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A Triangle Array of 1×4 Slots Antenna with Curved EBG Structures for Cellular Base Station

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Abstract—In this paper, a slot array with a new technique of metamaterial on Electromagnetic Band Gap (EBG) structure is used to demonstrate the possibility of building high gain top-mounted antenna for mobile base station. We describe the method for gain improvement by transferring the electromagnetic fields from a 1×4 slot array with a PEC reflector radiated through the cavity of curved woodpile EBG. The proposed technique not only has the advantages of reducing the total length of the slot array, but also provides higher gain and easier installation. In addition, to provide the azimuth patterns covering 360° around the base station, a triangular array configuration consisting of three panels of such an antenna array has also been presented, while the fabricated cavity of the curved woodpile EBG structure exhibits band gap characteristics at 2.1 GHz for realizing a resonant cavity of the slot array. This idea is verified by comparing between the results from Computer Simulation Technology (CST) software and the experimental results. Finally, it is found that the measured and simulated results are in a good qualitative agreement, and the antenna prototype yields directive gain of each panel around 17.1–17.2 dBi.

1. INTRODUCTION

Presently, the development of antennas with high performance becomes necessarily essential for new services and networks of telecommunication. Microstrip antenna (MSA) is an attractive choice for many modern communication systems due to its light weight, low profile with conformability, and low cost [1, 2]. However, because MSA is a resonant-type antenna, the antenna size and bandwidth are determined by the operating wavelength and Q factor of the resonant frequency, respectively. Therefore, the two major disadvantages of an MSA are low gain and very narrow impedance bandwidth due to its resonant nature. Parasitic patches have been used to form a multi-resonant circuit so that the operating bandwidth can be improved [3]. From the research of [4], a multi-layer MSA was investigated with parasitic patches stacked on the top of the main patch. Multi-resonant behavior can also be realized by incorporating slots into the metal patch. Furthermore, several single-layer single-patch MSAs have been reported, such as U-slot MSA [5] and E-shaped patch antenna [6]. In addition, narrow bandwidth can be expanded by increasing the substrate thickness, whereas it will launch stronger surface waves. As a result, the radiation efficiency and patterns of the antenna will be further degraded. However, an ultra-wideband circular MSA fed by strip line above wide-slot ground plane [7], which was developed by using a conventional circular MSA placing above the slot on the ground plane, can expand the bandwidth and the efficiency of antenna.

Many new technologies have come out in the modern antenna design, and one exciting breakthrough is the development of Electromagnetic Band Gap (EBG) structure. For antenna engineering, the applications of EBG structure have become a wondrous topic in antenna designs [8]. It is a new technology for the performance improvement of antennas since the EBG structures applicable to a

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frequency spectrum extremely wide covering from the acoustic until optical frequencies [9]. The EBG structure, also known as photonic crystals [10], is also used to improve antenna performance [11–13]. The EBG structures are capable to enhance the performance of slot antennas in terms of gain, side- and back-lobe levels, and mutual coupling. This is because EBG exhibits frequency band-pass and band-stop that can block the surface wave excitation in the operating frequency range of antennas [14]. Therefore, with the advantage of EBG structures, this paper presents a 1×4 slot array antenna for supporting the Universal Mobile Telecommunications System (UMTS) band of 2.1 GHz frequency covered with the cavity of curved woodpile EBG structures, providing high gain, frequency bandwidth and horizontal beamwidth around 15–17 dBi, 250 MHz, and 60°–65°, respectively. (Typical gain of the sector antennas for UMTS band of 2.1 GHz in the markets.) The proposed antenna is not only a high gain antenna, but also in smaller size and with half height of typical base station antennas, whose dimensions are too long, and weight is too heavy due to a lot of elements in the array. Moreover, the proposed antenna will be installed on the top of a tower; therefore, it is able to solve the problem of null bandwidth while the most sector antennas of base stations are often installed on the side of the tower. The simulated results from CST software and measured results of the return loss (S_{11}), radiation patterns, and gain of the proposed antenna show a good agreement which will be reported.

