

# ISOLATION ENHANCEMENT IN MIMO ANTENNA ARRAY FOR 5G APPLICATIONS

BY

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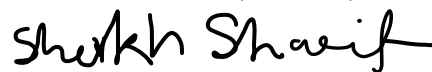
DEANSHIP OF GRADUATE STUDIES

This thesis, written by **OLUDAYO OLAOLUWA SOKUNBI** under the direction of his thesis adviser and approved by his thesis committee, has been presented to and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN ELECTRICAL ENGINEERING**.

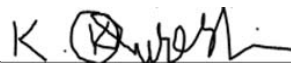
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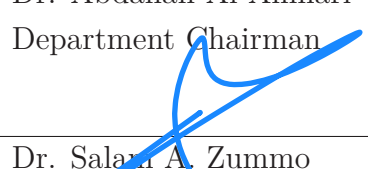
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### *Dedication*

To my PARENTS, especially my late Dad., Mr Samson Sokunbi who gave me the greatest gift (ability to think independently). Special thanks to my Mum also, who ensured I lacked nothing.

Also, to my fiancée (Lollipop) who inspired me to be dogged throughout this work. Finally, to my siblings, Oluwarantimisirere Alade, Oluyemi and Olutunde Sokunbi, you guys are the best siblings I can ever have.

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# THESIS ABSTRACT

**NAME:** Oludayo Olaoluwa Sokunbi

**TITLE OF STUDY:** Isolation Enhancement in MIMO Antenna Array for 5G Applications

**MAJOR FIELD:** Electrical Engineering

**DATE OF DEGREE:** March, 2020

Antenna engineers have been concerned about decreasing the interactions between antenna elements in MIMO antenna array because of mutual coupling between these elements. Patch antennas are particularly faced with mutual coupling issues in a multipath environment because of the substrate used, as well as the need to increase bandwidth and data rate. This has resulted in decrease in efficiency and gain of antennas. The aim of this thesis is to investigate the different methods of increasing isolation over a large bandwidth between closely-spaced MIMO antennas in the sub-GHz frequency and millimeter wave frequency. This work presents several MIMO patch antenna array design and the different methods of increasing isolation between them. First, novel slotted-EBG structure that can decouple 5G antenna array by 30 dB within a very narrow bandwidth at 28 GHz is presented. The novel unit cell

used consist of the conventional electromagnetic band gap structure (EBG), but with slot in the patches. The antenna was designed and optimised using simulations. Another novel multiresonance EBG structure with defective ground plane is presented. This multiresonance EBG structure can increase isolation between two slotted patch antenna array between 20-31 dB in the large impedance bandwidth of 48% between 4.2-6.5 GHz. The final design presents a dual layer dual patch (DLDP) EBG structure that can increase isolation in a patch antenna array by a maximum of 56 dB over the entire 4-6.5 GHz is presented. This antenna is fabricated and verified using measurements.

## ملخص الرسالة

الاسم: عنوان الدراسة:

عنوان الرسالة

التخصص: تاريخ الدرجة العلمية:

أدخل الشهر والسنة

ملخص الأطروحة

الاسم: أولودايو أولووا سوكونبي.

عنوان الدراسة: تحسين العزل في صفيق هوائي MIMO ل 5 تطبيقات.

المجال الرئيسي: الهندسة الكهربائية

تاريخ الدرجة: مارس 2020.

كان مهندسو الهوائي قلقين بشأن تقليل التفاعلات بين عناصر الهوائي في صفيق هوائي MIMO بسبب الاقتران المتبادل بين هذه العناصر. تواجه هوائيات التصحيح بشكل خاص مشاكل الاقتران المتبادل في بيئة متعددة المسارات بسبب الركيزة المستخدمة ، وكذلك الحاجة إلى زيادة عرض النطاق الترددي ومعدل البيانات. وقد أدى ذلك إلى انخفاض في الكفاءة وكسب الهوائيات. الهدف من هذه الرسالة هو البحث في الطرق المختلفة لزيادة العزلة عبر عرض نطاق كبير بين هوائيات MIMO المتقاربة في التردد تحت GHz وتردد الموجة المليمترية. يقدم هذا العمل العديد من تصميم مصفوفة هوائي التصحيح MIMO والطرق المختلفة لزيادة العزلة بينهما. أولاً ، يتم تقديم بنية EBG مشقوقة جديدة يمكنها فصل مجموعة الهوائي 5G بمقدار 30 dB ضمن عرض نطاق ضيق للغاية عند 28 GHz. تتكون خلية الوحدة الجديدة المستخدمة من هيكل فجوة النطاق الكهرومغناطيسي التقليدي (EBG) ، ولكن مع فتحة في البقع. تم تصميم الهوائي وتحسينه باستخدام المحاكاة. يتم تقديم هيكل EBG جديد متعدد الرنين مع

طائرة أرضية معينة. يمكن أن يزيد هيكل EBG متعدد الرنين هذا من العزلة بين صفيحتين لهوائي رقعة مشقوفة بين 20-31 ديسيل في عرض نطاق المعاوقة الكبير 48 بين 2.4-5.6 جيجا هرتز. يقدم التصميم النهائي بنية EBG مزدوجة الطبقة (DLDP) EBG التي يمكن أن تزيد من العزلة في صنف هوائي التصحيح بحد أقصى 56 ديسيل على كامل 4-5.6 جيجا هرتز. يتم تصنيع هذا الهوائي والتحقق منه باستخدام القياسات

# CHAPTER 1

## INTRODUCTION

### 1.1 Wireless Communication

Wireless technology has become an integral part of modern technology because of the ease of communication it has brought. It has enabled compactness, where different devices, operating at different frequencies can be brought together in a single device. Wireless technology usually uses radio frequencies to transmit electromagnetic signals over the air. It also allows more than one user to communicate without interference using the same medium .

The evolution of wireless technology stems from the first generation (1G) devices like Advanced Mobile Phone System (AMPS), Nordic Mobile Phone System (NMTS) and Total Access Communication System (TACS). This has a frequency range of about 800-900 MHz; and it's purely analogue. The 1G is quickly replaced by the 2G with the advent of the Global System for Mobile communication (GSM), which later became the basis for subsequent wireless development. The 2.5G and 2.75G were later introduced to enhance high data rates. The 2.5G and 2.75G includes Enhanced

Data GSM Evolution (EDGE) and General Packet Radio Service (GPRS). The 3G ushered in the Universal Mobile Terrestrial / Telecommunication Systems (UMTS) and made smart phones popular. Smartphones are able to handle many applications and functions like email, video call and social media. The 3G was later improved by introducing 3.5G and 3.75G systems based on High Speed Downlink Packet access (HSDPA) and High Speed Uplink Packet Access (HSUPA). 4G was later introduced with the advent of Long Term Evolution (LTE). It has the ability to incorporate both voice and data, and can be transmitted over Internet Protocol (IP) packets. Currently, the world is considering the 5G networks, which will use millimeter waves for transmission and reception of data. It will have very fast data rate (about 10 times the speed of 4G LTE ) and will be able to accommodate more bandwidths. It will be implemented in the idea of Internet of Things (IOT). Using mobile phone as an example, the evolution of wireless technology has enabled antennas and other electronic components to be more smaller. From Fig. 1.1, the antenna in 2G phone is obviously smaller than the antenna in 1G. With the advent of 3G and 4G, the antenna became a little bigger again, but with more functionalities, and multiple antennas so as to increase throughput [1]. Fig. 1.2 depicts the summary of the 1G to 5G evolution and its characteristics.

## 1.2 MIMO Systems

Wireless devices uses electromagnetic energy to transmit and receive information. Therefore, they are susceptible to interference or free space pathloss. To mitigate these



Figure 1.1: Mobile Phone Evolution.

| Generation                                 | Speed                                            | Technology                                    | Key Features                                                                                                                                                                                                  |
|--------------------------------------------|--------------------------------------------------|-----------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1G<br>(1970 –1980s)                        | 14.4 Kbps                                        | AMPS,NMT,<br>TACS                             | Voice only services                                                                                                                                                                                           |
| 2G<br>(1990 to 2000)                       | 9.6/ 14.4<br>Kbps                                | TDMA,CDMA                                     | Voice and Data services                                                                                                                                                                                       |
| 2.5G to 2.75G<br>(2001-2004 )              | 171.2 Kbps<br>20-40 Kbps                         | GPRS                                          | Voice, Data and web mobile internet, low speed streaming services and email services.                                                                                                                         |
| 3G<br>(2004-2005)                          | 3.1 Mbps<br>500- 700<br>Kbps                     | CDMA2000<br>(1xRTT, EVDO)<br>UMTS and<br>EDGE | Voice, Data, Multimedia, support for smart phone applications, faster web browsing, video calling and TV streaming.                                                                                           |
| 3.5G<br>(2006-2010)                        | 14.4 Mbps 1-<br>3 Mbps                           | HSPA                                          | All the services from 3G network with enhanced speed and more mobility.                                                                                                                                       |
| 4G<br>(2010<br>onwards)                    | 100-300<br>Mbps. 3-5<br>Mbps 100<br>Mbps (Wi-Fi) | WiMax, LTE and<br>Wi-Fi                       | High speed, high quality voice over IP, HD multimedia streaming, 3D gaming, HD video conferencing and worldwide roaming.                                                                                      |
| 5G<br>(Expecting at<br>the end of<br>2019) | 1 to 10 Gbps                                     | LTE advanced<br>schemes, OMA<br>and NOMA      | Super fast mobile internet, low latency network for mission critical applications, Internet of Things, security and surveillance, HD multimedia streaming, autonomous driving, smart healthcare applications. |

Figure 1.2: Summary of 1G to 5G Evolution.

issues, the channel capacity has to be increased. According to Shannon’s theorem, the cost-effective method of increasing the capacity of a channel is to make the number of antennas as many as possible. According to equation 1.1; to increase channel capacity (C), the bandwidth (B) and signal to noise ratio (SNR) is difficult to increase

because of the limitation in the frequency allocation [2]. Therefore, the only realizable parameter to be increased is the number of antennas used at the transmitting end ( $N_T$ ) and number of antenna used at the receiving end ( $M_R$ ). By doing this, multiple copies of both transmitted and received signals can be sent and received. Therefore, multiple antennas, generally called Multiple Outputs Multiple Input (MIMO) antennas have the ability to increase channel capacity according to Shannon–Hartley theorem [2] :

$$C = B \log_2(1 + N_T \times M_R \times SNR) \quad (1.1)$$

Fig. 1.3 depicts a MIMO system comprising of three transmitting antennas and four receiving antennas in a multipath environment. Fig. 1.4 shows the effect of increasing transmitting antennas ( $N_t$ ) and the receiving antennas ( $M_r$ ) on the channel capacity. It is evident that the channel capacity increases as the number of transmitting and receiving antenna increases.

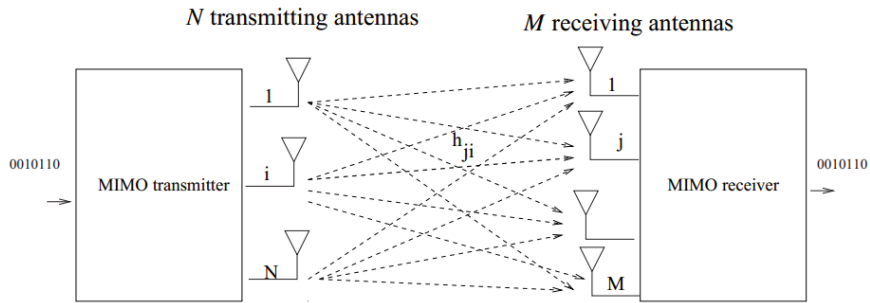


Figure 1.3: MIMO System

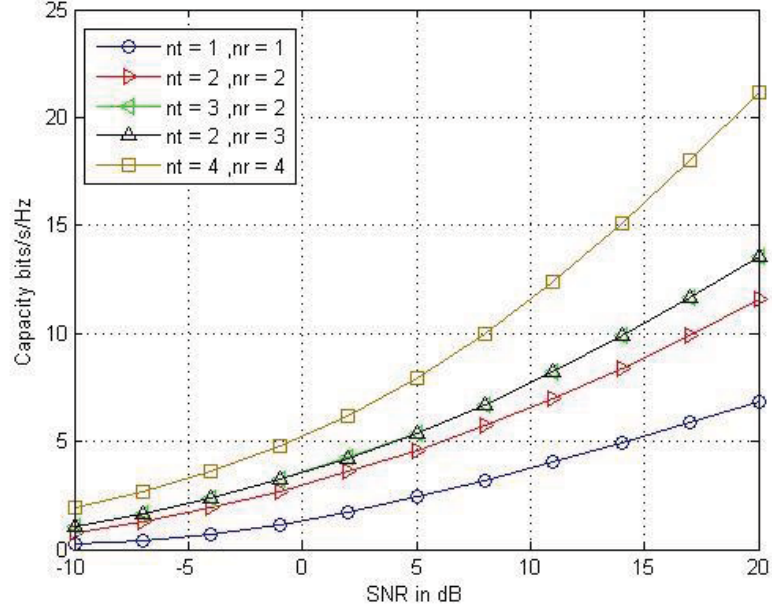


Figure 1.4: MIMO capacity Increase

### 1.3 Work Motivation

This research work is motivated by the need to have MIMO antennas in the same electronic device, yet with high isolation among the individual antennas, with each antenna having large isolation bandwidth. Diverse works have been conducted on isolation improvement between patch MIMO antennas. However, most of these works have concentrated on single, dual or multiple bands with minimal isolation. Therefore, this work is aimed at first investigating a new electromagnetic band gap (EBG) structure that can decouple MIMO 5G patch antenna array. This novel EBG is then used to decouple patch antenna array around 28 GHz over a narrow bandwidth. Then, another novel EBG structure is investigated to decouple patch antenna over a large bandwidth (about 44 %). The CST eigen mode analysis is be used to analyse the dispersion diagram of these novel unit cells. The antenna and EBG is fabricated on FR4

substrate and the radiation pattern, Gain, S-parameters, efficiency and most importantly, isolation, is investigated, and about 30dB isolation improvement is observed. Another unit cell based on dual layer dual patch (DLDP) EBG structure is used to decouple the patch antenna with a 56 dB maximum isolation improvement.

## 1.4 Thesis Contributions

In this thesis, different isolation techniques used in the design of 4G and 5G millimeter-wave MIMO antennas have been accomplished. The contributions are as follows:

1. A novel Electromagnetic Band Gap Structure (EBG) structure that can create stop band around 28 GHz millimeter wave frequency. This EBG is used to decouple wideband MIMO 2-element patch antennas over the same frequency range around 28 GHz.
2. A novel multiresonance EBG unit cell capable of creating bandgap between 4-6.3 GHz. Dispersion diagram is used to validate its stopband characteristics. The EBG structure is used to decouple patch antenna array by about 30 dB throughout the 4.2-6.5 GHz wide impedance bandwidth. The antenna is fabricated and tested.
3. A novel dual layer dual patch (DLDP-EBG) unit cell capable of creating bandgap between 3.5-7.5 GHz. Dispersion diagram is also used to validate its stopband. The EBG structure is used to decouple patch antenna array by about 56 dB throughout the 4-6.5 GHz wide impedance bandwidth. The antenna is fabricated and measured.

## CHAPTER 2

# THEORETICAL BACKGROUND

Antennas generally are part of the sending and receiving system that sends or receive information embedded in electromagnetic waves. Antennas convert electrical currents to electromagnetic waves and vice versa. They are basically referred to as the eyes and ears of all wireless communications because they help to transmit the intended information from the sender to the receiver. Hence, the sender and receiver systems must have transmitting and receiving antenna [3]. Antenna can be represented using the thevenin equivalent in the transmitting mode as having an input impedance  $Z_a$  connected to a source voltage  $V_g$  and source impedance  $Z_g$ . The impedance  $Z_a$  consist of both the conduction and dielectric losses ( $R_l$ ) incorporated with the antenna. It also consist of the loss due to radiation ( $R_A$ ) of the antenna. This loss due to radiation constitute the imaginary part ( $X_A$ ) as shown in Fig. 2.1 [4].

There are different types of antennas including microstrip antennas, array antennas, reflector antennas, lens antennas and aperture antennas among others. Among all, microstrip antenna is the most common because it has light weight, low cost, compact, low profile, ease of fabrication. However, it has low power handling capability,

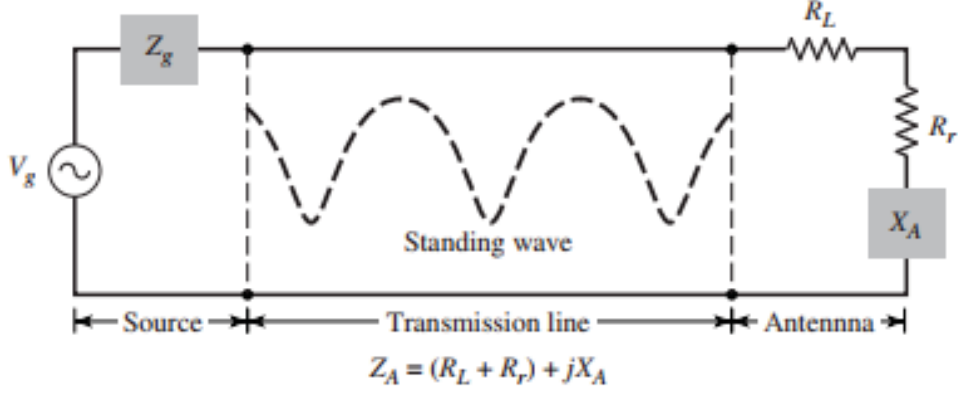


Figure 2.1: Thevenin Equivalent of Antenna.

low efficiency, poor isolation between the feed and radiation elements, narrow bandwidth, low radiation, low power handling capability and low gain. The bandwidth can be increased by increasing the height of the antenna. But this will introduce surface waves which are usually captured inside the substrate of the antenna. The surface waves degrade the antenna radiation pattern and reduces the available power for radiation. [4].

Simple antennas generally are expected to have high efficiency, high gain, large bandwidth, compact, and consistent radiation pattern over the entire bandwidth. MIMO antennas are expected to have low mutual coupling between the arrays, low envelope correlation co-efficient (ECC), high gain and also consistent radiation pattern across the bandwidth, depending on the application. These parameters and more will be explored in this chapter as they apply to MIMO antennas.

## **2.1 MIMO Antenna Performance yardstick**

### **2.1.1 Diversity Gain**

When the received signals from many antennas are combined at the output to produce a single output, the process is known as Antenna diversity. The concept of antenna diversity is to avoid identical fading of the antennas, hence fading in one antenna is made to be independent of the other antennas [5]. Diversity can either be space, polarization, frequency, time, pattern, directional or transmit-receive [6]. Therefore, for a particular Bit Error Rate (BER), the diminished desired Signal to Noise Ratio (SNR) over the fading channel is known as the diversity gain [5]. This means that as the number of antennas increases, the individual noise of each antenna is added incoherently while the signals are added coherently.

### **2.1.2 Mean Effective Gain (MEG)**

This is the actual gain of an antenna when environmental factors are observed. The external factors may be the propagation channel when the antenna is used in a system or anechoic chamber environment where the gain is measured. In [7], the MEG of uncorrelated signals are expressed in two terms with each term representing the contribution of the individual components to the MEG.

### 2.1.3 Isolation

In any MIMO antenna system, the isolation explains the amount of power transferred and received from antennas at close proximity with themselves. The power transferred or received is usually referred to as coupled power, and this can occur via the substrate, feeding ports, ground plane or even on top of the surface. For any MIMO system, it is desired that the isolation should be increased as much as possible so that the desired space waves can be radiated unhindered. Many techniques have been discussed in literature to increase this isolation between the individual elements of a MIMO antenna, and this is the crux of this project.

