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Design and Implementation of Dual-Band MIMO Antenna with Low Mutual Coupling Using Electromagnetic Band Gap Structures for Portable Equipments

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Abstract

A dual-band Multiple Input Multiple Output (MIMO) antenna system with enhanced isolation for LTE and WLAN applications is proposed. Using a double-rectangular Defected Ground Structure (DGS), the MIMO antenna gets two resonant frequencies of 2.6 GHz and 5.7 GHz with bandwidth of 5.7% and 4.3% respectively. To reduce much more mutual coupling between dual-band MIMO antenna ports, a novel double-side Electromagnetic Band Gap (EBG) structure with equivalent circuit model is proposed. Size of t gain of the antenna is getting better, especially at the low band. he EBG unit cell is 8.6x8.6 mm^2 that is built on FR4 substrate with height of 1.6 mm, so it is achieved more compact size than conventional EBG structures. With 1x7 EBG structures, the mutual coupling gets -40dB in the low frequency band and -30 dB in the high one with narrow distance of 0.11 from feeding point to feeding point. Furthermore, radiation efficiency as well as gain of the antenna is getting better, especially at the low band.

Keywords: MIMO antenna, DGS, double-side EBG, mutual coupling

1. Introduction

Recently, Multiple Input Multiple Output (MIMO) technology has attracted attention in most of modern wireless communication terminals such as: 802.11n, 802.11.ac, 802.11ad, 802.16m, LTE, and 5G. It is because MIMO system can increase channel capacity at both transmitting and receiving sides without bandwidth addition or transmission power increasing. However, has been well known, with compact size for application in portable devices, MIMO systems have a huge challenge of high mutual coupling between antenna elements that can degrade significantly data rate of wireless systemas well as total efficiency of antennas[1-2].

To solve this problem, many methods have been proposed such as using transmission line decoupling technique[3], neutralization line technique[4], covering antenna patch by additional dielectric layers[5], using shorting pins for cancellation of capacitive polarization currents of substrate[6] or using photonic band gap structures such as defected ground structure (DGS) and EBG[7-11]. Among these techniques, photonic band gap structures have gotten much attention recently because their periodic structures not only can suppress surface wave in certain frequency bands called “stop-band” and subsequently reduce mutual coupling between microstrip antennas but also improve other antenna characteristics such as gain, bandwidth or efficiency[9, 12].

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Various photonic band gap structures to subside the problem of mutual coupling have been proposed in previous researches. Most of these studies have focused on applications for single band antenna design. All of them have some benefits as well as drawbacks. Kiem [7] and Abdalla [8] use simple rectangular DGS structures to reduce significantly mutual coupling but distance between antenna elements from feeding point to feeding point rather long. Admanka [9], Moghadasi [10] and Abidin [11] design flexible shapes of EBG structures. There is also coordination between DGS and EBG structures. However, total size of these EBG structures is quite large. Ghosh [12] proposes a dual-layer EBG structure to get high isolation for MIMO systems, but this structure is so complexity and difficult to fabricate. All above mentioned EBG structures are one-side EBG ones. They can decrease significantly the mutual coupling for single-band MIMO antennas at different resonant frequencies. To improve isolation in dual-band MIMO system, Sharawi [13-14] use a DGS structure and capacitive loaded loops, respectively. These structure are quite complexity but get insignificant isolation improvement. Furthermore, the -10 dB bandwidth at low frequency band is narrow of 10 MHz (1.25%).

Recently, wireless communication system has advanced incredibly, especially in mobile phone system. It is not only dimensions of end use equipment more and more decrease but also number of internal antennas in one terminal increase rapidly[15,16]. These demand the internal antennas must be both small in size to build in practical mobile handsets and have multiband for multi technologies. Therefore, seeking for solution to make multi-band gap for multi-band antenna as well as minimize structure is attractive topic which many studies focus.

In this paper, it is the first time a double-side EBG unit cell is created. Equivalent circuit model is given for novel EBG structure. Using the double-side EBG of 1x7 unit cell not only can suppress the surface waves for increasing the isolation between patch antennas of dual-band MIMO system but also improve antenna gain and efficient. This improvement cannot get in previous EBG studies. Besides, making H shape and H shape with bridge of EBG structures on surface and on ground plane respectively reduced significantly the total size of EBG structures compare to conventional EBG one while keeping the same resonant frequency.

2. EBG unit cell design and modeling

Electromagnetic Band Gap (EBG) structures are periodic structures of dielectric materials and metallic conductors that can suppress the surface waves. So mutual coupling between antennas in array would be reduced if structure parameters are designed properly. The traditional mushroom EBG structure is used widely because of its simple structure and good effect of mutual coupling decrease. Center frequency of the band gap is calculated approximately by [17]:

$$f_c = 1/2\pi\sqrt{LC} \quad (1)$$

where C is equivalent capacitance, introduced by the gaps between conductor edges of adjacent cell and L is equivalent inductance, introduced by the strips connecting the adjacent cells.

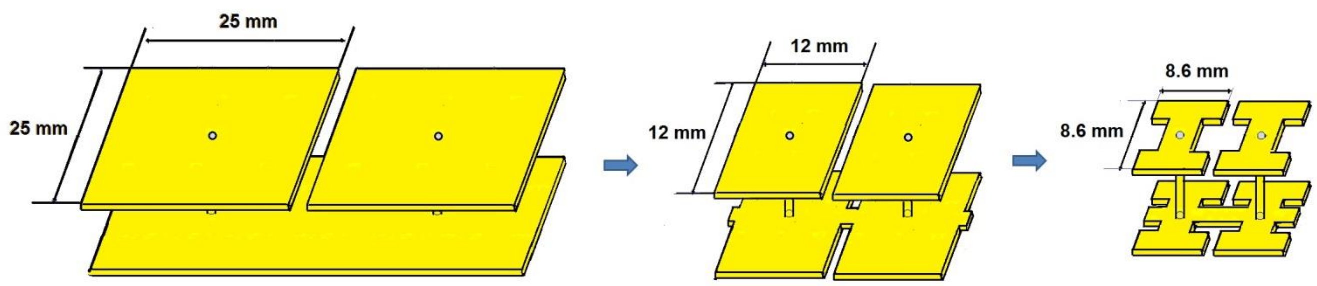


Fig. 1 Design procedure of the proposed EBG unit cell

However, this structure can make only one band gap for single band antenna application. At 2.6 GHz resonant frequency, size of conventional EBG cell, which is based on FR4 substrate with 1.6 mm height, is 25x25 mm^2. To reduce significantly total size of EBG structures compare to conventional EBG one while keeping the same resonant frequency, a double-side EBG using H shape on surface and H shape with bridge on ground plane is proposed. Design procedure of this EBG unit cell is illustrated in Fig. 1. The double-size EBG cell gets the size of 8.6x8.6 mm2, which is equal to 11.83% the size of conventional cell. The detail dimensions of EBG unit cell are shown in Fig. 2 and Table 1 where ε_0, ε_r is the permittivity of free space and the relative dielectric constant of the substrate, respectively.

