Design and performance comparison of rotated Y-shaped antenna using different metamaterial surfaces for 5G mobile devices

Original
Design and performance comparison of rotated Y-shaped antenna using different metamaterial surfaces for 5G mobile devices / Khan, J.; Sehrai, D. A.; Khan, M. A.; Khan, H. A.; Ahmad, S.; Ali, A.; Arif, A.; Memon, A. A.; Khan, S.. - In: COMPUTERS, MATERIALS & CONTINUA. - ISSN 1546-2218. - 60:2(2019), pp. 409-420. [10.32604/cmc.2019.06883]

Publisher:
Tech Science Press

Published
DOI:10.32604/cmc.2019.06883

Computers, Materials & Continua CMC, vol.60, no.2, pp.409-420, 2019

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

Jalal Khan[1], Daniyal Ali Sehrai[1], Mushtaq Ahmad Khan[1], Haseeb Ahmad Khan[2], Salman Ahmad[3], Arslan Ali[4], Arslan Arif[5], Anwer Ahmad Memon[6] 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.

CMC. doi:10.32604/cmc.2019.06883 www.techscience.com/cmc

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 mm^3. 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.

$$W = \frac{c}{2f_o\sqrt{\frac{(\varepsilon_r+1)}{2}}} \tag{1}$$

$$L = \frac{c}{2f_o\sqrt{\varepsilon_r}} - 0.824h\frac{(\varepsilon_{eff}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{eff}-0.258)(\frac{W}{h}+0.8)} \tag{2}$$

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

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.

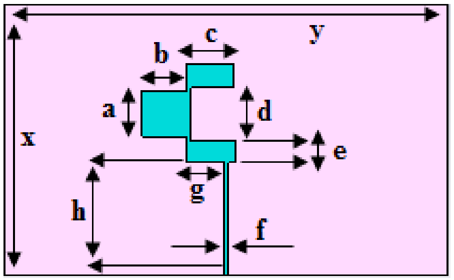


Figure 1: Geometry of the proposed 5G antenna

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.

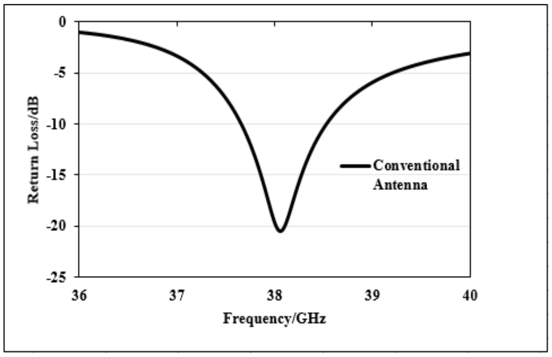
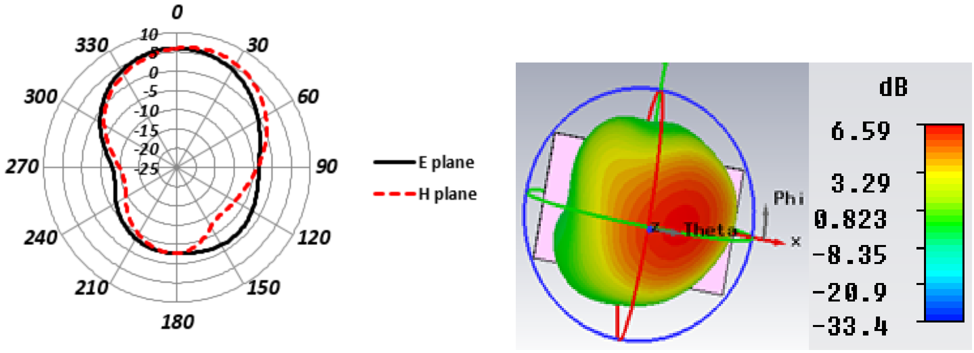


Figure 2: Simulated return loss of the proposed 5G antenna

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.



