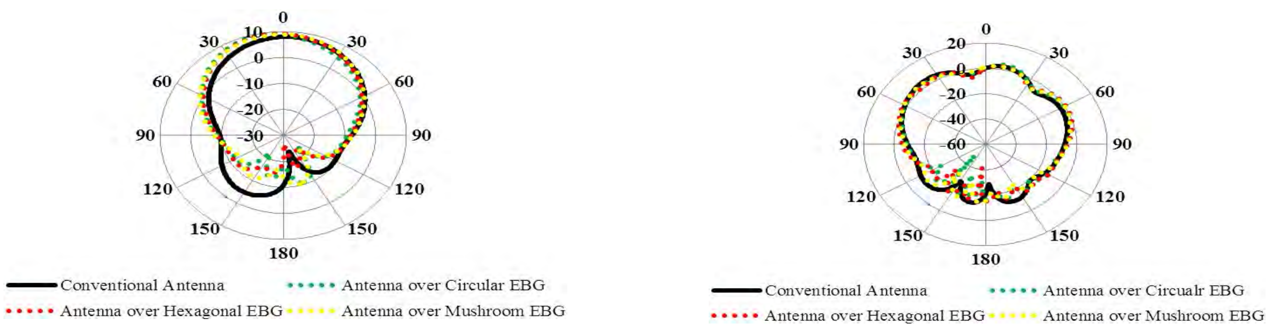


Fig. 11: Return loss of traditional antenna and EBG based antennas

The 2D directivity and gain polar patterns comparison is shown in Fig. 12 and Fig. 13 respectively. The directivity at the lower resonance frequency has been increased by 17.6, 14.8 and 11.5% by using circular-shaped, hexagon-shaped and square-shaped EBG ground planes respectively. For the upper resonance frequency, a negligible decrease in directivity is observed for the circular-shaped and square-shaped EBG ground planes while a small improvement has been noted for the hexagon-shaped EBG ground plane.



(a) 2.444 GHz (b) 5.4 GHz

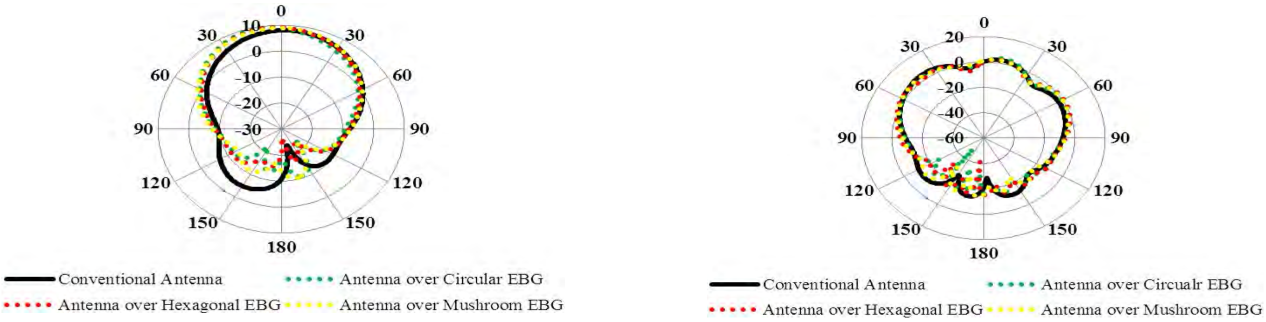
Fig. 12: Directivity patterns of traditional and EBG based antennas

Like directivity, a significant amount of improvement in gain for the lower frequency band has been achieved by employing the three different types of EBG ground planes while a negligible decrease in gain for the upper frequency band has been observed in the case of circular-shaped and square-shaped EBG ground planes. So in terms of directivity and gain, the hexagonal-shaped EBG ground plane serves the best among the all.

Tab. 3 presents the performance comparison summary between traditional and EBG ground planes based antennas.

