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Mutual Coupling Reduction Using Electromagnetic Band Gap Structures

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This paper introduces a novel technique to reduce mutual interference in antenna arrays. In a conventional antenna array, radiating elements placed on the same ground plane generate strong surface waves, which propagate through the ground plane and cause interference. When these radiating elements are closely spaced, strong mutual coupling occurs. This study involved designing a 1x2 patch antenna array on a FR-4 substrate with an edge-to-edge spacing of 0.2λ. To mitigate the effects of surface waves, a high-impedance surface was created using Electromagnetic Band Gap (EBG) structures. Incorporating Mushroom EBG (MEBG) unit cells with the antenna elements, mutual coupling was reduced by 2.3 dB, making the design suitable for wireless applications at 5.2 GHz. With the support of HFSS software, the proposed antenna array was designed and simulated.
Keywords: Mutual coupling, EBG, Surface waves, MEBG, High-impedance surface, HFSS.

1. Introduction

This Antenna arrays are serving for the applications of longer distance communication demand compared to single antenna. Patch antenna arrays are most commonly used due to having advantages like light weight, easy to manufacture and low profile [1]. However, conventional antenna arrays face challenge of interference. When the radiating elements are placed on a same ground plane, the surface waves are generated between the dielectric and ground plane, propagating through it and causing interference [2]. The distance between the radiating elements affects mutual coupling. Mutual coupling diminishes with increasing distance while decreasing distance results in increased mutual coupling. To meet the demands for modern wireless applications, compact antenna arrays with better performance are required [3].

Several techniques have been developed to mitigate mutual coupling in antenna arrays, such as introducing slots in patch antennas [4], using Defected Ground Structures (DGS) [5], employing meander-line slots [6], and attaching parasitic strips [7]. While these methods reduce mutual coupling, they often introduce drawbacks. For instance, the use of slots may increase back lobe radiation, while the deformation of ground and patch structures can lead to iterative, trial-and-error design processes, complicating the overall design. An alternative, more effective approach involves nullifying surface wave propagation by creating high-impedance surfaces through the periodic arrangement of band-gap structures, known as Electromagnetic Band Gap (EBG) structures.

Electromagnetic Band Gap (EBG) structures are a special class of metamaterials that possess high-impedance surfaces, effectively nullifying surface wave propagation within a specific frequency band. EBG-structured materials with an electromagnetic wave regulation purpose [8]. The phase velocity of electromagnetic plane waves will be directed in the opposite direction when they propagate inside the EBG. The term "backward wave media" (BWM) is thus applied to these LH materials [9]. The integration of such media with traditional dielectrics results in the inversion of Snell's Law and the production of an incident plane wave with negative refraction. It thus possesses simultaneous negative permeability and permittivity. The periodicity of EBG governs the Bragg resonance, also known as the macroscopic resonance. The properties of the element control the microscopic resonance [10]. The construction will create the widest band gap when the two resonances coincide. Because this structure will function as a mirror, no electromagnetic wave will be able to pass through at this stop band.

EBGs have two distinguishing characteristics: first, they can function as Artificial Magnetic Conductors (AMC), reflecting all incident waves with a 0^0-phase shift. This guarantees that the reflected and incident waves are in phase, decreasing back lobe radiation. Second, they produce surfaces with high impedance, which prevent surface waves from propagating [11]. EBG structures can function as lumped elements because of their periodic nature, which has a periodicity less than the wavelength.

EBG structures are 1D,2D and 3D. In this work 2D structures are constructed to stop the surface waves over 3D structures. 2D EBG structures are chosen over 3D EBG structures because they are easier to fabricate and can maintain similar control on wave propagation as 3D structures. Planar EBGs is the kind of EBGs, where there is no via connecting to the ground plane to patch. These are inefficient to suppress the surface waves within range of frequencies. One of the most popular 2D EBG is Mushroom Electromagnetic Band Gap (MEBG).

The incorporation of periodic EBG structures into antenna design has several applications, especially in enhancing antenna performance. EBG structures function as a stop-band filter for surface wave propagation, reducing back lobe radiation while increasing antenna gain [12]. EBG structures effectively limit mutual coupling between many radiating elements by suppressing surface waves on the same ground plane [13].

