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Design and Performance Comparison of Rotated Y-Shaped Antenna Using Different Metamaterial Surfaces for 5G Mobile Devices

Jalal Khan¹, Daniyal Ali Sehrai¹, Mushtaq Ahmad Khan¹, Haseeb Ahmad Khan², Salman Ahmad³, Arslan Ali⁴, Arslan Arif⁵, Anwer Ahmad Memon⁶ and Sahib Khan^{1, 4, *}

Abstract: In this paper, a rotated Y-shaped antenna is designed and compared in terms of performance using a conventional and EBG ground planes for future Fifth Generation (5G) cellular communication system. The rotated Y-shaped antenna is designed to transmit at 38 GHz which is one of the most prominent candidate bands for future 5G communication systems. In the design of conventional antenna and metamaterial surfaces (mushroom, slotted), Rogers-5880 substrate having relative permittivity, thickness and loss tangent of 2.2, 0.254 mm, and 0.0009 respectively have been used. The conventional rotated Y-shaped antenna offers a satisfactory wider bandwidth (0.87 GHz) at 38.06 GHz frequency band, which gets further improved using the EBG surfaces (mushroom, slotted) as a ground plane by 1.23 GHz and 0.97 GHz respectively. Similarly, the conventional 5G antenna radiates efficiently with an efficiency of 88% and is increased by using the EBG surfaces (slotted, mushroom-like) to 90% and 94% respectively at the desired resonant frequency band. The conventional antenna yields a bore side gain of 6.59 dB which is further enhanced up to 8.91dB and 7.50 dB by using mushroom-like and slotted EBG surfaces respectively as a ground plane. The proposed rotated Y-shaped antenna and EBG surfaces (mushroom, slotted) are analyzed using the Finite Integration Technique (FIT) employed in Computer Simulation Technology (CST) software. The designed antenna is applicable for future 5G applications.

Keywords: Fifth Generation (5G), rotated Y-shaped, EBG, CST.

¹ DTE, University of Engineering and Technology Mardan, 23200, Mardan, Pakistan.

² DEE, University of Engineering and Technology Mardan, 23200, Mardan, Pakistan.

³ DCSE, University of Engineering and Technology, Peshawar, 25000, Peshawar, Pakistan.

⁴ DET, Politecnico di Torino, 10129, Torino, Italy.

⁵ DEE, University of Central Punjab, Lahore, 54770, Lahore, Pakistan.

⁶ DEE, Mehran University of Engineering and Technology Jamshoro, Pakistan.

* Corresponding Authors: Sahib Khan. Email: sahib.khan@polito.it;

Jalal Khan. Email: jalal@uetmardan.edu.pk.

1 Introduction

In the past few years, the demand for higher bandwidth and data rate has been increased. As lower frequency bands are highly congested [Khan, Sehrai and Ali (2019)], and unable to provide higher bandwidth and data rate. Thus, one solution to this problem is to move towards the higher frequencies in the spectrum to achieve higher bandwidth and data rate requirements [Jilani, Abbas, Esselle et al. (2015); Alkaraki, Andy, Gao et al. (2018)]. The future Fifth Generation (5G) communication is mostly focused on the millimeter wave spectrum (30-300 GHz) [Khan, Sehrai and Khan (2018); Khan, Rehman, Ahmad et al. (2015); Hong, Baek and Ko (2017)] and is expected to provide 100-1000 times higher data rate as compared to the existing networks [Goudos, Tsiflikiotis, Babas et al. (2017); Khan, Rehman, Ahmad et al. (2015); Muirhead, Imran and Arshad (2016); Li, Sim, Luo et al. (2017)]. But there are some critical limitations, which need to be resolved at the millimeter wave spectrum. One of the most important limitations which gets more severe at higher frequencies is atmospheric attenuations and absorptions Khan, Rehman, Ahmad et al. (2015); Sulyman, Alwarafy, MacCartney Jr et al. (2016); Dahri, Jamaluddin, Abbasi et al. (2017)]. To develop a wireless network by integrating the advantages of a millimeter wave spectrum like higher bandwidth and data rate, while considering the limitations of the spectrum, is itself a challenging task [Khan, Sehrai and Ahmad (2018); Mak, Lai and Luk (2018)]. To overcome these atmospheric attenuations and absorptions at higher frequencies, high gain antennas are required [Chang, Yang, Chang et al. (2016)].