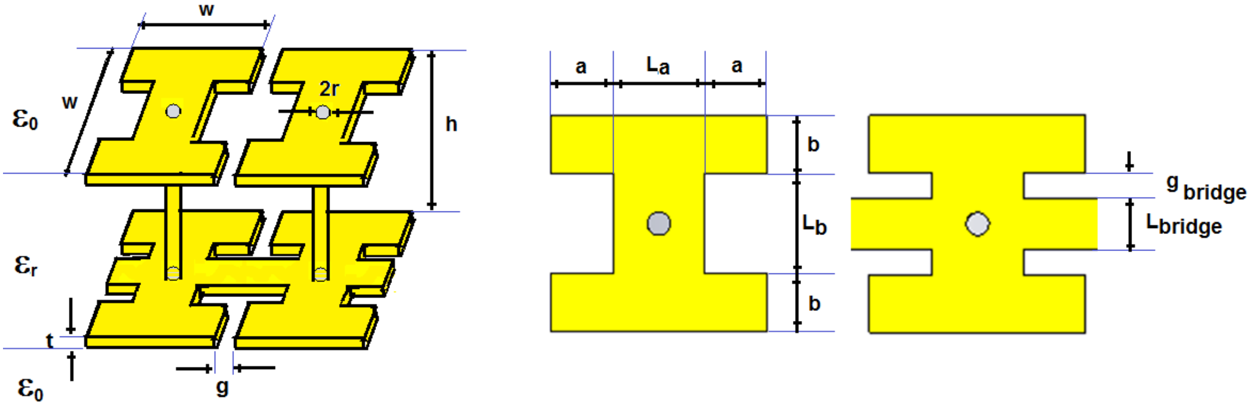


Fig. 2 Unit cell of double-side EBG structures

Table 1 Geometry dimensions of proposed EBG structure unit cell

Parameter	Geometry Dimension (mm)
w	8.6
h	1.6
t	0.035
g	1
r	0.5
a	2.5
b	2.3
g_{bridge}	1
L_{bridge}	2

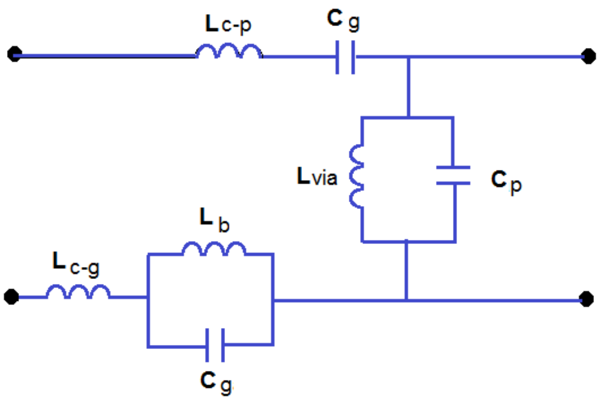


Fig. 3 Equivalent circuit of the proposed EBG unit cell

The equivalent circuit of proposed EBG structure unit cell is shown in Fig. 3. $L_{c\text{-}p}$ and $L_{c\text{-}g}$ are equivalent inductances mainly cause by the circuit which is based by patch cell of the surface and ground cell of ground plane, respectively. The value of $L_{c\text{-}p}$ and $L_{c\text{-}g}$ are calculated using the following quasi-static equations [18]:

$$L_{c-p} = L_{c-g} = \frac{\mu_0 h}{2} \qquad (2)$$

where μ_o is permeability of free space.

C_g is the gap capacitance between meta patch [17] and is calculated approximately as follows Eq. (3):

$$C_g = \frac{w\varepsilon_0(1+\varepsilon_r)}{\pi} cosh^{-1}\left(\frac{w+g}{g}\right) \tag{3}$$

C_p is the capacitance between meta patch of surface and metal cell of ground plane. It is calculated approximately by Eq. (4):

$$C_p = \frac{\varepsilon_0\varepsilon_r(w^2 - aL_b)}{h} \tag{4}$$

L_{via} is the inductance that is made of the via which is calculated using Eq. (5) as the following:

$$L_{via} = k_1 h\left[ln\left(\frac{2h}{r}\right) + 1\right] \tag{5}$$

where r is radius of the via in millimeters and k_1 = 0.2 nH/mm [18]. L_b is the inductance of the microstrip lines between the metal cells of ground plane and depends on the physical implementation of the bridge. Thus, it given by:

$$L_b = k_2(g + 2a)ln\left(2\pi\frac{h}{L_{bridge}}\right) \tag{6}$$

where k_2 = 0.2 nH/mm[18].

From all above equations, we construct Matlab program to determine the L, C values as well as optimize the EBG dimensions to calculate and plot working frequency of EBG structure on the graph. These results are illustrated in Fig. 4.