The paper is organized as follows. Section 2 is devoted to the configurations and design of the microstrip slot and curved woodpile EBG structure with its corresponding bandgap features. In Section 3, we apply this approach, using CST simulation software, to the simulation, and the results are discussed. Next, the fabricated and experimental results of the prototype antenna are discussed in Section 4. Finally, conclusions follow in Section 5.

2. ANTENNA AND EBG CONFIGURATIONS

2.1. Microstrip Slot Antenna Configuration

The microstrip slot antenna designed for working in the UMTS band of 2.1 GHz frequency is utilized as a prototype for our proposed antenna. The microstrip slot structure consists of an exciter made from a metallic circular patch of radius (a) printed on an FR4 substrate ($\varepsilon_r = 4.5$, $\tan\delta = 0.02$) with a dimension of $60 \times 60\,\mathrm{mm}^2$ in area and 1.6 mm in thickness as shown in Fig. 1(a). In this structure, the gap (t) between the strip line lengths (L_2) is used for adjusting the impedance matching to provide a 50 Ohm at the center frequency while its tuning stub is used to improve the level of return loss. In the back view in Fig. 1(c), the substrate of FR4 is mounted on the ground plane of width (W) and length (L), which is cut to form the wide-slot ground plane (size $W_1 \times L_1$), while its center frequency is specified at 2.1 GHz and the desired bandwidth around 1.92 GHz–2.17 GHz. However, we also varied the dimension of this wide-slot ground plane to enhance the bandwidth as illustrated in [7]. From the simulation results with such conditions, it is found that this single element of an antenna provides the bidirectional pattern and yields the antenna gain around 5 dBi at the operating frequency of 2.1 GHz.

To improve gain characteristics, the microstrip slot has been arrayed with element spacing of $3\lambda/4$ as shown in Fig. 1 (left). The simulated result shows that the gain of the 1×4 slot array at 2.1 GHz is around 11 dBi. In addition, the proposed antenna in this paper has added a PEC reflector of $300 \times 500\,\mathrm{mm}^2$ behind the panel of slot array structure to control the radiation pattern to be the directional pattern. From the simulated results by using CST software, the effects of the variation of the distance between the slot array and the PEC reflector (d_r) are also observed. It is found that such a distance can be used to control the resonant frequency of the slot array because its resonant frequency is changed when d_r is varied as shown in Fig. 2. Therefore, $d_r = \lambda/4$ is chosen, and its configuration is illustrated in Fig. 3. To better appreciate the gain improvement, the return losses or S_{11} (at -10 dB) and the radiation patterns of the 1×4 slot array with and without the PEC reflector are compared as shown in Figs. 4 and 5, respectively, while its gain from the simulated result of the 1×4 slot array with the PEC reflector at 2.1 GHz is 14 dBi, which is raised up around 3 dB compared to the 1×4 slot array without the PEC reflector. From such radiation patterns, it is found that the single panel of 1×4 slot array with the PEC reflector provides the directional patterns, whereas without the PEC reflector, it provides the bidirectional pattern in both the E- and H-planes. The Half-Power Beamwidth (HPBW) in both planes have been shown as the ratio of the azimuth pattern to the evaluation pattern (AZ : EL), of the 1×4 slot array with and without the PEC reflector are 98° : 17° and 89.6° : 16.5°, respectively.