In this paper, we designed and integrate MEBG cells with a 1×2 patch antenna array. The inclusion of MEBG cells mitigates mutual interference between the antenna elements by nullifying surface wave propagation. As compared to an antenna array without EBG integration, the results show that the mutual coupling in the antenna array with EBG cells is greatly reduced.

2. CONCEPT OF MEBG

There are four components to the MEBG. MEBG consists of four parts. Metallic patch, ground plane, substrate a via (a metallic rod) that connects the ground plane to the patch. The analysis of EBG structures can be carried out using different methods, such as lumped element modeling, the transmission line approach, and full-wave numerical analysis. Among these, lumped element analysis is the most basic approach and easy. EBGs are periodic elements with a period less than the wavelength, which is why they are commonly referred to as lumped elements. In this model, the MEBG behaves like an LC resonant circuit, as shown in Figure 1. Inductance is arisen due to metallic path between ground and substrate through via, while the capacitance is formed between adjacent metallic patches, separated by the dielectric substrate.

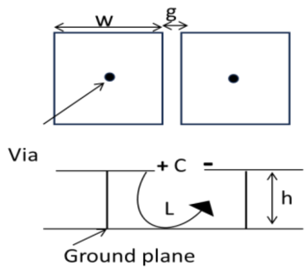

Fig.1. MEBG unit cells with top and side view

These L and C values are depended on geometry of MEBG parameters such as width of the patch (w), gap between two adjacent patches (g), radius of via (r) and dielectric constant of the substrate(εr). The following equations describe the L and C values [14].

$$L = \mu_0 h \quad (1)$$

$$C = \frac{w\epsilon_0(1+\epsilon_r)}{h} \cosh^{-1}\frac{(2w+g)}{g} \quad (2)$$

Depending on the L and C values, distinct stop band forms. Based on these L and C values, the resonant frequency (f_0) and surface impedance (Z) are determined using Eq (1) and (3).

$$f_0 = {}^{1}\!/_{2\pi(\sqrt{LC})} \quad (3)$$

$$Z = \frac{j\omega L}{1-\omega^2 LC} \quad (4)$$

It is evident from Eq. (4) that the EBG structure behaves capacitively at higher frequencies and inductively at lower frequencies. The high impedance caused by the EBG occurs at the resonant frequency f_0, efficiently reducing surface waves and resulting in a frequency band gap [15].

The design of the MEBG unit cell was carried out using HFSS to attain resonance at 5.2 GHz. A periodic boundary condition has been applied to the unit cell to guarantee the periodicity of the MEBG structure. The design parameters for the MEBG unit cell include a square patch width of 8.7 mm, a via radius of 0.2 mm, and a gap of 0.3 mm between the patch and the substrate. The substrate and ground plane dimensions are 9×9×1.6 mm3, 9×9 mm2 respectively.

There are two main methods for analyzing the stop-band characteristics of an EBG structure: the reflection phase and the dispersion diagram. The reflection phase method is easier to analyze. The EBG's reflection phase ranges from π to −π depending on frequency. The image's currents are in phase between π/2 and −π/2, which is similar to how an Artificial Magnetic Conductor (AMC) would behave [16]. A reflection phase of 0^0 corresponds to a high-impedance surface at the resonant frequency, and the band gap is formed within the π/2 to −π/2 range [17].

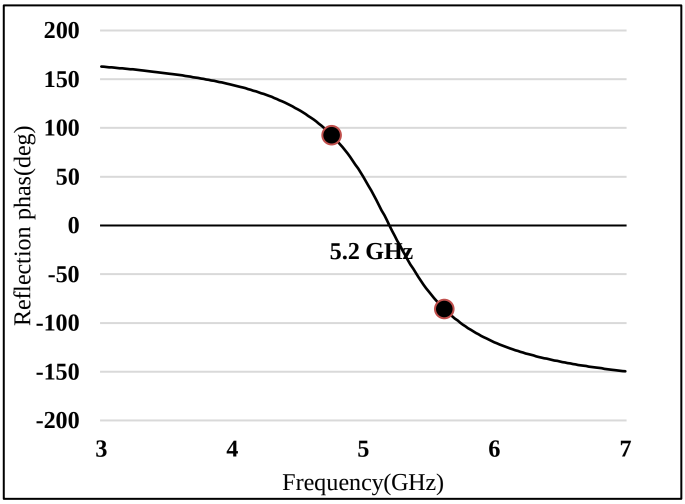

Fig.2. Reflection phase vs frequency for MEBG

From the fig. 2, the MEBG having a 0^0 reflection is at 5.2 GHz. And the band gap of MEBG is exhibit at 4.78-5.65 GHz.