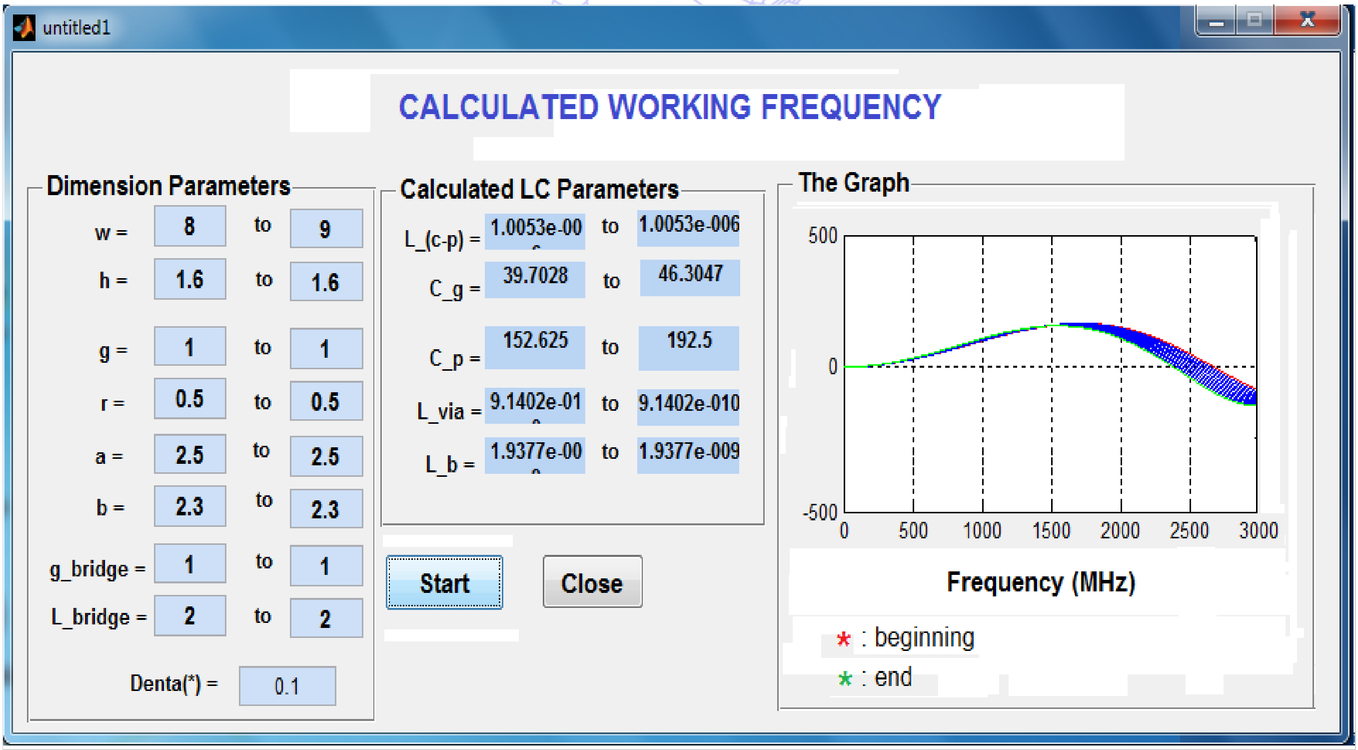


Fig. 4 Calculated working frequency of EBG structure

3. MIMO antenna design

In this paper, the dual-band MIMO antenna is designed for broadband wireless access service at two different operating frequencies which are 2.6 GHz for LTE applications and 5.7 GHz for WLAN applications. The antenna element is made up of a rectangular radiating unit and a ground board which is built on FR4 substrate of 1.6 mm thickness.

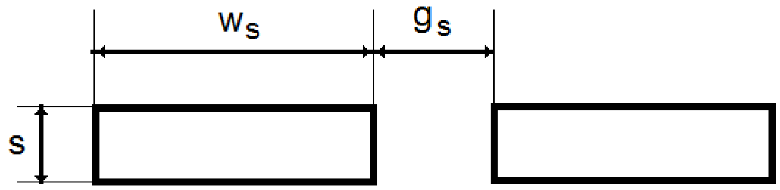
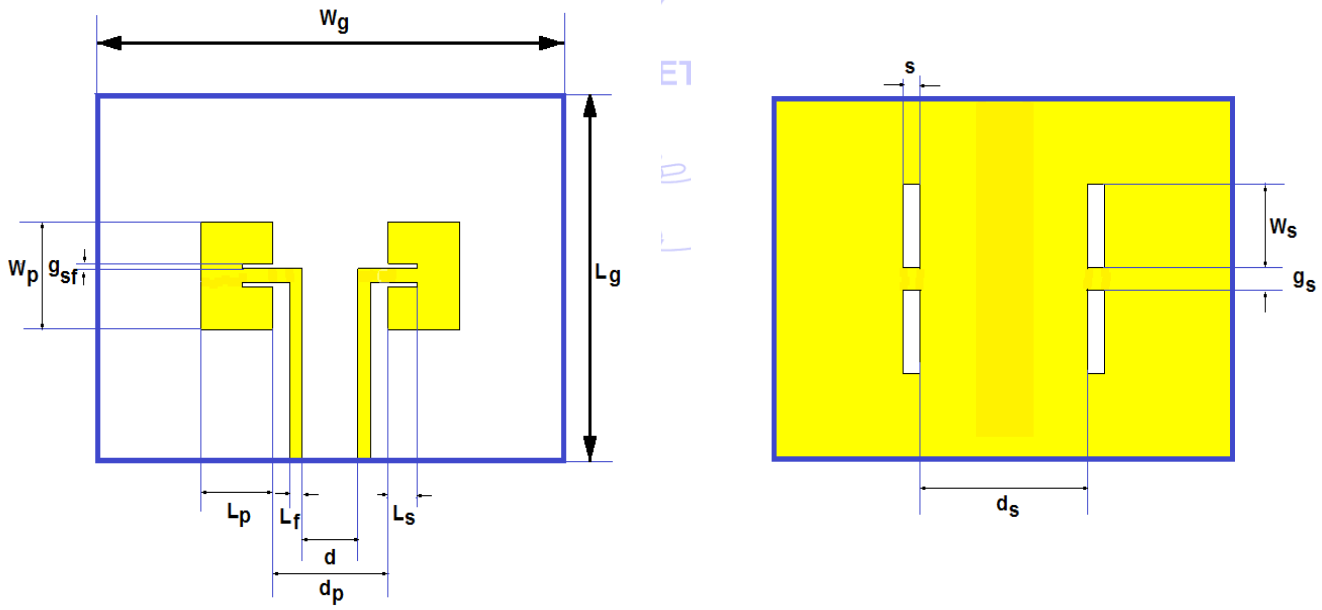


Fig. 5 The double rectangular DGS structure

At first, the total dimension of main radiating patch needs to be calculated according to the desired resonant frequency. There are two different operating frequencies for dual-band operation. Therefore, the lowest 2.6 GHz resonant frequency is chosen first to calculate total size. As antenna theory[19], the 2.6 GHz antenna gets patch size of 27x35x1.6 mm^3. To make another resonant frequency, a double-rectangular DGS structure which is used in the ground plane of antenna with serial position is proposed as illustrated in Fig. 5.

DGS is an etched periodic or non-periodic cascaded configuration defect in ground of a planar transmission line which disturbs shield current distribution in the ground plane cause of the defect in the ground. This disturbance will change characteristics of a transmission line such as line capacitance and inductance. There are a variety of slot geometries etched in the microstrip line ground plane such as spiral head, arrow head slot, and a square open-loop with a slot in the middle section, open-loop dumbbell and so on. Here we insert a serial of two rectangular shape DGS in length and width of 4 x 18.45 mm^2. The space between two rectangles is 5.1 mm. Using the serial DGS slots which are added to central ground just under the patch, near the fed port of antenna, the antenna gets the second resonant frequency of 5.7 GHz. Besides, it gets reduce the size as well as mutual coupling between MIMO elements[20].