### 2.1.4 Correlation Co-efficient (CC)

Correlation coefficient is a measure of independence of each antenna in a MIMO system. The more independent the antennas are, the higher their ability to transmit and receive independent streams of data. CC value for MIMO antenna systems is expected to be as low as possible. CC of 0 indicates that the antennas are completely independent and this may occur when one antenna is polarized horizontally while the other is polarized vertically. Any CC value of  $< 0.5$  is generally accepted [8]. Envelope Correlation Coefficient (ECC) results when the correlation coefficient is multiplied by itself .

ECC can be measured in terms of S-parameters or port isolation and it has a mathematical formula of [9]:

$$ECC = \frac{|S_{11}^* S_{12} + S_{21}^* S_{22}|^2}{|(1 - |S_{11}|^2 - |S_{21}|^2)(1 - |S_{12}|^2 - |S_{22}|^2)|} \quad (2.1)$$

Where  $S_{21}$  and  $S_{12}$  represent the coupled signals from antenna 2 to 1 and vice versa.  $S_{21}$  is always the same as  $S_{12}$  when there is no active element in the antenna, and also because of the principle of reciprocity. However, ECC using S-parameters is termed to be ineffective because it assumes that the antenna has efficiency of 100%, although it is very simple and fast [10].

ECC can also be measured using the radiation pattern of the antennas in the MIMO system. The mathematical demonstration is shown below [11] :

$$ECC = \frac{|\iint_{4\pi} [E_1(\theta, \phi) \cdot E_2(\theta, \phi)] d\Omega|^2}{\iint_{4\pi} |E_1(\theta, \phi)|^2 d\Omega \iint_{4\pi} |E_2(\theta, \phi)|^2 d\Omega} \quad (2.2)$$

Where  $E_1(\theta, \phi)$  and  $E_2(\theta, \phi)$  are the far field parameters from antennas 1 and 2 respectively. ECC using farfield is more reliable because it considers the radiation properties of the two antennas, although it is difficult to measure because it requires anechoic chamber which is usually expensive.

### 2.1.5 Total Active Reflection coefficient (TARC)

The TARC connects the combined power emanating from the input to the combined output power of all the antennas in the MIMO system. The output power is usually undesirable reflected power. TARC is actually the root of all powers exiting the ports of the MIMO antenna divided by the root of all powers coming from the ports of the MIMO antenna [12], [13]. The mathematical representation is shown below [12] :

$$\Gamma_a^t = \frac{\sqrt{\sum_{i=1}^N |b_i|^2}}{\sqrt{\sum_{i=1}^N |a_i|^2}}, \quad (2.3)$$

where  $\Gamma_a^t$  is the TARC,  $\sum_{i=1}^N |b_i|^2$  is the combined output power and  $\sum_{i=1}^N |a_i|^2$  is the combined input power. When TARC = 1, it indicates that all the available power is reflected. When TARC = 0, it means that all input power from all ports in the MIMO antenna system is received by the antenna [13].

## 2.2 Mutual Coupling in MIMO Antennas

In a MIMO antenna system that comprises of two or more antennas placed at proximity to one another, the energy from one antenna intended for a certain antenna can be picked up by another antenna. The amount of these unintended energy can be influenced by the distance between antennas, radiation attributes of each antenna and their orientations. This exchange of unintended energy between antennas in a MIMO system is referred to as mutual coupling. This coupling reduces the efficiency of any MIMO antenna system. Coupling can occur in antennas in both the transmitting and receiving mode [4].

To understand the coupling in the transmission mode, consider two antennas  $m$  and  $n$  with a source attached to both antennas as shown in Fig. 2.2. If antenna  $n$  radiates electromagnetic waves (1) via (0), some of the radiated energy will be transferred to antenna  $m$  as (2) towards (4), some of these energy received by antenna  $m$  may be re-scattered into the space (3), while some may be re-transferred (5) back to antenna antenna  $n$ .

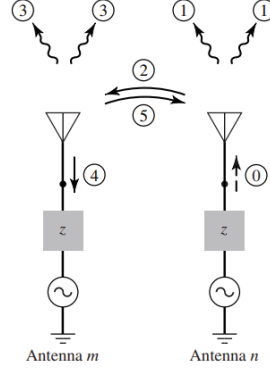


Figure 2.2: Transmission mode Analysis of two-antenna mutual coupling.

Therefore, in any MIMO antenna array, the total far-field of any element is the addition of the radiations from its excitations as well as the radiations due to other parasitic elements surrounding it, which is a function of all the energies due to mutual coupling from these parasitic elements [14].

## 2.3 Electromagnetic band gap (EBG) structures.

Electromagnetic band gap (EBG) structures can be classified under the category of metamaterials or engineered materials. They are called metamaterials because they do not exist in nature. They can also be called double negative materials (DNG), artificial magnetic conductors (AMC), left-handed (LH) materials or negative refractive index (NR1) materials [15]. The advent of metamaterials into antenna technology brought about the ease to control, harness and manipulate electromagnetic waves to design antenna with improved capabilities [4]. Metamaterial usually consist of multitude of unit cells which can also be referred to as meta-atoms. Each of these meta-atoms have sizes that are usually smaller than the wavelength they interact with. The

unit cells are built from metals and dielectric materials. These EBG structures have the ability to create resonances or stop bands within a particular frequency range depending on the shape, size, orientation, arrangement and geometry of the unit cell. Therefore, the overall performance of any EBG structure is largely a function of the configuration of the unit cell, and not the response of the atoms that make up the unit cell. EBG structures usually exhibit very high impedance surface (HIS) in their reflection bandwidth. Hence, they are useful in the increment of the bandwidth of planar antennas [16], suppress simultaneous switching noise in high speed circuits [17], suppress side lobes of horn antennas [18], improve gain of patch antenna [19] and reduce mutual coupling [20].

### 2.3.1 Operation mechanism of EBG structures

According to [21], EBG structures have the special ability to mitigate surface and space waves at a specific frequency range. The conventional mushroom EBG structure has periodic patches printed on the top of a substrate. The patches are joined to a common ground through the metallic through-plate via as shown in Fig. 2.3 and Fig. 2.4 below [22]:

Considering a unit cell of Fig. 2.3 , there is lumped capacitance and inductance in the EBG structure. When this EBG structure is exposed to electromagnetic waves, the metallic pad or patch will induce current; and this current will be locked in the region that is bounded by the plated via. The current will induce magnetic field which is equivalent to the inductance,  $L$ . The built-up charges on the top surface around the patch edges create capacitance  $C$ . This combination will result into  $LC$  resonant

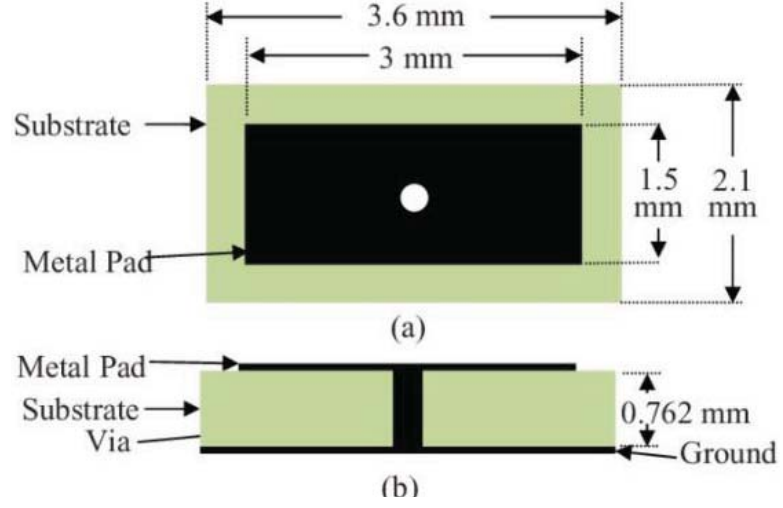


Figure 2.3: Regular mushroom-like EBG (a) Front view (b) Side view.

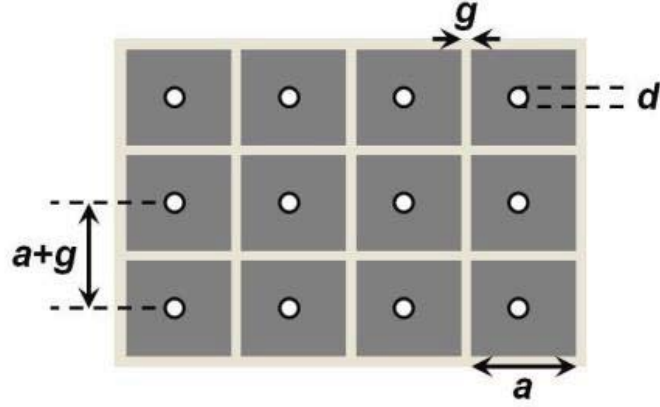


Figure 2.4: top-view with its design parameters.

circuit which has an associated impedance  $Z$  which is given as:

$$Z = \frac{j\omega L}{1 - \omega^2 LC} \quad (2.4)$$

The surface impedance is inductive when the frequency is small and capacitive when the frequency is high. Hence, it can be referred to as high impedance surface.

The resonant frequency ( $\omega_0$ ) of the mushroom unit cell is given by:

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad (2.5)$$

Therefore, to increase the resonant frequency of the EBG structure, the capacitance and inductance of the unit cell must be made smaller, so that the current and voltage induced may pass through very short path. Also, to reduce the resonant frequency, the capacitance and inductance of the unit cell must be made larger, so that the current and voltage induced may pass through a very long path. This concept has been used to produce compact electromagnetic band gap structure in [23].

## 2.4 5G Antenna Technology

The millimeter wave 5G technology evolved as a result of the ever growing demand for wireless network capacities to meet service demands. 5G technology will enable millimeter wave spectrum, possibility of 'Internet of things', high data rate, wider channel bandwidth, low latency, low energy and cost [24]. One of the most important considerations for 5G antennas is the need for high radiation efficiency and gain. Other important considerations include multiple polarizations and frequency, excellent feeding networks having very low insertion loss, beam formation, isolation enhancement, massive MIMO, compactness and easy integration to handheld devices, ability to support multiple communication standards (high bandwidth), specific absorption rate (SAR) which must be less than 1.6 KW/Kg defined by FCC guidelines, mutual

coupling lower than the threshold value, envelope correlation coefficient which must be lower than 0.5 industrial standard [25]. The 5G frequency spectrum is broadly categorised into sub-6 GHz (around 3.5 GHz) and the millimeter-wave (mmW) (above 24 GHz). In Europe, Japan and United States, 24-40.5GHz have been approved for mmW 5G spectral frequencies. MIMO antennas will also be an important consideration in the 5G antenna implementation because of superior capacity as exhibited in 4G networks.

### **2.4.1 Mobile Antennas at 5G sub-6 GHz**

The antennas at this frequency level tend to leverage on the existing 4G spectrum (around 3.5 GHz), but with multi-connectivity. The concern of antenna engineers at this frequency range is the maximum number of MIMO antennas elements required to ensure very low envelope correlation coefficient (ECC), as well as low mutual coupling, using the techniques already available in 4G and Wi-Fi smart phones. This is because the data rate of 5G antenna is expected to be 100 times compared to the current 4G. MIMO antennas placed at close proximity will help achieve high data rate with low latency. However, mutual coupling and correlation coefficient will be very high. Also, antenna miniaturization at this frequency range is imperative because of hand-held demands with larger display areas by consumers. This can be achieved by physical reduction of the patch sizes or meandering. Another important issue to be addressed is the radiation blockage due to reflections in metallic smartphones. This issue has been curbed by the introduction of inverted-F antennas, loop antennas and folded monopoles to create good open boundaries for antenna radiation efficiencies.

### **2.4.2 Mobile Antennas at 5G millimeter-wave (mmW)**

In millimeter-wave frequency, the frequency is very high (greater than 24 GHz). As such, the wavelength is very low, which makes dielectric and conduction losses worse. This is because the antenna components behave as parasitic elements at this frequency and are more sensitive to any changes. This will deteriorate the noise figure and EIRP. Also, antennas at this frequency range will exhibit localized current distribution, and there will also be restrictions on the effect of the antenna's ground plane on the radiation characteristics of the antenna. Mobile packaging trends for compact packaging schematics at 5G mobile antenna has been classified into 2 groups: system-on-chip (SoC) and system-in-package (SiP). The SiP allows antenna engineers to choose different substrate materials and fabrication processes for the radio frequency integrated circuit (RFIC) and the mmW 5G antenna. The SoC allows the RFIC and mmW 5G antenna to be integrated together in one system [26].

Initially, the mmW band is idle because it was not deemed fit for mobile communication because of the strong pathloss, rain and atmospheric absorption, object penetration, costly equipment requirements and very strong phase noise. However, the power consumption and costs of semiconductors are reducing, making these obstacles to be considered surmountable [24].

### **2.4.3 Millimeter-wave 5G Mobile Antenna Design**

Just like the microwave frequency antennas, the mmW 5G antennas also have design criteria like omnidirectional radiation patterns, good radiation efficiency and

bandwidth. However, mmW 5G antennas also require array or MIMO configurations because of high loss, and also adequate polarisation loss factor compensation because of the misalignment in the transmitting and receiving antennas. Dual, tri and multi-bands mmW 5G antennas are likely to dominate due to their ability to reduce 5G antenna's footprint.

It is noteworthy that the implementation of mmW 5G smartphones will create additional uncertainties and complexities because of the frame and chassis materials of the phone. This will distort the beams, diffraction and access control of the mmW 5G phone. This is why there is need to document all the electrical properties of the major compositions of the phone.

#### **2.4.4 5G Base Station Antennas**

For 5G antennas to be used in base stations, some requirements have to be considered by antenna engineers. This includes the integration of 3G and 4G systems and services with 5G systems and services, the antenna's ability to serve multiple users in its coverage area by the use of massive MIMO antenna. The antenna must also be able to generate multiple independent and concurrent beams. It must be able to exhibit EIRP emission level of less than  $1\text{mW}/\text{cm}^2$  threshold for health and safety.

## CHAPTER 3

# LITERATURE REVIEW

This chapter presents an exposition of several works done in the past to reduce mutual coupling in MIMO antenna array. The effect of these methods over the properties of the antenna will be examined and the exact value of isolation provided will be examined too. Mutual coupling reduction techniques are broadly divided into the following:

1. Defected Ground Surfaces (DGS)
2. Split Ring Resonator (SRR)
3. Neutralization lines
4. Parasitic or slot structures
5. Electromagnetic Band Gap Structures (EBG)
6. Decoupling Networks
7. Combination of two or more methods

### 3.1 Defected Ground Surfaces (DGS)

Defected ground surfaces are the ground planes of microwave structures that have slots or defects of specific size, shape, orientation and numbers. They are usually done to improve characteristics of antennas like gain, bandwidth, isolation, polarization, etc. They can be viewed as paraphrased form of Electromagnetic Band Gap Structures (EBG). Therefore, they can either have periodic or aperiodic structures. When DGS are integrated on the ground plane, they mainly distort the current distribution, thereby effect some changes in the characteristics of the antenna by introducing parameters like slot inductance, capacitance and resistance. This will alter the overall parameters of the antenna [27]. DGS can have shapes like circular dumbbell [28], spiral [29], 'U' or 'V' [30]. DGS are also used to increase isolation in MIMO antenna array by disturbing distribution of the surface current on the ground plane by creating extra capacitance and inductance on the ground plane.

Fig. 3.1 below shows a periodic S-shaped DGS structure inserted between two microstrip patch elements at 2.57 GHz. Without the three periodic S-shaped structures, the mutual coupling is as high as -15 dB. When the three periodic s-shaped structure are inserted, the isolation is about -55 dB. Therefore, the isolation has increased by more than 40 dB.

From the allocation of the surface current shown in Fig. 3.2, the effect of the S-shaped DGS is obvious. When the antenna on the left is excited, coupled current is induced by the parasitic right antenna. When the DGS is inserted, the coupled current is absorbed by the DGS so that less current is induced by antenna on the right. This

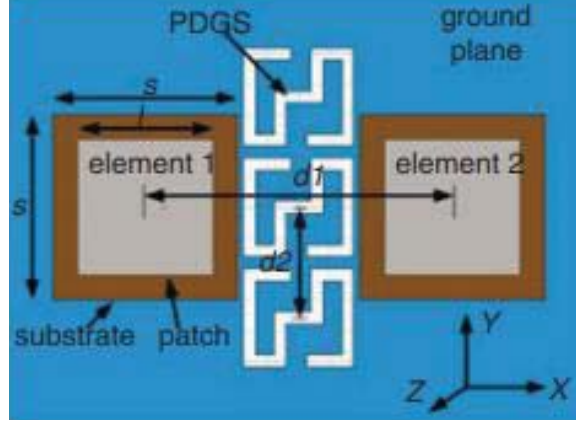


Figure 3.1: MIMO antenna with S-shaped periodic DGS

will obviously reduce the transmission between the antennas. The radiation pattern is also observed to be very good at the operating band.

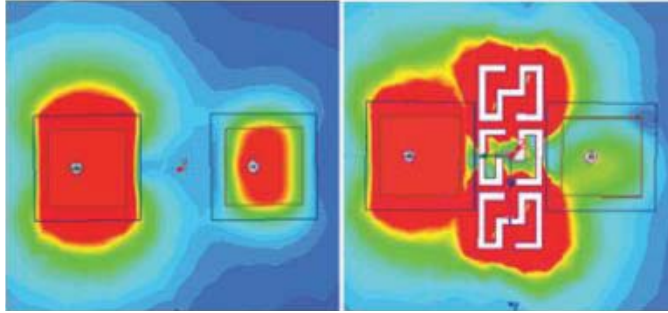


Figure 3.2: Distribution of current on the surface of S-shaped DGS .

### 3.2 Complimentary Split Ring Resonator (CSRR)

CSRR has been proven to be used for miniaturization of microwave filters and to create band pass with high bandwidth. This has made CSRR a good candidate for isolation in planar resonators and antennas [31], [32]. A 2 X 5 CSRR is used by [32] to decouple 2 patch antenna array as it's obvious in Fig. 3.3. An observable 25 dB mutual coupling reduction was noticed at 25 GHz when the CSRR is used.

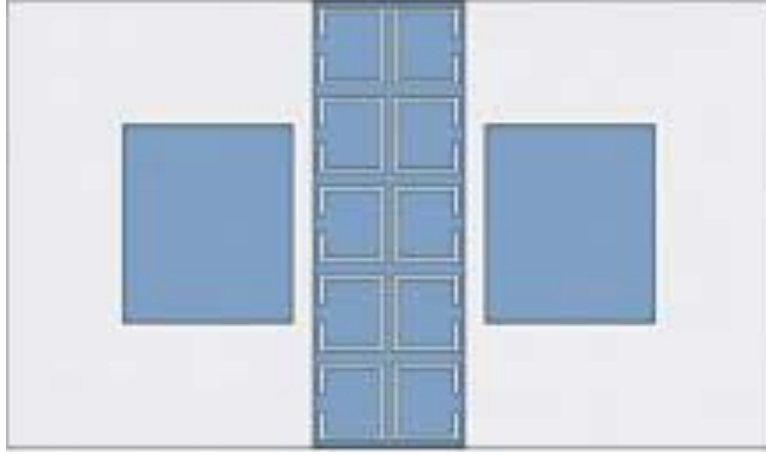


Figure 3.3: CSRR Loaded microstrip patch antenna

### 3.3 Neutralization lines

Neutralization lines are metallic slits that are used to transfer electromagnetic waves from one antenna to another. This will generate opposite coupling to improve the isolation between the antenna elements at certain frequencies [33].