5 Free space bending analysis

As already discussed, it is not possible for a wearable antenna to remain in stable (flat) conditions all the time and bending may occur which alters the performance of an antenna. This alteration may be due to



(a) 2.444 GHz (b) 5.4 GHz

Fig. 13: Gain patterns of traditional and EBG based antennas

Table 2: Summary of the three unit cells parameters

Parameters	Traditional dual band antenna		Circular-shaped EBG based antenna		Hexagon-shaped EBG based antenna		Square-shaped EBG based antenna	
Frequency (GHz)	f_1= 2.44	f_2=5.4	f_1=2.412	f_2=5.308	f_1=2.428	f_2=5.3	f_1=2.424	f_2=5.312
Return Loss (dB)	21.87	13.6	22.26	16.08	26.32	15.02	23.77	15.46
Bandwidth (MHz)	81.6	161.8	80.6	211.8	90.2	203.5	84.9	216.9
VSWR	1.17	1.52	1.16	1.37	1.1	1.43	1.13	1.4
Gain (dBi)	4.26	6.96	5.85	6.92	5.76	7.08	5.44	6.64
Directivity (dB)	8.08	8.55	9.51	8.54	9.28	8.6	9.01	8.25
Radiation Efficiency (% age)	41.46	69.33	43.06	68.76	44.47	70.52	43.99	69.05
Angular Width (Degree)	59.6	49.2	74.7	21.4	70.4	44.9	75.6	47.3

mismatching of the impedance bandwidth of the antenna [6, 27] or decrease or increase in the electrical length of the antenna. It is needed to analyze the performance of a wearable antenna in different bending conditions. Therefore, the proposed traditional ground plane and EBG ground planes based antennas given in Figure 1 and Figure 10 respectively are bended around cylinders of different radii (40, 60, and 70 mm). In this work, performance analyses based on radiation patterns and return loss characteristics due to different bending radii of the considered four types of antennas has been made which is given below.

5.1 Traditional antenna

Fig. 14 shows the traditional antenna bended with various bending radii (40, 60, and 70 mm). Effect on the return loss of the traditional antenna due to different bending radii is demonstrated in Fig. 15. A small amount of shift in both frequency bands towards the right side has been occurred due to bending of the traditional antenna. This shift decreases, as the bending approaches towards the flat condition. It can be also noted that instead of reduction, an increase in return loss is occurred.

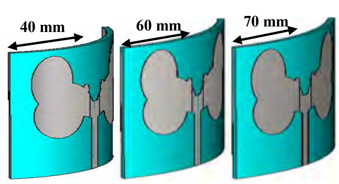


Fig. 14: Traditional antenna bended with various bending radius

The bending effect on the directivity and gain patterns of the traditional antenna is shown in Fig. 16 and Fig. 17 respectively. It can be concluded from both figures that bending has a negligible amount of effects on

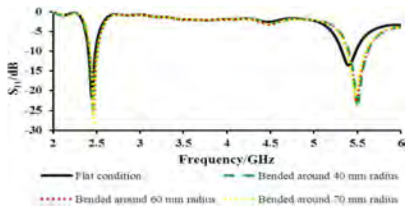
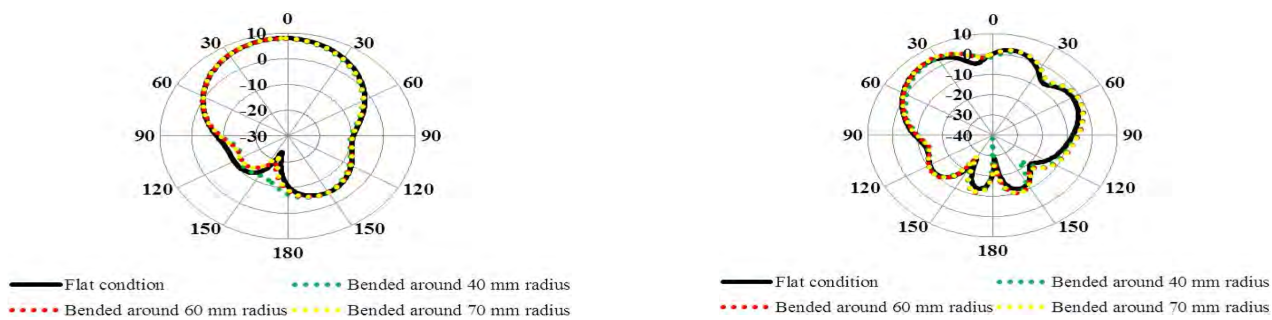