(a) (b)

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

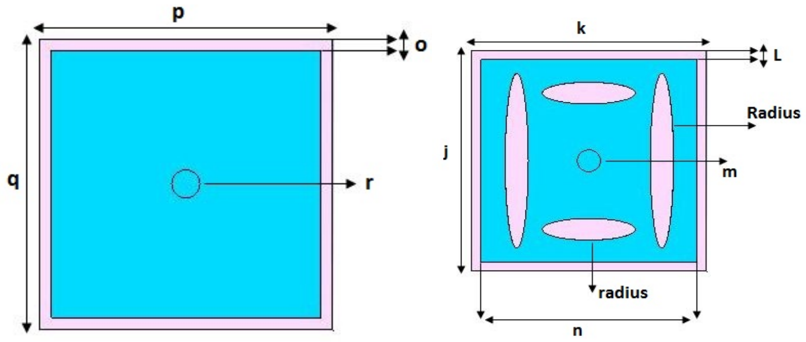
The 2D and 3D radiation patterns (gain) in Fig. 3 shows that the proposed 5G antenna provides a peak gain of 6.59 dB at the resonant frequency of 38.06 GHz. The designed 5G antenna radiates efficiently with an efficiency of 89% at 38.06 GHz frequency band.

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.



(a) (b)

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.,

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{4}$$

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

$$L = \mu_o h \tag{6}$$

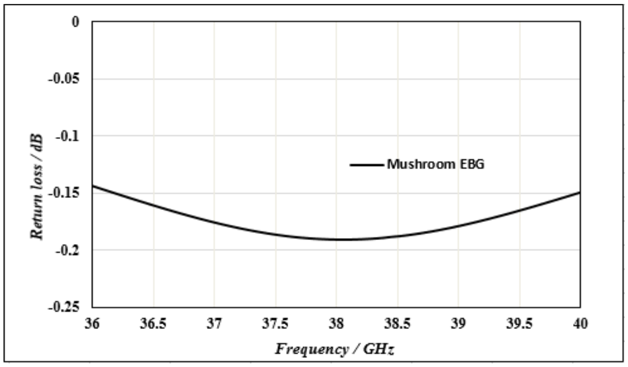
where ε_o is the vacuum's permittivity, w is the width of the unit cell and μ_o is the free space permeability, while g is the gap between the adjacent unit cells. The summary of the dimensions of the proposed EBG unit cell (mushroom, slotted) is shown in Tab. 2.

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

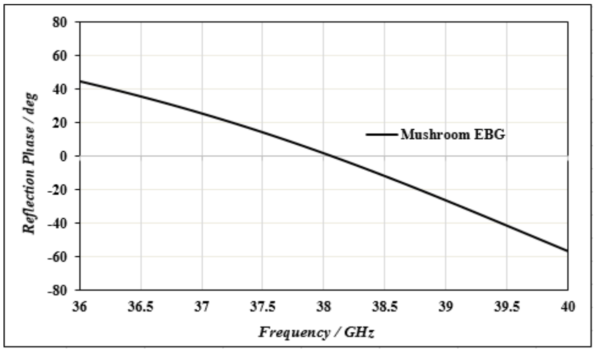
Parameter	Value	Parameter	Value
p	2.07	j	2.02
q	2.07	L	0.16
r	0.10	m	0.10
o	0.16	n	1.85
k	2.02	radius	0.40
Radius	0.80	-	-

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).

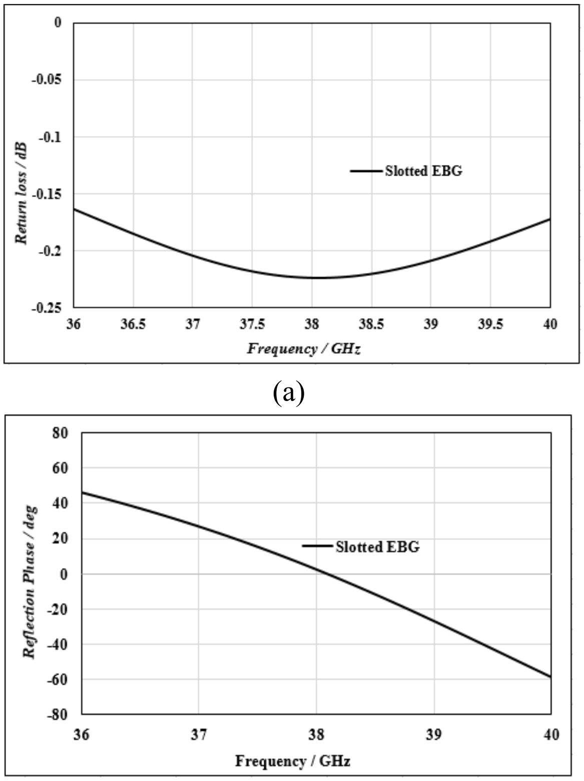


(a)



(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.

