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COMPACT EBG STRUCTURE FOR ALLEVIATING MUTUAL COUPLING BETWEEN PATCH ANTENNA ARRAY ELEMENTS

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Abstract—The periodic structure like electromagnetic band gap (EBG) is a hot research topic in the academia and RF-microwave industry due to their extraordinary surface wave suppression property. This study involved in designing a compact uni-planar type EBG structure for a 2.4 GHz resonant frequency band. Double folded bend metallic connecting lines are successfully utilized to realize a low frequency structure while a size reduction of 61% is achieved compared to the theoretically calculated size. From the transmission response, the surface wave band gap (SWBG) is found to be 1.2 GHz (1.91–3.11 GHz) whereas the artificial magnetic conductor (AMC) characteristic is observed at 3.3 GHz. The FEM based EM simulator HFSS is used to characterize the EBG structure. The SWBG property is utilized for alleviation of mutual coupling between elements of a microstrip antenna array. A 2×5 EBG lattice is inserted between the E-plane coupled array which reduced the coupling level by 17 dB without any adverse effect on the radiation performances.

1. INTRODUCTION

The recent advancement in the research on metamaterials and electromagnetic band gap materials is continuously stimulating new antenna applications and new technological solutions [1–5]. Microstrip antennas are very attractive from the perspective of designing compact and cost effective wireless communication systems. In contrast to the merits such as light weight, low profile, ease of integration with

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printed circuits, microstrip antennas suffers from excitation of surface waves, poor radiation efficiency and low gain [6]. To overcome these limitations, various techniques such as thin-high permittivity or thick-low permittivity substrate, stacked configurations, ferrite composition and combinations of slot-slit etc. have been introduced [7–9]. On the other hand, multiple antennas are configured as an array, for high gain applications, beamforming or diversity purposes [10–13], where compactness is considered as an important issue. The surface wave propagation is a major problem with microstrip antenna which leads to worse performance of the antenna and even for arrays. The excitation of surface waves instigates mutual coupling between the adjacent elements of an antenna array and it turns into worse at higher operating frequencies with increasing substrate permittivities and thicknesses [14, 15]. The coupling depends on the element separation and their orientation which causes scan blindness and forms blind spots. By increasing the element separation, mutual coupling can be lessened, but this would introduce undesirable grating lobes [16–18].

To overcome the problem of mutual coupling, some conventional structures have been studied in the literature such as cavity backing, substrate removal, and defected ground structures (DGS) [19–24]. These approaches are associated with fabrication complexities since the cavity making with PEC wall or the partial substrate removal required precise micro-machining techniques and there are chances of performance degradation. On the other hand, the DGS increases back radiation from an antenna and it can alleviate the mutual coupling but that is less than the cavity backing case [25]. Thus, among these methods, the EBG structures are found to be the most effective and a comparison is shown in [19] which demonstrates the unique capability of the EBG structures. Considering the surface wave blocking ability in a particular frequency band, various types of EBG configurations have been investigated with microstrip antenna arrays in the literature [19, 23, 24, 26]. Compared to the other configurations, it is revealed that EBG structures can significantly reduce the mutual coupling effect between radiating elements of an antenna array [19, 20]. EBG structures are a periodical configuration of metallic or dielectric elements that exhibit band stop or band gap characteristics [27, 28]. Among the different planar EBG configurations such as mushroom shape, fork-like shape, spiral shape etc. [21, 29, 30], the uni-planar types are the most attractive and suitable for completely planar RF and microwave systems [31]. The uni-planar EBG structures has drawn great attention from the researchers due to their design and fabrication easiness and exclusion of the grounding vias or plated-through-holes [18].

Among the various attempts, the mutual coupling is reduced by 8.53 dB at 5.4 GHz with a fork-like planar EBG [29], 10 dB at 5.8 GHz with a mushroom-EBG matrix [17], 4 dB at 5.6 GHz with a dumbbell-shape structure [32] and 10 dB with a C-shaped EBG array [33]. Reported other studies showed mutual coupling reduction by −13 dB at 4.18 GHz [16] and 20.5 dB at 12.2 GHz with two different uni-planar EBG arrays [34], and approximately 4 dB at 5.2 GHz with different shapes (H, I, X etc.) of planar designs [35]. A 17 dB reduction of mutual coupling is noticed with a dual-layer configuration [36] while it is only 10 dB for a multi-layer [24] and 13 dB for a single layer [16] configuration. In [37], a dual band split-ring slotted (SRS)-EBG structure is proposed which reduced the mutual coupling by 20 dB at 13 GHz.