(a) top view (b) back view

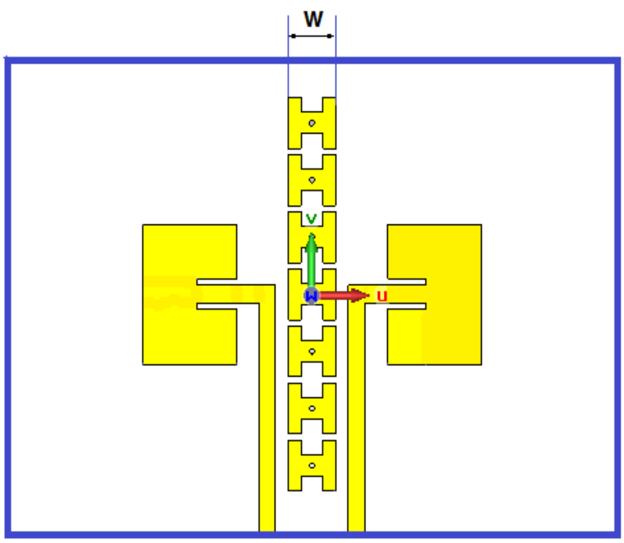
Fig. 6 The dual-band MIMO antenna

After that, the MIMO antenna which operates at 2.6 GHz and 5.7 GHz resonant frequencies is constructed as shown in Fig. 6. In this design, the patches of antenna are placed opposite each other using microstrip line feeding to ensure the high isolation between elements over all frequencies with narrow distance between antenna elements. From feeding point to feeding point, distance is 13.2 mm which is equivalent 0.11λ_0 at 2.6 GHz or 0.25λ_0 at 5.7 GHz. From center to center, it is 38.3 mm which equals 0.3λ_0 at 2.6 GHz, the resonant frequency that is chosen to calculate the patch dimensions of antenna. Detail dimensions of MIMO antenna structure are presented in Table 2.

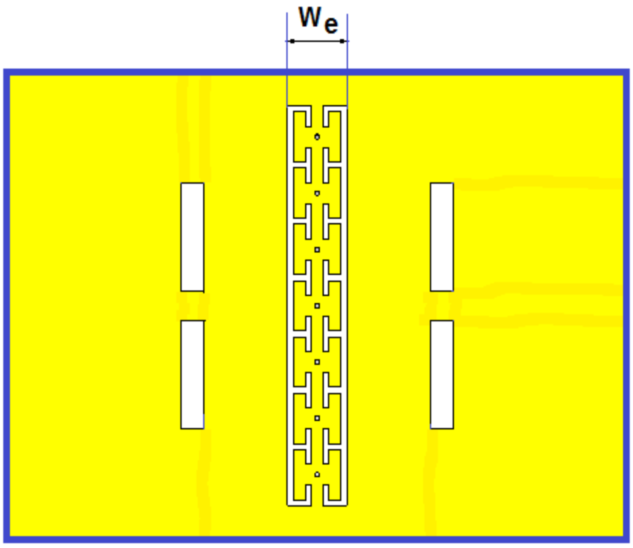
Table 2 Geometry dimensions of the proposed MIMO antenna

Parameter	Geometry Dimension (mm)
W_p	23.5
L_p	17.1
W_g	110
L_g	80
d	13.2
d_p	27.4
L_s	7.1
L_f	3.1
g_{sf}	1
s	4
w_s	18.45
g_s	5.1
d_s	40.5

To improve much more mutual coupling between antenna elements in these bands as well as enhance antenna gain and efficiency, 1x7 double-side EBG structure is used as illustrated in Fig. 7. Size of EBG cell on the patch (w) and on the ground (we) are 8.6 and 10.6 mm respectively. The double-side EBG looks to be a hybrid structure of conventional EBG and DGS hence it gets benefits of both structures. They are antenna gain and radiation efficiency improvement besides mutual coupling reduction.



(a) top view



(b) back view

Fig. 7 MIMO antenna with double-side EBG structures

4. Simulation results

4.1. *MIMO antenna*

The MIMO antenna is designed on FR4 substrate with thickness is 1.6 mm, relative permittivity is 4.4 and loss tangent is 0.02. Fig. 8 and Fig. 9 illustrate how surface current distribute on antenna at 2.6 and 5.7 GHz resonant frequency, respectively. From the Fig. 8, it is clearly seen that at 2.6 GHz resonant frequency, the serial DGS structures make the electric current on the antenna going from feeding line to W size of antenna patch into round the slots. Electric length of antenna, therefore, is increased. It means that the antenna size is reduced while resonant frequency is the same. Here, the patch size is 23.5x17.1 mm^2, which is nearly 42.5% theoretical antenna size (27x35 mm^2) at the same resonant frequency of 2.6 GHz.

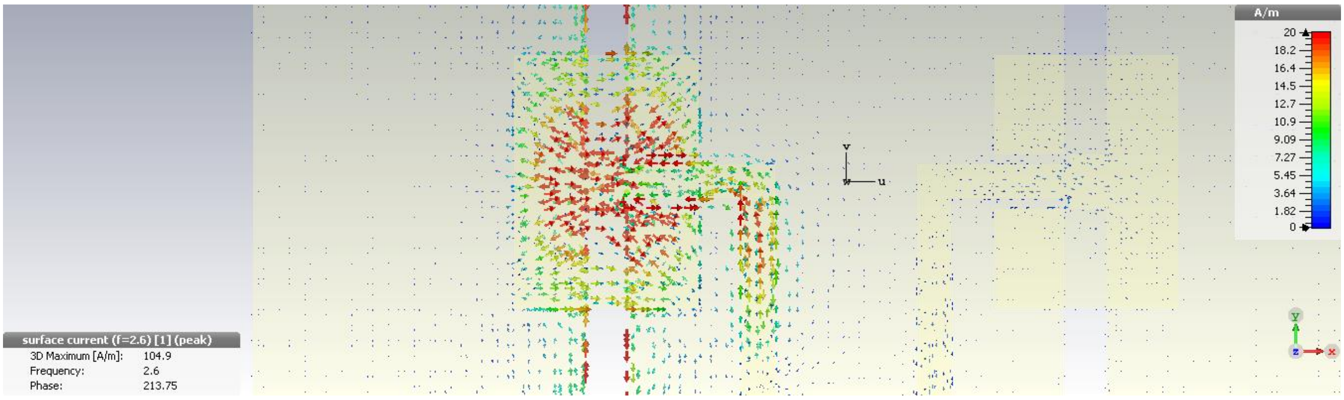


Fig. 8 Surface current distribution on antenna at 2.6GHz resonant frequency

From the Fig. 9, there is a different between 2.6 GHz and 5.7 GHz in surface current distribution on antenna. At 5.7 GHz, the serial DGS structures change the electric current going from feeding line to W size into perpendicular to L size of antenna patch. This, therefore, makes the second resonant frequency of antenna (5.7 GHz). From surface current distribution, it is concluded that using serial rectangular DGS, the proposed antenna not only reduces the antenna patch size but also gets the dual band.