In [34], two MIMO monopole antennas are proposed. The two monopoles are separated by a small ground plane. The neutralization line consist of a very thin printed line used to connect the two antennas, and it occupies very little space, so does not need any ground plane modification. The neutralization lines helps to effectively isolate the two monopole antennas. Fig. 3.4 shows the front view of the monopole antenna. Points C and D in Fig. 3.5 shows that the length and width of the short circuited strips can be varied to influence the impedance matching. Also, the isolation between the two monopoles can be controlled by altering the length of the neutralization line and changing the length and location of the connecting points E ad F. The isolation was improved by 9 dB using this neutralization line. The sur-



Figure 3.4: Front view of a printed monopole line short-circuited by printed neutralization line

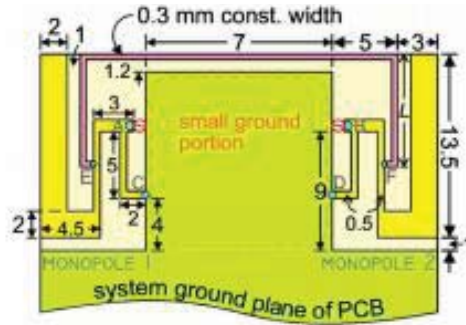


Figure 3.5: Dimension of the two-monopole line short-circuited by printed neutralization line

face current, radiation pattern, Total Active Reflection Coefficient (TARF) was also analyzed, and the results obtained conformed to expected standards.

### 3.4 Slot or Parasitic structures

Parasitic elements help to provide more coupling paths in radiators of antennas so that the original coupling created can be cancelled . A USB dongle MIMO antenna was presented in order to validate the isolation-improving capability of this parasitic elements. A minimum of 30 dB isolation improvement was observed using planar inverted-F (PIFA) MIMO antenna with very close edge to edge separation between 2.4-2.48 GHz [35]. Parasitic elements have the same working principle as the neutralization line, but unlike the neutralization line, parasitic elements do not have any physical link between the radiation elements. The configuration and dimension of the parasitic elements should be in such way that it can produce phase currents that are  $180^\circ$  out of phase so as to eradicate the coupling-causing unwanted currents. The authors also compared the result obtained with other methods and this result was better.

Also, in [36] and [37], the authors proposed a dual-polarized antenna having a resonance of 3-12 GHz. The slots etched from the ground and feeding points help to manoeuvre the isolation and matching. Isolation improvement was more than 20 dB throughout the impedance bandwidth. The distribution of the electric field and far-field pattern proved that the antenna can also be dual polarized. The slot has narrow middle section which is narrow to allow maximum feed line coupling. It also has wide outer section to allow large radiation aperture Lines C1 and C2 that are introduced to further reduce the coupling as shown in Fig. 3.6.

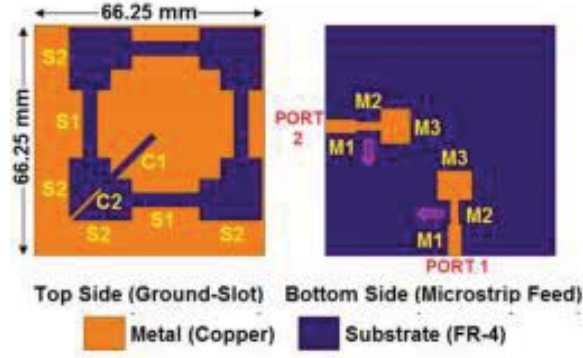


Figure 3.6: Mutual coupling reduction using neutralization lines on the ground plane.

### 3.5 Electromagnetic Band Gap Structures (EBG)

As discussed in previous sections, EBG structures are periodic structures that can have properties that are beyond natural materials. When carefully structured, they can exhibit amazing properties, and antenna engineers have exploited these attributes to enhance the performance of antennas, mutually coupling reduction inclusive.

In [38], the authors used 2X4 Z-Shaped EBG structure to decouple microstrip patch antenna at 5.59 GHz. The two microstrip patch antennas have a square shape and they are fed by coaxial lines as shown in Fig.3.7. 8 dB isolation improvement was achieved using the Z-shaped EBG.

Also, the authors in [39] used dual-layer traditional mushroom structure for miniaturization and isolation improvement between two closely spaced patch antenna. The inner structure of the EBG enabled miniaturization while the upper layer enables mutual coupling reduction. The isolation improvement was between 28 dB to 50 dB.

A wall containing double layer traditional mushroom EBG was used to decouple four MIMO substrate integrated cavity backslot antenna in [40]. The wall was placed

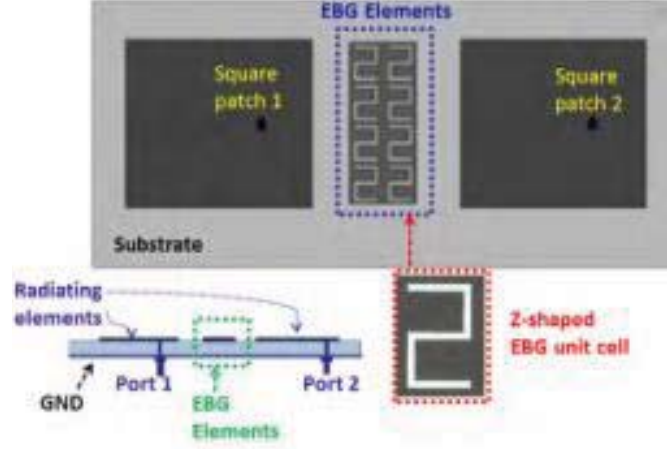


Figure 3.7: 2X4 Z-shaped EBG structure for Isolation improvement.

in between the four antennas and an isolation of about 16dB was achieved at 2.4 GHz. The antenna also showed good radiation properties with very minimal ECC. As the double layer of the mushroom EBG increases, the isolation is observed to increase too.

### 3.6 Decoupling networks

Decoupling schemes make use of discrete components or transmission lines basis to transform cross-admittance term to purely imaginary value [41], [42]. Some of the decoupling schemes reported in literature includes coupled resonator filter network [43], floating parasitic structures [44], [45] and lossless network [46].

In [47] the authors optimized the length of the radiators so as to control the radiation features and also reduce mutual coupling in a two-element, four-element and eight element MIMO antenna configuration. The radiators are placed very close in order to distort the radiations in the near field. The two-element MIMO antenna exhibited 20 dB isolation improvement while the eight-element exhibited 15 dB isolation

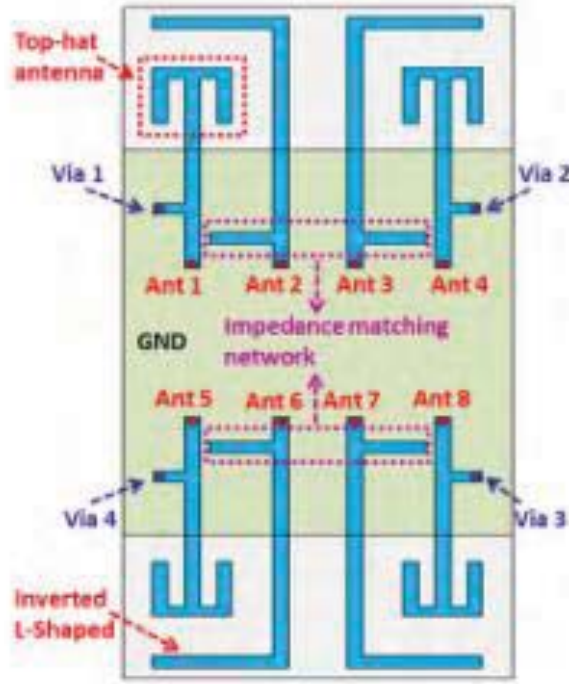


Figure 3.8: Mutual coupling reduction using change of radiator length for pattern diversity structure.

improvement as shown in Fig. 3.8. The antennas are all resident at the corners of the substrate; and stubs are also added to enable impedance matching.

### 3.7 Combination of two or more methods

In [48], the authors used a combination of one dimensional EBG structure and Split Ring Resonators (SRR) to increase isolation between monopole antennas. This combine structure improve the isolation by more than 42 dB with a corresponding reduction in backlobe radiation. The EBG structure traps the surface waves while the SRR reflects the coupling waves as shown in Fig. 3.9. The SRR also helps to improve the matching impedance. Fig. 3.10 depicts the performance of the monopole antenna

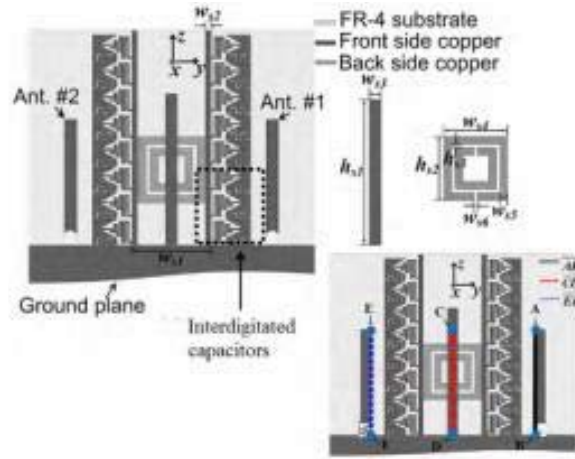


Figure 3.9: Multiantenna mutual coupling reduction using SRR structure coupled with 1 dimensional EBG.

|                                                   | Reference antenna            | Antenna with EBG             | Antenna with EBG and SRR     |
|---------------------------------------------------|------------------------------|------------------------------|------------------------------|
| Structure                                         |                              |                              |                              |
| Spacing between antenna elements                  | 24 mm<br>(0.19 $\lambda_0$ ) | 24 mm<br>(0.19 $\lambda_0$ ) | 24 mm<br>(0.19 $\lambda_0$ ) |
| Mutual coupling $S_{21}$ , $S_{12}$ at $f_0$ (dB) | -11.6                        | -16.3                        | -53.7                        |
| Operating frequency, $f_0$ (GHz)                  | 2.46                         | 2.46                         | 2.46                         |
| -30 dB bandwidth ( $S_{21}$ , $S_{12} < -30$ dB)  | •                            | •                            | 110 MHz<br>(2.43–2.54 GHz)   |
| -10 dB impedance bandwidth                        | 620 MHz<br>(2.29–2.91 GHz)   | 560 MHz<br>(2.20–2.76 GHz)   | 450 MHz<br>(2.32–2.77 GHz)   |
| Front-to-back ratio (dB)                          | 3.1                          | 4.8                          | 9.3                          |
| Correlation coefficient                           | 0.138                        | 0.068                        | 0.002                        |
| Radiation efficiency (%)                          | 73                           | 76                           | 82                           |

Figure 3.10: Performance characteristics of the antenna.

alone, compared to when EBG is added and SRR. It is clear that that the correlation coefficient reduces , mutual coupling reduces and the radiation efficiency increases.

# CHAPTER 4

## ISOLATION ENHANCEMENT IN MICROSTRIP 5G ANTENNA ARRAY

In this chapter, a novel EBG structure that can decouple microstrip patch antenna is presented. Researchers are recently considering the millimeter wave band of 28 GHz for 5G applications because of the miniaturized nature of hand-held devices, limitation of frequency usage, and the need for antennas to be tightly packed together. Also, there is need for more data rate and frequency bandwidth so that multiple streams of data can be sent and received simultaneously. This section presents slotted-ring EBG structure placed between two nearby microstrip antennas placed at a distance of  $0.28\lambda$  from each other. The metamaterial EBG structure is first optimized to produce a band gap around 28 GHz. The EBG can therefore suppress surface waves within this frequency range.. The EBG is then inserted between the two microstrip antennas

and simulated.

The EBG structure described above can only provide reduction over small bandwidth. Therefore, another antenna is simulated and fabricated to resonate at 4.2-6.5 GHz. Another EBG multi-resonance EBG structure and defective ground plane is presented and is used to decouple this antenna over the large bandwidth.

## 4.1 Design of EBG unit Cell

The unit cell of the EBG structure used in this section has a mushroom-like square patch of dimensions 1.3 x 1.3 mm. However, unlike the conventional mushroom-like structures, a square slotted-ring of 0.9 mm length and thickness of 0.017 mm is etched off the square patch. This enabled more capacitance and inductance to be formed within the EBG and therefore makes the EBG resonate at lower frequencies. Also, the via is placed between the etched slot and the patch. This ensures that the current travels a longer path and hence, more inductance is formed. The EBG structure can, therefore, resonate at more lower frequencies hence, enabling miniaturization. The via has a radius of 0.07 mm and height of 0.762 mm. The patch and ground also have the same thickness 0.017 mm. The substrate used is Rogers R04350B with a dielectric constant of 3.48 and loss tangent of 0.0037. Fig. 4.1 and 4.2 shows various views of the novel unit cell.

The dispersion diagram of the unit cell is depicted in Fig. 4.3. The dispersion diagram explains the bandgap characteristics of EBG structures. It is conspicuous that the unit cell has band gap of 22-45 GHz between mode 1 and 2. This implies

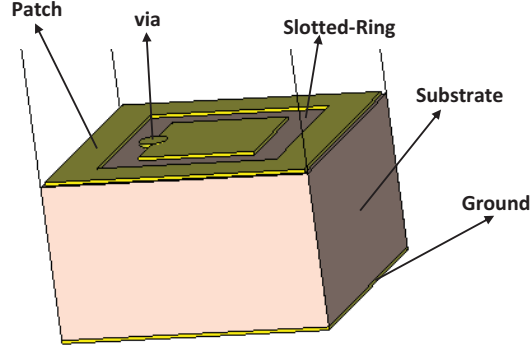


Figure 4.1: EBG Unit Cell of the proposed structure.

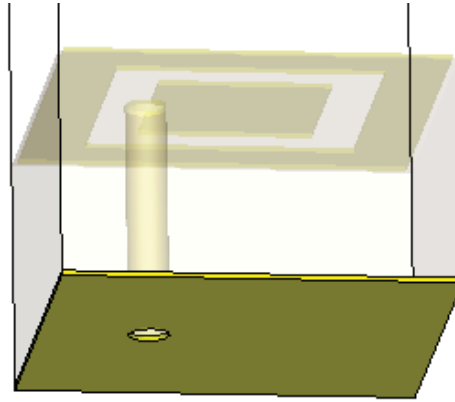


Figure 4.2: Transparent view of the proposed unit cell.

that at this frequency band, the EBG structure is able to impede the transmission of electromagnetic waves.

## 4.2 5G Antenna Structure

The antenna structure consists of two microstrip patch of dimensions 2.46 mm X 3.58 mm. These dimensions are chosen to enable the antenna resonate at the intended millimeter wave frequency of 28 GHz. The substrate used is Rogers R04350B with dielectric constant 3.48, thermal conductivity 0.62 W/K/m, loss tangent 0.0037, height

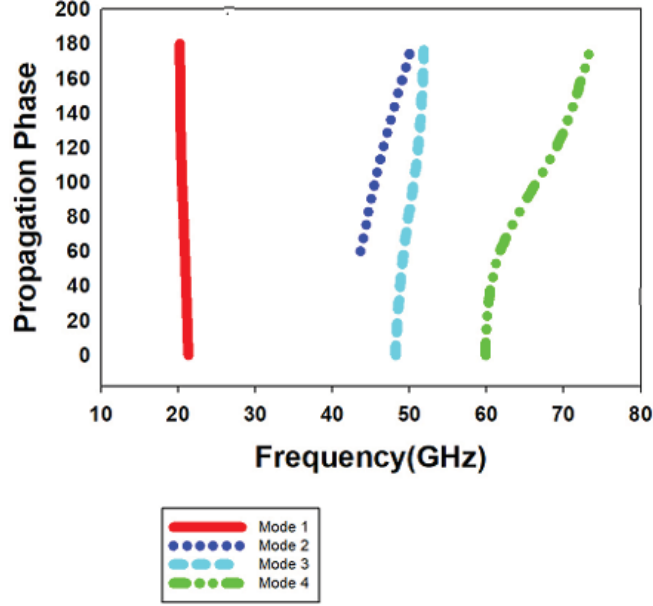


Figure 4.3: Dispersion diagram of the slotted-ring EBG unit cell.

0.762 mm and dimension 11 mm by 8.5 mm. The ground is made of copper and has the same dimension as the substrate. The ground and patch have the same thickness of 0.017 mm. The two patches are fed by 50 ohms coaxial cables and inserted at 15 mm from both edges of the patches. The 15 mm distance is the exact point on both patches that matches the 50 ohm coaxial cables. Hence, the impedance of the coaxial cable can correctly match the impedance of the patch. The distance between the two antennas is 3.07 mm which is corresponding to  $0.28\lambda$  ( $\lambda$  is the free-space wavelength at 28 GHz). Fig. 4.4 and 4.5 show the front view and 3D view of the propounded 5G antenna. Fig. 4.6 shows the S-parameters of the antenna. It is lucid that the antenna exhibit a resonance at 28 GHz with 3 GHz bandwidth between 26.6 GHz and 29.6 GHz. The transmission co-efficient between the two antennas over the working bandwidth is around 26.6 dB to 29.7 dB.

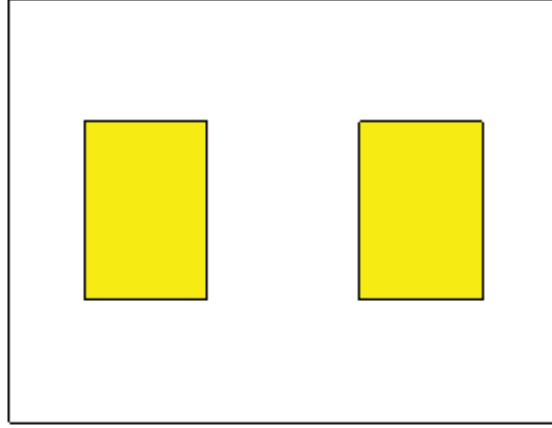


Figure 4.4: 5G Antenna Array: Front View .

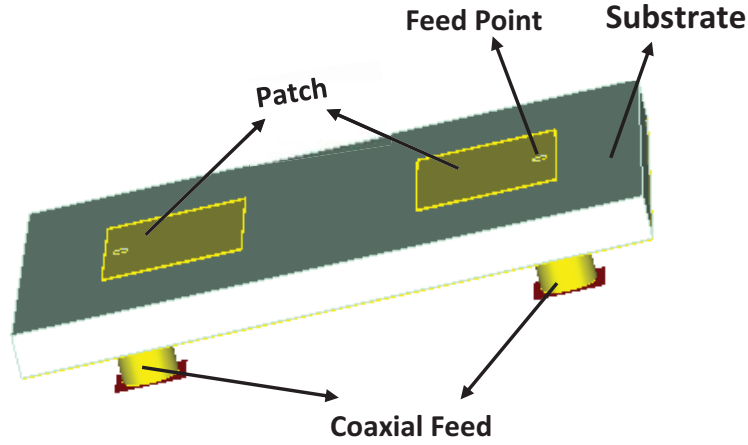


Figure 4.5: 5G Antenna Array: 3D View.

### 4.3 5G Antenna Structure with EBG

A 2X5 slotted-ring EBG structure is introduced between the two printed antennas separated by 3.07 mm which is equivalent to  $0.28\lambda$ . Fig. 4.7 depicts the front view of the antenna array structure while Fig. 4.8 shows the 3D structure of the slotted EBG. Fig. 4.9 delineates the extended view of the slotted EBG .