In this paper, we propose a novel compact double folded bend uni-planar EBG configuration with a band gap centered at 2.4 GHz. The band gap informations are calculated from their transmission responses and reflection phase characteristics. By inserting this structure between elements of a 2.4 GHz patch antenna array, the coupling reduction ability is investigated. Regardless of smaller size, inclusion of the proposed EBG improves the isolation and effectiveness of the array design.

2. EBG GEOMETRY & BANDGAP CHARACTERIZATION

The attractive property of an EBG structure is the stop band (band gap) response for a particular frequency band. Because the periodic dimension of an EBG structure must be about half-wavelength of

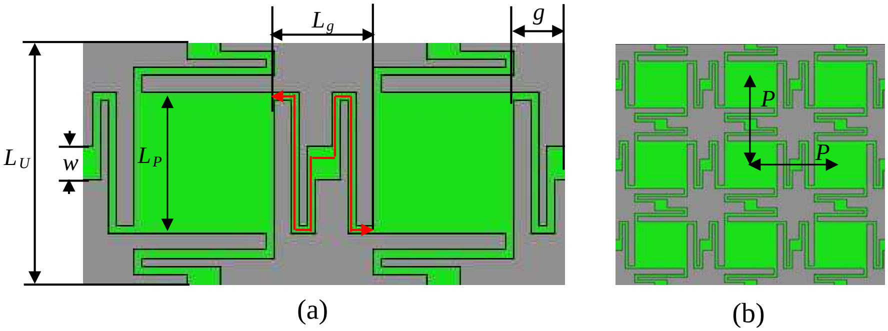


Figure 1. Geometry of the proposed EBG structure, (a) cell dimensions, and (b) a 3 × 3 array of EBG cells.

the band gap, their use in low frequency applications is restricted by the physical size. According to the Equations (1) and (2), for a resonant frequency of 2.4 GHz, the resonant wavelength (λ_0) and EBG unit cell length (λ_{EBG}) would be 74.7 mm and 37.35 mm, respectively, considering an FR4 substrate (relative permittivity, $\varepsilon_r = 4.6$ and thickness, $h = 1.6\,\mathrm{mm}$). As seen in the Equations (3) and (4), the resonance and the width of the band gap are generally determined by the inductive and capacitive effects that arises from the patterned metallic surface. A conventional EBG surface is capacitive itself between the adjacent metallic components, thus double folded bend metallic connecting lines are introduced into our design to obtain lower resonant stop band. The proposed EBG geometry is depicted in Figure 1, where the electric current path is lengthened by the double folded bends and the magnetic current path is extended by the longer edge-coupling effect. Thus the effective inductance and capacitance are increased which helps to shift the energy band-gap to lower frequency. The required unit cell dimension (λ_{EBG}) and patch length (L_P) for 2.4 GHz resonance is reduced from $0.5\lambda_0$ (37.35 mm) to $0.19\lambda_0$ (14.5 mm) and $0.11\lambda_0$ (8.5 mm) respectively. This size reduction increased its structural fitness for compact devices and the possibility to accommodate more EBG cells in a limited area. The EBG design attributes can be computed as follows [21, 38]:

$$f_r = \frac{c}{\lambda_0\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{1}$$

$$\lambda_{EBG} = \frac{\lambda_0}{2} \tag{2}$$

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{3}$$

$$BW = \frac{1}{\eta}\sqrt{\frac{L}{C}} \tag{4}$$

where c is the speed of light in free space, ε_r the equivalent dielectric constant, λ_{EBG} the wavelength of metallic component periodic dimension, λ_0 the wavelength of light in free space, f_r the resonant frequency, and η is the free space wave impedance.

After calculating some basic dimensions from the above equations, the geometry of periodic pattern are optimized utilizing the FEM (finite element method) based full-wave electromagnetic solver Ansoft's HFSS. The optimized design attributes are tabulated in Table 1. A 3×3 EBG structure is investigated and its simulated and measured transmission behaviors are illustrated in Figure 3, whereas Figure 2 shows photographs of the fabricated prototype. The surface wave

Table 1. Design attributes of the double folded bend EBG configuration.

Parameters	Values (mm)	Parameters	Values (mm)
L_P	8.5	L_g	24.5
L_U	14.5	g	3
w	2	P	14.5

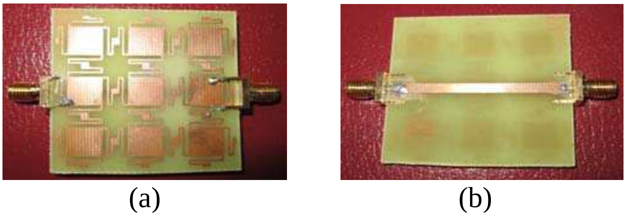


Figure 2. Fabricated EBG structure to measure the band gap response, (a) front, and (b) back view.

