Improving Characteristics of 28/38GHz MIMO Antenna for 5G Applications by Using Double-Side EBG Structure

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Abstract — Multiple Input Multiple Output (MIMO) antenna is expected to form a major technique of 5G communication to get a high channel capacity. However the antenna performance is degraded significantly because of mutual coupling between close elements in portable equipments. In this paper, a novel EBG structure for 28/38GHz dual-band MIMO antenna with its equivalent is proposed. Having round shape and double side design, the proposed double-side EBG (DS-EBG) structure is able to improve significantly both mutual coupling and gain without any decoupling structure between antenna elements. Thus the MIMO antenna gets compact size of 15.3x8.5x0.79mm^3 with no distance between antenna elements from edge to edge. The antenna radiation efficiency is also refined at both bands. This improvement has not attained from any previous EBG structure studies. At 28GHz, the radiation efficiency is increased from 83.2% to 87.6% while it is raised from 83.1% to 91.1% at 38GHz. Besides, the antenna achieves wide bandwidth of 7.1% and 13.16% at 28GHz and 38GHz, respectively that is suitable for 5G terminals. All dimensions of EBG cell as well as antenna are optimized by using Computer Simulation Technology (CST) software.

Index Terms—DS-EBG, 5G, millimeter wave antenna, mutual coupling

I. Introduction

5G which is known as the fifth-generation mobile network or fifth-generation wireless system is an interested topic of many scientific researches recently. It is desired to establish the 5G network by 2020 that is be able to provide a multi-gigabit-per-second-based data rate for communication by using Multiple Input Multiple Output (MIMO) and millimeter wave antenna. MIMO antenna will be used in 5G network because it can get a high channel capacity increasing without bandwidth addition or transmission power increasing. However, mutual coupling is a challenge in applying massive MIMO in base station as well as MIMO in UE handsets [1]. Thus, the key design parameters for antenna operating at 5G band not only are high gain, planar in nature, and small size but also are MIMO with low mutual coupling between antenna elements.

Electromagnetic Band Gap (EBG) structures are periodic or aperiodic of dielectric material and metallic conductor that can prevent or assist the propagation of electromagnetic wave in a certain frequency band [2]. In previous studies, various EBG structures have been proposed to improve characteristics of single and MIMO antenna which operating bands are less than 10GHz [3]. In current time, EBG structure still attracts the researchers who concentrate on improving gain or decreasing mutual coupling of MIMO antenna for 5G applications [4]-[9]. Osama M.Haraz [4], Almir Soura e Silva Neto [5], and Sanae Dellaoui [6] obtains a gain increase but only for single antenna [4]-[6] with array structure addition [4], [6]. Mu'ath J. Al-Hasan [7] presents a compact uni-planar EBG to reduce mutual coupling but it is only for single band at 60GHz with the distance of 0.5λ Besides, the MIMO antenna using that proposed EBG got the low gain of 5.2dBi at 60GHz. Mohammad S. Sharawi [8] uses a combination of EBG and SRR structure which is so complex with four layers to improve significantly antenna gain but the isolation is not good (S12 about -15dB). Ahsan Altaf [9] uses a structure of 3x5 EBG cell to decrease 20dB mutual coupling but the distance between elements rather long. It is 0.45λ from edge to edge. There are still a few studies which get low mutual coupling for MIMO antenna at millimeter wave bands [10]-[13]. Mohammadmahdi Farahani [10] and Reza Karimian [11] use the defected wall structure but the decoupling structure is placed in vertical. Thus its height is higher than the height of antenna. So the antenna is not easy to fabricate. In addition, these structures are able to apply only for one band of 60GHz. Naser Ojaroudi Parchin [12] and Menna El Shorbagy [13] have reduced mutual coupling for dual band antenna at 28/38GHz but they use spacing solution with long distance between antenna elements. Moreover, most of previous researches on MIMO antenna have to use a decoupling structure between radiation elements to decrease mutual coupling [14], [15].

In this paper, a novel double-side EBG (DS-EBG) structure which has round patch is proposed. Applying DS-EBG structures of 1x10 and 1x11 unit cell which are placed above and below to radiation antenna patch, the proposed DS-EBG helps to improve not only gain of both single and MIMO antennas but also reduces significantly mutual coupling at lower band without adding any decoupling structure between elements. Besides, the proposed antennas get wide band and high

Manuscript received May 20, 2018; revised December 16, 2018.
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doi:10.12720/jcm.14.1.1-8

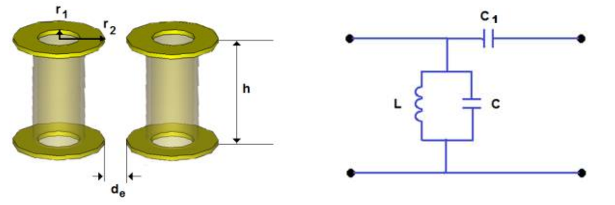
radiation efficiency which is suitable for 5G portable equipments.

The rest of this paper is organized as follows. In Section II, the design of round shape DS-EBG structure with its equivalent circuit is presented. The stop-band of DS-EBG structure to prove the mutual coupling reduction and the in-phase reflection of DS-EBG unit cell for explaining gain improvement are also presented in this section. The designs of single and dual-band MIMO antenna without and with EBG structure as well as their simulated and measure results are shown in Section III while some conclusions are provided in Section IV.