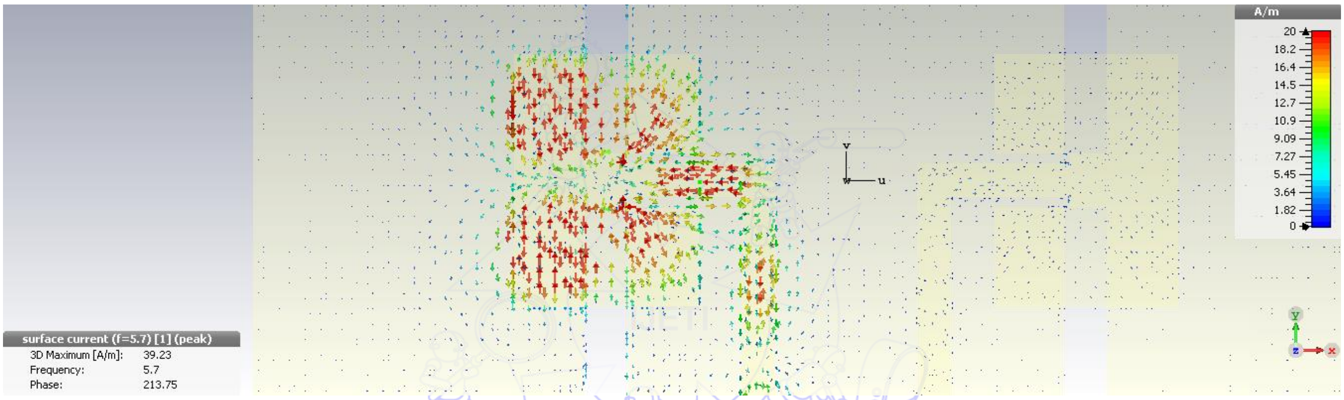


Fig. 9 Surface current distribution on antenna at 5.7GHz resonant frequency

In addition, the S11 and S12 values of MIMO antenna are computed by CST microwave studio for full wave simulation and drawn in Fig. 10. From this plot, it is clearly seen that the antennas operate at two resonant frequencies: 2.6 GHz for LTE application and 5.7 GHz for WLAN application. At low frequency, antenna reflection coefficient is -40.13 dB and antenna bandwidth is 150 MHz that is suitable for LTE applications. At high frequency, antenna reflection coefficient is nearly -30 dB and antenna bandwidth is 250 MHz that completely suits for WLAN applications. Moreover, the MIMO antenna is constructed by placing two single antennas opposite each other with microstrip line feeding as well as using double-rectangular DGS structures on ground plane. Thus, the proposed MIMO antenna gets the high isolation which S12 parameter is stable and around -20 dB over all frequencies.

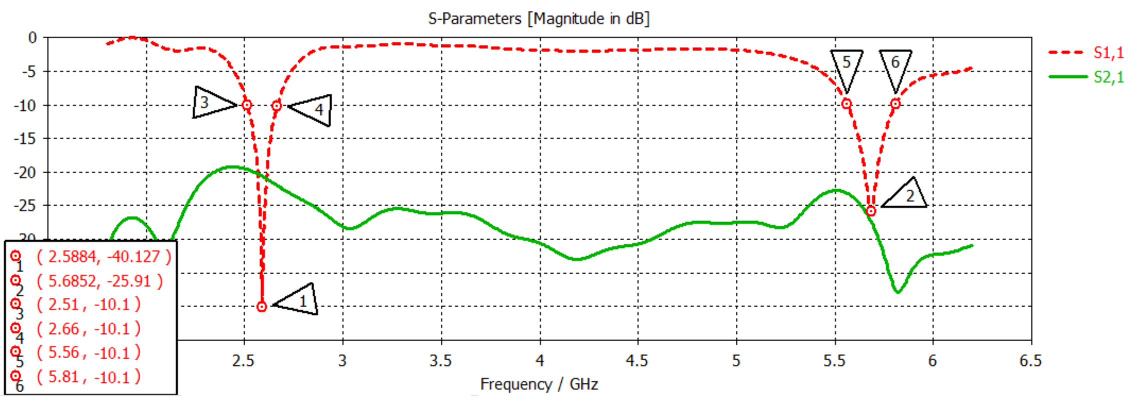
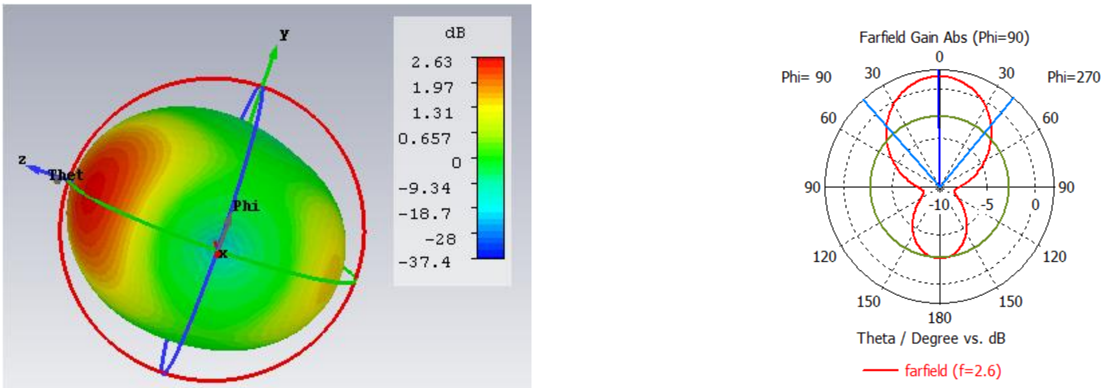
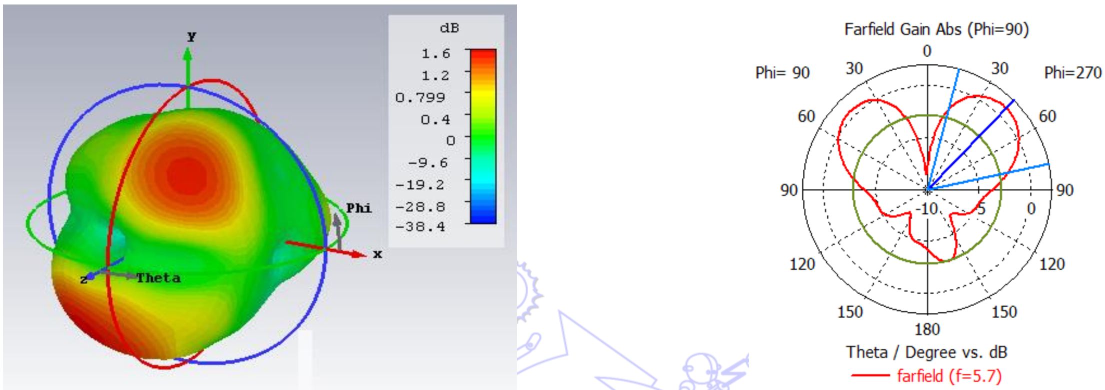