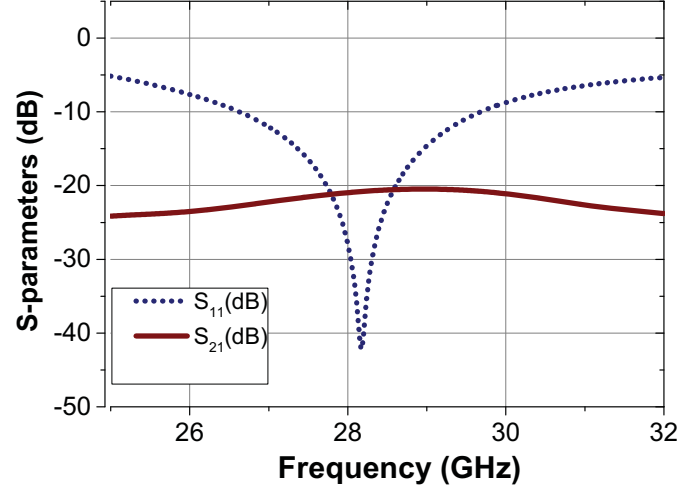


Figure 4.6: S-Parameters of the 5G Antenna array

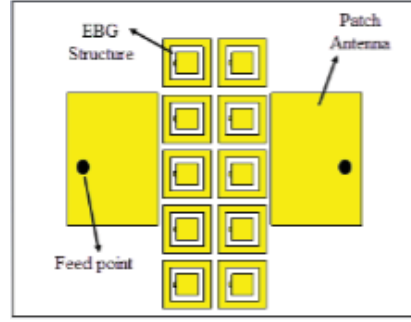


Figure 4.7: Slotted-ring EBG structure incorporated with Microstrip Patch Antenna array: Top View.

## 4.4 S-Parameters of the 5G MIMO Antenna

Fig. 4.10 depicts the effect of the slotted EBG structure on both reflection and transmission coefficients of the antenna. It is clear that the antenna now has wide bands between 25-28 GHz, and the isolation improvement is only evident around 27.6 dB.

Fig. 4.11 compares the s-parameters of the antenna array when the slotted-ring EBG is inserted and when it is not. A mutual coupling reduction from -21 dB to -51

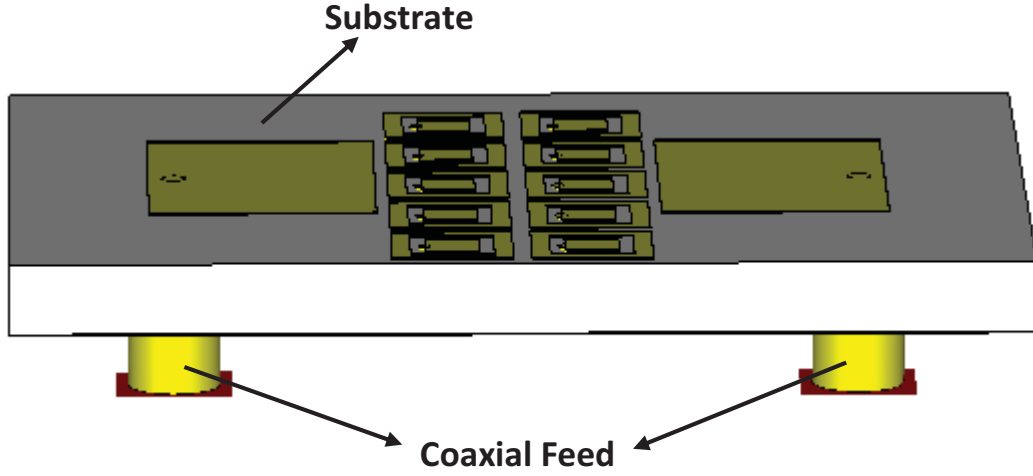


Figure 4.8: Slotted-ring EBG structure incorporated with Microstrip Patch Antenna array: 3D View.

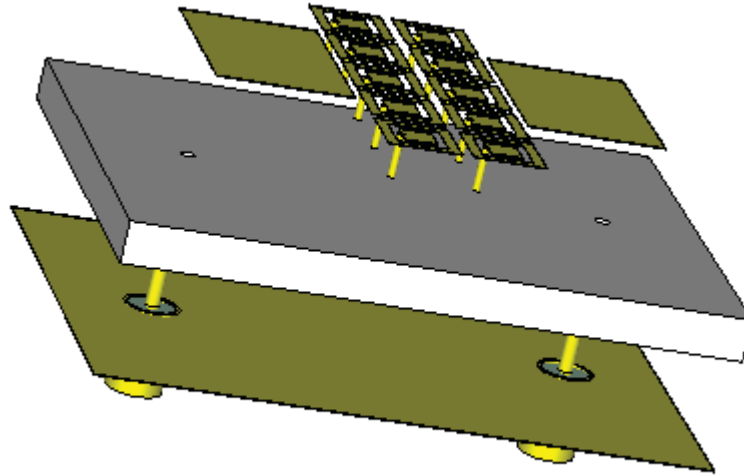


Figure 4.9: Slotted-ring EBG structure incorporated with Microstrip Patch Antenna array: Extended view.

dB can be observed from the graph when the EBG structure is inserted. Moreover, the antenna array demonstrates dual-band operation at 26.5 GHz and 27.6 GHz compared with a single band of 28.2 GHz before the insertion of EBG. This shows the isolation improvement capability of the EBG structure.

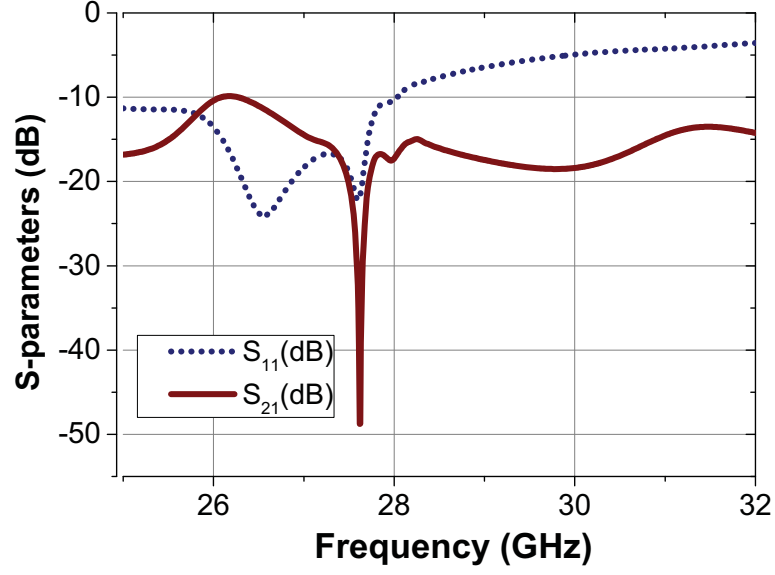


Figure 4.10: S-Parameters of the slotted EBG 5G Antenna array.

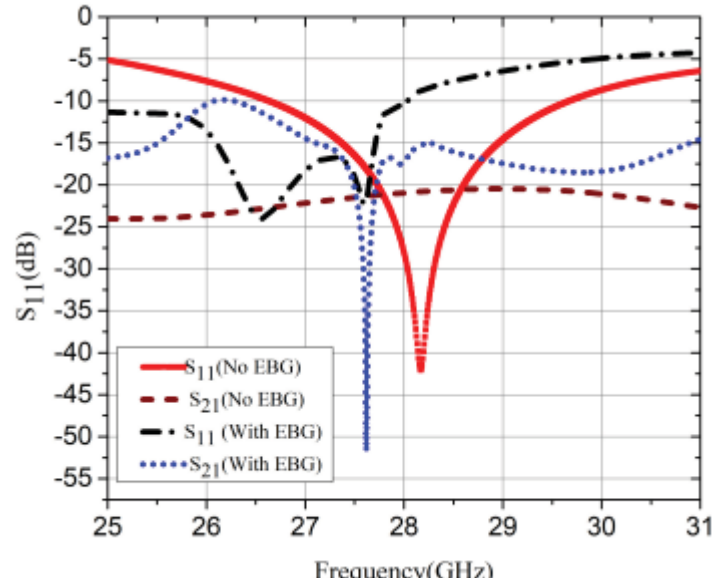


Figure 4.11: S-Parameters of the 5G Antenna.

## 4.5 Surface Current Distribution

To verify the effect of the slotted EBG, the current distribution of the antenna before and after the slotted EBG is shown in Fig. 4.12. Before EBG was inserted, elec-

Electromagnetic waves from antenna 1 is transmitted to antenna 2. This is undesirable especially for MIMO antennas where less interaction is desired. After the EBG is inserted, there is less interfering with antenna 2. The EBG has obviously absorbed the surface current emanating from antenna 1.

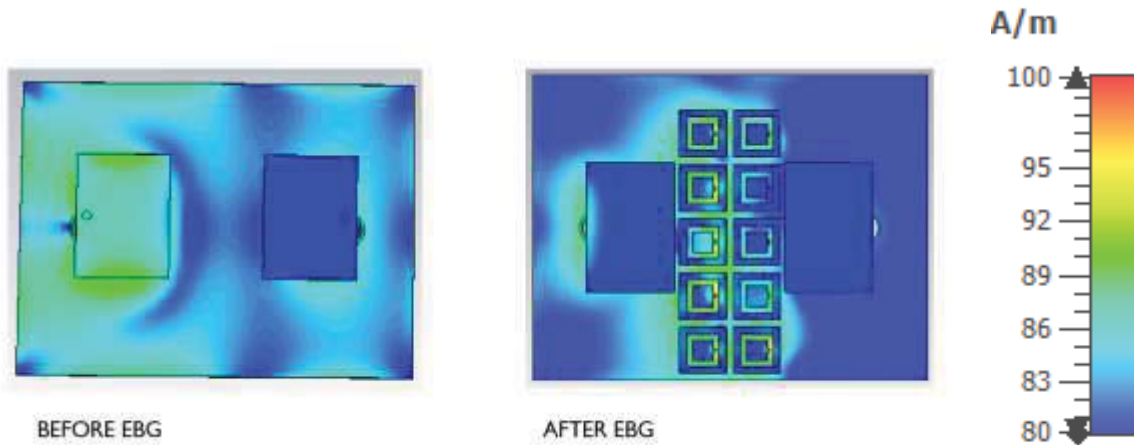


Figure 4.12: Current distribution of the 5G microstrip antenna.

## 4.6 Radiation pattern

Fig. 4.13 delineates the radiation pattern of the reference antenna without EBG at 28 GHz. It is clear that the antenna has broadside radiation with almost no side lobes, with no tilted beam.

Fig. 4.14 depicts the radiation patterns of the two antenna after the EBG was inserted. It can be observed that the antenna exhibit beam tilting. The beam tilting is apparently due to the insertion of the EBG structure which can be design specification.

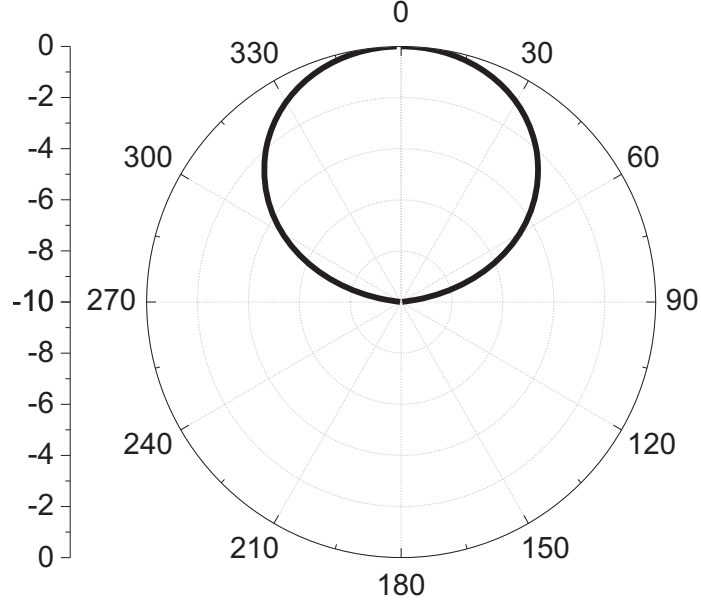


Figure 4.13: Radiation pattern of the reference array antenna

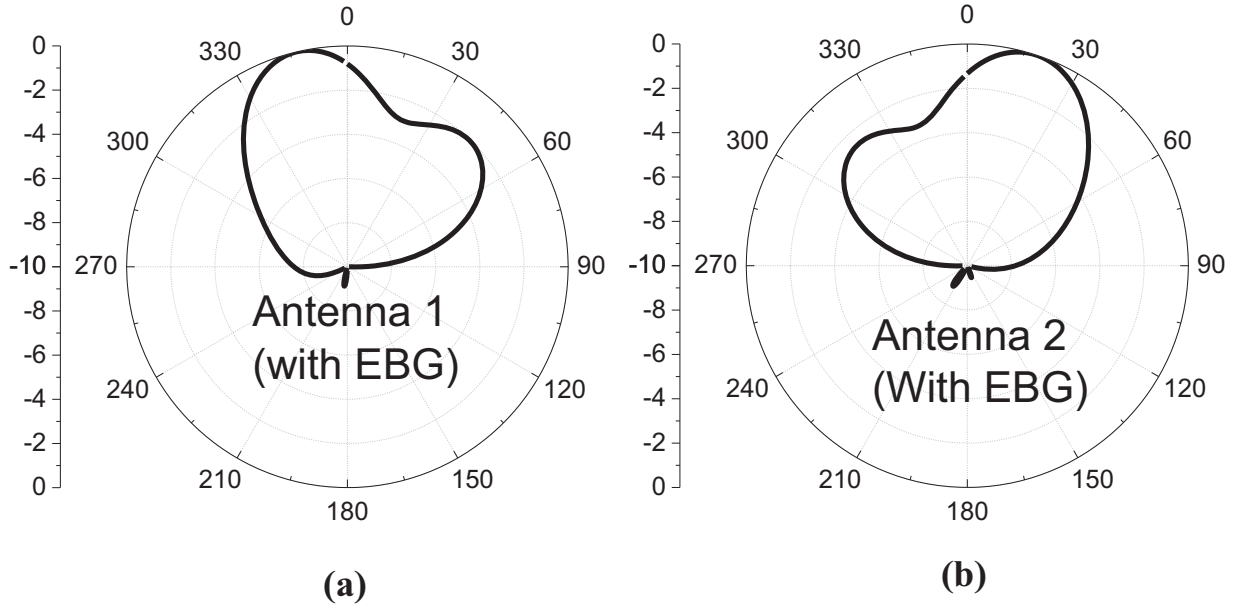


Figure 4.14: Radiation pattern of the proposed 5G antenna

## 4.7 Conclusion

In this chapter, a novel slotted-ring EBG structure is first presented to decouple two 5G patch antenna array operating at 28 GHz with narrow bandwidth by 30 dB. The

EBG structure slightly deflects the beam which may also be a design consideration

## CHAPTER 5

# WIDEBAND ARRAY WITH MULTIRESONANCE EBG AND DEFECTIVE GROUND

### 5.1 Design of Multiresonance EBG Unit Cell

The multiresonance EBG unit cell consist of four traditional mushroom-like EBG structure with different dimensions of patch sizes  $L_1 = 6$  mm,  $L_2 = 3$  mm,  $L_3 = 2.4$  mm, and  $L_4 = 1.8$  mm. Via of outer radius of 0.78 mm , inner radius of 0.6 mm and height of 3.2 mm is placed in the middle of all the 4 patches. The via extends from the ground through two FR4 substrates to the top of the patch. The two FR4 substrates are separated by 0.09 mm; and two copper rings each occupy the 4 via positions in the 0.09 mm space between the two FR4 substrates. The copper rings have external diameter 0.2 mm, internal diameter 0.78 mm and thickness 0.035 mm. The two FR4

substrates have individual height of 1.6mm, loss tangent 0.025 and permittivity 4.3. The patch and ground also have thickness 0.035mm. The combination of the four patches, via and rings create multiple stopband resonances that can suppress surface wave propagation at large impedance bandwidths. Fig. 5.1 (a) depicts the front view of the EBG structure, which contains the patches and substrate; while Fig. 5.1 (b) delineates the side view. This structure is extended for a more clearer view.

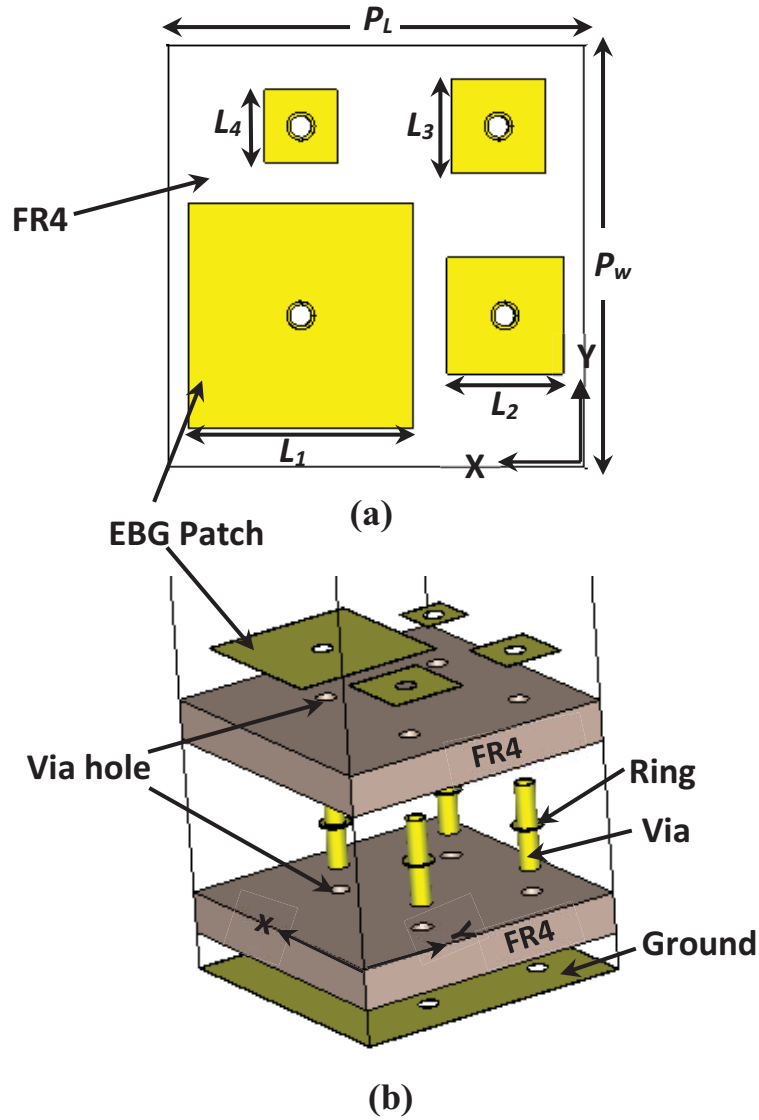


Figure 5.1: Multiresonance EBG structure using CST microwave studio : (a) Front View (b) Side View (Extended for clearer view).

Fig. 5.2 shows the dispersion diagram as obtained from the Eigen mode analysis of CST microwave studio. From the diagram, it can be observed that the irreducible brillouin zone zone where no propagation occurs is around 4 - 6.2 GHz between mode 1 and 2. At this frequency range, the unit cell is able to provide stop band to impede surface waves propagation. Modes 3 and 4 possess continuous wave, and no band gap between them.