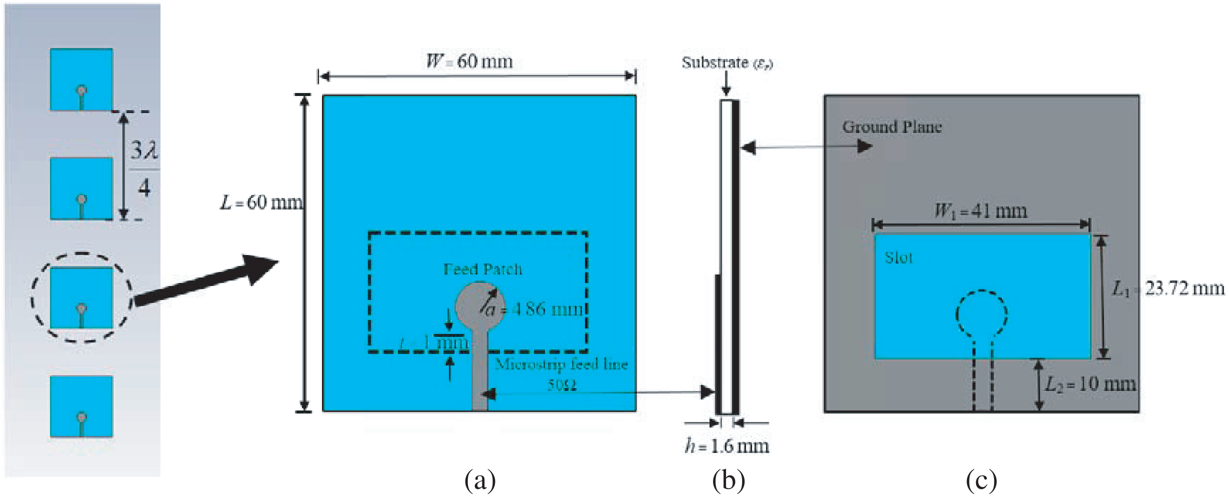

Figure 1. A 1 × 4 slot array antenna. (a) Front view. (b) Side view. (c) Back view.

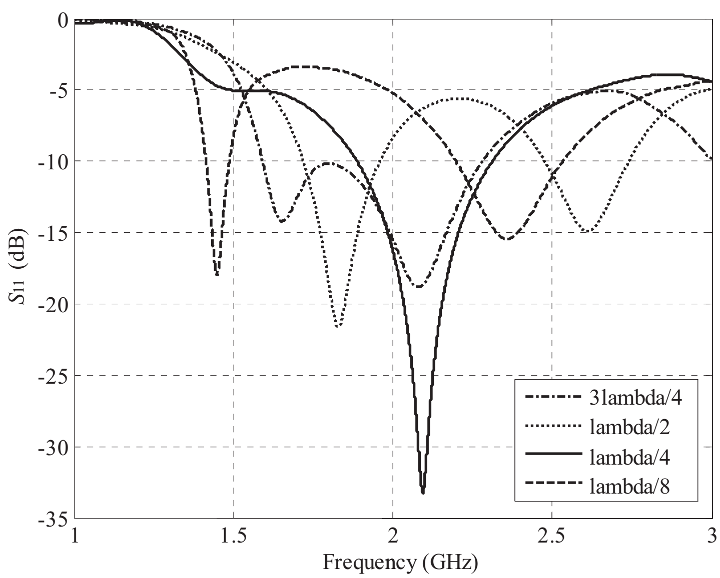

Figure 2. Simulated results of return loss (S_{11}) variation of d_r.

2.2. Curved EBG Configuration

Traditionally, the high gain antennas were implemented by using either parabolic antennas or large antenna arrays. However, the curved surface of parabolic antennas made it difficult to conform with mobile platforms, while large antenna arrays always cause too long and too heavy antennas. Furthermore, the great amount of electromagnetic energy was attenuated inside its phasing line. From our study [15, 16], we presented one sector of the slot array antenna providing a fan-shaped radiation pattern, wide in the horizontal direction and relatively narrow in the vertical direction, which is suitable for the mobile phone base station. We found that the proper structure of EBG was capable to enhance the gain of the slot array as the additional resonant circuit when being placed in the front of the array panel. Actually, in theory, the EBG material has created new possibilities for controlling and manipulating the flow of electromagnetic waves. Within the EBG material, there is a range of frequencies where propagating modes can be fully suppressed in one or more dimensions. This range of frequencies is known as the EBG that can provide significant advantages for suppressing and directing radiation when being used in antennas. Moreover, the EBG structures could be appropriately shaped such as planar