Fig. 10 S parameter of the proposed MIMO antenna



(a) 3D radiation pattern (b) 2D radiation pattern

Fig. 11 The antenna radiation pattern at 2.6 GHz resonant frequency



(a) 3D radiation pattern (b) 2D radiation pattern

Fig. 12 The antenna radiation pattern at 5.7 GHz resonant frequency

3D and 2D antenna radiation pattern at 2.6 GHz resonant frequency are shown in Fig. 11. Antenna gain gets 2.63 dB and radiation efficiency is 59%. The 2D radiation pattern of MIMO antenna is smooth with angular width (3 dB) is 81.8 degree. At 5.7 GHz resonant frequency, 3D and 2D antenna radiation pattern are shown on Fig. 12. Gain of antenna is 1.6 dB, angular width (3 dB) is 63.5 degree and antenna radiation efficiency is 39.8%.

4.2. MIMO antenna with double-side EBG structure

To reduce much more the mutual coupling between antenna patch in two resonant frequencies as well as improve the other antenna parameters, a novel double-side EBG structure is used. The S parameters of the proposed MIMO antenna with EBG structure are shown in Fig. 13. From the graph, it is clearly seen that the mutual coupling between antenna element decrease sharply by 20 dB (from -20 dB down to -40 dB) at 2.6 GHz resonant frequency and reduce lightly by approximate 5 dB at 5.7 GHz resonant frequency while ensuring the bandwidth.

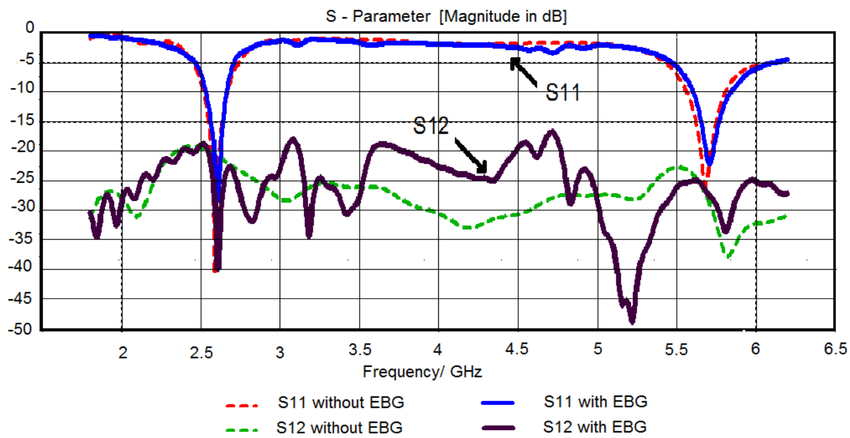
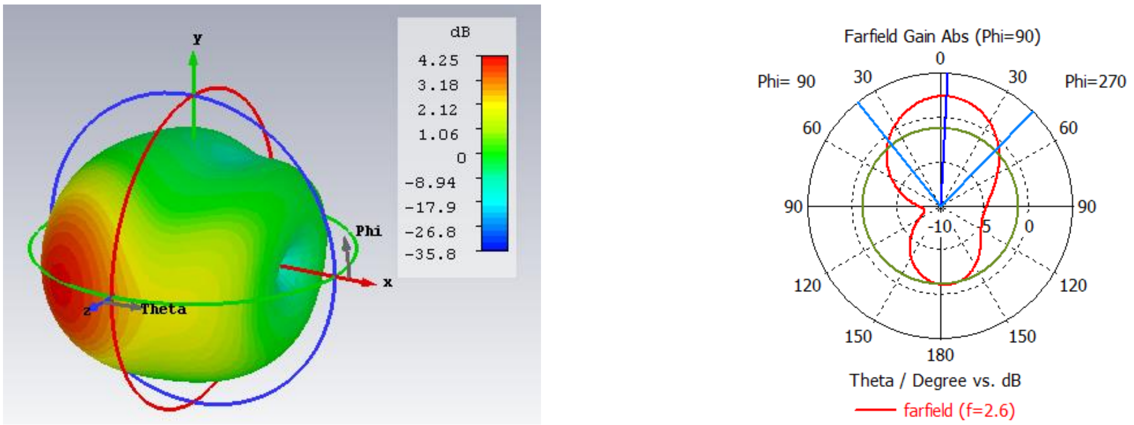
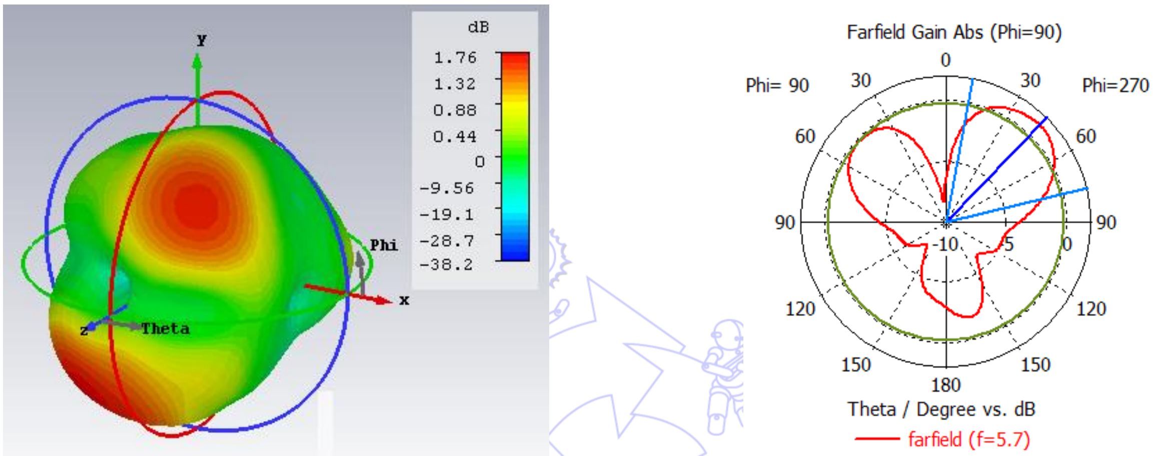