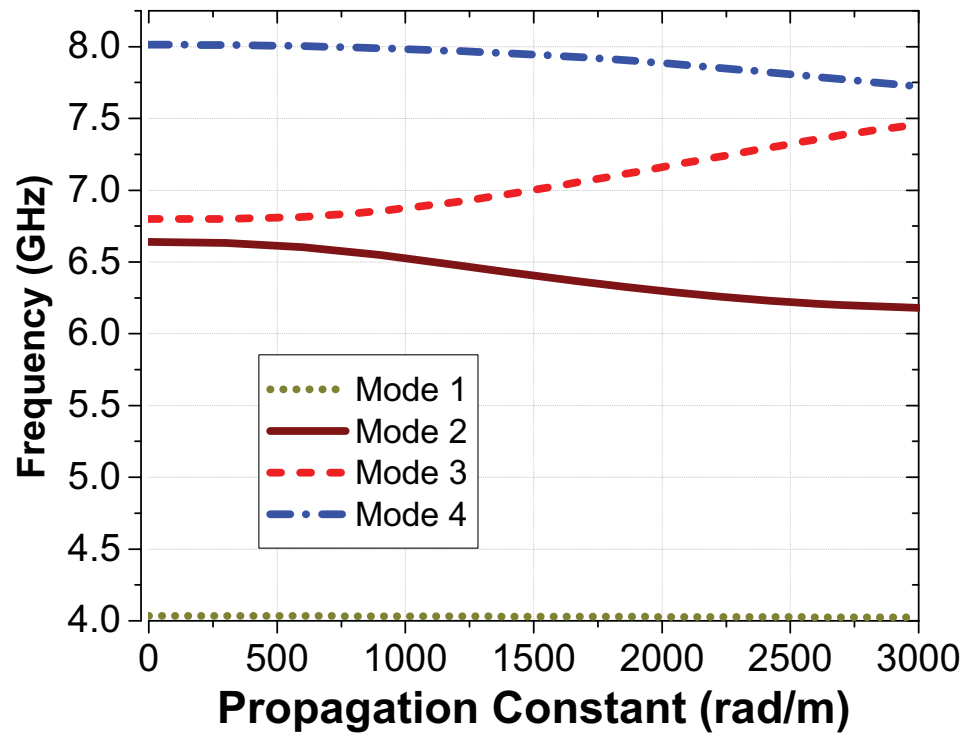


Figure 5.2: Dispersion diagram of the multiresonance EBG unit cell.

## 5.2 Multi-resonance EBG Based Array Antenna

### 5.2.1 Antenna Design

The antenna consist of two FR4 substrates of height 1.6 mm, loss tangent 0.02 and dielectric constant 4.3 separated by 0.09 mm, just exactly like the unit cell. The two substrates are stucked together with glue of the same properties as the FR4 and thickness 0.02 mm. The top plane of the antenna has two microstrip patch each of dimensions  $e \times P$ , where  $e = 34$  mm and  $P = 33.54$  mm [49]. A square slot of dimension 20mm X 20 mm is removed from the centre of the patch and tilted by  $45^\circ$ . Attached at 0.54 mm away from the top corner of the slot is a stub of length 7 mm and has 1.9 mm as its width. The antenna is fed using aperture coupled strip line of length 37.5 mm and width 3.5 mm. The etched slot and two substrates are responsible for the wideband characteristics of the antenna, while the stub and stripline dimensions are responsible for the impedance matching of the antenna at this wideband. Parametric analysis is done on the patch, etch, stub and strip line dimensions; and the best result is presented. The two antennas have  $d = 25.2$  mm ( $0.42\lambda_0$ ) edge-to-edge separation, where  $\lambda_0$  is the wavelength of the antenna at the centre frequency of 5.5 GHz. A 2x5 multiresonance EBG structure is positioned in-between this separation and the result is analysed. The EBG structure has the same structure and dimension as explained in the unit cell design above. Fig. 5.3 (a) depicts the geometry of the proposed antenna. Each layer is raised for better view. Fig. 5.3 (b) shows the defective ground plane. It consist of three 4-shaped structure with a rectangular shape beside each shape. The dimensions and separations of these three etches are optimized to obtain the best

result. The dimensions as shown in Fig. 5.3 (b) are:  $z = 4.7$  mm,  $f = g = 10.5$  mm,  $h = 3.37$  mm,  $k = 14.7$  mm,  $v = 2.05$  mm,  $n = 26.3$  mm,  $s = 8.7$  mm. The overall dimension of the antenna is  $L = 57.5$  mm X  $W = 120.8$  mm. Fig. 5.4 reveals the fabricated prototype antenna.

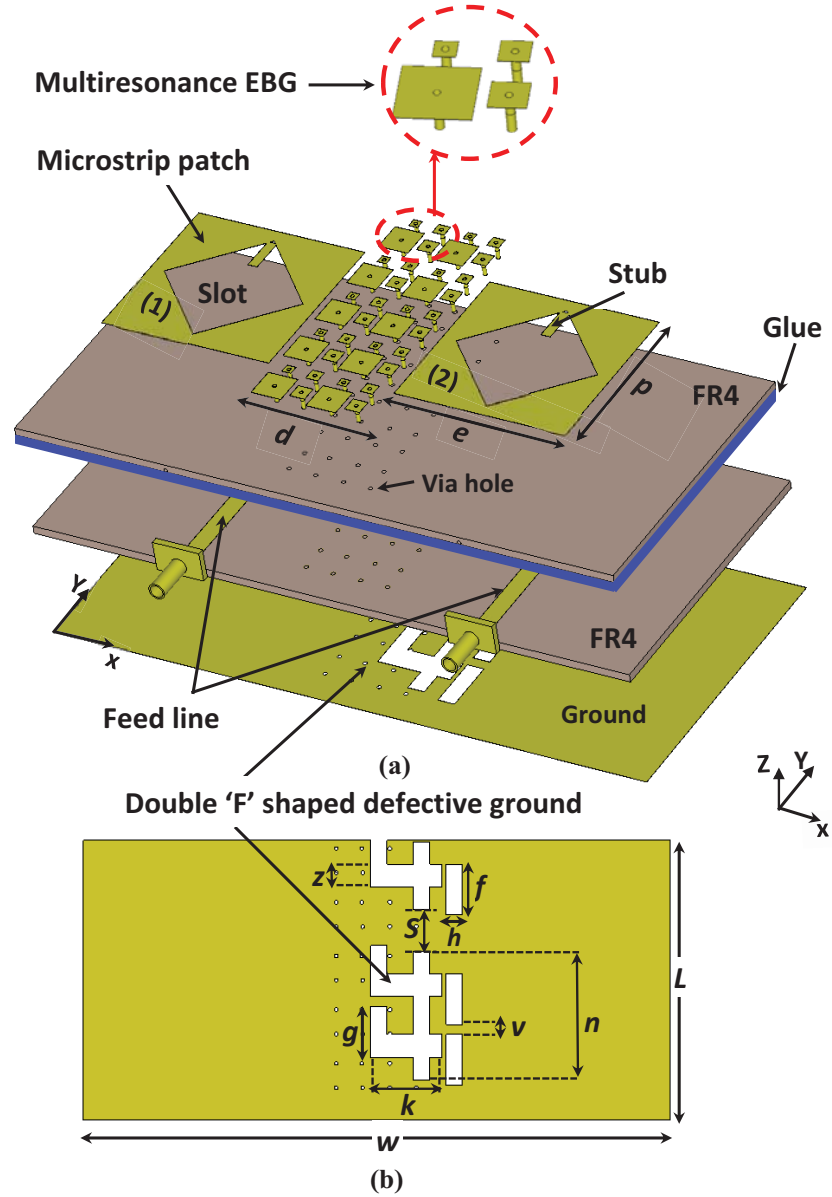


Figure 5.3: Geometry of the antenna array: (a) whole antenna extended vertically for clearer view. (b) Defective ground plane, viewed from the top.

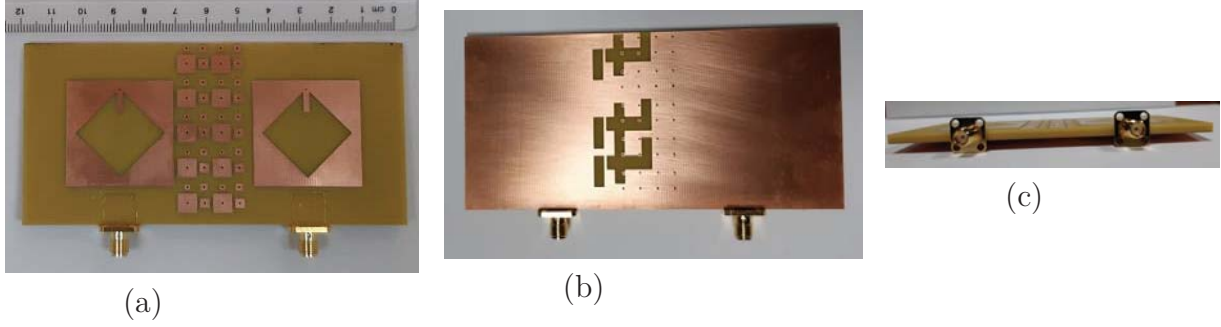


Figure 5.4: Fabricated prototype antenna (a) Top View (b) Back View (c) Lateral View

The reference antenna array is first simulated with neither the multiresonance EBG nor the defective ground plane. From Fig. 5.5, it is clear that the antenna is matched between 4.4 GHz and 6.4 GHz. The isolation ( $S_{21}$ ) between the two antennas is also observed from -25 dB to -38 dB across the entire bandwidth. When the 2 X 5 multiresonance EBG structure is inserted, it can be seen that the reduction is evident only between 5.8-6.4 GHz with about 10-50 dB isolation enhancement over the entire band.

To further widen the isolation bandwidth, three double 'F' shape slots are removed from the ground plane; and their dimensions are optimized. The etched slots on the ground enable the path passed by the surface currents on the ground to be increased and therefore, suppress the surface currents. This reduces the mutual coupling between the two antennas over a large bandwidth. It is evident from Fig. 5.5 that the reduction has been extended to cover the entire matching bandwidth (i.e., 4.4 to 6.4 GHz), with about 10-31 dB isolation improvement maintained, except at 5 GHz where there is no observable reduction. It can also be observed that the introduction of EBG and etchings do not degrade the antenna impedance bandwidth.

Fig. 5.6 compares the simulated and measured s-parameters of the propounded antenna array with EBG and etchings. It is obvious that the simulated and measured reflection coefficients almost match at 4.4 to 6.4 GHz for both antennas. The measured reflection coefficient is almost 4 to 6.5 GHz.

However, according to Fig. 5.7 that compares the simulated and measured transmission coefficients ( $S_{21}$ ) of the proposed antenna, the measured isolation improvement is better, with about 20-31 dB measured isolation improvement over the entire bandwidth compared to 10-31dB from simulation results. It should, however, be noted that there is no observable isolation improvement around 4.8 GHz.

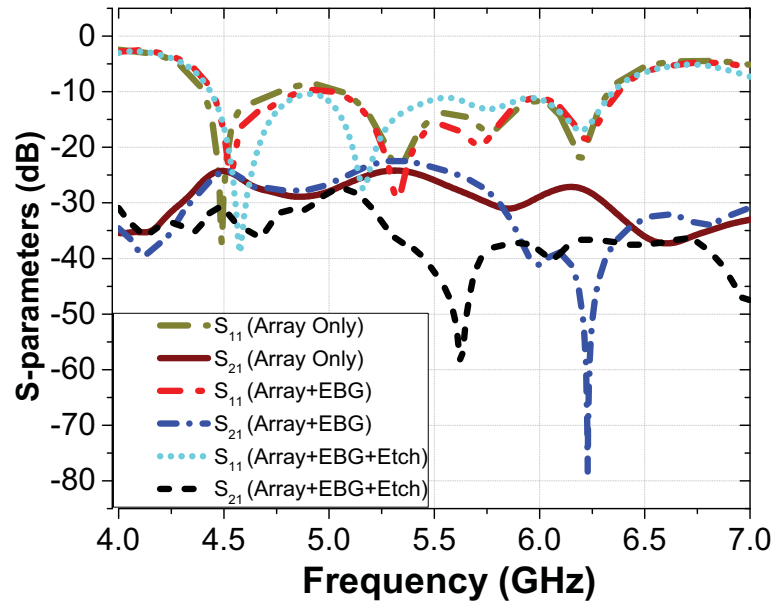


Figure 5.5: S-parameters (simulated) of the presented antenna multiresonance antenna compared with antenna array only , Array and EBG, and combination of Array and EBG and Etch.

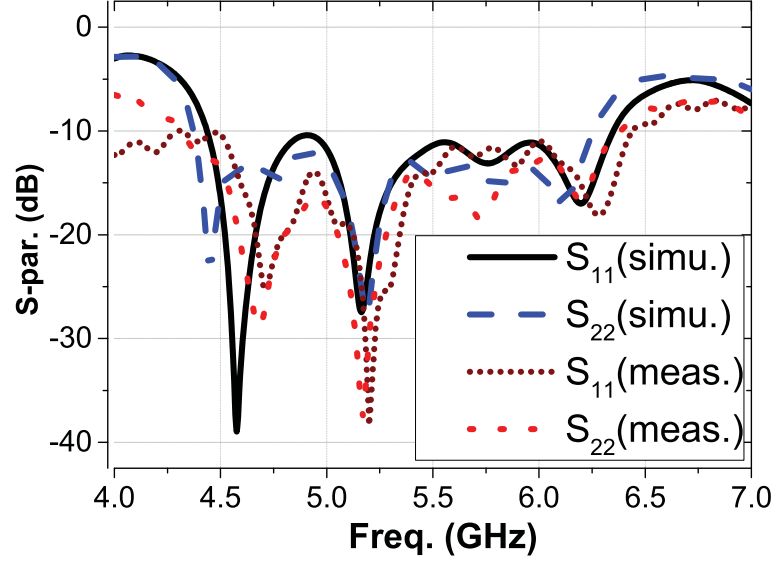


Figure 5.6: Simulated and measured s-parameters of the presented antenna structure (Array + EBG + Etch).

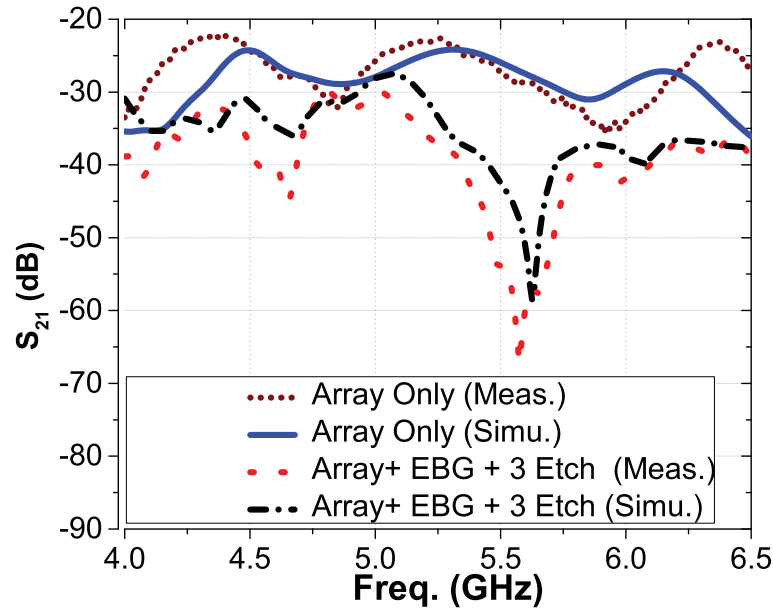


Figure 5.7: Transmission coefficients (simulated and measured) of the antenna array only, and the proposed antenna (Array + EBG + Etch).

### 5.2.2 Effect of the Defective Ground Plane

To further understand the consequence of the defective ground plane, the double ‘F’ etched slots are removed from the ground while the multiresonance EBG structure is still between the two antennas. The effect on isolation enhancement is observed.

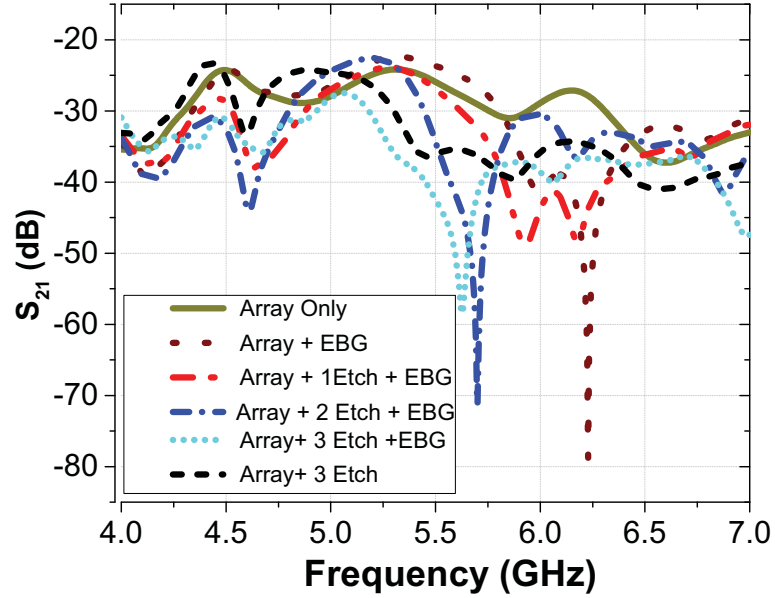


Figure 5.8: Effect of the number of double ‘F’ shaped slots etched from the ground, on the mutual transmission co-efficient characteristics of the proposed antenna array.

From Fig. 5.8, it can be observed that when the EBG is used with the array only excluding the three double ‘F’ etched slots, it can be observed that the isolation is only evident from 5.8 to 6.4 GHz with a very large reduction at 6.22 GHz. When one double ‘F’ etched slot is removed from the ground plane while the multiresonance EBG is left between the two antennas, it is obvious that the current on the surface of the ground plane is further cancelled, enabling an increased isolation from 4 - 4.9 GHz and 5.4 - 6.5 GHz, with the biggest isolation of 21 dB observed around 6.2 GHz. When the second double ‘F’ etched slot is removed, the isolation bandwidth changes

to 4 - 4.8 GHz and 5.3 - 6.4 GHz, with the highest isolation of about 41 dB observed at 5.7 GHz. This is obviously a better improvement in the isolation, although the bandwidth is not necessarily increased. The third double 'F' slot is then etched off from the ground plane at a distance  $S = 8.7$  mm from the second double 'F' etched slot. This widened the isolation bandwidth from 4.2-6.5 GHz with the highest isolation (about 32 dB) observed around 5.6 GHz. However, it should be noted that there is no isolation improvement around 5 GHz. The array antenna with the three 'F' etched slots (with no EBG) is also simulated, and mutual coupling reduction is observed over about 2 GHz bandwidth with only 10 dB maximum isolation improvement as depicted in Fig. 5.8. Therefore, we can undoubtedly conclude that the wideband mutual coupling reduction observed is as a result of the combination of the defective ground plane and the multiresonance EBG structure. This conclusion is true because using the defective ground plane alone can only give a maximum of 10 dB as shown Fig. 5.8. Also, using the multiresonance EBG structure alone between the antenna array can only produce reduction over narrow frequency band of 5.8-6.4 GHz.

Fig. 5.9 shows the effect of changing the distance 'S' (See Fig. 5.3 (b)) on the isolation improvement of the antenna. It is observable that the isolation is gradually improved as 'S' increases from 1.5 to 6.3 mm over a limited bandwidth. The best result of wideband isolation is obtained when  $S = 8.7$  mm although with no improvement at 5 GHz.

To further substantiate the isolation improvement capability of the multiresonance EBG structure with the defective ground plane, the current on the surface of the whole structure when antenna 1 is excited and antenna 2 is terminated by 50-ohm load is

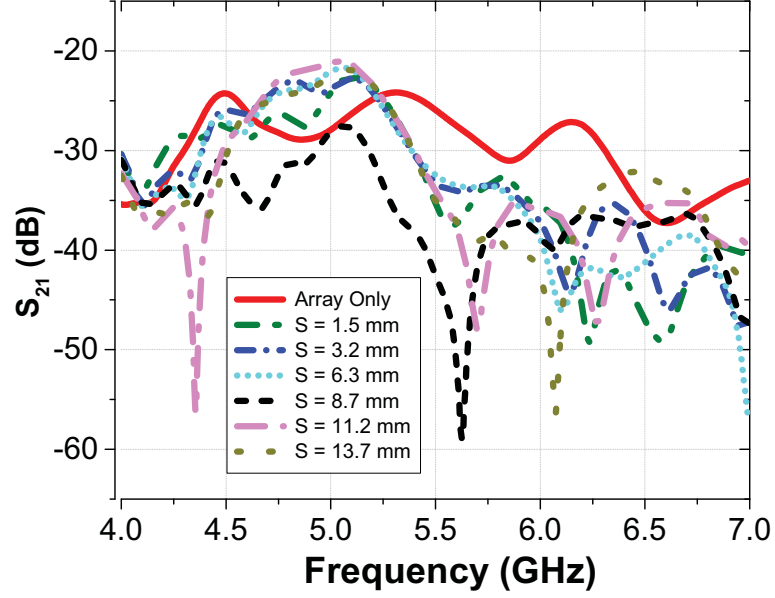


Figure 5.9: Effect of change in the distance 'S' on the transmission coefficients of the proposed antenna array with EBG and defective ground.

shown in Fig. 5.10.