Microstrip patch antennas have gathered huge success for using in wireless communication systems due to their moderate performance and robust structures [Sunthari and Veeramani (2017); Mekki, Hamidon, Ismail et al. (2015); An, Li, Fu et al. (2018)]. But the major limitation of patch antennas is pronounced surface waves [Ahmad, Faisal, Khan et al. (2015)]. To overcome this issue, one of the most efficient approaches is to use an electromagnetic band gap (EBG) structures. These structures not only reduce the propagation of surface waves but, also improve the performance of antennas in terms of gain, efficiency, and bandwidth [Ali, Ullah, Khan et al. (2014); Alam, Misran, Yatim et al. (2013); Ali, Ullah, Shafi et al. (2019)].

In literature, different metamaterial surfaces encompassed with conventional antennas have been presented for various applications. A phased array antenna covering the frequency band 28 GHz in combination with metamaterial circular split ring resonator (CSRR) has presented in Essid et al. [Essid and Samet (2017)], to enhance the gain and directivity of the antenna. In Lucena et al. [Lucena, Silva, Pedrosa et al. (2017)], an antenna backed by a frequency selective surface (FSS) has presented to enhance the gain of an antenna. Similarly, a 5G antenna operating at the frequency band of 15 GHz integrated with Electromagnetic Bandgap (EBG) structure has presented in Xu et al. [Xu, Zhao, Ying et al. (2016)] to reduce the radiations of antenna towards the human body. A double negative (DNG) metamaterial surface in combination with antenna operating at 5.2 GHz frequency band has reported in Waqas et al. [Waqas, Bashir and Khan (2015)] to improve the overall performance of an antenna. A 5G antenna design operating at 28 GHz frequency band has presented in Haraz et al. [Haraz, Elboushi, Alshebeili et al. (2014)], employing EBG unit cell to improve the antenna's performance. In Liu et al.

[Liu, Wang and Zeng (2013)], a microstrip antenna has reported with a negative permeability metamaterial to improve the gain of an antenna. A dual beam bowtie antenna employing a metamaterial has presented in Jiang et al. [Jiang, Si, Hu et al. (2019)], to achieve the enhancement in gain of an antenna. Similarly, a metamaterial based antenna operating in the ka-band has reported in Pepino et al. [Pepino, Mota, Martins et al. (2018)], to improve the antenna’s gain. In this paper, a 5G antenna is proposed and its performance is analyzed using EBG surfaces (mushroom, slotted) and the significance of the EBG surfaces is clearly observed. The proposed antenna covers the widely used 5G (38 GHz) standard frequency band.

The remaining paper is sequenced as follows: Section 2 presents the design methodology of the proposed antenna, as well as the performance of the proposed antenna without a metamaterial surface, is discussed in this section. While the detailed discussion is made on the design methodology of the metamaterial surface in Section 3. The performance comparison of the proposed antenna with and without metamaterial surfaces is discussed in Section 4 and Section 5 concludes the paper.

2 Design methodology

2.1 Rotated Y-shaped antenna

In this section, the geometry of the proposed 5G antenna is presented in Fig. 1. The geometry of the nominated antenna consists of a 0.254 mm thicker low loss dielectric substrate material (RT 5880) having relative permittivity and loss tangent of 2.2 and 0.0009 respectively. A finite ground plane is used to back the substrate having length y and width x , 10 mm×6 mm respectively. The total volume of the antenna is 10×6×0.254 mm³. The dimensions of the antenna (Fig. 1) listed in Tab. 1. have been calculated from the well-known transmission line theory.

The design formulae to calculate the width (W) and length (L) of the patch antenna are given below.

$$W = \frac{c}{2f_0 \sqrt{\frac{\epsilon_r + 1}{2}}} \tag{1}$$

$$L = \frac{c}{2f_0 \sqrt{\epsilon_r}} - 0.824h \frac{(\epsilon_{eff} + 0.3) \left(\frac{W}{h} + 0.264\right)}{(\epsilon_{eff} - 0.258) \left(\frac{W}{h} + 0.9\right)} \tag{2}$$

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + 12 \frac{h}{W} \right]^{-\frac{1}{2}} \tag{3}$$

where, c is the velocity of the light, ϵ_{eff} , effective relative permittivity of the substrate, while h is the thickness of the substrate and f_0 , the resonant frequency of the antenna.