3. CONVENTIONAL ANTENNA ARRAY DESIGN

In this section initially discussed the designing of conventional antenna and then array design is described.

3.1 SINGLE CONVENTIONAL ANTENNA DESIGN

Considering a microstrip patch antenna with rectangular shape built on FR-4 substrate. The feed is given as edge feed technique, where patch is connected to feed line by quarter wave transmission line for impedance matching. The substrate height was fixed at 1.6mm.

The edge-feed method is preferred because of its simplicity and ease of fabrication, though it typically results in higher input impedance, which is reduced through matching the 50-ohm impedance of the feed line to the quarter-wave transformer. This technique helps to reduce reflections and improve power transfer efficiency. The dimensions of the patch are determined based on the desired resonant frequency using the following standard equations for a rectangular microstrip patch antenna, considering factors like the effective dielectric constant and fringing effects [18].

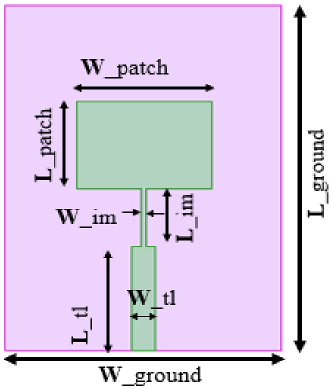

Fig.3. Layout of conventional single rectangular patch antenna

The arrangement of design for the patch antenna is displayed in fig. 3 and design parameters are listed in table.1.

$$\mathrm{W\_patch} = \frac{c}{2f}\sqrt{\frac{2}{\epsilon_r+1}} \quad (5)$$

$$\mathrm{L\_patch} = \frac{c}{2f\sqrt{\epsilon_{reff}}} - 2*0.412h\frac{(\epsilon_{reff}+0.3)(\frac{W\_patch}{h}+0.264)}{(\epsilon_{reff}-0.258)(\frac{W\_patch}{h}+0.8)} \quad (6)$$

Where f and c represent the operating frequency and speed of light. Here ϵ_r is dielectric constant and h is the height of substrate. ϵ_{reff} is effective permittivity and calculated from Eq. (7). Table 1 contains a list of the conventional antenna parameters.

$$\epsilon_{reff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}(1+12h/w)^{-1/2} \quad (7)$$

Table.1. Dimensions of conventional antenna

Parameters	Dimensions (mm*mm)
Substrate	35.9*58.9
Ground	35.9*58.9
Patch	12.56 *17.56
L_im*W_im	7.29*0.723
L_tl*W_tl	14.59*3.059

3.2 CONVENTIONAL ANTENNA ARRAY DESIGN

A conventional antenna array consists of two radiating elements arranged in an H-plane form. Each patch antenna has its own feeding mechanism, which ensures that both elements are activated independently. The substrate for this 1x2 patch antenna array is FR-4, with a thickness of 1.6 mm. To accommodate the two radiating elements, the dimensions of the ground plane are modified from the single antenna design to suit the array configuration. The distance between the two patches is carefully maintained at 0.2λ, which corresponds to 12.4 mm. The array layout is shown in fig.4.

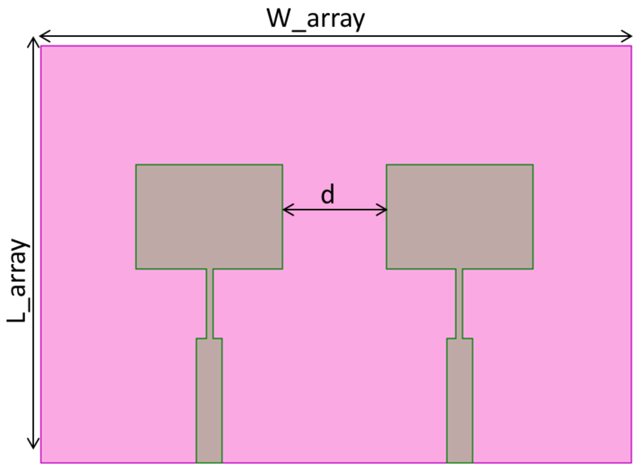

Fig.4. Layout of 1x2 conventional antenna array

The key design considerations, such as element spacing, substrate parameters, and feed mechanism, are summarized in Table 2.