It is obvious that the EBG and defective ground surface together absorb the surface waves emanating from antenna 1 to antenna 2. This will enable most of the interfering waves coming from antenna 1 to antenna 2 to be minimal, hence the mutual coupling reduced.

The measured and simulated radiation patterns of the proposed antenna at 4.4 GHz, 5.7 GHz and 5.9 GHz in both E- and H- planes are shown in Fig. 5.11. It is clear that the radiation pattern is fairly consistent over the entire operating bandwidth. Also, the main beam is slightly tilted as a result of the multiresonance EBG and the defective ground inserted between the two antennas. This can also be a design consideration in some applications like air-defense equipment where focus is paramount. The measurements and simulations results also agree to a good extent.

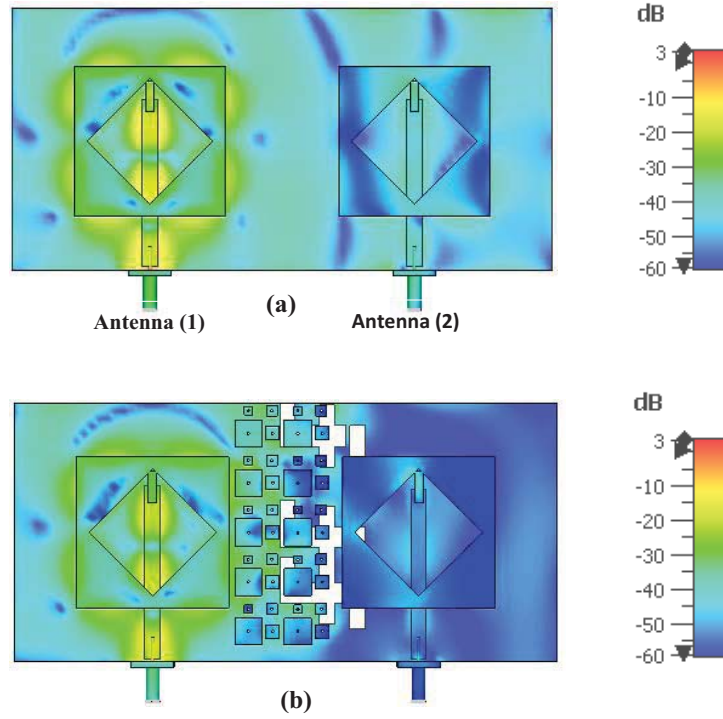


Figure 5.10: Surface current allocation of the antenna structure at 5.3 GHz: (a) Array only (b) Proposed antenna array with EBG and defective ground.

Fig. 5.12 depicts the simulated radiation efficiency and broadside gain of the proposed antenna over the operating bandwidth. The highest efficiency is about 62% and the maximum gain is around 7 dB. The reduced efficiency is as a result of high loss low-cost FR4 substrates used.

Table 6.1 shows this work compared with previous literature. It is obvious that this work exceeds previous works, especially in isolation improvement bandwidth and mutual coupling reduction.

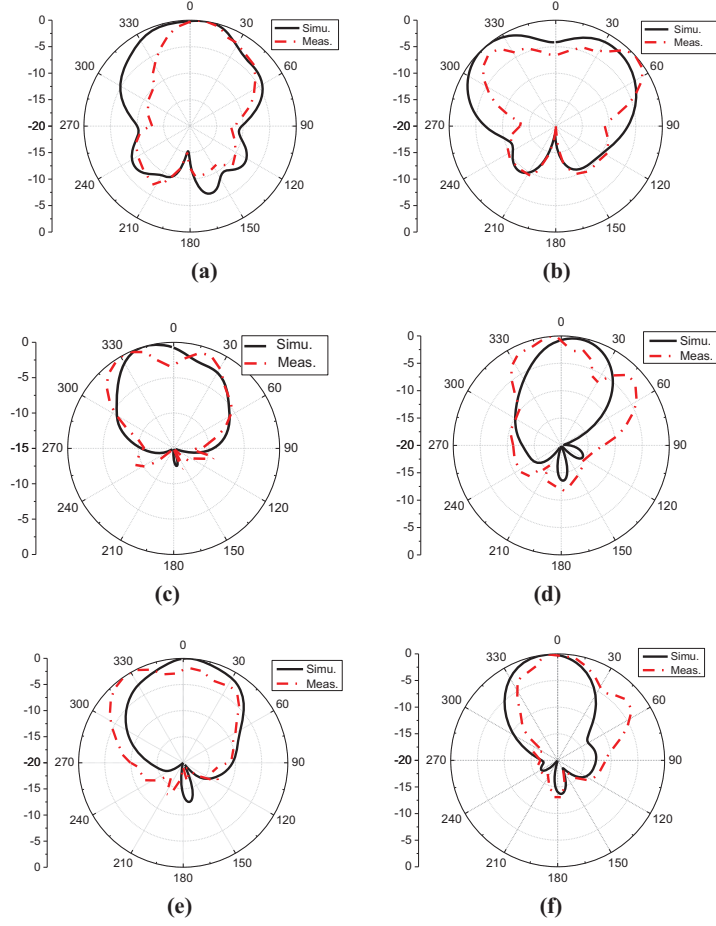


Figure 5.11: Radiation patterns of the proposed antenna array: (a) 4.4 GHz (X-Z Plane). (b) 4.4 GHz (Y-Z Plane) (c) 5.7 GHz (Y-Z Plane)(d) 5.7 GHz (Y-Z Plane) (e) 5.9 GHz (Y-Z Plane)(f) 5.9 GHz (Y-Z Plane)

Table 5.1: Proposed design compared with past literature

| Ref.             | $S_{11}$ BW (%) | $S_{21}$ BW (%) | Max. Mutual Coupling Reduction | Edge to Edge distance             |
|------------------|-----------------|-----------------|--------------------------------|-----------------------------------|
| [50]             | 3.4             | 3.4             | 19.6 dB                        | $0.2\lambda_0$                    |
| [51]             | 4               | 4               | 18 dB                          | $0.22\lambda_0$                   |
| [52]             | 14.5            | 14.5            | 22.7 dB                        | $0.5\lambda_0$                    |
| [53]             | 6.4             | 6.4             | 22 dB                          | $0.16\lambda_0$                   |
| [54]             | 0.5             | 0.5             | 20 dB                          | $0.5\lambda_0$                    |
| [55]             | 7.5             | 7.5             | 20 dB                          | $0.5\lambda_0$                    |
| <b>This work</b> | <b>48</b>       | <b>48</b>       | <b>32 dB</b>                   | <b><math>0.42\lambda_0</math></b> |

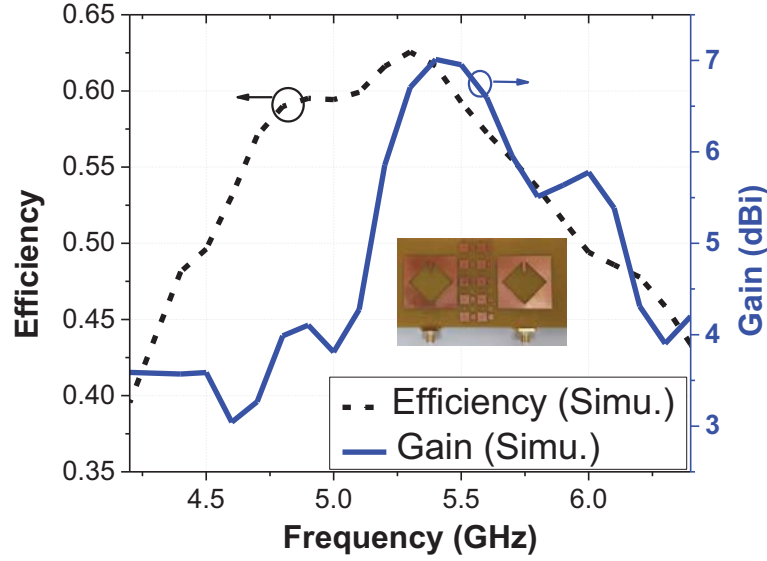


Figure 5.12: Radiation efficiency and gain along broadside direction for the proposed antenna array with EBG and defective ground.

### 5.3 Conclusion

In this chapter, multiresonance EBG structure with defective ground surface is presented to decouple patch antenna array over a large bandwidth in the sub-6 GHz band. An isolation of 10-51 dB is first observed around 5.8-6.4 GHz when only the multiresonance EBG structure is inserted between the patch antenna array. By adding three ‘F’ etched slots to the ground plane, the isolation bandwidth is observed to increase to 4.0 - 6.5 GHz and a measured isolation of 15-32 dB is maintained throughout the operational bandwidth. The simulated and measured far-fields of the antenna are also analyzed, and the results are acceptable. This behavior makes the proposed novel antenna a good candidate for MIMO applications.

## CHAPTER 6

# DUAL-LAYER DUAL-PATCH EBG STRUCTURE FOR ISOLATION ENHANCEMENT IN MIMO ARRAYS

### 6.1 Dual-Layer Dual-Patch EBG (DLDP-EBG)

#### Unit Cell Design

The DLDP-EBG unit cell used in this work exhibits periodic dimension  $L_p \times W_p$  where  $L_p = 13$  mm and  $W_p = 5.032$  mm as shown in Fig. 6.1. It comprises a total of six EBG patches arranged vertically from top to bottom, and the ground. Moving upwards from the ground, first there are two EBG patches of unequal dimensions  $L_1 \times W_p$  where  $L_1 = 6$  mm, and a square-shaped EBG of dimensions  $L_2 \times L_2$  where  $L_2 =$

4.6 mm. The dimensions of the two unequal patches, as well as the diameter of the via are obtained using parametric analysis in CST microwave studio, and the optimum values are employed. The EBG patches are separated by  $g = 0.125$  mm. Moving upwards, the third and fourth EBG patches and the fifth and sixth EBG patches are also separated by  $g$ . Two FR4 substrates red each with a relative permittivity of 4.3, thickness of 1.6 mm, and loss tangent of 0.025 are used between the ground and the first two EBGs, as well as between third, fourth and fifth, sixth EBGs. The EBG patches are located at  $s = 1.1375$  mm away from the substrate edge on both sides. Four vias are used in this unit cell, each extending from top of all the six patches to bottom of each substrate; and are located at the centre of the patches. Each via has 0.6 mm and 0.78 mm as inner and outer diameters, respectively. A glue having the same material properties as the FR4 substrate but with thickness 0.02 mm is used in between the two substrates. This glue is used due to the fabrication requirement. The EBG patches and the ground plane have been made to the same thickness of 0.035 mm.

The dispersion diagram of this DLDP-EBG unit cell is depicted in Fig. 6.2. It is clear from Fig. 6.2 that the bandgap is around 3.38 - 7.40 GHz between modes 1 and 2. This large rejection band is made possible by the combined multiple resonances created by the dual layers of EBG structures. Therefore, the dual layers of this EBG-Unit cells can mitigate surface wave propagation over the rejection band of 3.37-7.40 GHz. The dispersion diagram of the proposed DLDP-EBG unit cell was calculated using the commercial EM software CST Eigenmode Solver, in which the periodic boundary conditions are used on the four side walls of the unit-cell to

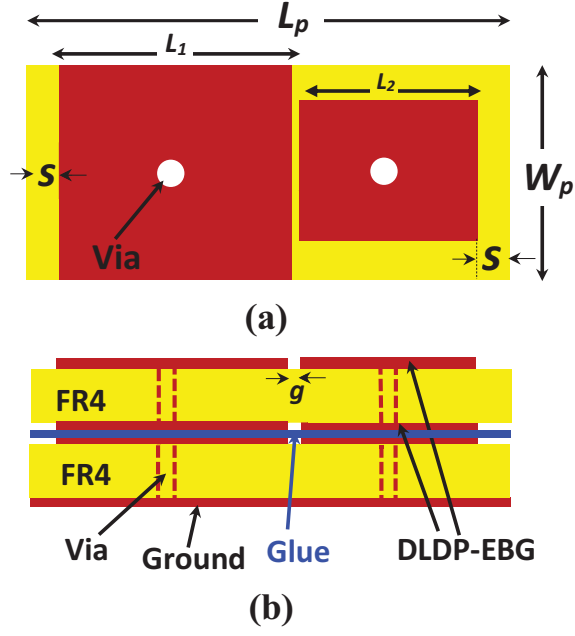


Figure 6.1: Dual-layer dual-patch EBG (DLDP-EBG) unit Cell: (a) Top view, and (b) Side view.

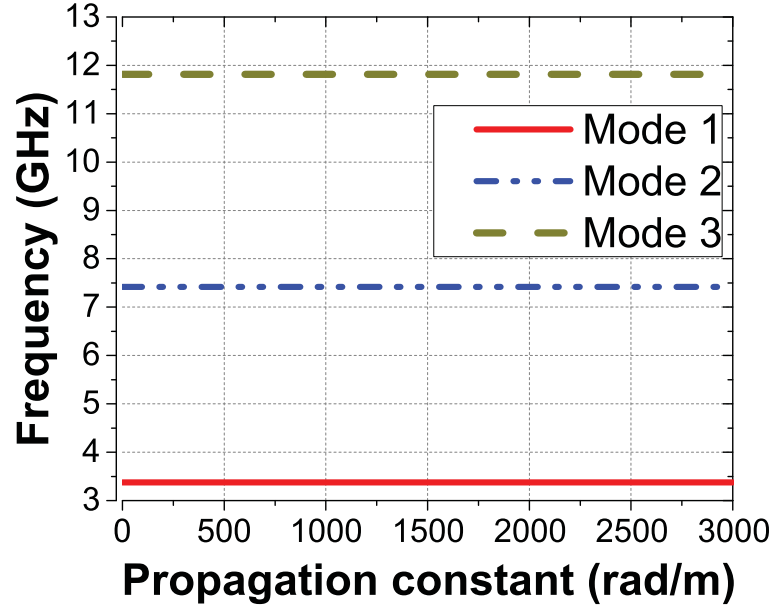


Figure 6.2: Dispersion diagram of the DLDP-EBG unit cell employed to create a wide stop band between 3.37-7.40 GHz.

mimic an infinite two-dimensional structure. The Eigenmode Solver calculates the electromagnetic fields, as well as the frequency bandwidth in the absence of any excitation. Over the frequency range of interest, the unit cell behaves as a high impedance surface, in order to inhibit the propagation of electromagnetic waves. It should be noted that the 3.38 - 7.40 GHz stop-band illustrated by the dispersion diagram assumes that the unit cell is infinite. However, in reality, only a limited number of unit cells can be placed between the MIMO slot antenna array elements to reduce mutual coupling and ECC. Specifically, a finite two-dimensional array of 2x7 unit cells is used in this work to reduce the mutual coupling and ECC over the frequency range of 4.2 - 6.5 GHz as illustrated in the next sections.

### 6.1.1 DLDP-EBG MIMO Slot Array

The whole MIMO slot antenna array measures 57.5 mm x 120.8 mm as shown in Fig. 6.3. The slot antenna array consists of two printed patches on the top surface of two stacked FR4 substrates in order to increase the impedance bandwidth of the antenna. Each printed patch has dimensions of  $e \times c$ , where  $e = 33.54$  mm and  $c = 34$  mm. A square slot of dimensions  $d \times d$ , where  $d = 20$  mm, is etched on the two printed patches and rotated by  $45^\circ$ . A stub of dimensions  $L = 7$  mm x  $W = 1.9$  mm is printed at a distance of 0.542 mm from one end of the slots in order to match the antenna [56]. The MIMO slot antenna is fed by an aperture-coupled stripline (indicated by black dotted line in Fig. 6.3), printed on the bottom substrate. The length of the stripline is 38 mm, and the width is 3.5 mm, with 0.035 mm thickness. The slots are etched on

the patch of the antenna in order to realise the required larger bandwidth in addition to the stacked substrates. The slots help to further increase the current paths (i.e., adding extra effective inductance) in the antenna which can increase the impedance bandwidth. Additionally, the slots can also enable antenna miniaturisation for PCB technology while realising bigger bandwidth. The stubs are added to the slots in order to match the antenna over such a larger impedance bandwidth. The parameters of the stub are also optimized to obtain the best results. The length and width of the feeding strip line are also calculated using microstrip line equations in order to correctly match the impedance of the line to the antenna. The spacing between the two antennas is  $f = 25.2 \text{ mm}$  ( $0.42\lambda_0$ ) ( $\lambda_0$  is the wavelength in free space at the centre frequency of 5 GHz).

The two substrates are separated by 0.09 mm; and a glue of thickness 0.02 mm, with the same dielectric constant as FR4 is used to stick the two substrates together as shown in Fig. 6.3. It should be noted that the via does not extend from the top patch to the ground. Instead, it extends only from the top to bottom of each substrate, just as it is presented in the unit cell. This is implemented in order to allow fabrication as discussed in the previous section. A 2 x 7 array of the DLDP unit cells is arranged between the two MIMO slot antennas. Figure 6.4 shows the top view of the fabricated proposed antenna while Fig. 6.5 shows the measurement setup in an anechoic chamber where one antenna is being fed and the other is terminated by a 50-ohm matched load.

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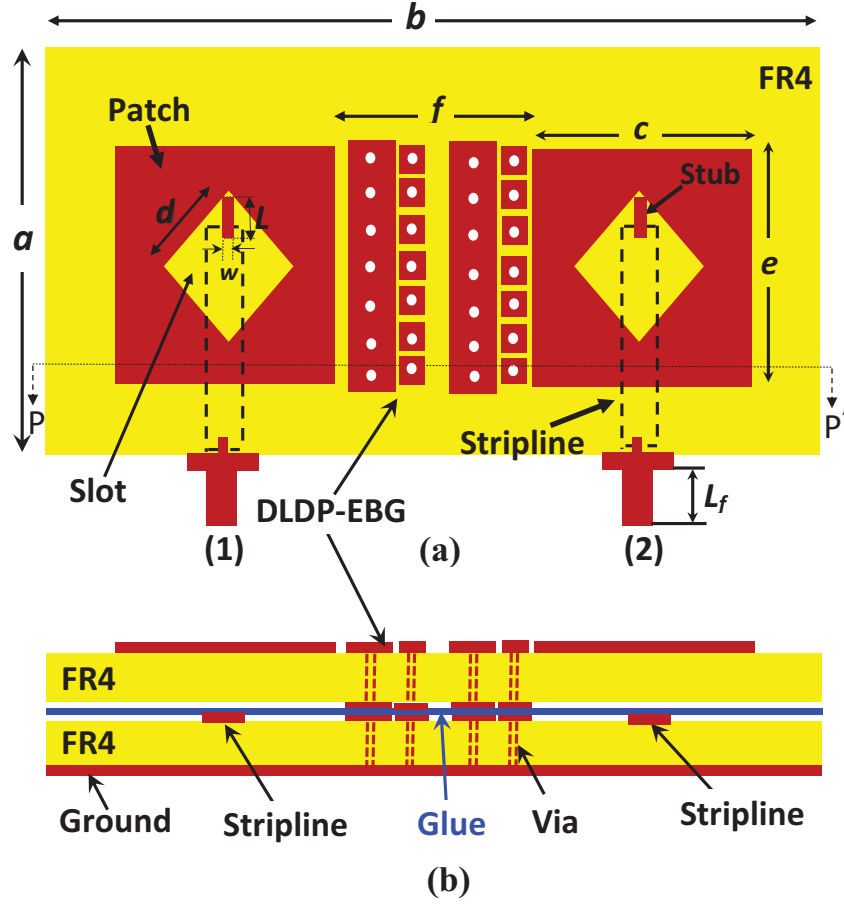


Figure 6.3: DLDP-EBG MIMO antenna (a) Top view (b) Cross section view along the dash line PP'.