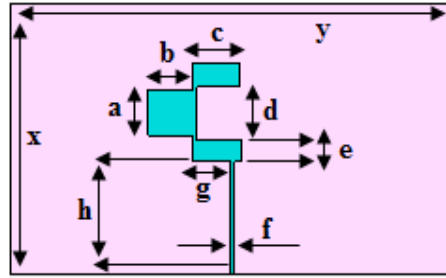


Figure 1: Geometry of the proposed 5G antenna

The summary of the dimensions of the rotated Y-shaped antenna is depicted in Tab. 1.

Table 1: Summary of the dimensions of rotated Y-shaped antenna

Parameter	Value	Parameter	Value
a	1.00	f	0.10
b	1.00	g	0.85
c	1.08	h	2.50
d	1.20	x	6.00
e	0.48	y	10.0

2.2 Results and discussion

2.2.1 Return loss

The return loss versus frequency of the designed rotated Y-shaped 5G antenna is portrayed in Fig. 2. The design and simulation of the proposed antenna are made using the Finite Integration Technique (FIT) exercised in CST MWS [Hirtenfelder (2007)]. The return loss of the proposed 5G antenna is -20.56 dB at 38.06 GHz. The proposed rotated Y-shaped 5G antenna resonates with a -10 dB bandwidth of 0.87 GHz at the resonant frequency of 38.06 GHz, which is sufficient for 5G cellular communication systems.

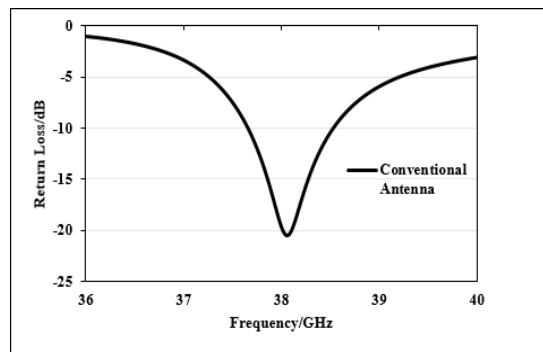


Figure 2: Simulated return loss of the proposed 5G antenna

2.2.2 Radiation pattern (2D & 3D)

The radiation pattern (gain) of the proposed rotated Y-shaped 5G antenna at the 38.06 GHz frequency band is shown in Fig. 4.

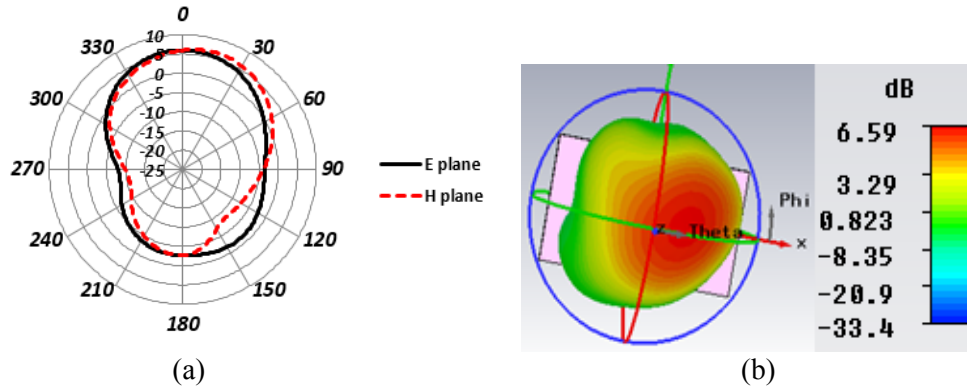


Figure 3: Radiation pattern (gain) of 5G antenna at 38.06 GHz (a) 2D plot (b) 3D plot

The 2D and 3D radiation patterns (gain) in Fig. 3 shows that the proposed 5G antenna provides a peak gain of 6.59 dB at the resonant frequency of 38.06 GHz. The designed 5G antenna radiates efficiently with an efficiency of 89% at 38.06 GHz frequency band.

3 Metamaterial surfaces (mushroom & slotted)

This section presents the design methodology of Mushroom like and slotted EBG unit cells. Also, the in-phase reflection response of both EBG unit cells (Mushroom, Slotted) is discussed in this section.

3.1 Design methodology of EBG unit cell (mushroom & slotted)

Fig. 4 portrays the geometry of the EBG unit cell (mushroom, slotted) employing a Rogers-5880 as a substrate with a thickness of 0.254 mm, backed by a finite ground plane. To design EBG unit cell (mushroom & slotted), Sievenpiper’s [Bashir (2009); Alam, Misran, Yatim et al. (2013); Iqbal, Saraereh, Bouazizi et al. (2018)] square shape model is used.