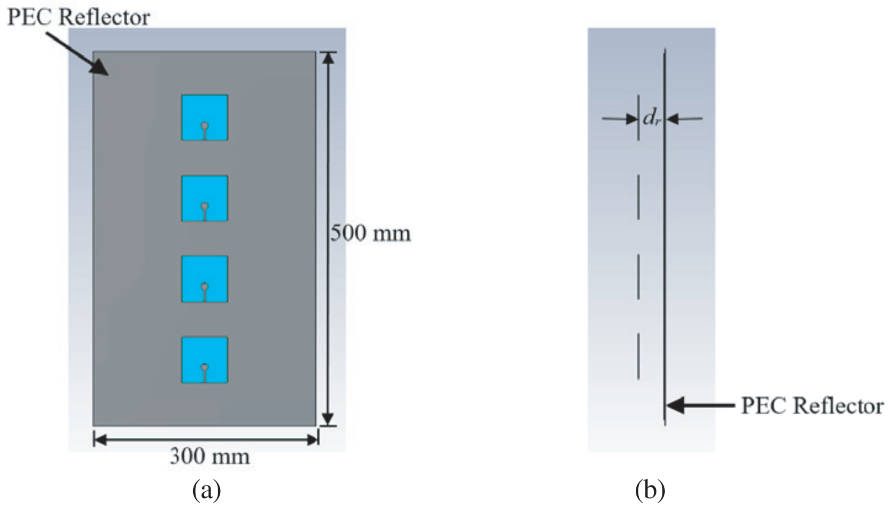

Figure 3. A 1×4 slot array antenna with PEC reflector. (a) Front view. (b) Side view.

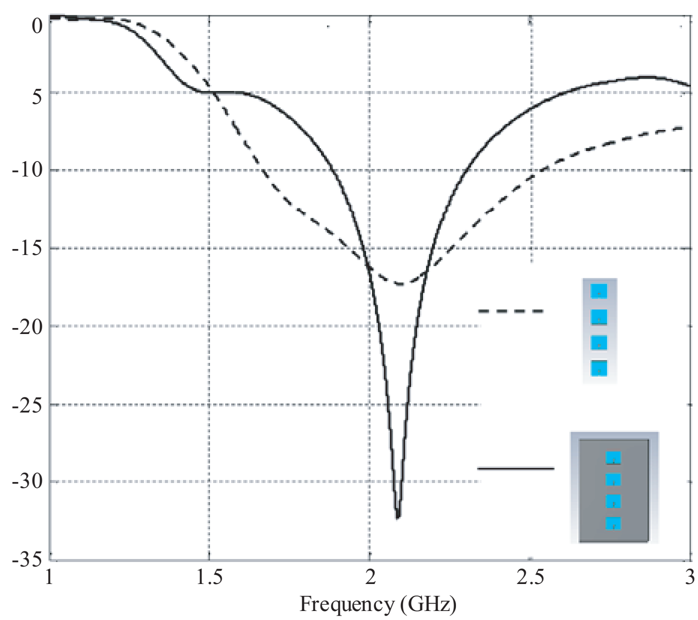

Figure 4. Simulated results of return loss (S_{11}) of 1×4 slot array with and without PEC reflector.

woodpile EBG structures for reducing the side and back lobes of the directional antenna as mentioned in [17, 18]. In this paper, a cylindrical woodpile EBG is designed and based on the geometry of the planar woodpile structures. However, the horizontal filaments will not be inserted in the cylindrical woodpile structure as planar one but are aligned at the same horizontal location. Therefore, the resonance of wave propagation mode in the cylindrical cavity is the transverse magnetic mode. Thus, the cylindrical structures do not demand the three-dimensional bandgap whereas only require the bandgap along the radial direction. Furthermore, when this structure is excited with vertical polarization of 1×4 slot array (along the axis of the cylinder), the horizontal filaments will be stacked vertically crossing at the same location and become the desired EBG grating for placing in the front of such a slot array. While the report in [19] describes that, the sector of cylindrical woodpile EBG structures is more suitable for beam shape of the 1×4 slot array with the PEC reflector. Therefore, in this paper, we propose a triangular