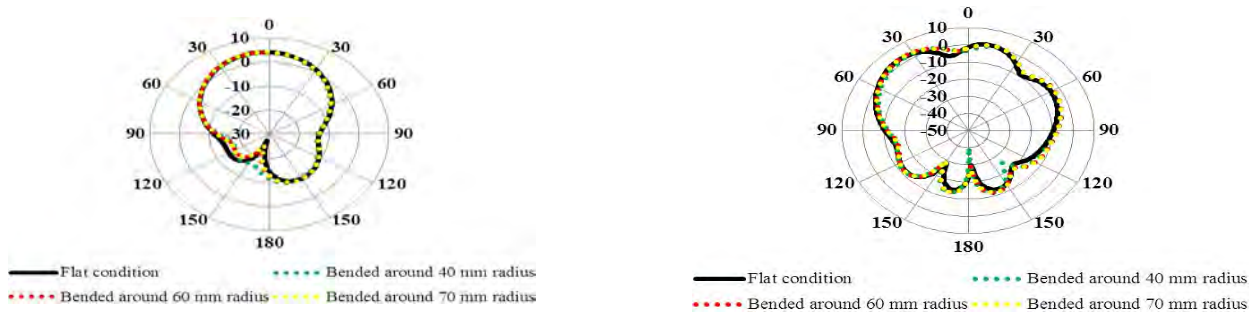
Fig. 15: Bending effects on return loss of traditional antenna

the directivity and gain of the traditional antenna. A negligible amount of reduction in gain and directivity is noted. In 40 mm radius bending which represents the worst bending condition, the directivity at lower and upper resonance frequency is 7.75 and 8.33 dB respectively. The gain at lower and upper resonance frequency in the same bending condition is 4.04 and 6.5 dBi respectively.



(a) 2.444 GHz (b) 5.4 GHz

Fig. 16: Bending effects on directivity patterns of traditional antenna



(a) 2.444 GHz (b) 5.4 GHz

Fig. 17: Bending effects on gain patterns of traditional antenna

It can be concluded that the proposed traditional antenna remains tuned all the time irrespective of the bending radii and bending has negligible effects on the return loss, directivity, and gain of the traditional antenna.

5.2 Circular-shaped ebg based antenna

The circular-shaped EBG based antenna with different bending radii (40, 60, and 70 mm) is shown in Fig. 18.

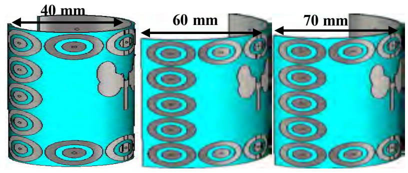


Fig. 18: Circular-shaped EBG based antenna bended with various bending radius

Fig. 19 shows the effects of bending on the reflection coefficient of the circular-shaped EBG based antenna. It is worth observing that for both frequency bands, the return loss increases with bending of the antenna. In the worst bending situation (40 mm radius bending), the return loss at 2.444 and 5.4 GHz is -29.31 and -48.41dB and it decreases for both resonance frequencies as the bending of antenna decreases or as the antenna approaches towards the flat condition.

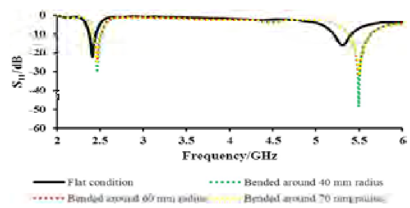
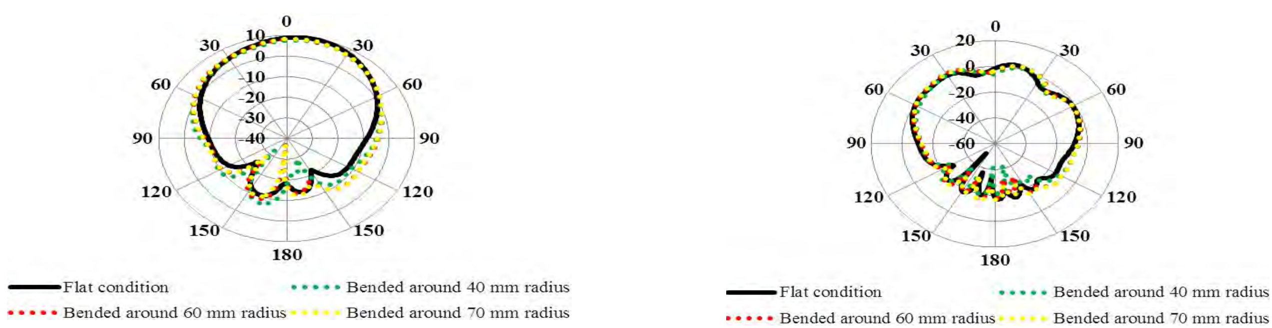