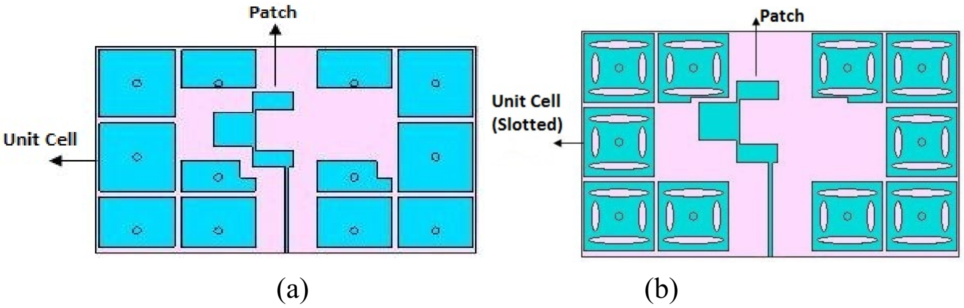


Figure 7: Layout of the proposed 5G antenna using a) Mushroom like EBG ground plane b) Slotted EBG ground plane

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.

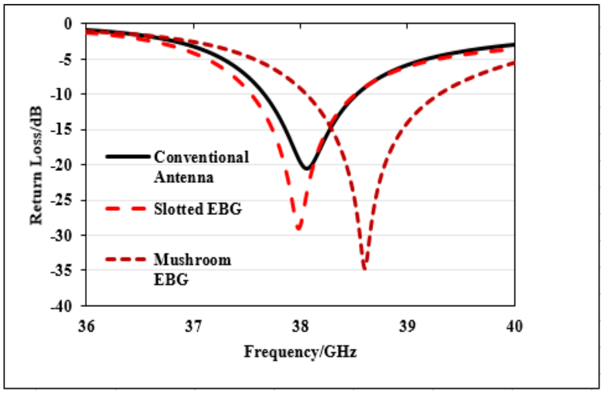
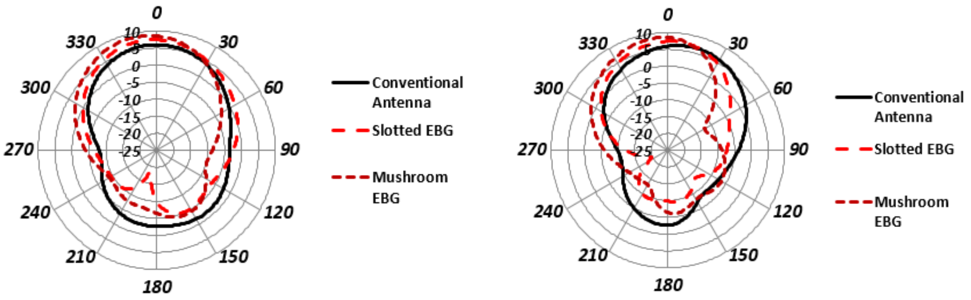


Figure 8: Return loss comparison of conventional and metamaterial based 5G antennas

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.

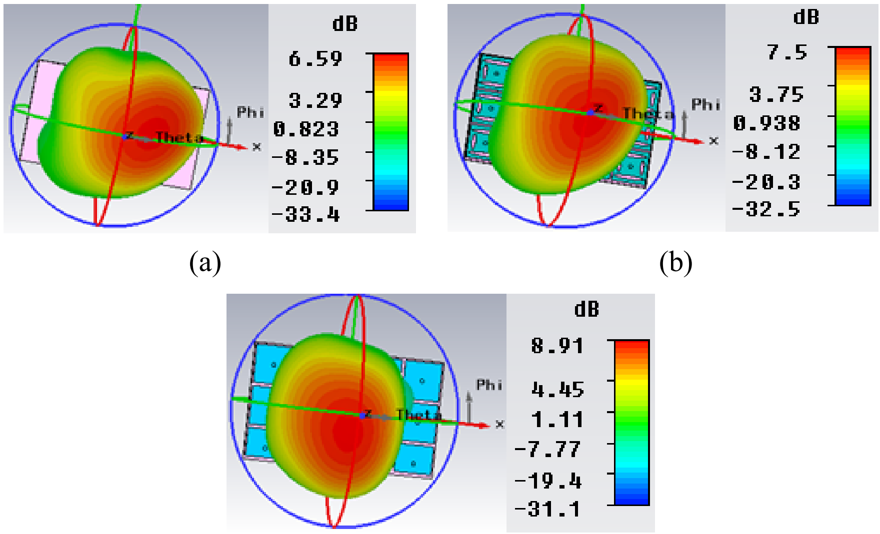
4.2 Radiation pattern (2D & 3D)

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.