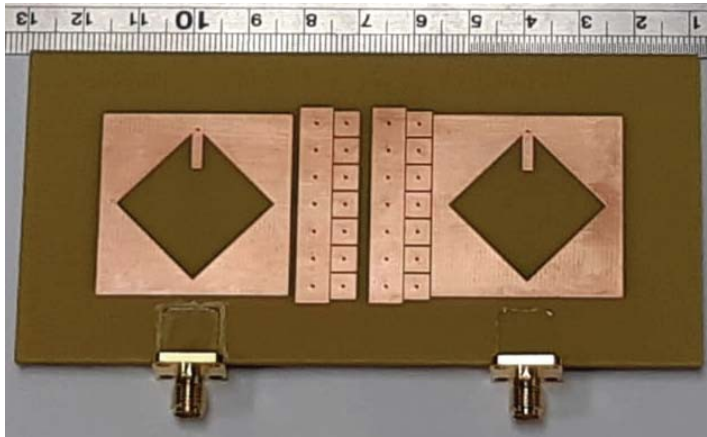


Figure 6.4: Top view of the fabricated DLDP-EBG MIMO antenna

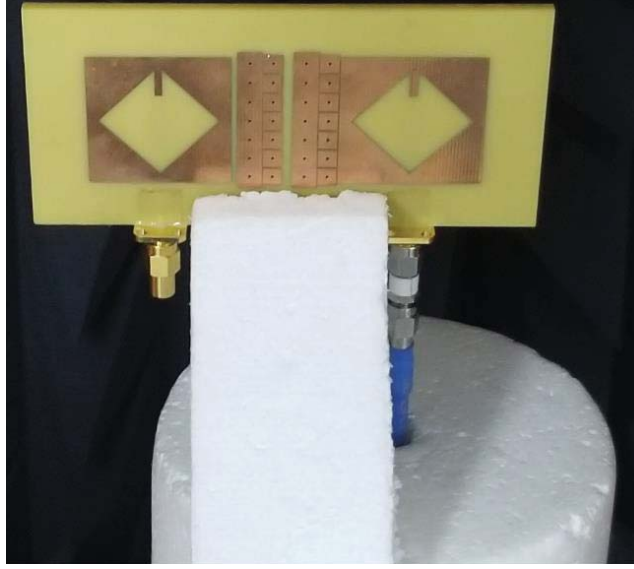


Figure 6.5: Radiation pattern measurement setup of the fabricated DLDP-EBG MIMO antenna.

### 6.1.2 Analysis of Results

This sub-section elaborates on the measured and simulated results of the DLDP-EBG MIMO antenna. Figure 6.6 depicts the simulated and measured red S-parameter magnitudes of the DLDP-EBG MIMO antenna. The measured impedance bandwidth (i.e.,  $S_{11}$ ) covers the bandwidth 4.2-6.5 GHz. It is clear that the simulated and measured S-parameters of the antennas have a strong correlation. The slight discrepancy is linked to the difference in the electrical properties of the FR4 material used in simulation and fabrication. Also, it can be observed that the  $S_{11}$  and  $S_{22}$  of the antenna are not exactly the same due to the unsymmetrical shape of the unit cell used in the DLDP-EBG structure that is composed of two unequal patches. Figure 6.7 compares the simulated and measured isolation of the array only (i.e the MIMO slot patch antenna array only without the DLDP-EBG unit cells between them) and the

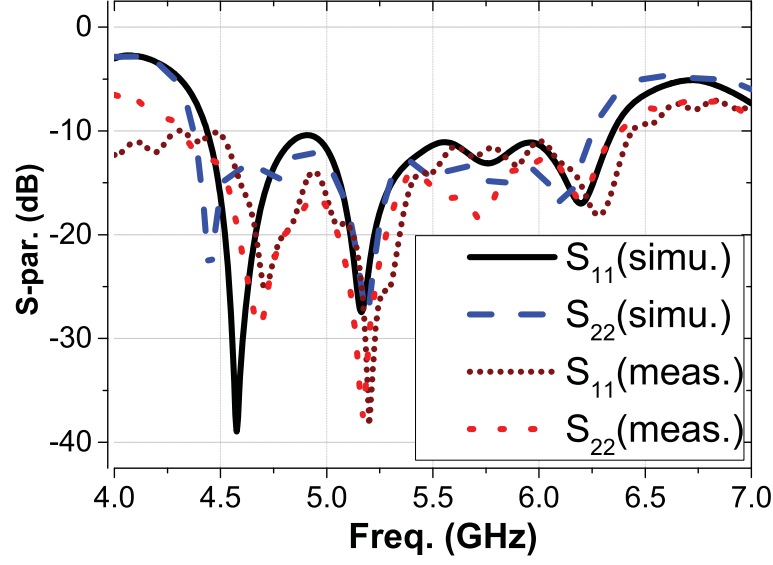


Figure 6.6: Simulated and measured S-parameter magnitudes of the DLDP-EBG MIMO antenna.

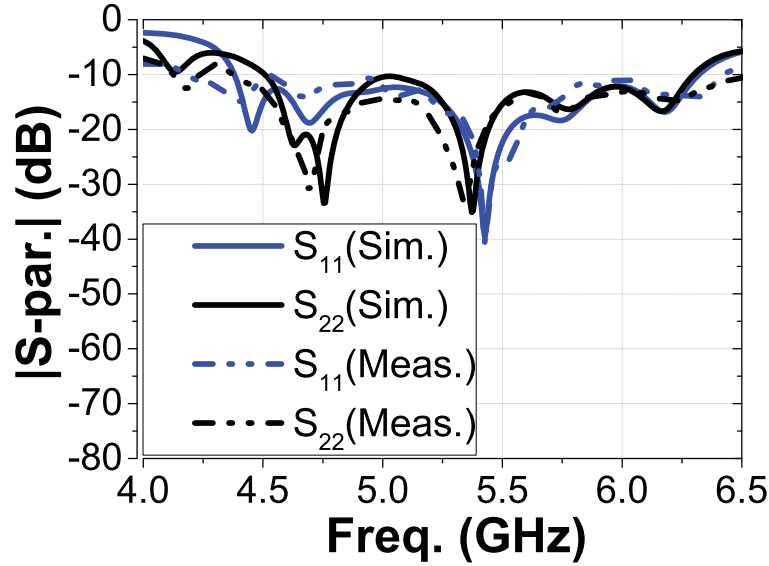


Figure 6.7: Comparison between  $S_{21}$  magnitudes of the array only and proposed DLDP-EBG MIMO antenna array.

DLDP-EBG MIMO antenna. It is obvious that the coupling is reduced by 10-56 dB over the bandwidth of 4-7 GHz, with the highest reduction observed around 5.25 GHz. Also, the simulated and measured  $S_{21}$  magnitudes are closely matched. The disparity between the simulated and measured results in Figure 6.7 is as a result of the predicted differences between the practical electrical properties (permittivity, conductivity and loss tangent) of the FR4 material employed in measurements and the standard values used in CST simulations by default. In fact, the sophisticated two-layer layout of the proposed antenna may be misaligned in the assembly process. This is because the fabrication requirements allow the use of glue with the same material properties as the substrate, but with a thickness of 0.02 mm, as shown in Fig. 6.1. This was required to enable through-hole plating. Hence, simulation results of 56 dB highest reduction at 5.25 GHz is accounted in this work.

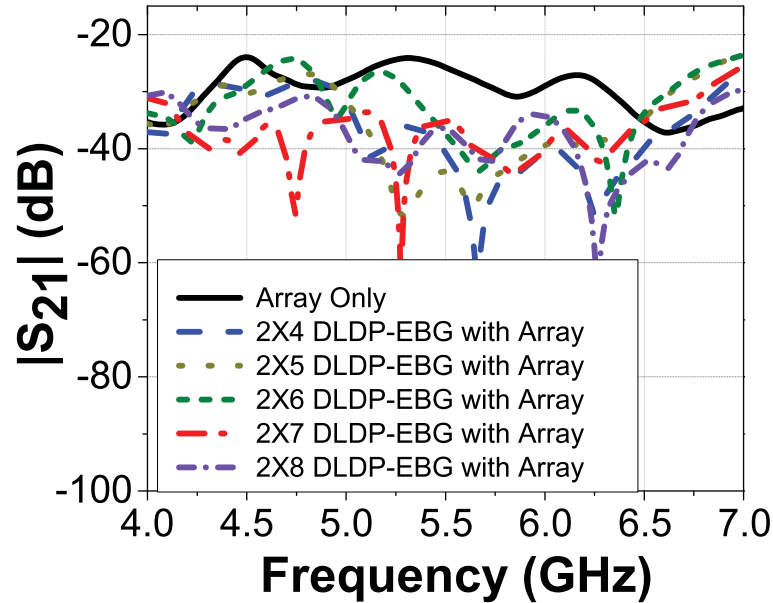


Figure 6.8: Effect of changing the number of DLDP-EBG unit cells on the isolation improvement of the proposed DLDP-EBG MIMO antenna.

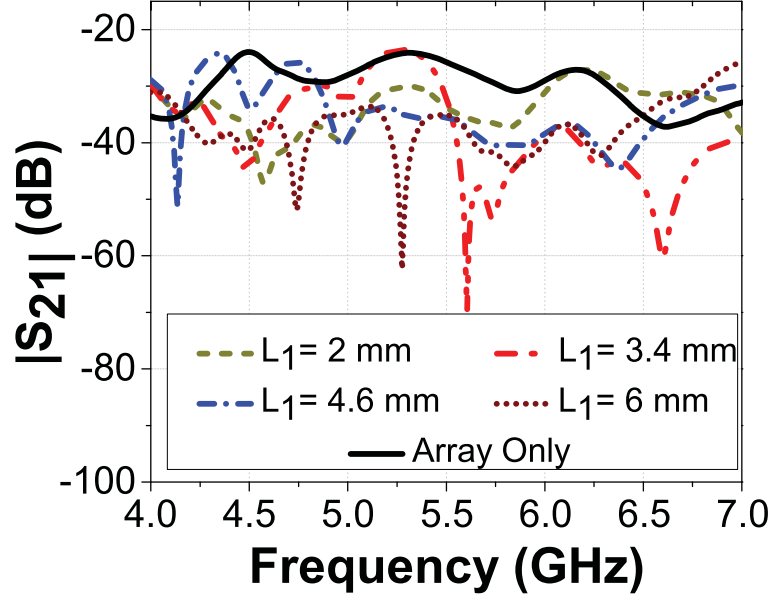


Figure 6.9: Effect of changing the size of the bigger patch of the unit cell size on the isolation improvement of the proposed DLDP-EBG MIMO antenna.

Figure. 6.8 shows the consequences of changing the number of DLDP-EBG unit cells on the isolation characteristics of the antenna. It is evident that the proposed DLDP-EBG array size of  $2 \times 7$  exhibits the best isolation over the 4-7 GHz bandwidth. Choosing any array size of the EBG structure above or below this optimum value will clearly decrease the isolation bandwidth or reduce the isolation between the two antennas. Figure 6.9 depicts the effect of changing  $L_1$ , which is the size of the bigger patch of the unit cell as seen in Fig. 6.1. The best isolation over large bandwidth is observed to be that of the proposed structure (i.e.,  $L_1 = 6$  mm). Using any other length of the unit cell patch will clearly decrease the isolation bandwidth or increase the coupling between the two slot antennas. These results show the significant effect of the unit cell dimensions on the isolation bandwidth and size of the proposed MIMO slot antenna array.

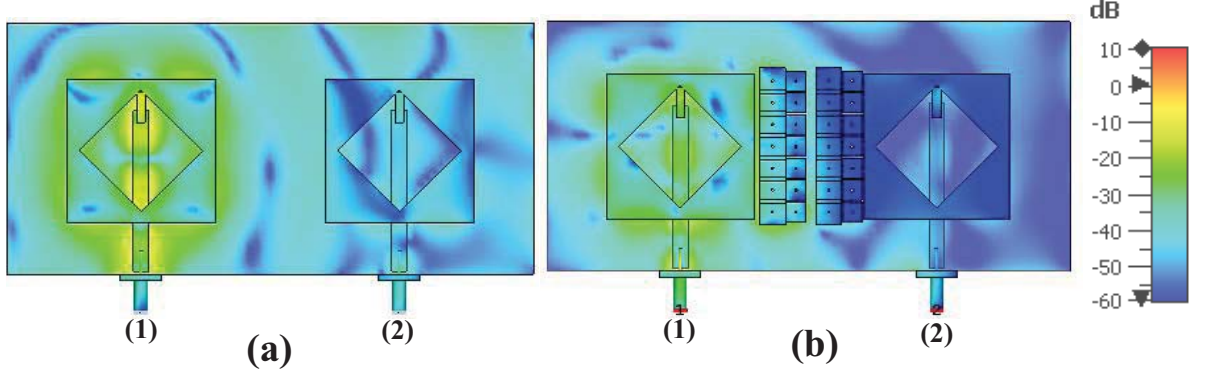


Figure 6.10: Surface current distribution at 5.25 GHz: (a) Array only, and (b) DLDP-EBG MIMO antenna.

The impact of the DLDP-EBG unit cells on isolation enhancement is further analyzed by studying the current distribution on the surface of the array only (with no DLDP-EBG unit cells) when compared with the proposed structure at 5.25 GHz. As evident in Fig. 6.10, the DLDP-EBG unit cells have absorbed most of the current travelling from antenna 1 to antenna 2 when port 1 is excited and port 2 is terminated by a matched load. The current absorption is possible because the DLDP-EBG unit cells act as a high impedance surface at this frequency range. The same scenario will be observed if port 2 is excited and port 1 is terminated by a matched load.

Figure 6.11 depicts the simulated and measured radiation patterns of the proposed DLDP-EBG MIMO antenna and antenna array only (without DLDP-EBG unit cells) at 4.7, 5, 5.2, and 6.4 GHz. The patterns have been measured with Microwave Vision Group (MVG), France [57]. The beams of the two antennas are observed to deflect in different directions with the addition of the DLDP-EBG unit cells at 5, 5.2, and 6.4 GHz. Consequently, the correlation between the two MIMO antennas is decreased as a result of the far-field interference reduction. This property demonstrates the

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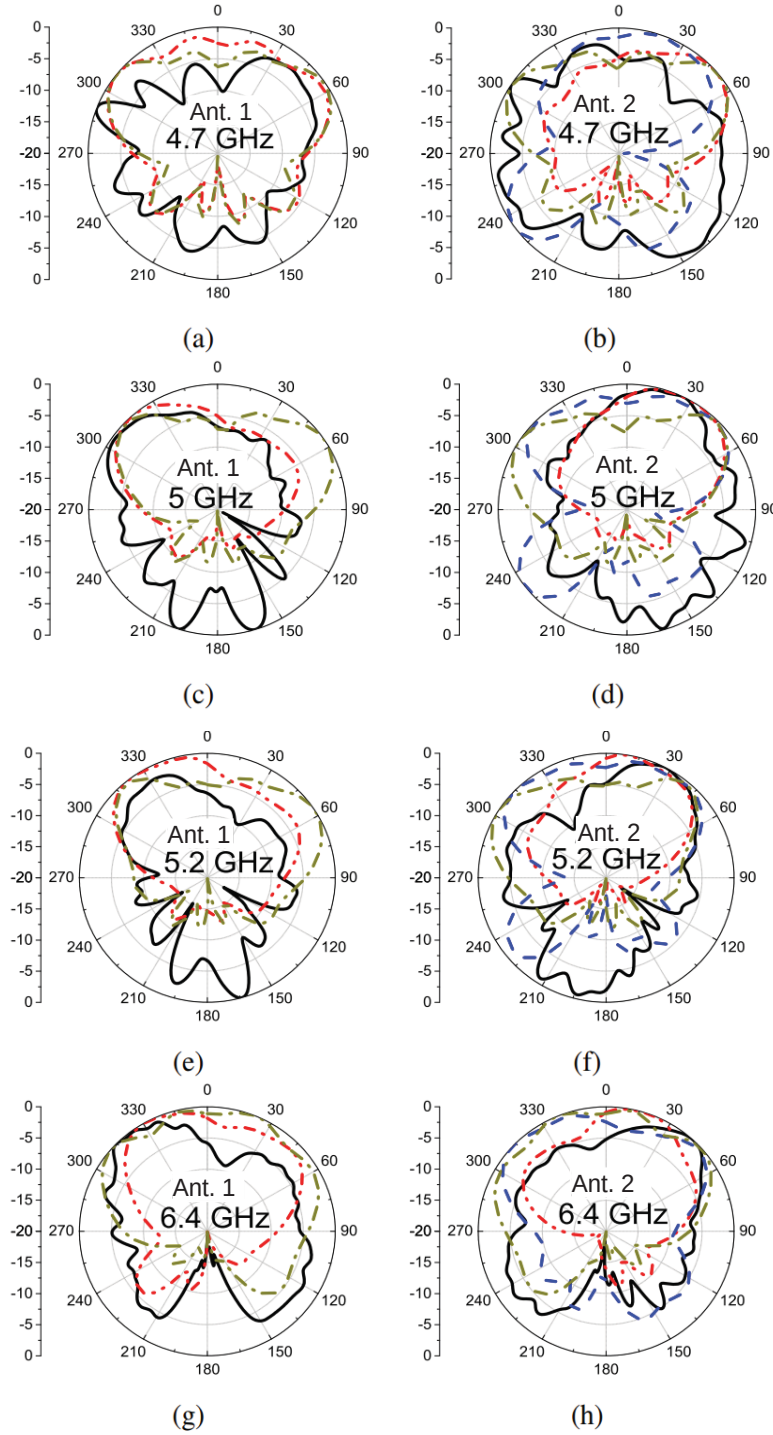


Figure 6.11: Radiation patterns of the DLDP-EBG MIMO antenna compared with the array only; the first and second columns of the figure are the patterns of antenna 1 and antenna 2, respectively. (— Measured DLDP-EBG MIMO antenna (Extended feed), - - - Simulated DLDP-EBG MIMO antenna (short feed), - - - Simulated DLDP-EBG MIMO antenna (Extended feed), - - - Simulated array-only (short feed)). (Extended feed: additional 8 mm feedline length, Short feed: normal SMA connector length).

usefulness and uniqueness of the proposed antenna, because the DLDP-EBG unit cells are able to simultaneously deflect the beams, as well as reduce coupling over a relatively large bandwidth.

However, beam deflection is not conspicuous at 4.7 GHz. Also, a closer look at Fig. 6.5 shows the blue cable used to feed antenna 2 while measuring the patterns. This cable exhibits high loss, leading to spurious radiation, hence, the increase in the backlobes of the measured radiation patterns as seen in Fig. 6.11. To verify this claim, the length of the coaxial feed of antenna 2 was increased by  $L_f = 8$  mm (see Fig. 6.3) in CST simulations to almost match the length of the blue cable used for measurement. This results into increasing the simulated backlobes as seen by the blue dotted curves in Fig. 6.11. These updated results almost match the measured backlobes. On the other hand, the simulated patterns in the upper hemisphere agree considerably with the measured results.