Table.2. Dimensions of conventional antenna

Specifications	Dimensions (mm*mm)
W_array	50
L_array	70.8
W_patch	17.56
L_Patch	12.56
d	12.4

3.3 PROPOSED ANTENNA ARRAY DESIGN

The proposed antenna array is designed on the same ground plane as the conventional antenna array with the integration of MEBG unit cells to reduce the mutual coupling. The uniform arrangement is maintained by keeping the radiating elements spaced the same as in a conventional array. Both the proposed and conventional arrays share equal dimensions, and the proposed antenna is shown in Figure 6.

In the suggested antenna array, MEBG unit cells are placed around the radiating elements with a spacing of 1 mm from the antenna edges. Furthermore, MEBG unit cells are inserted between the radiating elements to create a high-impedance surface, which helps in nullifying surface wave propagation. The distance between the MEBG unit cells at the center is varied in different configurations, and the resulting mutual coupling is observed and analyzed.

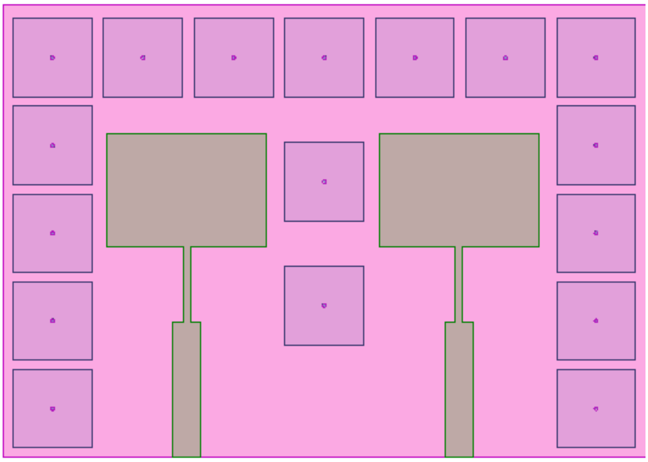

Fig.5. Layout of 1x2 proposed antenna array

4 RESULTS AND DISCUSSION

The proposed antenna array was simulated using HFSS software to evaluate its performance. The key performance metrics are presented through the simulation results, with particular emphasis on mutual coupling between the radiating elements. Mutual coupling occurs when one of the radiating elements is excited by an input signal, and part of the radiated field couples into the adjacent radiating element, leading to interference and degraded performance.

The scattering parameters (S-parameters) are used to assess this effect. The parameter S12 quantifies the mutual coupling at the operating frequency, indicating how much power is transferred from one element to the other. A lower S12 value represents reduced mutual coupling, which is desirable for improved array performance. In contrast, S11 and S22 describe the return loss, or reflection coefficient, at the resonant frequency for the two antenna elements, indicating how well each element is matched to its input port.

From Fig. 7, the S-parameters for both conventional and proposed antenna arrays were simulated and analyzed. The return loss and mutual coupling for both configurations are obtained as 23.3 dB, -19.7 dB at 5.1 GHz, and 30.7 dB, -22.0 dB at 5.2 GHz, respectively. This shows a 7 dB increment in return loss and 2.3 dB reduction in mutual coupling. The integration of MEBG unit cells with the conventional structure significantly enhances the performance of the proposed antenna array.