II. Round Shape DS-EBG Unit Cell

A. The Proposed Round Shape DS-EBG Structure

The geometry of the proposed double-side and round-shape EBG unit cell consists of a meta round of both side and a metal hollow cylinder via which connect patch and ground plane as shown in Fig. 1 (a). The design is based on RT5880 substrate with the thickness of 0.79mm and the relative permittivity of 2.2. The LC equivalent circuit of this structure is illustrated in Fig. 1(b). It is consist of L, C and C_1. The inductor L result is got from the current which is flow along adjacent patch through the via. Capacitor C_1 is used to model the gap effect between the patches of unit cell. The capacitor C is made from the gap effect between meta patches on the surface and ground plane.



(a) Unit cell (b) Equivalent circuit

Fig. 1. Double side EBG structure with round patch shape.

The C value is calculated approximately by Equation (1).

$$C = \frac{\varepsilon_0 \varepsilon_r (r_1 - r_2)^2}{h}, \quad (1)$$

where ε_0; ε_r is the permittivity of free space and the relative dielectric constant of the substrate, respectively. The L value is calculated using (2) as the following:

$$L = kh\left[ln\left(\frac{2h}{r_2}\right) + 1\right], \quad (2)$$

where k = 0.2nH/mm [16]. C_1 value is calculated approximately as follows (3):

$$C_1 = 2\varepsilon_0(1 + \varepsilon_r)cosh^{-1}\left(\frac{\pi r + d_e}{d_e}\right), \quad (3)$$

Thus, the resonant frequencies of the proposed EBG structure are calculated by Equation (4) and (5).

$$f_1 = \frac{1}{2\pi\sqrt{LC}} \quad (4)$$

$$f_2 = \frac{1}{2\pi\sqrt{L(C + C_1)}}. \quad (5)$$

The detail dimensions of DS-EBG unit cell are presented in Table I.

TABLE I: DIMENSIONS OF SINGLE ANTENNA (MILLIMETERS)

Parameter	h	d_e	r_1	r_{f2}
Dimension	0.79	0.21	0.35	0.2

B. Band-gap Characteristic

Fig. 2 shows the simulated transmission coefficient of the EBG structure whose number of round patch DS-EBG cell increases from seven to ten elements. Simulation is carried out using the CST-MW software. It is clearly seen that there are two bands with 20dB reduction in the transmission coefficient and the more number of unit cells increases the lower reduction gets. With number of EBG cells is seven, we get two stop bands of 24.58GHz - 30.76 GHz and 35.59GHz – 40.53 GHz frequency band. Over this bandwidth, no surface-wave propagation is allowed. Thus, it is suitable for decreasing mutual coupling for dual-band MIMO antenna which operates at 28 GHz and 38 GHz bands of 5G.

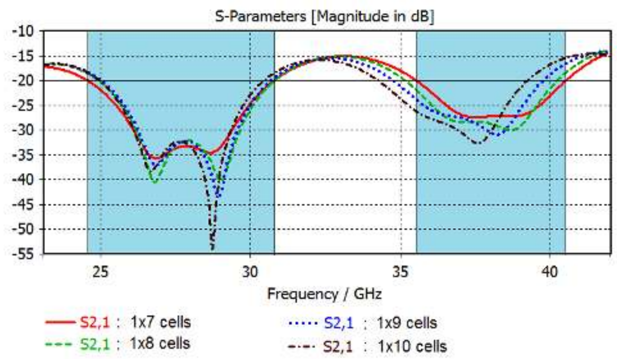


Fig. 2. Simulated transmission coefficients of the round patch DS-EBG structure with different number cells

C. Reflection Phase

One of the interesting characteristics of the EBG structures is in-phase reflection. A periodic EBG structure has an identical reflection phase for a normally incident plane wave in spite of its polarization [2]. The in-phase reflection mainly occurs when the incident plane wave is at the resonant frequency [17]. Besides, at the places which the phase difference is zero, the amplitude of the total wave is the sum of component amplitudes [18] thus the antennas using EBG structure are able to enhance gain.

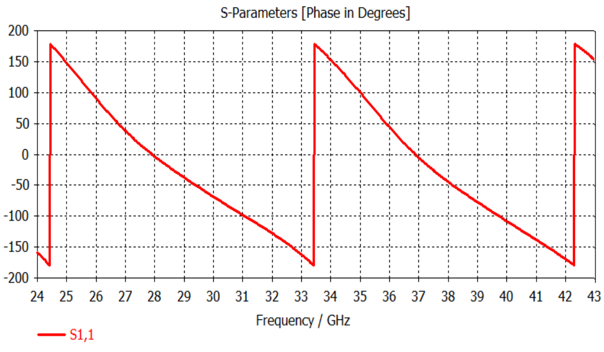


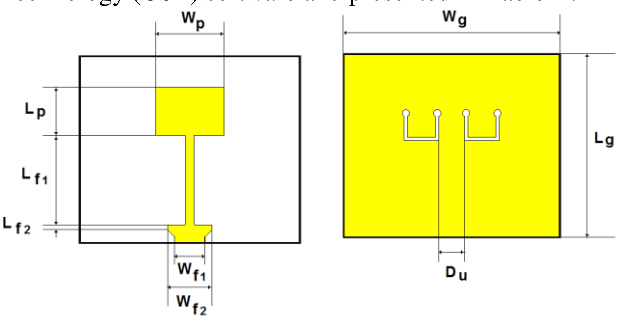
Fig. 3. Reflection phase of the proposed DS-EBG

The reflection phase of round patch DS-EBG structures in Fig. 1 has been calculated and the result is given in Fig. 3. The in-phase reflection frequency of the proposed DS-EBG structure is about 28 GHz and 37GHz. From this result, it can be seen that this DS-EBG is able to improve gain for 28GHz/37GHz antenna of 5G applications.