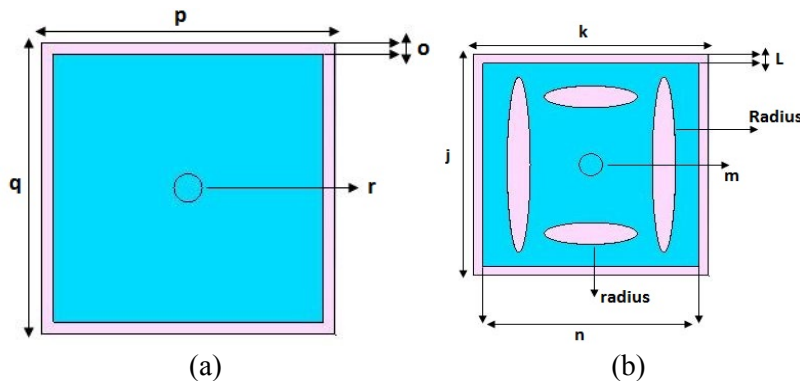


Figure 4: Front view of the EBG unit cell (a) Mushroom like (b) Slotted

The inductance (L) and effective capacitance (C) are the two important parameters on which the resonant frequency (f_r) of the unit cell depends, i.e.,

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad (4)$$

$$C = \frac{w\varepsilon_o(1+\varepsilon_r)}{\pi} \cosh^{-1} \frac{a}{g} \quad (5)$$

$$L = \mu_o h \quad (6)$$

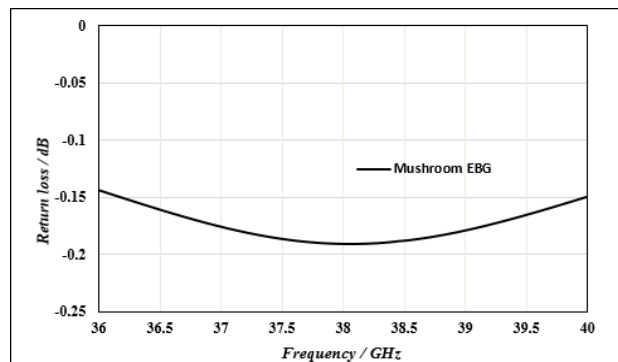
where ε_o is the vacuum's permittivity, w is the width of the unit cell and μ_o is the free space permeability, while g is the gap between the adjacent unit cells. The summary of the dimensions of the proposed EBG unit cell (mushroom, slotted) is shown in Tab. 2.

Table 2: Summary of the dimensions of rotated y-shaped antenna

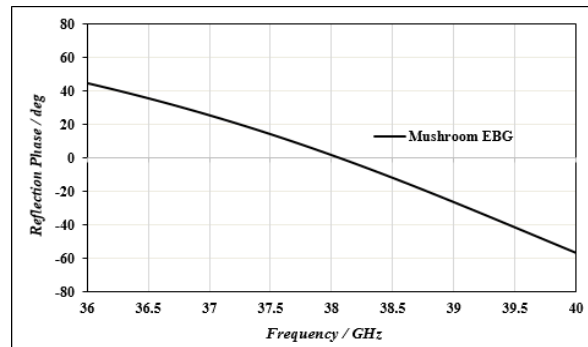
Parameter	Value	Parameter	Value
p	2.07	j	2.02
q	2.07	L	0.16
r	0.10	m	0.10
o	0.16	n	1.85
k	2.02	radius	0.40
Radius	0.80	-	-

3.2 Characterization of EBG

The return loss and reflection phase of the EBG unit cell (Mushroom and slotted) is shown in Figs. 5-6. It is observed that both the unit cells (mushroom, slotted) give an in-phase reflection at the desired frequency band (38.06 GHz).

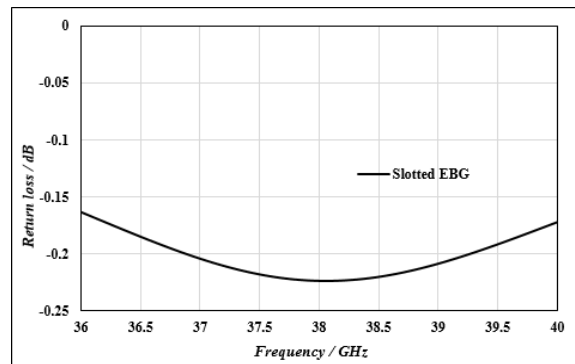


(a)