To establish the leverage of the presented DLDP-EBG MIMO antenna over the conventional array only (with neither slot nor stub inserted in its elements), the slotted patch elements in Fig. 6.3 have been replaced with conventional patch as shown in Fig. 6.12. As depicted from Fig. 6.13, the achieved impedance bandwidth is just 2.6 % (5.75-5.9 GHz) compared to the 43 % (4.2-6.5 GHz) of our proposed DLDP-EBG MIMO design. Also, the maximum isolation enhancement that can be achieved when the DLDP-EBG unit cells are inserted between the conventional patch array is about 10 dB within the 5.6-6.1 GHz bandwidth, compared to our proposed DLDP-EBG MIMO array that achieves 56 dB maximum isolation enhancement within 4-7 dB isolation bandwidth.

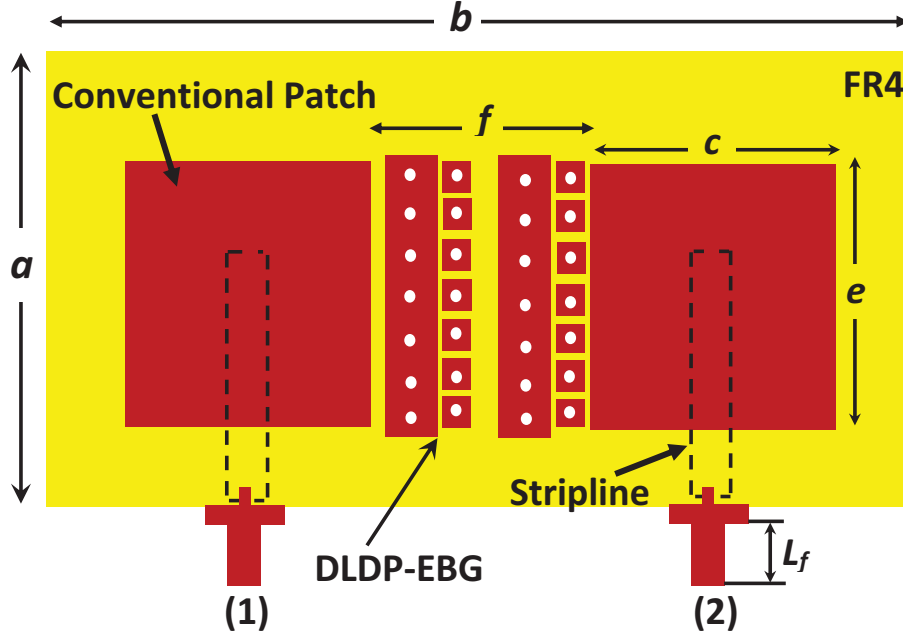


Figure 6.12: Conventional array only (with neither slot nor stub inserted in its elements) integrated with DLDP-EBG unit cells.

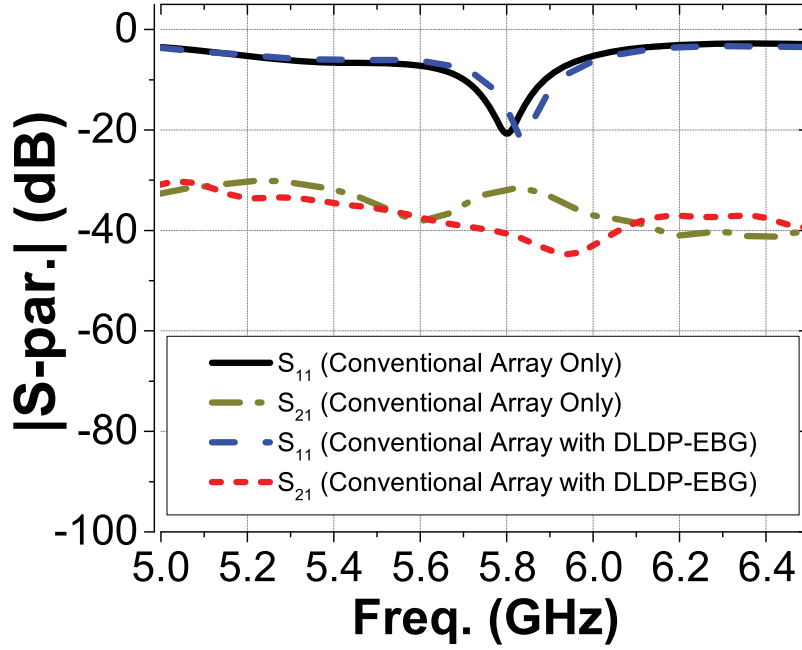


Figure 6.13: Comparison between the simulated S-parameter magnitudes of the conventional array only (with neither slot, stub, nor DLDP-EBG unit cells between its elements) and the same array (with neither slot nor stub inserted in its elements) with DLDP-EBG unit cells.

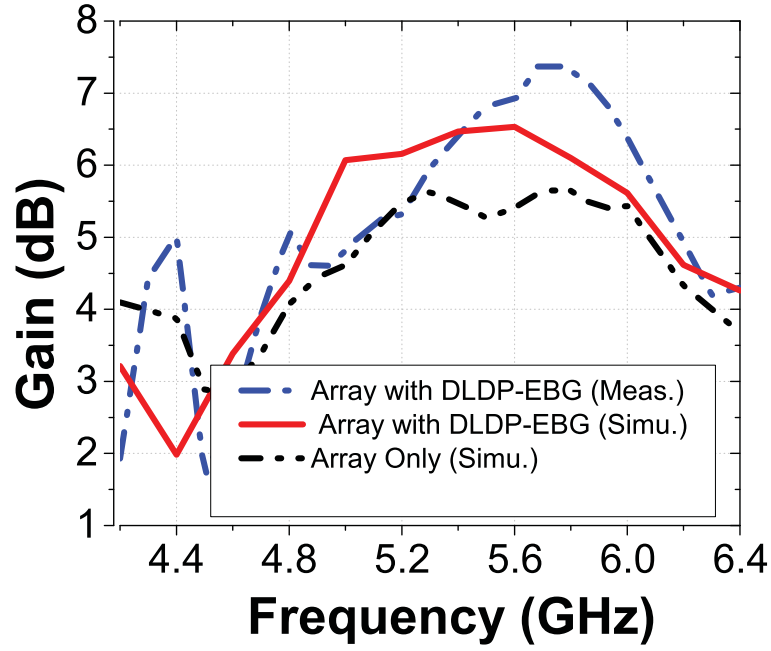


Figure 6.14: Measured and simulated gain of the DLDP-EBG MIMO antenna and the array only.

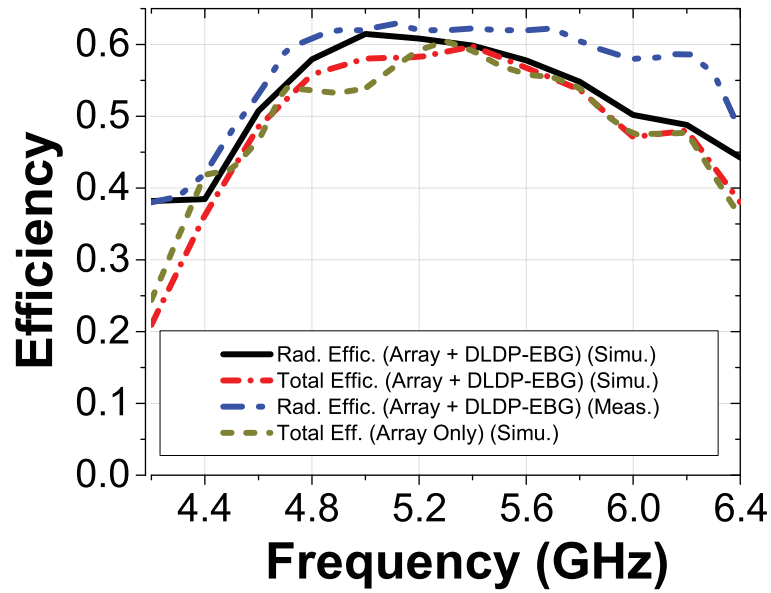


Figure 6.15: Measured and simulated efficiency of the DLDP-EBG MIMO antenna and the array only.

Figure. 6.14 shows that the insertion of the DLDP-EBG unit cells have increased the gain of the slotted antenna array by about 2 dB over that of the array only.

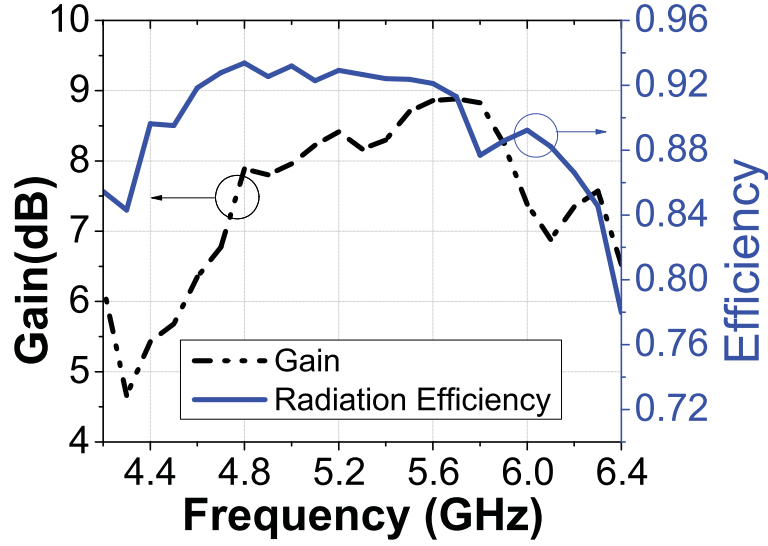


Figure 6.16: Simulated efficiency and gain of the DLDP-EBG MIMO antenna array using the low-loss Rogers TMM4 material as the antenna dual-layer substrate.

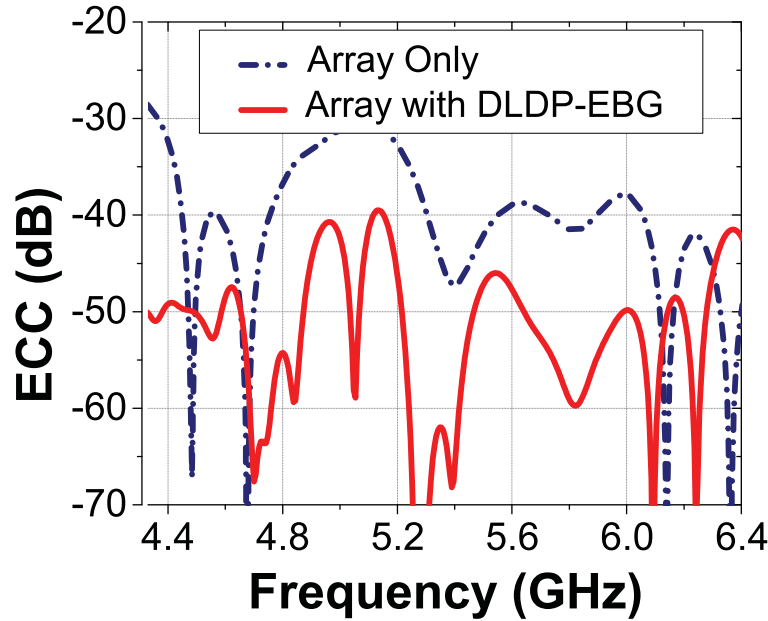


Figure 6.17: ECC of the array only and DLDP-EBG MIMO antenna based on s-parameters.

This improvement is largely attributed to surface wave suppression between the two slot DLDP-EBG MIMO antenna. The two antennas can send and receive signals independently with less disruptions. It can be observed also that the measured gain is

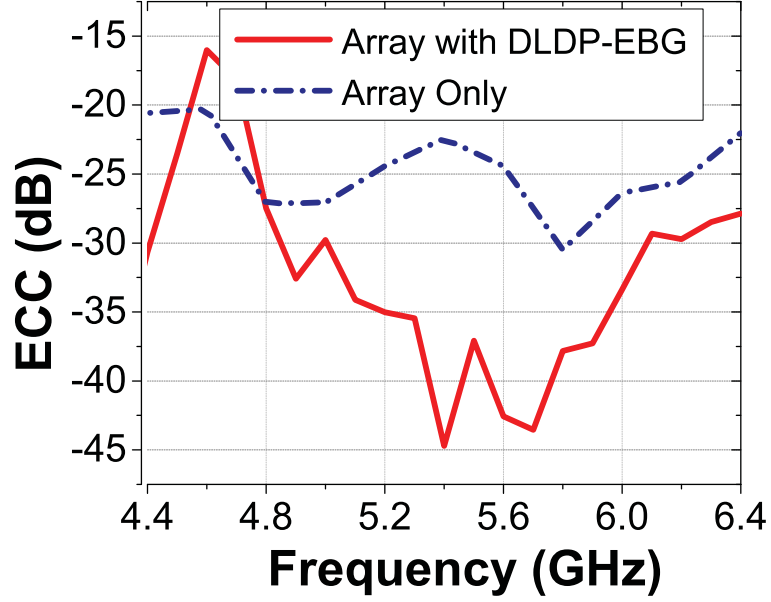


Figure 6.18: ECC of the array only and DLDP-EBG MIMO antenna based on far-field parameters.

about 1 dB higher than the simulated gain mainly due to the alignment process, as well as the difference in the electrical properties of the FR4 material used in simulations and measurements as explained in the previous section. Also, Fig. 6.15 depicts a slight improvement in the total efficiency at 5 GHz when the DLDP-EBG MIMO antenna is compared to the array only; and this is due to the increased gain and surface wave mitigation between the two antennas. The overall efficiency is low because of the high-loss and inexpensive dual-layer FR4 substrate material used. The FR4 material is used as a proof-of-concept. In order to achieve better efficiency and gain, the FR4 substrates were replaced with the low-loss Rogers TMM4 material with dielectric constant of 4.7 and loss tangent of 0.002. As seen from Fig. 6.16, the radiation efficiency and gain have maximum of 94% and 8.9 dBi, respectively, over the entire working bandwidth of the antenna. This proves that by using another low-loss substrate, the efficiency

and gain of the DLDP-EBG MIMO antenna can be significantly improved.

Envelope correlation coefficient (ECC) is one of the essential performance metrics of a MIMO antenna. ECC gives an indication about how independent (i.e., less correlated) the radiation patterns of MIMO antennas are. A Lower ECC value indicates that the radiation patterns of the two antennas do not overlap and, hence, the adjacent MIMO antennas can send and receive independent data packages simultaneously. Moreover, less correlated MIMO antenna systems result in an enhanced data rate without the need for additional bandwidth or transmitted power. The ECC can be measured using port isolation, which is based on S-parameters. This method, however, is acceptable when the efficiency of the antenna is assumed to be ideal [58]. ECC based on S-parameters can be expressed as [59]:

$$ECC = \frac{|S_{11}^* S_{12} + S_{21}^* S_{22}|^2}{|(1 - |S_{11}|^2 - |S_{21}|^2)(1 - |S_{12}|^2 - |S_{22}|^2)|} \quad (6.1)$$

Figure 6.17 reveals the ECC of the two antennas using S-parameters. It is evident from Figure 6.17 that there is correlation reduction of about 10-35 dB across the entire bandwidth of the proposed DLDP-EBG MIMO antenna. Another method for calculating the correlation between two MIMO antennas is using the radiation pattern given by [59]:

$$ECC = \frac{|\iint_{4\pi} [A_1(\theta, \phi) \times A_2(\theta, \phi)] d\Omega|^2}{\iint_{4\pi} |A_1(\theta, \phi)|^2 d\Omega \iint_{4\pi} |A_2(\theta, \phi)|^2 d\Omega} \quad (6.2)$$

where  $A_1(\theta, \phi)$  is the field pattern when antenna 1 is fed and antenna 2 is terminated by a 50  $\Omega$  load. Calculation of ECC using the radiation pattern is more efficient

because it considers the far-fields of the two antennas and is more reliable for lossy antennas [59]. Figure 6.18 shows the ECC of the antennas using 3D radiation pattern. After placing the DLDP-EBG unit cells between the antennas, ECC is reduced by about 5-22 dB across the entire bandwidth. It is widely believed that the reason for the high value of ECC around 4.7 GHz, as seen in Fig. 6.18, is because of the fact that there is no beam tilting from both antennas at this frequency, as shown in the radiation patterns of Fig. 6.11.

From Fig. 6.18, it can be observed that isolation between the two antennas is considerably better before inserting the EBG structure. However, MIMO two-way (i.e., full-duplex) wireless communication systems and asynchronous two-way links (advantageous in networking applications) require ideally no mutual coupling between adjacent antennas in order to ensure concurrent data transmission and reception over the entire frequency band. Hence, the  $S_{21}$  of such systems is required to be between -40 to -70 dB as illustrated in [60]-[62]. Therefore, the proposed DLDP-EBG MIMO antenna can be employed in such systems.

Table 6.1 shows a detailed comparison between the latest work in this area and the proposed design. It is evident that this work substantially outperforms previous work, especially in isolation improvement and  $S_{21}$  isolation bandwidth. Some of the cited work in the table show lower edge-to-edge separation, they however, do not show high impedance and isolation bandwidths compared to our work. Besides, this work also exhibits beam tilting and lower ECC based on far-fields; these achieved enhancements are clearly absent in most of the previous literature.

Table 6.1: Proposed Design Compared with Recent Literature

| Year/Ref.       | $S_{11}$ BW (%) | $S_{21}$ BW (%) | Isolation improvement | Edge to Edge separation           |
|-----------------|-----------------|-----------------|-----------------------|-----------------------------------|
| 2019 [63]       | 2               | 22              | 27-40 dB              | $0.35\lambda_0$                   |
| 2019 [64]       | 16              | 40              | 25 dB                 | $0.27\lambda_0$                   |
| 2018 [65]       | 14.5            | 14.5            | 22.7 dB               | $0.5\lambda_0$                    |
| 2014 [66]       | 5               | 9.7             | 12 dB                 | $0.54\lambda_0$                   |
| 2017 [67]       | 11.6            | 10              | 30 dB                 | $0.50\lambda_0$                   |
| <b>Proposed</b> | <b>43</b>       | <b>55</b>       | <b>10-56 dB</b>       | <b><math>0.42\lambda_0</math></b> |

## 6.2 Conclusion

In this chapter, a novel dual layer dual patch (DLDP) EBG structure that can increase isolation up to 56 dB and reduce correlation coefficient by about 30 dB in the 4-6.5 GHz frequency in a slotted-patch is presented. The DLDP-EBG structure is also observed to deflect the main radiation beams of the antenna, hence, the reduction in envelope correlation coefficient.

## CHAPTER 7

# CONCLUSIONS AND FUTURE WORK

### 7.1 Conclusions

This thesis presents some brief discussions about wireless communications in general and the need for MIMO antennas to increase the data rates and enhance the system link capacity. MIMO antenna performance metrics were also discussed which are very important for any MIMO antenna designer. Then, the mutual coupling was also discussed which is a major problem in MIMO antenna design. Various methods of mitigating mutual coupling were also discussed as well as literature that used the methods.

A novel unit cell that can decouple patch antenna array at the millimeter wave band by about 30 dB within just narrow frequency range was introduced. After that, a wideband antenna design with a novel unit cell that can decouple the antenna elements by 20-31 dB within 48% impedance bandwidth was proposed. Compared

to previous literature, the novel antenna exhibited higher isolation and impedance bandwidths. Another design that can isolate patch antenna array by more than 56 dB was presented with its ability to reduce envelope correlation coefficient as well as deflect the main radiation beams of the antenna.

## **7.2 Future Work**

1. To design and fabricate a novel wideband self-decoupled antenna in the millimeter-wave 5G band.
2. To increase the 3dB gain bandwidth of millimeter-wave 5G antennas over a very large bandwidth.

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