Fig. 13 S parameters of the proposed antenna with and without EBG structures



(a) 3D radiation pattern (b) 2D radiation pattern

Fig. 14 The antenna radiation pattern at 2.6 GHz resonant frequency of MIMO system using double-size EBG



(a) 3D radiation pattern (b) 2D radiation pattern

Fig. 15 The antenna radiation pattern at 5.7 GHz resonant frequency of MIMO system using double-size EBG

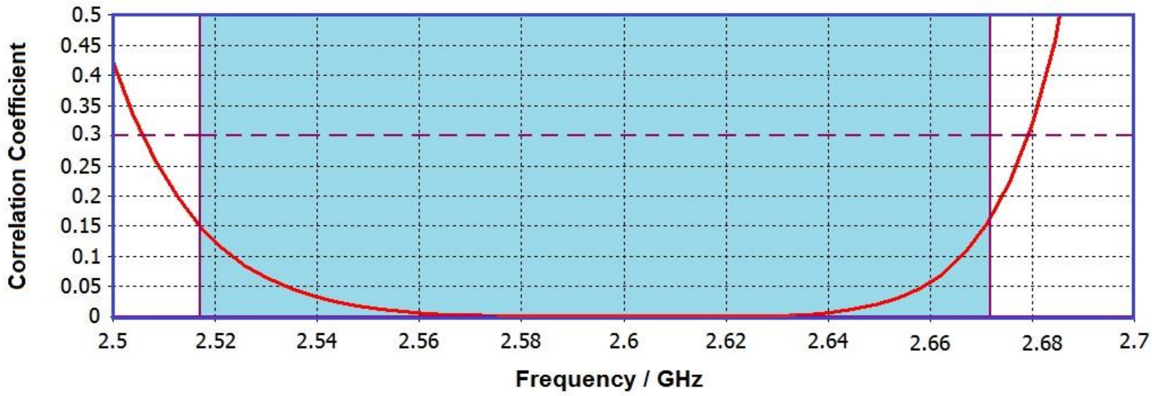
The 3D and 2D radiation pattern of MIMO antenna using EBG structures are shown in Fig. 14 and Fig. 15 at 2.6 GHz and 5.7 GHz resonant frequencies, respectively.

At 2.6 GHz resonant frequency, the gain of antenna as well as radiation efficiency is improved significantly. The antenna gain gets 4.25 dB that is high gain at 2.6 GHz and increases by 160% (from 2.63 dB to 4.25 dB). Specially, the antenna radiation efficiency increases from 59% to 68.7%. This improvement cannot get in previous studies of one-side EBG structures (single layer as well as dual layer). The 2D radiation pattern of MIMO antenna using double-size EBG structures is still smooth like previous MIMO antenna with angular width (3 dB) is 83 degree. At 5.7 GHz resonant frequency, the gain of antenna is improved lightly from 1.6 dB to 1.76 dB while the 2D radiation pattern is the same with angular width (3 dB) is 65.9 degree and the radiation efficiency is 39.8%.

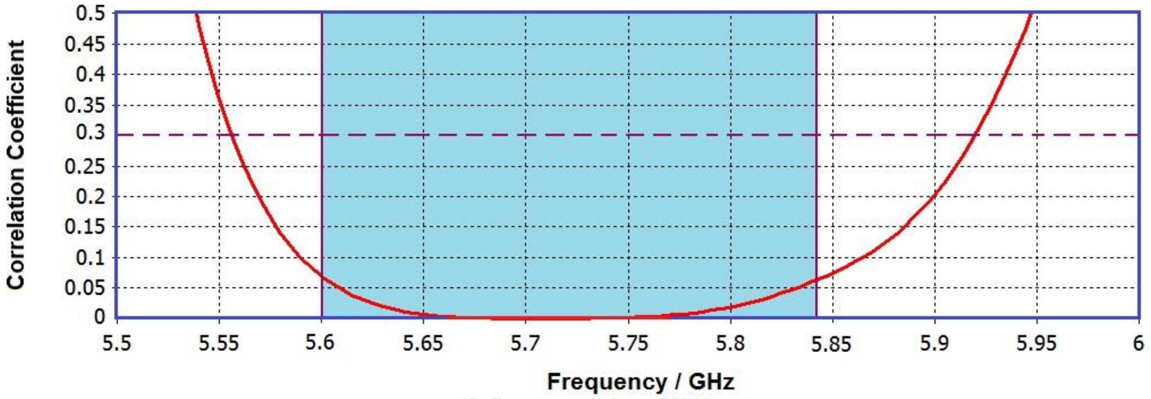
In MIMO antenna system, correlation factor, which is so-called enveloped correlation coefficient (ECC), will be significantly degraded with higher coupling levels. The factor can be calculated from radiation patterns or scattering parameters. For a simple two-port network, assuming uniform multipath environment, the enveloped correlation (ρ_e), simply square of the correlation coefficient (ρ), can be calculated conveniently and quickly from S-parameters [21], as follows:

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

The correlation factor curves of proposed MIMO antenna at lower band and higher band are shown on Fig. 16 (a) and (b) respectively.



(a) Lower band of operation



(b) higher band of operation

Fig. 16 Correlation Factor $|\rho 12|$ curve for MIMO antenna

From this figure, the MIMO antenna has the simulated ECC lower than 0.15 at lower band and 0.07 at higher one. Therefore, the proposed antenna is suitable for mobile communication with a minimum acceptable correlation coefficient of 0.5 [22] as well as for LTE equipment with value of $|\rho| \leq 0.3$ for the bands of interest [23].

Table 3 shows comparison between current structure and some previous EBG designs. While the total EBG structure size is the same and the mutual coupling is low of -40 dB, the distance between two antenna elements from feeding point to feeding point has been about 18% - 45% in comparison to similar previous researches. Specially, the antenna radiation efficiency has been improved that cannot get in previous EBG studies.