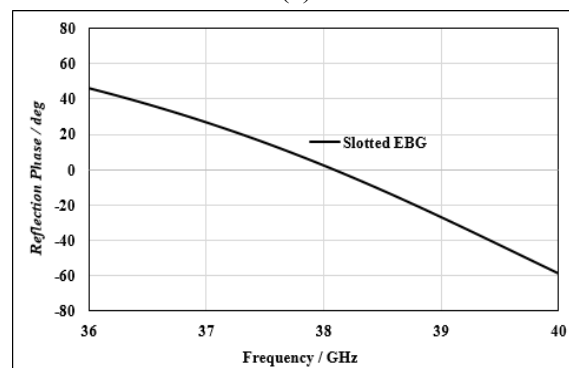


(b)

Figure 5: Simulated response of the mushroom like EBG unit cell at the desired 38.06 GHz frequency band (a) Return loss (b) Reflection phase



(a)



(b)

Figure 6: Simulated response of the slotted EBG unit cell at the desired 38.06 GHz frequency band (a) Return loss (b) Reflection phase

This in-phase reflection response to the proposed EBG unit cell (mushroom & slotted) is further helpful in improving the performance of the presented rotated Y-shaped 5G antenna in terms of gain and efficiency.

4 5G antenna with metamaterials

The performance of the proposed 5G antenna is analyzed utilizing CST MWS on a 3 x 4 size, Mushroom like and slotted EBG surfaces as a ground plane as shown in Fig. 7.

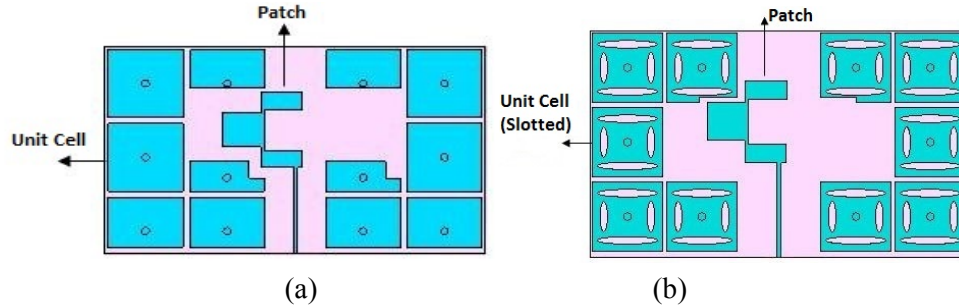


Figure 7: Layout of the proposed 5G antenna using a) Mushroom like EBG ground plane b) Slotted EBG ground plane

4.1 Return loss comparison

The return loss of the proposed 5G antenna is compared with the metamaterial-based antennas in Fig. 8. It is observed that that conventional antenna employing the slotted and mushroom-like EBG ground planes give better return loss response.

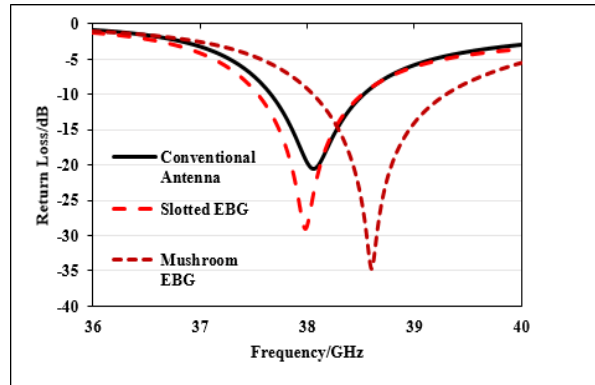


Figure 8: Return loss comparison of conventional and metamaterial based 5G antennas

The return loss of the conventional 5G antenna and metamaterial based antenna (mushroom, slotted) is below -10 dB, with a bandwidth of 0.87, 1.23 and 0.97 GHz respectively, which is adequate for 5G cellular communication systems.

4.2 Radiation pattern (2D & 3D)

In Fig. 9, the radiation patterns (gain) of the proposed 5G antenna and the metamaterial-based antennas are compared in the two principal planes i.e., E plane and H plane.