III. Applying the DS-EBG to Dual-Band Antenna

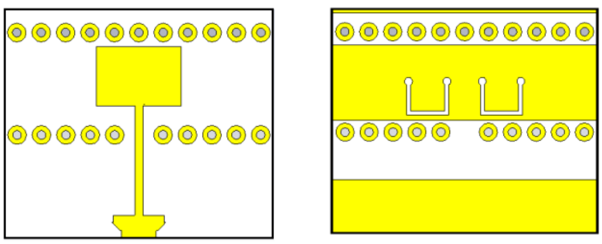
A. Antenna Design

The effectiveness of the proposed DS-EBG is evaluated for both single and MIMO dual band antenna. Firstly, the dual-band single antenna is designed basing on RT5880 substrate with the thickness of 0.79mm, the relative permittivity of 2.2, and loss tangent of 0.0009. The dimensions of antenna patch are calculated and optimized for operation at the first band of 38GHz using standard formulas introduced by Balanis [19]. The second resonant frequency, 28GHz band, is made by using a couple of U-shape Defected Ground Structure (DGS). This structure is placed in horizontal direction and just under radiation element of antenna to change both current distribution and E field of antenna [20] as shown in Fig. 4. Next, to improve the antenna gain, DS-EBG structures of 1x10 and 1x11 unit cell are placed above and below to radiation antenna patch as shown in Fig. 5. The details of antenna are optimized by using Computer Simulation Technology (CST) software and presented in Table II.



(a) Top view (b) Bottom view

Fig. 4. Dual-band single antenna

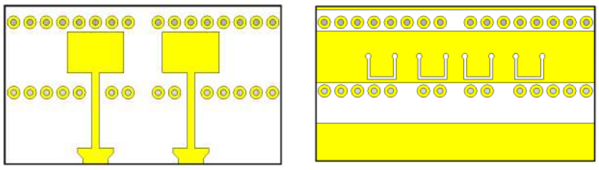


(a) Top view (b) Bottom view

Fig. 5. Dual-band single antenna with DS-EBG

TABLE II: Dimensions of Single Antenna (Millimetres)

Parameter	Dimension	Parameter	Dimension
W_g	10	W_{f1}	1.4
L_g	8.5	W_{f2}	2
W_p	3.16	L_{f1}	4.07
L_p	2.2	L_{f2}	0.25
D_u	1.2		



(a) Top view (b) Bottom view

Fig. 6. Dual-band MIMO antenna with DS- EBG

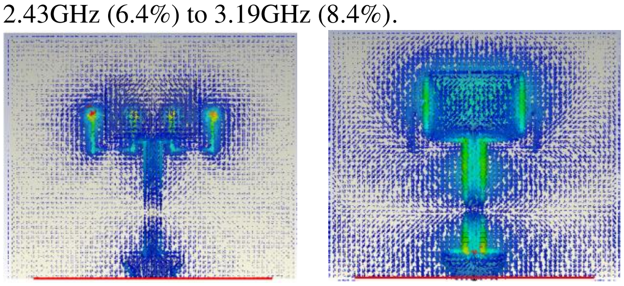
Finally, the MIMO antenna is constructed by place two single antennas side by side without any distance from edge to edge. From feeding point to feeding point, it is nearly a half of wavelength at lower band. There is a little difference in the number of DS-EBG cells, the distance between DS-EBG cells and the distance between U shape of DGS structure because of ensuring the compact size as well as the proper ground. The geometry of dual-band MIMO antenna with DS-EBG is presented in Fig. 6 with the dimensions is optimized by using Computer Simulation Technology (CST) software. The total size of MIMO antenna is 15.3x8.5x 0.79 mm^3 that is suitable for 5G terminal.

B. Simulation Results

1) Single antenna

The mechanics of dual-band antenna is proved by current distribution which is presented in Fig.7. At 28GHz, the electric current goes from the microstrip line to distribute on the U shape of DGS while at 38 GHz, it is concentrated on rectangular patch. Thus the proposed antenna is able to operate at two desired resonant frequencies.

It can be seen more clearly from the plot of the reflection coefficient of single antenna with and without DS-EBG. From Fig.8, it is obvious that the antennas operate at both bands of 28GHz and 38GHz. They are from 27.6GHz to 29.9GHz and 36.542GHz to 39.72GHz which are suitable for 5G bands of USA, Korea, and Japan [20]. In addition, the antenna with DS-EBG gets the larger bandwidths. At 28GHz band, it is increased by 790MHz which is from 1.5002GHz (5.3%) to 2.3 GHz (8.2%). At 38 GHz band, the bandwidth is enlarged from 2.43GHz (6.4%) to 3.19GHz (8.4%).