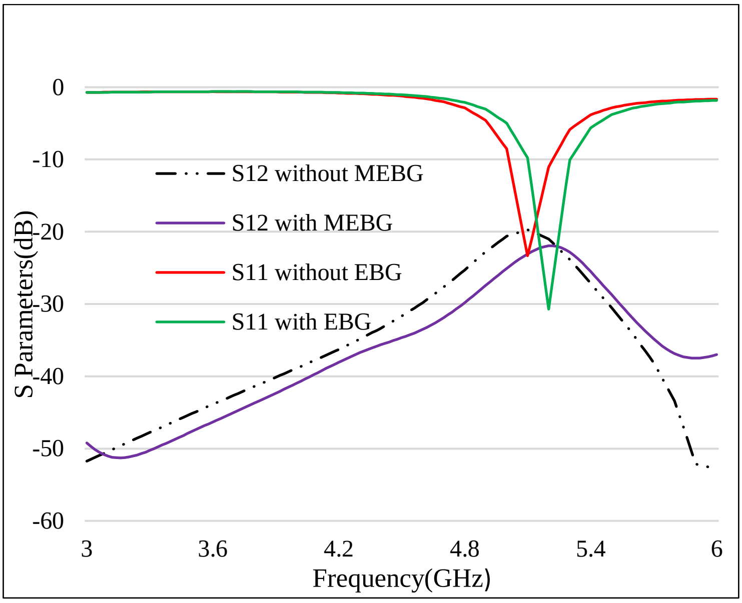

Fig.6. Scattering parameters of conventional and proposed antenna array

Figs. 8 and 9 illustrate the E-plane and H-plane radiation patterns for both the conventional and the newly designed antenna arrays. It is clear that the proposed array shows a reduction in back lobe radiation compared to the traditional design. The gain achieved by the new array is 5.5 dB. Moreover, while the antenna elements are arranged in an H-plane configuration, the presence of EBG unit cells does not impact the H-plane radiation pattern.

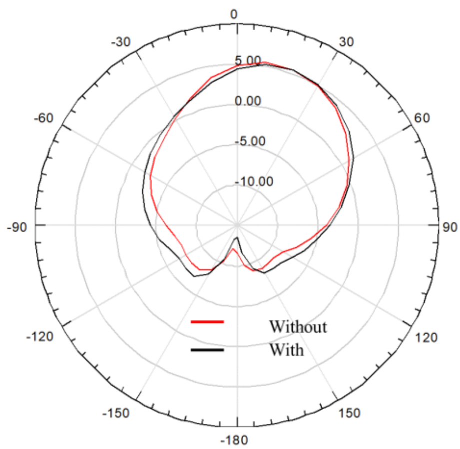

Fig.7. E plane radiation pattern with and without EBG antenna array

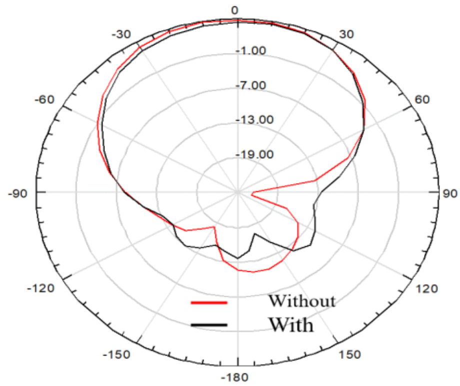

Fig.8. H plane radiation pattern with and without EBG antenna array

As the gap between MEBG unit cells, placed at the centre of antenna elements, is varied as 1mm, 2mm, 3mm, and 5mm, there is variation in mutual coupling. Variation of level of mutual coupling with respect to gap between MEBG unit cells is shown in Fig. 10. At resonating frequency 5.2 GHz, the level of mutual coupling is observed as -21.5 dB, -21.7 dB, -21.6 dB, and -22 dB, respectively. It is evident that as the gap increases, there is a reduction in mutual coupling.

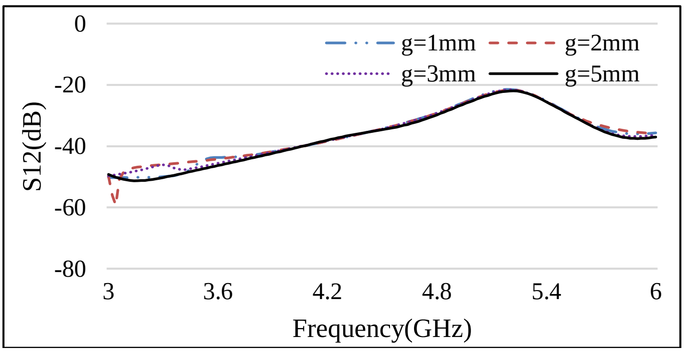

Fig.9. Parametric variation in gap between MEBG unit cells

5 CONCLUSION

This paper introduces a method to minimize mutual coupling in antenna arrays. The spacing between antenna elements within an array plays a crucial role in influencing the extent of mutual coupling. A closely spaced ($d = 0.2\lambda$) two-element antenna array was designed, which resulted in a mutual coupling of -19.7 dB. To mitigate this interference, the conventional antenna array was integrated with MEBG unit cells on the same ground plane. The proposed antenna array reduced mutual coupling to -22 dB, achieving a 2.3 dB reduction in interference at 5.2 GHz. This compact antenna array can be utilized in modern wireless applications.

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