Fig. 19: Effect of bending on the return loss of the circular-shaped EBG based antenna

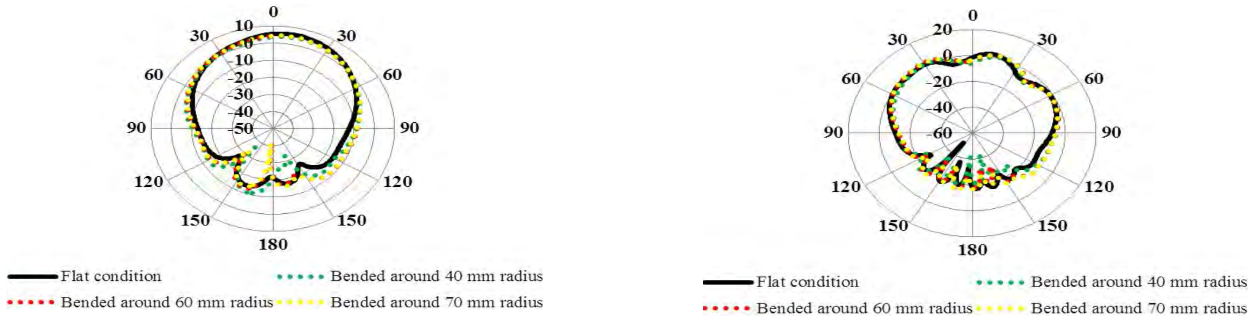
Like traditional ground plane based antenna, the resonance frequencies shift towards the right side with bending of the circular-shaped EBG based antenna. It can be observed from Fig. 19, that the bending has no prominent effect on the reflection coefficient of the considered circular-shaped EBG based antenna. The bending effects on the directivity and gain patterns of the circular-shaped EBG based antenna is demonstrated in Fig. 20 and Fig. 21 respectively. A small amount of decrease in gain and directivity is observed for the lower and upper resonance frequencies with bending of the circular-shaped EBG based antenna. Like traditional ground plane based antenna, no eminent effect of bending is noted on the radiation patterns of the circular-shaped EBG based antenna.



(a) 2.444 GHz (b) 5.4 GHz

Fig. 20: Bending Effects on directivity patterns of the circular-shaped EBG based antenna

It has been concluded that overall performance of circular-shaped EBG based antenna in terms of reflection coefficient and radiation characteristics remains stable irrespective of the bending.



(a) 2.444 GHz (b) 5.4 GHz

Fig. 21: Bending Effects on gain patterns of the circular-shaped EBG based antenna

5.3 Hexagon-shaped and square-shaped ebg based antenna

Hexagon-shaped and square-shaped EBG based antennas in different bending conditions are shown in Fig. 22 and Fig. 23 respectively. Both antennas have bended over 40, 60, and 70 mm radius. Among the three bending radii, 40 mm represents worst bending condition.