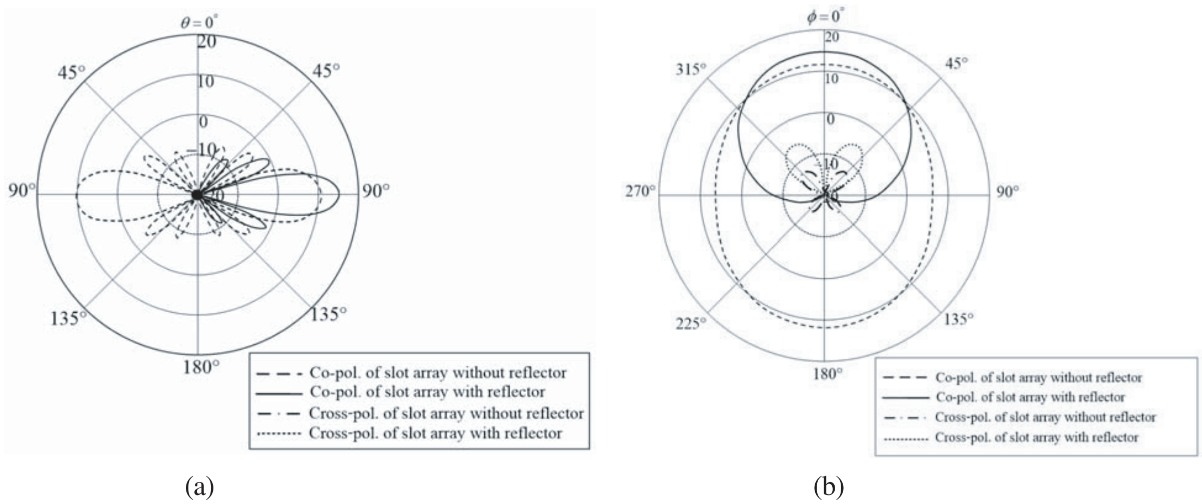

Figure 5. Simulated radiation pattern of 1×4 slot array with and without PEC reflector. (a) E-plane. (b) H-plane.

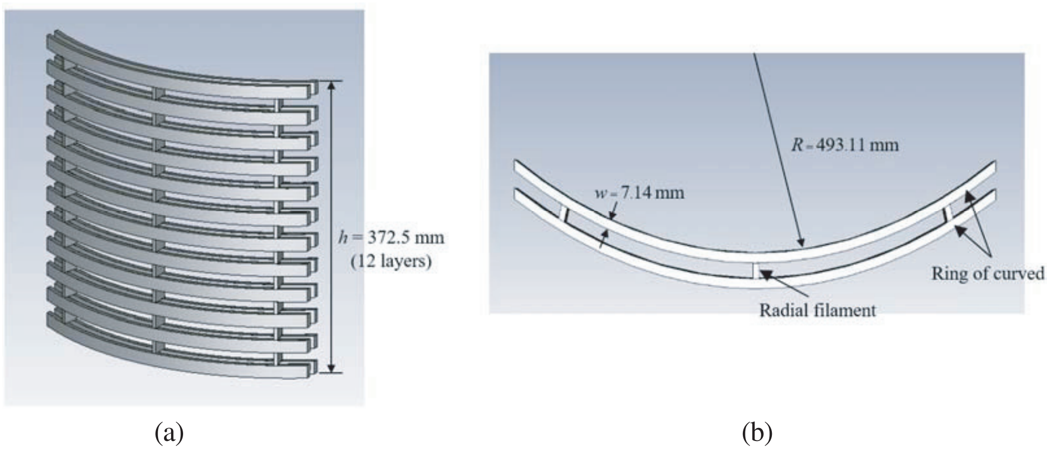

Figure 6. The geometry of a sector of curved woodpile EBG structures. (a) Perspective view. (b) Top view.