(a) At 28GHz (b) At 38GHz

Fig. 7. Current distribution of the proposed single antenna

Moreover, one of significant features of EBG structure is in-phase reflection. With EBG structure which is placed surround, the antenna gain is able to enhance without increasing total antenna size if the reflection phase of EBGs is zero at antenna operation band. As can be seen from Fig. 9, the 2D radiation patterns of single antennas are the same dipole shape at 28GHz but the antenna released gain with DS-EBG is improved by 1.73dB.

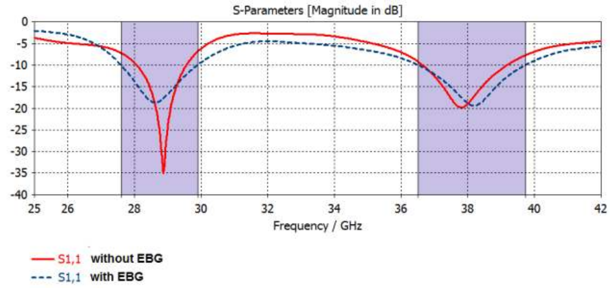
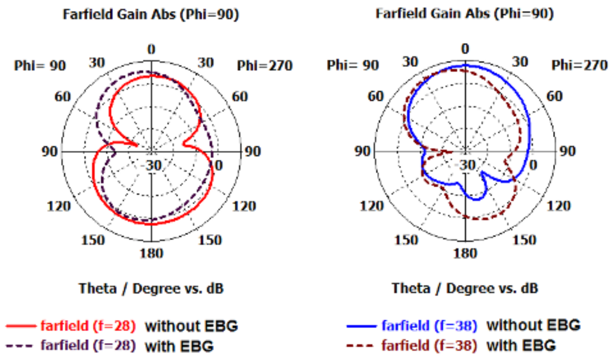


Fig. 8. The reflection coefficient of single antenna



(a) At 28GHz (b) At 38GHz

Fig. 9. 2D radiation pattern of single antenna

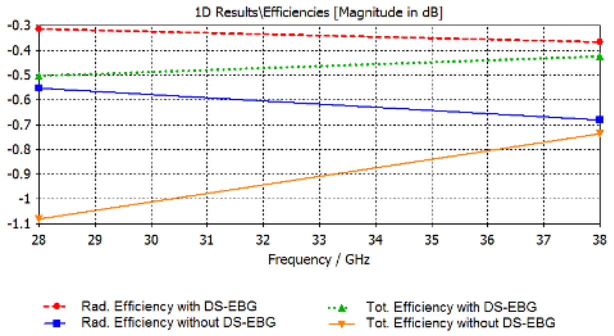


Fig. 10. Efficiency of single antenna

At 38GHz, the 2D radiation pattern change from directive shape to dipole shape while ensure the gain. This means the antenna gain is not only improved but also suitable for handheld devices.

The efficiency of single antenna with and without DS-EBG is presented in Fig.10. There are efficient improvements in both bands for both radiation efficiency and total efficiency. At 28GHz, there is a radiation efficient increase of 5% which is from 88% to 93% while it is a 6% which is from 85.9% to 91.9% at 38GHz. This improvement was not presented at any previous studies of conventional EBG structures.

2) MIMO antenna

The simulation results of the transmission/ reflection coefficients of dual-band MIMO antennas with and without DS-EBG structure are shown in Fig. 11 and Fig. 12.

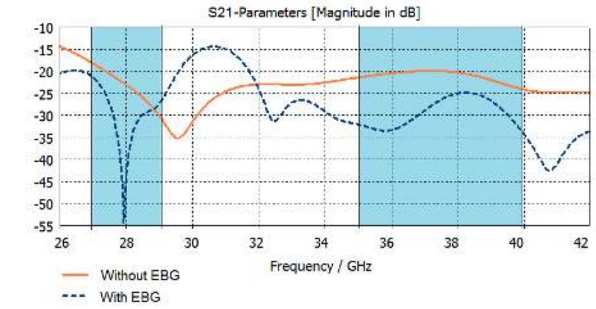


Fig. 11. The S21 parameter of MIMO antenna

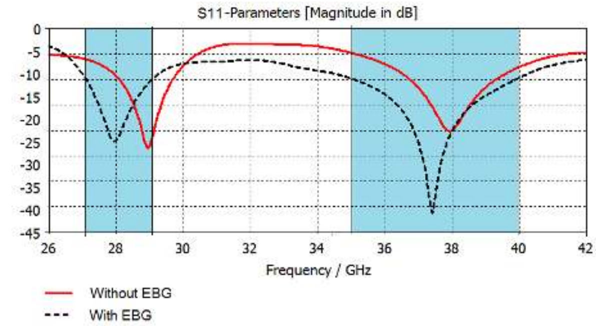


Fig. 12. The S11 parameter of MIMO antenna

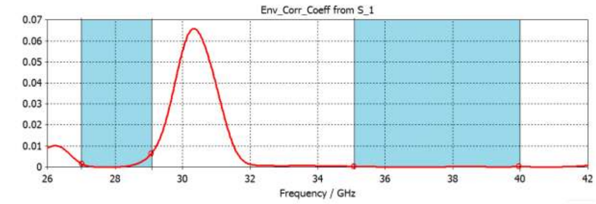


Fig. 13. Correlation Factor |ρ12| curve for the proposed MIMO antenna

By using a double DGS of U shape, the S21 parameter of MIMO antenna without EBG is nearly -20dB at 28/ 38GHz bands [21] but it can not meet the isolation demand of good MIMO antenna [22]. Moreover, the lower S21 is the less correlation between antenna elements occurs thus the less performance of MIMO system is degraded [23]. Appling the DS-EBG structure, the mutual coupling is reduced significantly. At 28GHz resonant frequency, the S12 gets -55dB which is decreased by about 30dB. There is also the mutual coupling enhancement at 38GHz band of 5dB reduction.