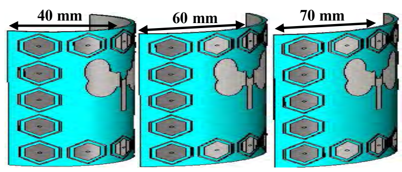


Fig. 22: Hexagon-shaped EBG based antenna bended with various bending radius

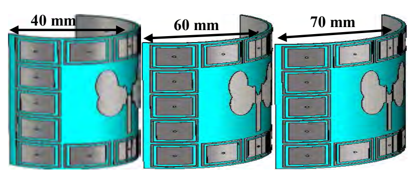


Fig. 23: Square-shaped EBG based antenna bended with various bending radius

Fig. 24 and Fig. 25 depicts the effect of bending on the reflection coefficient of hexagon-shaped and square-shaped EBG based antenna respectively. In the case of hexagon-shaped EBG based antenna, return loss at the lower resonance frequency decreases with bending while that at the upper resonance frequency increases with bending. The return loss at 5.4 GHz is improved by 37.15 and 22.35 dB for bending radius of 70 and 40 mm respectively.

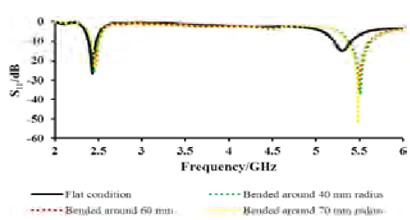


Fig. 24: Effects of bending on return loss of the hexagon-shaped EBG based antenna

For square-shaped EBG based antenna, the return loss at 5.4 GHz is improved by 28.95 and 19.4 dB for bending radius of 40 and 70 mm respectively. A small shift in resonance frequencies towards the right side has been observed with bending in the case of both hexagon-shaped and square-shaped EBG based antennas.

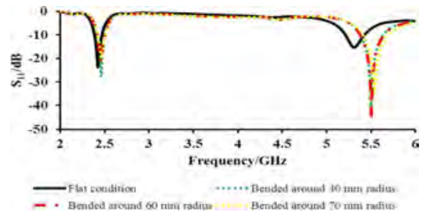


Fig. 25: Effects of bending on return loss of the square-shaped EBG based antenna

It is concluded that bending has no prominent effect on the return loss and directivity/gain of the hexagon-shaped and square-shaped EBG based antennas and the performance of both antennas remain stable irrespective of the bending radii. Table III summarizes bending effects on the return loss, gain, and directivity of the hexagon-shaped and square-shaped EBG based antennas.

Table 3: Effects of bending on the reflection coefficient, directivity and gain of hexagon-shaped and square-shaped EBG based antennas

Parameter	Hexagon-shaped EBG based antenna								Square-shaped EBG based antenna							
	Bending Radii								Bending Radii							
	Flat(0 mm)		40 mm		60 mm		70 mm		Flat(0 mm)		40 mm		60 mm		70 mm	
Frequency	f1	f2	f1	f2	f1	f2	f1	f2	f1	f2	f1	f2	f1	f2	f1	f2
Return Loss (dB)	26.3	15	25.6	37.3	23.4	35.4	23.9	52.1	23.7	15.4	27.9	44.4	21.2	44.6	19.5	34.8
Directivity (dB)	9.2	8.6	7.9	7.7	8.4	7.8	8.5	8	9	8.2	7.8	7.7	8.1	8.2	8.2	8.2
Gain (dBi)	5.76	7	4.5	5.8	4.9	6	5	6.1	5.4	6.6	4.1	5.9	4.4	6.4	4.4	6.5

6 Conclusion

Four different types of wearable dual-band antennas have been designed in this work. The first one was a traditional ground plane based antenna while the other three types of antennas were based on EBG ground planes. A wearable material called felt has been used as a substrate material in the design of traditional and EBG based antennas. The traditional dual-band antenna was novel shape with a compact size of $85 \times 64 \times 2$ mm. The hexagon-shaped EBG based antenna was about 44.163% more compact than circular-shaped EBG based antenna while square-shaped EBG based antenna was about 1.77% more compact than the hexagon-shaped EBG based antenna. In the flat as well as in the bending conditions, the performance of the traditional ground plane based antenna has been improved by employing different EBG ground planes. It was concluded that bending has no eminent effects on the performance of the considered four types of antennas and performance of all the proposed antennas remain stable. All the four types of wearable antennas were good impedance matched with resulting $VSWR < 2$ at both the resonance frequencies. The proposed antennas operate in dual frequency mode (2.444 and 5.4 GHz) and can be used for ISM and WLAN applications.

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