(a) (b)

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



(a) (b)

(c)

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.

References

Ahmad, A.; Faisal, F.; Khan, S.; Ullah, S.; Ali, U. (2015): Performance analysis of a wearable and dual band planar antenna using a mushroom-like electromagnetic bandgap (EBG) ground plane. *IEEE International Conference on Open Source Systems and Technologies*, pp. 24-29.

Alam, Md. S.; Misran, N.; Yatim, B.; Islam, M. T. (2013): Development of electromagnetic band gap structures in the perspective of microstrip antenna design. *Journal of Antennas and Propagation*, vol. 2013, pp. 1-22.

Ali, U.; Ullah, S.; Khan, S.; Flint, J. A. (2014): Comparative study of rectangular microstrip patch antenna on various types of metamaterials surfaces. *IEEE International Conference on Open Source Systems and Technologie*, pp. 186-191.

Ali, U.; Ullah, S.; Shafi, M.; Shah, S. A. A.; Shah, I. A. et al. (2019): Design and comparative analysis of conventional and metamaterial-based textile antennas for wearable applications. *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, e2567.

Alkaraki, S.; Andy, A. S.; Gao, Y.; Tong, K. F.; Ying, Z. et al. (2018): Compact and low cost 3D-printed antennas metalized using spray-coating technology for 5G mm-wave communication systems. *IEEE Antennas and Wireless Propagation Letters*, vol. 17, no. 11, pp. 2051-2055.

An, W.; Li, Y.; Fu, H.; Ma, J.; Chen, W. et al. (2018): Low-profile and wideband microstrip antenna with stable gain for 5G wireless applications. *IEEE Antennas and Wireless Propagation Letters*, vol. 17, no. 4, pp. 621-624.

Bashir, S. (2009): *Design and Synthesis of Non-Uniform High Impedance Surface Based Wearable Antennas* (*Ph.D. Thesis).* Department of Electronics and Electrical Engineering, Loughborough University, Leicestershire, United Kingdom.

Chang, W.; Yang, C.; Chang, C.; Liao, W.; Cho, L. et al. (2016): Pattern reconfigurable millimeter-wave antenna design for 5G handset applications. *IEEE 10th European Conference on Antenna and Propagation*, pp. 1-3.

Dahri, M. H.; Jamaluddin, M. H.; Abbasi, M. I.; Kamarudin, M. R. (2017): A review of wideband reflectarray antennas for 5G communication systems. *IEEE Access*, vol. 5, pp. 17803-17815.

Essid, C.; Samet, A. (2017): A design of phased array antenna with metamaterial circular SRR for 5G applications. *IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications*, pp. 1-4.

Goudos, S. K.; Tsiflikiotis, A.; Babas, D.; Siakavara, K.; Kalialakis, C. et al. (2017): Evolutionary design of a dual band E-shaped patch antenna for 5G mobile communications. *IEEE 6th International Conference on Modern Circuits and Systems Technologies*, pp. 1-4.

Haraz, O. M.; Elboushi, A.; Alshebeili, S. A.; Sebak, A. R. (2014): Dense dielectric patch array antenna with improved radiation characteristics using EBG ground structure and dielectric superstrate for future 5G cellular networks. *IEEE Access*, vol. 2, pp. 909-913.

Hirtenfelder, F. (2007): Effective antenna simulations using computer simulation technology microwave studio. *2nd International ITG Conference on Antennas*, pp. 239-239.

Hong, W.; Baek, K. H.; Ko, S. (2017): Millimeter-wave 5G antennas for smartphones: overview and experimental demonstration. *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 12, pp. 6250-6261.

Iqbal, A.; Saraereh, O. A.; Bouazizi, A.; Basir, A. (2018): Metamaterial-based highly isolated MIMO antenna for portable wireless applications. *Electronics*, vol. 7, no. 10, pp. 267.

Jiang, H.; Si, L. M.; Hu, W.; Lv, X. (2019): A symmetrical dual-beam bowtie antenna with gain enhancement using metamaterial for 5G MIMO applications. *IEEE Photonics Journal*, vol. 11, no. 1, pp. 1-9.