Besides, enveloped correlation coefficient (ECC) is one of important factors in MIMO antenna. It can be calculated by Equation (6) [24]:

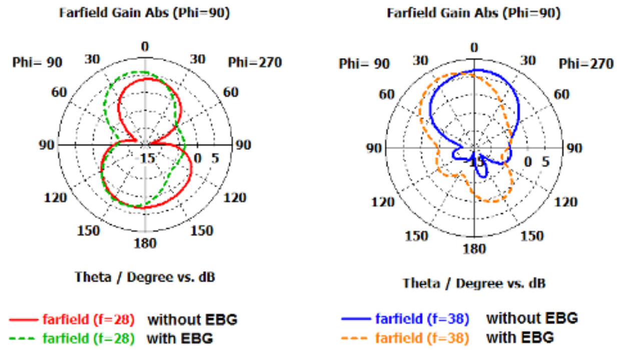
$$|\rho_e(i,j,N)| = \frac{\left|\sum_{n=1}^{N} S_{i,N}^{*} S_{N,j}\right|}{\sqrt{\left|\prod_{k(=i,j)}\left[1-\sum_{n=1}^{N} S_{i,N}^{*} S_{N,k}\right]\right|}}. \quad (6)$$

For a two element antenna system, the enveloped correlation (ρ_e) can be calculated conveniently and quickly from S-parameters as follows [11]:

$$\rho_e = \frac{|S_{11}^{*}S_{12} + S_{21}^{*}S_{22}|^2}{(1-|S_{11}|^2-|S_{21}|^2)(1-|S_{22}|^2-|S_{12}|^2)}. \quad (7)$$

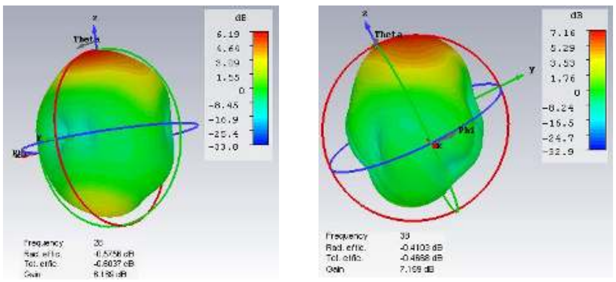
It is able to see more clearly the low mutual coupling between elements of the proposed MIMO antenna by the plot of correlation Factor |ρ12| curve in Fig. 13. For all operating band of dual-band antenna, the |ρ12| is under 0.01which is quite suitable for mobile communication [23].

Moreover, in the same way as single antenna, the DS-EBG MIMO antenna bandwidths are also enlarged notably at two bands which are compared with MIMO antenna without DS-EBG as seen in Fig. 12. The DS-EBG MIMO gets a larger bandwidth of 2GHz (7.14%) and 5GHz (13.16%) at 28GHz and 38GHz, respectively.



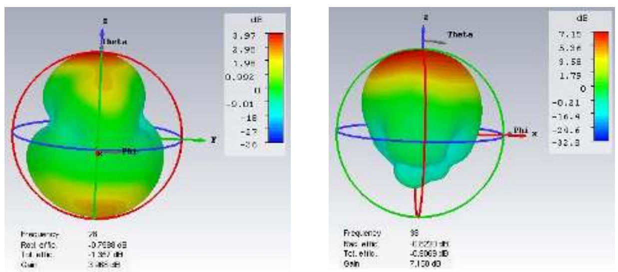
(a) At 28GHz (b) At 38GHz

Fig. 14. 2D radiation pattern of MIMO antenna



(a) At 28GHz (b) At 38GHz

Fig. 15. 3D radiation pattern of MIMO antenna with DS-EBG



(a) At 28GHz (b) At 38GHz

Fig. 16. 3D radiation pattern of MIMO antenna without DS-EBG

From the Fig. 14, the 2D radiation patterns of MIMO antenna with and without EBG are smooth and nearly the same shape. In addition, the antenna gain is enhanced. Here, the proposed MIMO antenna with DS-EBG structure not only achieves gain improvement but radiation efficiency increase at both bands. This improvement has not attained from any previous EBG structure studies. This can see obviously from the 3D radiation pattern of MIMO antenna with and without DS-EBG which are shown in Fig. 15 and Fig. 16 or from the efficiency plot which is in Fig. 17. At 28GHz, the gain of DS-EBG MIMO gets 6.19dB and is refined by 2.22dB. The radiation efficiency is increased from 83.2% to 87.6%. At 38GHz, the antenna gain is 7.16dB and the radiation efficiency is increased from 83.1% to 90.1%.