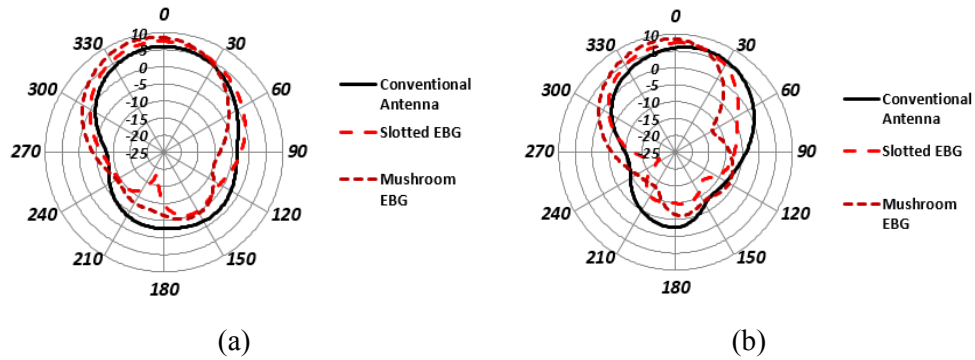


Figure 9: Radiation pattern (gain) comparison of (conventional antenna, mushroom EBG, slotted EBG) in (a) E-Plane (b) H-plane

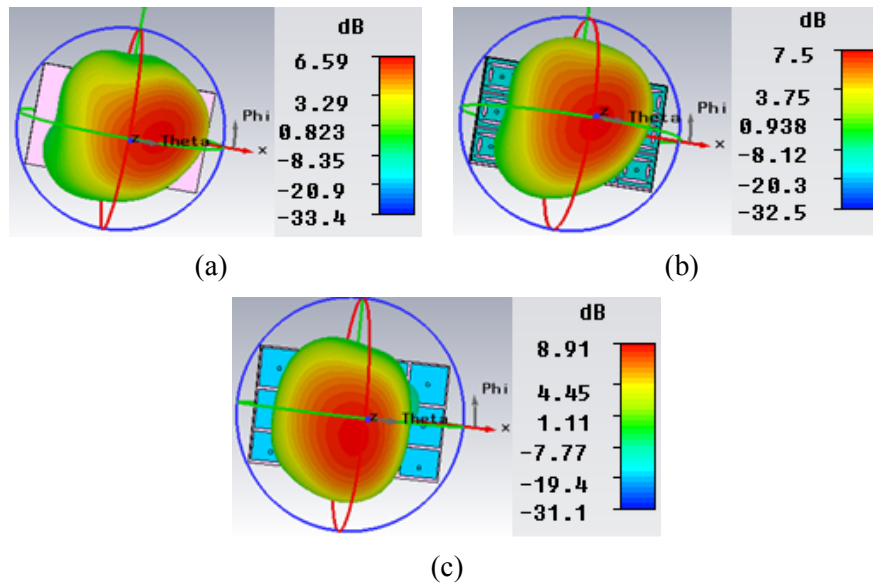


Figure 10: Radiation pattern (gain) of (a) Conventional 5G antenna (b) Slotted EBG (c) Mushroom EBG

The gain patterns (3D) of the conventional rotated Y-shaped 5G antenna and the metamaterial-based antennas (slotted, mushroom-like) are depicted in Fig. 10. As it can be seen that when the slotted EBG ground plane is used, so the gain of the antenna is improved from 6.59 dB to 7.5 dB. Similarly, the gain enhancement achieved by employing mushroom-like EBG as a ground plane is from 6.59-8.91 dB. All the proposed antennas i.e. conventional antenna, metamaterial-based antennas (slotted, mushroom) radiates efficiently with an efficiency of 89, 90 and 94% respectively.

5 Conclusion

In this paper a conventional rotated Y-shaped 5G antenna and two metamaterial-based antennas (mushroom and slotted) are designed for 5G cellular communication systems,

using a low loss substrate material (RT-5880). The simulation, comparison, and analysis of the proposed antennas (conventional rotated Y-shaped 5G antenna, metamaterial-based antennas) is made in terms of return loss, gain, efficiency, and bandwidth. The improvement in the performance of the proposed 5G antenna is observed by employing EBG ground planes (mushroom, slotted). The gain of the conventional 5G antenna is enhanced by using the metamaterial surfaces (slotted, mushroom) from {6.59-7.50 and 6.59-8.91} dB at the desired frequency band respectively. The proposed antennas (conventional, slotted EBG, mushroom EBG) radiate efficiently with an efficiency of 89, 90 and 94 % respectively at the desired frequency band. The proposed antennas provide a good impedance matching, high efficiency, acceptable gain, and bandwidth. Thus, the proposed antennas can be used in 5G based cellular applications. The prototype of the antenna will be fabricated and tested to validate the results.

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