array of the 1×4 slot antenna providing the azimuth pattern that can cover 360° of user's areas by using the geometry of the curved woodpile EBG structures with two layers of the different diameters as shown in Fig. 6. The parameters of this structure are the filament thickness or diameter (w), radius (R), height (h), number of radial filaments (N_{rad}), and number of rings (N_{ring}) of the curve. To implement the curved woodpile EBG, we use alumina rods (rectangular cross section) with parameters $\varepsilon_r = 8.4$ and $\tan\delta = 0.002$. The parameters are given in [16] with $w = 0.05\lambda$. It is observed that the appropriate HPBW in the H-plane appears to have the same radius (R) of the curved woodpile EBG, while its HPBW is enlarged when the radius of R is increased. The highest gain provided at R is around 334λ. After that, we study the effect of h variation versus the gain, and it is found that its gain is increased from 14 dBi to 17 dBi at h equal to 2.61λ (12 layers) approximately. Furthermore, we find that although the gain will be increased when h is also increased, if h is higher than 525λ, the antenna impedance will mismatch immediately because the phases of wave transmission from slot array through EBG grating are not equal, while its operating frequency will be shifted to the undesired frequency [16]. From our investigation of the parameters of the N_{ring}, we find that the bandgap is increased with the number of rings, so that $N_{ring} = 2$ is selected, while the number of radial filaments, $N_{rad} = 3$ because it yields the highest directivity, resulting in ultimate resonance.

3. SIMULATED RESULTS AND DISCUSSIONS

In this section, we present a triangular array of three panels of the 1×4 slot array with PEC reflectors and curved woodpile EBG structures to form the antenna beam directed around the base station tower, as shown in Fig. 7. The triangular array configuration consisting of 1×4 slot array on each side of the triangle and cavity of curved woodpile EBG is used to cover an angular sector of 120° of user areas. However, the design parameters of the gain improvement for an antenna system are: the radius of the curved woodpile EBG structures (R), distance between the 1×4 slot array and the curved woodpile EBG structure (d), and the height of the curved woodpile EBG structure (h), which are optimized with $R = 3.34\lambda$, $d = 0\lambda$, and $h = 2.61\lambda$, respectively [17].

After the optimized parameters of each panel are known, the simulated results are calculated by using CST software. The reflection coefficients (S_{11}) of each slot array panel are plotted and combined in one graph, as shown in Fig. 8. It is found that S_{11} (at -10 dB) of this proposed antenna is in the frequency range of 1.92 GHz–2.17 GHz, which are wide enough and can be well utilized for a mobile phone base station. In Fig. 9, the normalized radiation patterns at 2.1 GHz are illustrated. It is noted

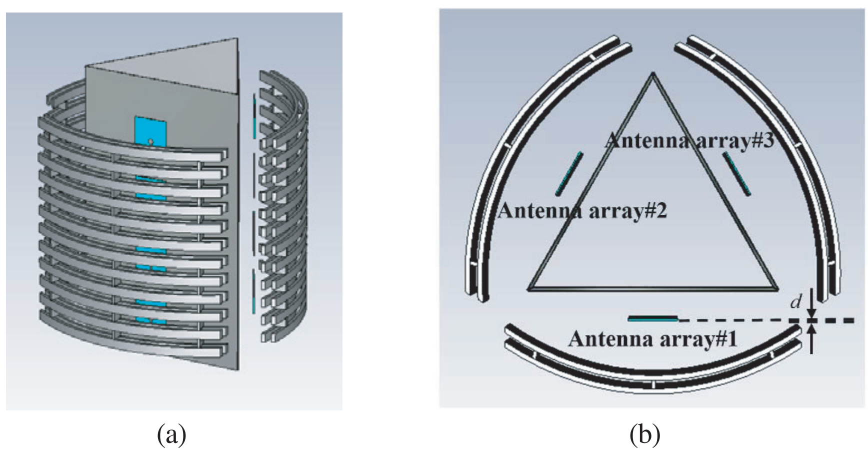

Figure 7. The configuration of triangular array antenna. (a) Perspective view. (b) Top view.