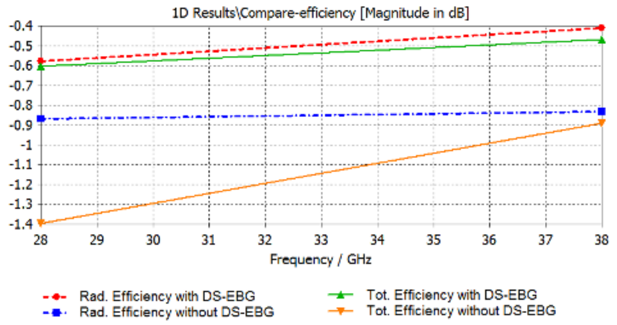


Fig. 17. Efficiency of MIMO antenna

Mean effective gain (MEG) and diversity gain are also the parameters to evaluate MIMO antenna characteristic. The MEG is defined as the ratio of the mean received power to the mean incident power of the antenna. Based on approximations, the MEG can be expressed as [25]:

$$MEG = \frac{1}{2\pi}\int_0^{2\pi}\left[\frac{\Gamma}{\Gamma+1}G_\vartheta\left(\frac{\pi}{2},\varphi\right)+\frac{\Gamma}{\Gamma+1}G_\varphi\left(\frac{\pi}{2},\theta\right)\right]d\varphi \quad (8)$$

where G_θ and G_φ are the θ and φ polarized components of antenna power gain pattern; Γ is the cross polarization discrimination (XPD). Simulated radiation pattern values were used to calculate the MEG. For the isotropic environment, the MEG becomes equal to half the classical radiation efficiency [26]. Thus, MEG of the proposed MIMO antenna gets -0.29dBi and -0.21dBi which is suitable for MIMO antenna [27].

Diversity gain is the increase in signal-to-interference ratio due to some diversity scheme, or how much the transmission power can be reduced when a diversity scheme is introduced, without a performance loss. The effective diversity gain (EDG) of the multi-antenna system is calculated using Equation (9):

$$G_{eff} = \eta(1-|S_{11}|^2-|S_{21}|^2).10.\sqrt{1-|\rho_e|^2} \quad (9)$$

where η is radiation efficiency and ρ_e is ECC which is calculated in Equation (7).

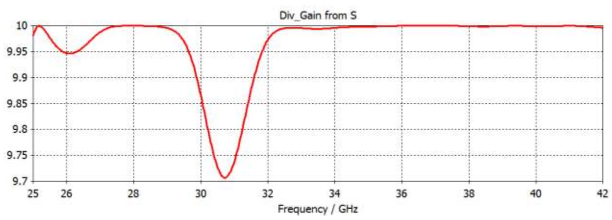


Fig. 18. Diversity gain of the proposed antenna

The plot of diversity gain of the proposed MIMO antenna is shown in Fig. 18. At both the antenna operating band, the diversity gain get 10dB which is suitable for MIMO antenna system [26].

3) Comparison

The comparison between current antenna with the proposed DS-EBG and some previous EBG designs for millimeter wave antenna is shown in Table III. The operation frequency of antennas is around 28GHz band. All antennas and EBG structures are designed basing on RT5880, ε=2.2, and loss tangent = 0.0009.

From the Table III, it is clearly seen that the proposed antenna with DS-EBG have achieved all advantages of EBG. They are bandwidth enlargement, gain enhancement, and mutual coupling reduction. The EBG structure with multi-layer [4] are able to improve antenna gain significantly thanks to not only EBG structure but also the much higher total substrate thickness as Chu criterion [28]. It is similar to the EBG structure with array [6]. However, both of the structures can not improve the antenna bandwidth.

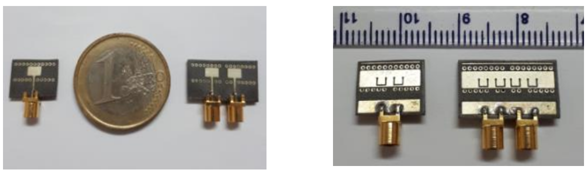
TABLE III: COMPARISON BETWEEN PRESENT DESIGN AND PREVIOUS EBG RESEARCH FOR 28GHZ ANTENNA

Ref	Freq (GHz)	Technique	Dimension (mm^3)	Bandwidth (%)	Gain (dBi)	Radiation efficiency	Mutual coupling (dB)	Distance from edge to edge (λ)	Single/ MIMO
[4]	28	Multi-layer + EBG	20 x 20 x 7	No improvement	Increase of 3.84	Decrease of 20.5%	-	-	Single
				No improvement	Increase of 4.32	Decrease of 14.7%			
[5]	28	EBG on substrate/ ground	10.5 x 7.9 x 0.5	Increase of 0.97%	Increase of 0.09	No given	-	-	Single
	60			Increase of 5.97%	Increase of 0.26	No given			
[6]	25	Array + EBG	25.9 x 27.6 x 6.57	A little increase	Increase of 1.0	No given	-	-	Single
	28			No improvement	Increase of 2,3	No given			
	38			No improvement	Increase of 5.5	No given			
[9]	24	Uni EBG on substrate		Increase of 0.08%	Increase of 1.22	No given	Decrease of 20	0.45	MIMO
Our design	28	DS-EBG	15.3x8.5x 0.79	Increase of 1.17%	Increase of 2.22	Increase of 5.4%	Decrease of 30	0	MIMO
	38			Increase of 3.84%	Increase of 0.01	Increase of 7%	Decrease of 5		

Specially, the radiation efficiency of DS-EBG antenna has been improved for two operating bands. This improvement can not get in almost previous EBG [4]-[9]. That is reason why this parameter is usually not given in many EBG studies [5], [6], and [9].