Jilani, S. F.; Abbas, S. M.; Esselle, K. P.; Alomainy, A. (2015): Millimeter-wave frequency reconfigurable T-shaped antenna for 5G networks. *IEEE 11th International Conference on Wireless and Mobile Computing, Networking and Communications*, pp. 100-102.

Khan, S.; Ahmad, N.; Wahid, M.; Baloch, B.; Naeem, M. (2015): Design and characterization of rectangular stud antenna. *Sindh University Research Journal-SURJ (Science Series)*, vol. 47, no. 1, pp. 29-34.

Khan, S.; Ahmad, N.; Wahid, M.; Naeem, M.; Baloch, B. (2015): Design of circular stud antenna and parametric analysis. *Sindh University Research Journal-SURJ (Science Series)*, vol. 47, no. 2, pp. 231-236.

Khan, S.; Rehman, A.; Ahmad, N.; Naeem, M. (2015): The reduction of specific absorption rate at different frequencies. *Journal of Engineering and Applied Sciences*, vol. 34, no. 2, pp. 71-75.

Khan, J.; Sehrai, D. A.; Ahmad, S. (2018): Design and performance comparison of metamaterial based antenna for 4G/5G mobile devices. *International Journal of Electrical, Electronic and Communication Sciences*, vol. 12, no. 6, pp. 382-387.

Khan, J.; Sehrai, D. A.; Ali, U. (2019): Design of dual band 5G antenna array with SAR analysis for future mobile handsets. *Journal of Electrical Engineering & Technology*, vol. 14, no. 2, pp. 809-816.

Khan, J.; Sehrai, D. A.; Khan, S. (2018): Next generation mobile phone antenna and its SAR investigation. *Sindh University Research Journal-SURJ (Science Series)*, vol. 50, no. 1, pp. 27-32.

Li, Y.; Sim, C. Y. D.; Luo, Y.; Yang, G. (2017): 12-port 5G massive MIMO antenna array in sub-6 GHz mobile handset for LTE bands 42/43/46 applications. *IEEE Access*, vol. 6, pp. 344-354.

Liu, Z.; Wang, P.; Zeng, Z. (2013): Enhancement of the gain for microstrip antennas using negative permeability metamaterial on low temperature co-fired ceramic (LTCC) substrate. *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 429-432.

Lucena, F. A. C. S.; Silva, C. P. N.; Pedrosa, T. L.; de Melo, M. T. (2017): Gain enhancement of dual-band antenna using square loop FSS. *IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting*, pp. 2169-2170.

Mak, K. M.; Lai, H. W.; Luk, K. M. (2018): A 5G Wideband patch antenna with antisymmetric L-shaped probe feeds. *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 2, pp. 957-961.

Mekki, A. S.; Hamidon, M. N.; Ismail, A.; Alhawari, A. R. H. (2015): Gain enhancement of a microstrip patch antenna using a reflecting layer. *International Journal of Antennas and Propagation*, vol. 2015, pp. 1-7.

Muirhead, D.; Imran, M. A.; Arshad, A. (2016): A survey of the challenges, opportunities and use of multiple antennas in current and future 5G small cell base stations. *IEEE Access*, vol. 4, pp. 2952-2964.

Pepino, V.; Mota, A.; Martins, A.; Borges, B. H. V. (2018): 3D-printed **d**ielectric metasurfaces for antenna gain improvement in the ka-band. *IEEE Antennas and Wireless Propagation Letters*, vol. 17, no. 11, pp. 2133-2136.

Sulyman, A. I.; Alwarafy, A.; MacCartney Jr., G. R.; Rappaport, T. S.; Alsanie, A. (2016): Directional radio propagation path loss models for millimeter-wave wireless networks in the 28, 60, and 73 GHz bands. *IEEE Transactions on Wireless Communications*, vol. 15, no. 10, pp. 6939-6947.

Sunthari, P. M.; Veeramani, R. (2017): Multiband microstrip patch antenna for 5G wireless applications using MIMO techniques. *IEEE First International Conference on Recent Advances in Aerospace Engineering*, pp. 1-5.

Waqas, M.; Bashir, S.; Khan, M. J. (2015): High gain microstrip patch antenna using double negative metamaterial. *IEEE International Conference on Emerging Technologies*, pp. 1-5.

Xu, B.; Zhao, K.; Ying, Z.; He, S.; Hu, J. (2016): Investigation of surface waves suppression on 5G handset devices at 15 GHz. *IEEE 10th European Conference on Antennas and Propagation*, pp. 1-4.