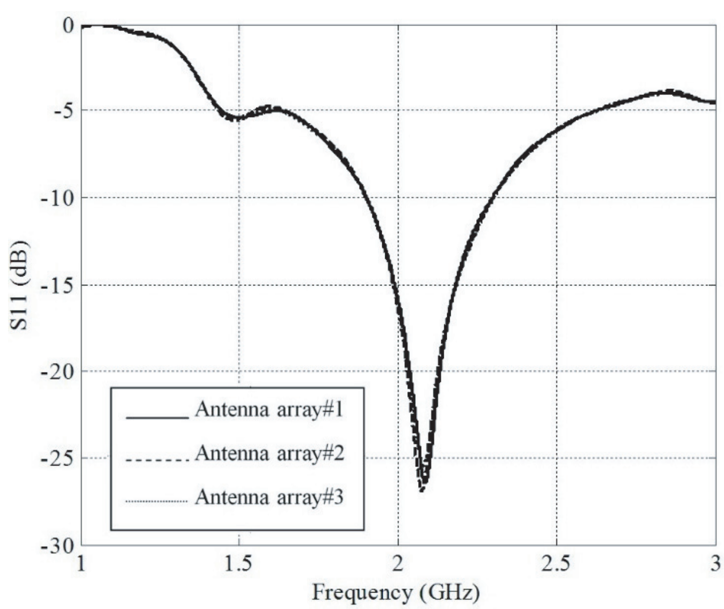

Figure 8. Simulated results of return loss (S_{11}) of each panel of the proposed triangular array antenna.

that in any front view of this triangular array, we are able to see only two patterns in elevation plane (E-plane) because one remaining pattern is behind the first two patterns, while the radiation pattern in azimuth plane (H-plane) of such an array antenna is able to cover 360° around the array structure as required. However, the cross-polarization both in E- and H-planes are also calculated to consider its polarization performance. In Figs. 5 and 9, we find that the cross-polarization levels in both planes are very low. Especially in E-plane, they are very small and tufted around the center point of polar plot format, while the patterns and levels of cross-polarization in H-plane can be observed clearly. In addition, the performance of gains, radiation efficiencies, bandwidths and HPBWs of a 1×4 slot array antenna with and without PEC reflector and each four-element slot array with EBG structure are summarized in Table 1. It is observed that the gain of a 1×4 slot array antenna with PEC reflector and EBG structure is increased around 3 dB compared to a 1×4 slot array antenna with only PEC reflector. Furthermore, it is evidently seen that the radiation efficiency of the proposed antenna is higher than the others, approaching to 0 dB or 100% of efficiency. However, the height of the proposed antenna is around 500 mm, whereas the height of the typical sector antenna is around 1,000–1,300 mm. Therefore, the height of this designed antenna structure is shorter than the height of the typical sector antenna around 50%–61.5%.

Table 1. Results of simulation.

Antenna	**Gain (dBi)**	**Radiation Efficiency (dB)**	**Bandwidth (%)**	**HPBW AZ:EL**
A 1 × 4 slot array antenna	11.05	−0.84	41.1	98° : 17° (5.8 : 1)
A 1 × 4 slot array antenna with PEC reflector	14	−0.44	19.7	89.6° : 16.5° (5.4 : 1)
Antenna panel#1 with EBG Structure	17.2	−0.06	18.9	62.6° : 8.6° (7.3:1)
Antenna panel#2 with EBG Structure	17.1	−0.06	19.1	62.8° : 8.6° (7.3:1)
Antenna panel#3 with EBG Structure	17.1	−0.06	18.9	62.8° : 8.6° (7.3:1)