C. *Measurement Results*

To verify the performance of the proposed dual-band antenna for 5G application, the antenna is fabricated on RT5880 substrate with permittivity of 2.2 and the thickness of 0.79 mm.



(a) Top view (b) Bottom view

Fig. 19. Fabricated antenna

Fig. 19 shows photography of both 28/38 GHz dual-band antenna using DS- EBG structure. The total size of single antenna is 10x8.5mm^2 while MIMO antenna is 15.8x8.5 mm^2.

The measurement results of antenna are got by using Vector Network Analyzer (VNA) and shown in Fig. 20 and Fig. 21. From the Fig. 20, it is clearly seen that the antenna operates at 28 and 38 GHz. It is the same resonant frequencies for simulation results. From the Fig. 21, the mutual coupling is nearly -60dB at 28GHz and -35dB at 38GHz resonant frequency. There are variable in measurement results but they are acceptable because the measurement results are so sensitive at high frequencies, especially at millimeter wave and for MIMO antenna.

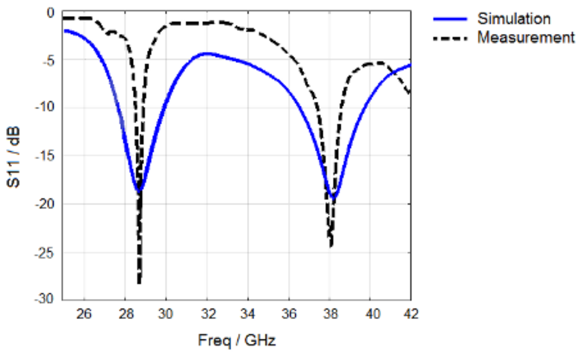


Fig. 20. Comparison between measurement and simulation result of S11 parameter of antenna

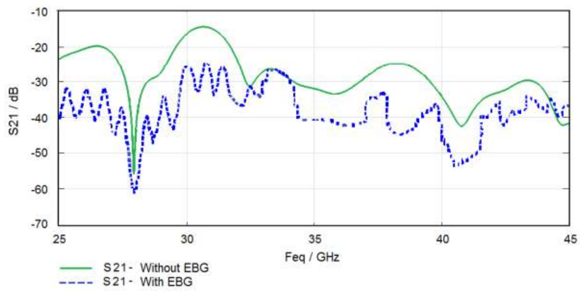


Fig. 21. Comparison between measurement and simulation result of S21 parameters of antenna

IV. CONCLUSIONS

In this paper, a novel DS-EBG structure with round shape is proposed. Applying this structure for dual-band single and MIMO antenna, the bandwidth and gain are both improved. Besides, the radiation efficient of both bands is increased and get over 87% that no previous EBG studies have achieved. Moreover, the MIMO antenna get low mutual coupling of -55dB at lower band with no distance from edge to edge without adding any decoupling structure between antenna elements. The proposed MIMO antenna operates at 28GHz and 38 GHz with good gain of 6.19dB and 7.16dB, wide bandwidth of 2GHz and 5GHz, and high radiation efficiency of 87.6% and 90.1% respectively. All parameters are suitable for 5G application.

ACKNOWLEDGMENT

This work is partly supported by Motorola Solutions Foundation under Motorola scholarship and research funding program for ICT education.

REFERENCES

[1] D. Muirhead, M. A. Imran, and K. Arshad, "A survey of the challenges, opportunities and use of multiple antennas in current and future 5G small cell base station," *IEEE Access*, vol. 4, pp. 2952-2964, 2016.

[2] F. Yang and Y. R. Samil, "EBG characterizations and classifications," in *Electromagnetic Band Gap Structures in Antenna Design*, 1st edn, Cambridge University Press, 2009, pp. 59–87.

[3] M. S. Alam, N. Misran, B. Yatim, and M. T. Islam, "Development of electromagnetic band gap structures in the perspective of microstrip antenna design," *International Journal of Antenna and Propagation*, p. 22, 2016.

[4] O. Haraz, A. Elboushi, S. Alshebeili, and A. Razik Sebak, "Dense dielectric patch array antenna with improved radiation characterizes using EBG ground structure and dielectric ground superstrate for future 5G cellular network," *IEEE Access*, vol. 2, pp. 909-913, 2014.

[5] A. S. S. Neto, *et al.*, "Dual band patch antenna for 5g applications with EBG structure in the ground plane and substrate," in *Recent Advances in Information Systems and Technologies*, Á. Rocha, *et al.*, Eds., 1st edn., pp. 1044-1049, 2017.

[6] S. Dellaoui, A. Kaabal, M. E. halaoui, and A. Asselman, "Patch array antenna with high gain using EBG superstrate for future 5G cellular networks," in *Proc. 11th International Conference Interdisciplinary in Engineering*, October 2017, pp. 463-467.