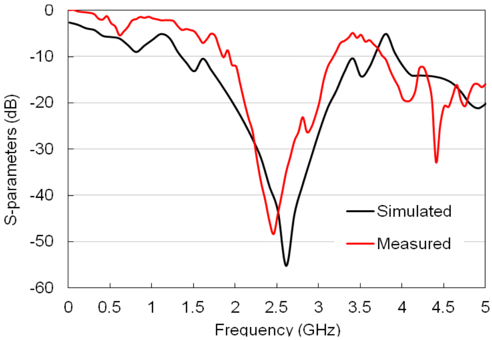


Figure 3. Transmission responses of the proposed EBG structure, (a) simulated, and (b) measured.

band gap (SWBG) is characterized by using the periodic structure as the ground plane for a suspended microstrip transmission line [37, 39]. In contrast to the classical coplanar microstrip method and monopole method, the suspended structure shows the strong coupling nature and eliminates the effect of other parasitic propagation modes, which helps to achieve the band gap characteristics more obviously [40]. The thin microstrip has a 50-Ω characteristic impedance and connected to two excitation ports at the ends of the line. At the −20 dB attenuation level, the simulated and measured bandwidth of the stop bands are 1.2 GHz (1.91–3.11 GHz) and 0.85 GHz (2.1–2.95 GHz), respectively. With respect to the simulated bandwidth (47.80%), the measured one is found to be 29.16% less and the resonance of the SWBG is shifted slightly though it is still within our desired frequency range. These discrepancies can be attributed to the design and fabrication tolerances. The uni-planar EBG designed in [31] with unit cell of $12.5 \times 12.5\,\mathrm{mm}^2$, exhibited a band gap of 2.57 GHz but at a higher frequency (at 3.5 GHz) than this double folded bend structure. The SRS-EBG proposed in [37] has a unit size of $12 \times 18\,\mathrm{mm}^2$ and dual wide band gap at 7 and 13 GHz, whereas this folded bend configuration is of only $14.5 \times 14.5\,\mathrm{mm}^2$ for 2.4 GHz operation.

In addition to the above analysis, the reflection phase characteristic is also examined with the simulation model as shown

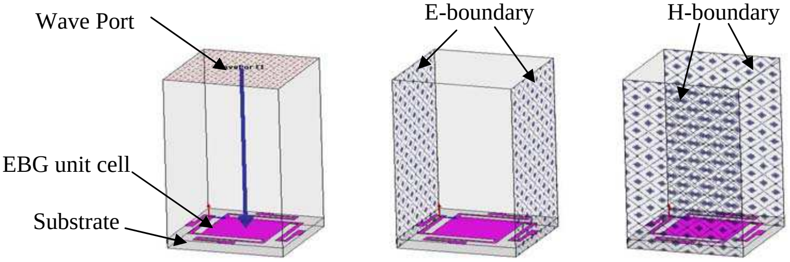


Figure 4. Simulation model for reflection phase analysis.

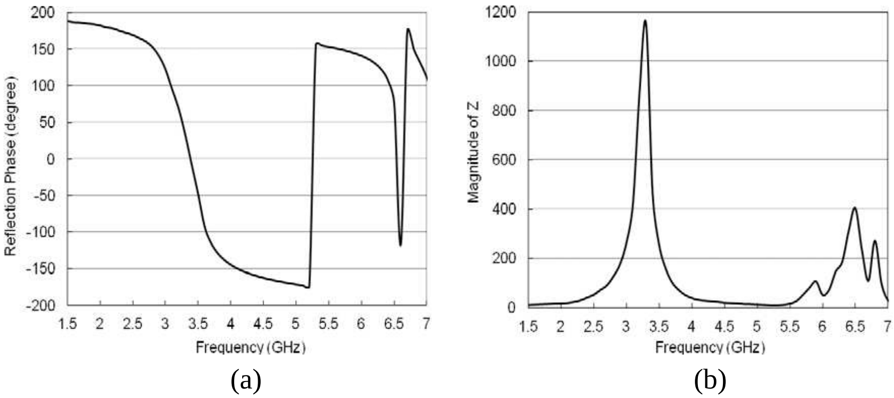


Figure 5. (a) Reflection phase diagram of an EBG cell at normal incidence, and (b) surface impedance of a unit cell of the proposed EBG structure.