Table 3 Comparison between presented design and previous EBG researches

	Resonant Frequency	Total EBG Structure Size (mm^3)	Distance from feeding point to feeding point	Mutual Coupling	Gain	Radiation Efficiency	Single / Multiple
Ref. [9] (RT6010, ε=10.2)	5.75 GHz	13.2 x72.2 x 1.27	0.5λ	-25dB	Not given	Not given	Single
Ref. [10] (FR4, ε=4.4)	5.35 GHz	13.4 x 36.5 x 1.6	0.6λ	-43dB	6.86 dB	Decreased from 65% down to 53%	Single
Ref. [11] (FR4, ε=4.5)	2.4 GHz	29.1 x 48.5 x 1.6	0.24λ	-20dB	Not given	Not given	Single
Ref. [12]	2.5 GHz	10.4 x 26 x 3.2	0.5λ	-28 dB	2.6 dB	55.44%	Single
Our design (FR4, ε=4.4)	2.6 GHz	10.6 x 67.2 x 1.6	0.11λ	-40 dB (L)	4.24 dB	Increased from 59% to 68.7%	Multiple
	5.7 GHz		0.35λ	-30 dB (H)	1.76 dB	39.8%	

Table 4 shows comparison between dual-band MIMO antenna using double-side EBG structure and some previous dual-band MIMO designs. The mutual coupling has been reduced about 70% ÷ 150% in comparison to similar distance from feeding point to feeding point of previous researches.

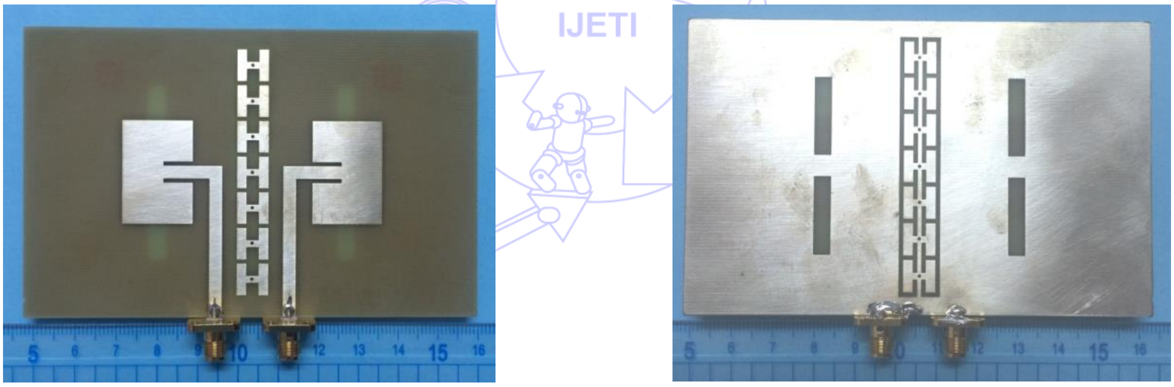
Table 4 Comparison between presented design and other dual-band MIMO researches

	Resonant Frequency	-10dB Bandwidth	Total size of Mutual Coupling Structure	Distance from feeding point to feeding point	Mutual Coupling	Gain	Radiation Efficiency
Ref. [13] (FR4, ε=4.4, h= 1.56mm)	813 MHz	1.25%	6.77 x 67.54 mm	0.12λ	-22 dB	-4dBi (max)	39.9 - 41.6%
	2.67 GHz	14.98%		0.4λ	-12 dB	2.4dBi (max)	33.6 - 67%
Ref. [14] (FR4, ε=4.4, h= 1.56mm)	840 MHz	1.25%	9 x 64.127 mm	0.12λ	-24 dB	-4dBi (max)	5% reduction 35%
	2.84 GHz	3.8%		0.42λ	-17 dB	2.5dBi (max)	5% reduction 67%
Our design (FR4, ε=4.4, h=1.6mm)	2.6 GHz	5.7%	10.6 x 67.2 mm	0.11λ	-40 dB	4.24 dB	9.7% increase 68.7%
	5.7 GHz	4.3%		0.35λ	-30 dB	1.76 dB	39.8%

5. Measurement Results

The proposed dual-band MIMO antenna using double-side EBG structures and serial rectangular DGS is fabricated on the FR4 substrate as shown in Fig.17. The MIMO system is constructed by 1x2 rectangular patches on the surface, two double rectangular DGS structures on the ground plane and 1x7 EBG structure unit cell between antenna elements. The antenna patch size is $24x17mm^2$ which is much more compact than theoretical antenna size at the same 2.6 GHz resonant frequency.

The measure result of S parameters is compared with simulation result in Fig. 18.



(a)Top view (b)Bottom view

Fig. 17 Fabricated dual-band MIMO antenna using double-size EBG structure

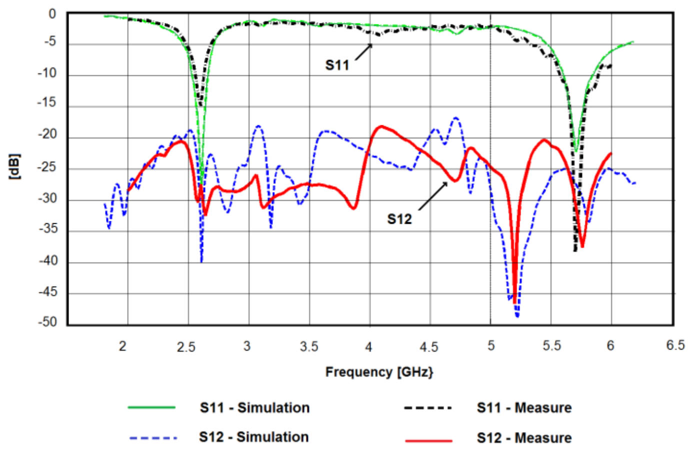


Fig. 18 Measured values of S11 and S12 of MIMO antenna

It is clearly seen that the MIMO antennas operate at 2.6 GHz and 5.7 GHz with 150 MHz and 250 MHz bandwidth, respectively. At the 2.6 GHz resonant frequency, the antenna reflection coefficient is -15 dB and the mutual coupling is -30 dB. At the 5.7 GHz resonant frequency, the antenna reflection coefficient gets much better of -38 dB and the mutual coupling gets -37 dB. From this measurement, it can be concluded that the measured results agree well with the simulated ones. Moreover, using double-size EBG structures can reduce significantly the mutual coupling between antenna elements in dual band MIMO system.

6. Conclusions

In this paper, the dual-band MIMO antenna using double-size EBG structure and serial rectangular DGS is proposed. The EBG structure which uses H shape on the patch plane and H shape with bridge on the ground one makes the size of EBG cell much more compact. Using this structure, the dual band MIMO antenna not only reduces the mutual coupling between antenna elements of 20 dB but also improves the antenna gain. Especially at 2.6 GHz, the antenna gain gets 4.25 dB. This value is rather high to compare with other antennas operating at the same resonant frequency. Furthermore, the antenna radiation efficiency at this band has been improved that cannot get in previous EBG studies. The proposed dual-band MIMO antenna at 2.6 GHz and 5.7 GHz is suitable for LTE and WLAN applications in the portable terminals.

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