[7] M. J. Al-Hasan, T. A. Denidni, and A. R. Sebak, "Millimeter-wave compact EBG structure for Mutual-Coupling Reduction Applications," *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 2, pp. 823–828, 2015.

[8] M. S. Sharawi, S. K. Podilchak, M. T. Hussain, and Y. M. M. Antar, "Dielectric resonator based MIMO antenna system enabling millimeter-wave mobile devices," *IET Microwaves, Antennas & Propagation*, vol. 11, no. 2, pp. 287–293, 2017.

[9] A. Altaf, M. A. Alsunaidiy, and E. Arvas, "A novel EBG structure to improve isolation in MIMO antenna," *USNC-URSI Radio Science Meeting (2017 URSI)*, pp. 105-106, July 2017.

[10] M. Farahani, J. Pourahmadazar, M. Akbari, M. Nedil, A. R. Sebak, and T. A. Denidni, "Mutual coupling reduction in millimeter-wave MIMO antenna array using a metamaterial polarization-rotator wall," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 2324-2327, June 2017.

[11] R. Karimian, A. Kesavan, M. Nedil, and T. A. Denidni, "Low-mutual-coupling 60-GHz MIMO antenna system with frequency selective surface wall," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 373-376, June 2017.

[12] N. O. Parchin, M. Shen, and G. F. Pedersen, "End-Fire phased array 5G antenna design using leaf-shaped bow-tie elements for 28/38 GHz MIMO applications," in *Proc. Int. Conf. Ubiquitous Wireless Broadband (ICUWB)*, Nanjing, China, Oct. 2016.

[13] M. E. Shorbagy, R. M. Shubair, M. I. AIHajri, N. K. Mallat, "On the design of millimetre-wave antennas for 5G," in *Proc.* 16th Mediterranean *Microwave Symposium (MMS)*, Abu Dhabi, United Arab Emirates, Nov. 2016.

[14] M. S. Sharawi, "Isolation enhancement techniques for printed MIMO anntenna system," in *Printed MIMO Antenna Engineering*, Artech House, 2014, 1st edn. , pp. 215 – 272.

[15] B. Mohamadzade and M. Afsahi, "Mutual coupling reduction and gain enhancement in patch array antenna using a planar compact electromagnetic bandgap structure," *IET Microw. Antennas Propag*., vol. 11, no. 12, pp. 1719-1725, 2017.

[16] K. H. Kim, J. E. Schutt-Ainé, "Analysis and modeling of hybrid planar-type electromagnetic-bandgap structures and feasibility study on power distribution network application," *IEEE Transactions on Microwave Theory and Techniques*, vol. 56, no. 1, pp. 178-187, 2008.

[17] Y. Q. Fu and N. C. Yuan, "Reflection phase and frequency bandgap characteristics of EBG structures with anisotropic periodicity," *Journal of Electromagnetic Waves and Applications*, vol. 19, no. 14, 2005.

[18] V. V. Yem and N. N. Lan, "Gain and bandwidth enhancement of array antenna using novel metamaterial structure," *Journal of Communications*, vol. 13, no. 3, March 2018.

[19] C. A. Balanis, *Antenna Theory: Analys and Design*, John Wiley & Sons, 2nd edn, 2005.

[20] J. Barrett, *5G Spectrum Bands*, GSAcom.com, Feb. 2017.

[21] D. T. T. Tu, N. V. Hoc, H. Quan, and V. V. Yem, "Compact MIMO Antenna with Low Mutual Coupling Using Defected Ground Structure," in *Proc. Int. Conf. on Communications and Electronics*, HaLong Vietnam, pp. 242-247, 2016.

[22] I. Szini, A. Tatomirescu, and G. F. Pedersen, "On small terminal MIMO antennas, harmonizing characteristic modes with ground plane geometry," *IEEE Antenna Propag. Trans. on*, vol. 63, no. 4, pp. 1487-1497, 2015.

[23] L. Malviya, R. K. Panigrahi, and M. V. Kartikeyan, "MIMO antennas with diversity and mutual coupling reduction techniques: A review," *International Journal of Microwave and Wireless Technologies*, Tutorial and review paper, vol. 9, no. 8, pp. 1763-1780, 2017.
[24] Leeladhar, *et al*., "A 2x2 dual-band MIMO antenna with polarization diversity for wireless applications," *Progress in Electromagnetics Research C*, vol. 61, pp. 91-103, 2016.
[25] Z. Chen, W. Geyi, M. Zhang, and J. Wang, "A study of antenna system for high order MIMO device," *International Journal of Antennas and Propagation*, vol. 2016, p. 14, 2016.
[26] P. Kildal and K. Rosengren, "Correlation and capacity of MIMO systems and mutual coupling, radiation efficiency, and diversity gain of their antennas: Simulations and measurements in a reverberation chamber," *Adaptive Antennas and MIMO Systems for Wireless Systems, IEEE Communications Magazine*, 2004, pp. 104-112.
[27] A. Jain, P. K. Verma, and V. K. Singh, "Performance analysis of PIFA based 4 3 4 MIMO antenna," *Electronics Letters*, vol. 48, no. 9, 2012.
[28] K. Fujimoto, J. L. Volakis, and C. C. Chen, "Small antenna: Miniaturization techniques & applications," *Mc Graw Hill*, 2010.

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