in Figure 4. A EBG unit cell is surrounded symmetrically by a pair of electric boundary and a pair of magnetic boundary planes whilst a wave port illuminated the surface from the top. The reflected phase from the EBG structure is normalized to the reflected phase from a PEC surface placed at the same height of EBG [21]. Figure 5(a) illustrates the calculated reflection phase characteristic of the double-folded bend EBG structure. The reflection phase decreases continuously from 180° to $-180°$ as frequency increases. At low and high-frequency regions, the EBG surface show a similar phase to a perfect electric conductor (PEC) case, and at the resonant frequency, the EBG reflection phase close to 0°, which resembles the unique property of an artificial magnetic conductor (AMC) surface. In our proposed design, the AMC point is located at 3.3 GHz, having a narrow bandwidth of 0.3 GHz (3.1–3.4 GHz) within ±90° phase value. Besides, as depicted in Figure 5(b), the patterned surface exhibits a very high impedance nature at the resonance around 3.3 GHz. It is worth to be noted that the AMC point did not coincide but nearby the SWBG resonant point. As the computation schemes are different and they are concerned with two different properties, thus the resonances are apart from each other. In general, the reflection phase analysis is important in designing low-profile antennas especially wire antenna [21]. However, this work intended to examine the proposed EBG configuration for reducing mutual coupling between array elements, so we have considered only the surface wave suppression characteristics for this purpose.

3. EBG FOR MUTUAL COUPLING IMPROVEMENT

The proposed periodic structure exhibits a band gap (SWBG) of 1.2 GHz at 2.5 GHz, where it can suppress the unwanted surface waves. These characteristics are utilized to improve the mutual coupling (or isolation) between a two-element E-plane coupled microstrip antenna array. Usually, arrays are configured by arranging multiple elements in

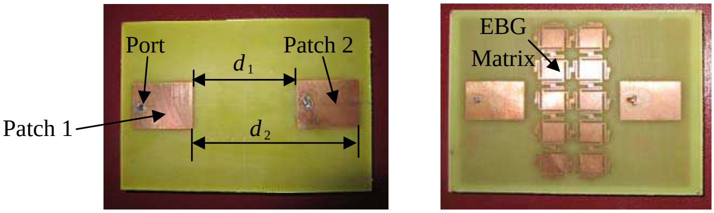
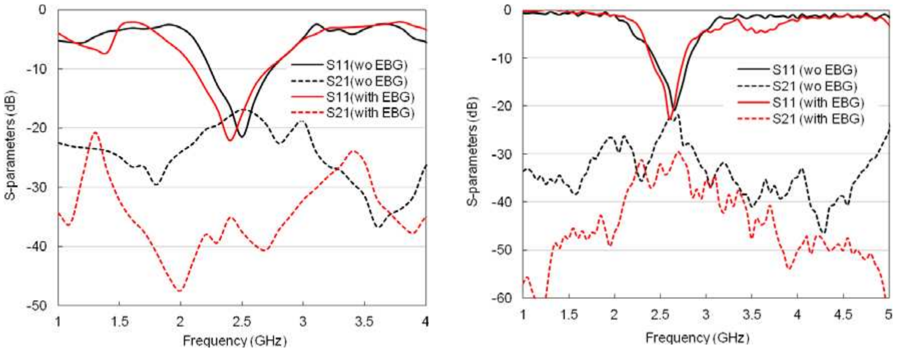


Figure 6. Fabricated rectangular patch antenna array with and without EBG.

a periodic manner. But the array elements suffers from strong mutual coupling due to surface waves, space waves and near field overlapping and it is stronger in E-plane coupled array than in the H-plane coupled array [19]. Thus, mutual coupling effect in E-plane direction is mainly investigated here. As depicted in Figure 6, a 2×5 EBG matrix is inserted between two rectangular elements of an array. Each element has a size of $24.25 \times 18.2\,\text{mm}^2$ and their internal distance (d_1) is 35.5 mm ($0.47\lambda_0$) while the edge to edge separation (d_2) is 59.75 mm ($0.8\lambda_0$).

The array resonates at around 2.5 GHz, which almost coincides with the resonance of the SWBG. Figure 7(a) illustrates the simulated scattering parameter (S-parameter) curves for the array with and without the EBG matrix. With EBG, the resonance is slightly shifted



(a) (b)

Figure 7. Scattering parameters of the patch antenna array, (a) simulated, and (b) measured.

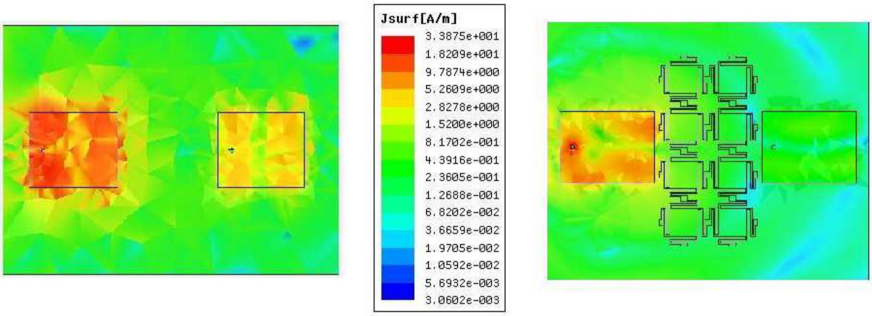
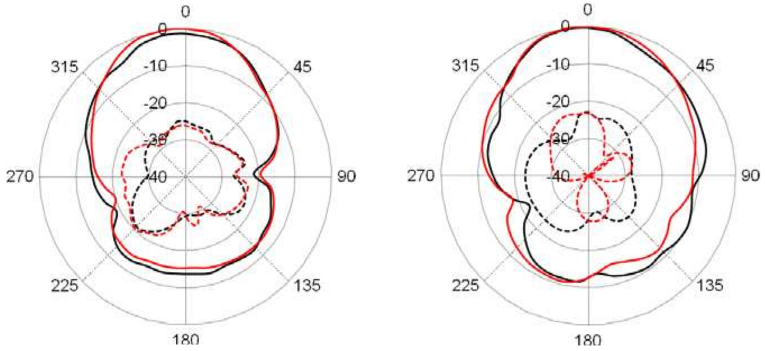


Figure 8. Surface current distribution with and without EBG structure.

from 2.55 to 2.47 GHz but the mutual coupling (S_{21}) is lowered from -18 dB to -35 dB. Thus, a 17 dB mutual coupling reduction is found in the simulated results. For validating these results, two arrays (with and without EBG) were fabricated and their scattering parameters are measured with a Agilent's PNA network analyzer E8362C. The measured S-parameters are plotted in Figure 7(b). It can be seen that both arrays resonates very closely at 2.53 GHz which matched well enough with the simulated results. The measured mutual coupling levels are -21 and -32 dB at resonance, respectively, for the normal and EBG case. Compared to the simulated part, the difference of the measured S_{21} levels is smaller which may be due to the fabrication and soldering imperfection. These results are found better than the performance studied by other researchers for different arrays [16, 17, 24, 29, 32, 33, 35]. Moreover, the investigation performed in [37] has an element spacing of $0.8\lambda_0$ (at 13 GHz) which is only $0.47\lambda_0$ (at 2.4 GHz) for this double folded bend configuration. Thus, the packing density is increased and compact structure is developed at lower frequency.

Figure 8 shows the surface current distribution of the antenna array in the presence and absence of EBG matrix. Clearly, both of the patches are well coupled at the resonant frequency which become restricted as the EBG cells are inserted and the coupling effect is reduced. The folded bend EBG structures blocked the surface waves along the E-plane direction and contributed in alleviating the mutual coupling between the elements. Furthermore, the radiation



(a) (b)

Figure 9. Radiation characteristics of the array at 2.5 GHz, (a) E-plane, and (b) H-plane [pure line: co-pol and dashed line: cross-pol; black line: without EBG and red line: with EBG].

characteristics for the both array configurations are computed and presented in Figure 9. Despite of the insertion of EBG structure, the radiation patterns are not disturbed in considerable amount although it is slightly improved. In addition the radiation efficiencies for both cases are observed which is improved by 5% in the EBG array case.

4. CONCLUSION

A new uni-planar type EBG structure with a double folded bend connecting bridge is proposed which resonates at 2.4 GHz and exhibits a band gap of 1.2 GHz. The folded bend lines are found very useful in achieving compactness (61% size reduction) of the EBG structure for applications in the lower frequency band. The band gap characteristics are examined through the suspended microstrip line method and the reflection phase is also analyzed using the FEM based EM simulator HFSS. The configuration is investigated for mutual coupling reduction of an E-plane coupled patch antenna array which operates within the stop band of the EBG. A 17 dB reduction of mutual coupling is obtained in simulation which is found to be 11 dB in measurement. The EBG structure and the array with and without EBG matrix are fabricated and the measured results are found in good agreement with their simulated counterparts. Moreover, the radiation characteristics are not affected by the presence of the EBG structure rather it is slightly improved.

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