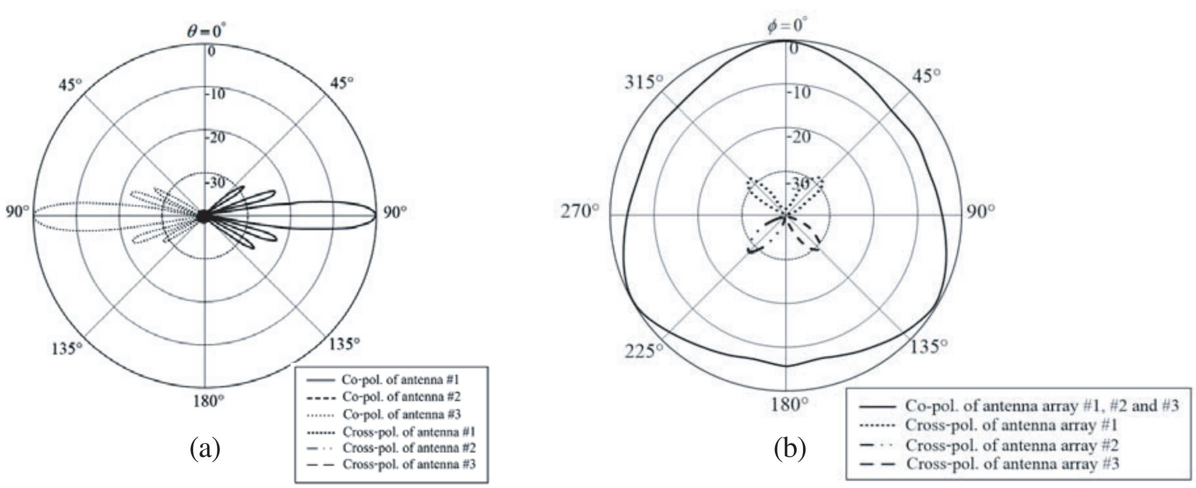

Figure 9. Simulated radiation pattern of the proposed antenna. (a) E-plane. (b) H-plane.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

After this antenna is completely simulated with the CST software, the antenna prototype is fabricated as shown in Fig. 10 for validating the proposed concept. Its geometry consists of a triangular array configuration containing three panels of 1×4 elements of the slot antenna arrays with the PEC reflector to decrease their back and side lobes, while the cavity of the curved woodpile EBG structures of each panel exhibiting the bandgap characteristics of 2.1 GHz. The simulated and measured reflection coefficients, S_{11}, of this antenna are shown in Fig. 11. It is observed that the calculated and measured results are in a good agreement. From the measured result, we find that the frequency bandwidth is achieved from 1.92 GHz to 2.33 GHz (a fractional bandwidth of 0.41 GHz or 19.3%), which is enough to cover the 3.9 G mobile phone base station, UMTS band of 2.1 GHz (1.92–2.17 GHz). The further study of this proposed antenna is focused on its radiation performance, as shown in Fig. 9. The radiation patterns of the prototype antenna array are measured in an outdoor area, far away from any base station of mobile phone and compared to the simulated results, in dBi unit of antenna gain, as shown in Fig. 12. It is noted that the measured and simulated results have a good agreement with each other. In addition, the measured and simulated results of the gains, bandwidths and HPBWs of the proposed antenna are summarized in Table 2.

Table 2. Results of measurement.

Antenna	**Gain (dBi)**		**Bandwidth (%)**		**HPBW AZ:EL**	
	Simula*	**Meas****	**Simula***	**Meas****	**Simula***	**Meas****
Antenna panel#1	17.2	16.7	18.9	19.3	62.6° : 8.6° (7.3 : 1)	63.2° : 8.9° (7.1 : 1)
Antenna panel#2	17.1	16.6	19.1	19.3	62.8° : 8.6° (7.3 : 1)	63.4° : 8.9° (7.1 : 1)
Antenna panel#3	17.1	16.5	18.9	19.3	62.8° : 8.6° (7.3 : 1)	63.5° : 8.9° (7.1 : 1)

Simula* is simulation and Meas** is measurement.

(a) (b)

Figure 10. The prototype of the proposed triangular array antenna. (a) Front view. (b) Side view.

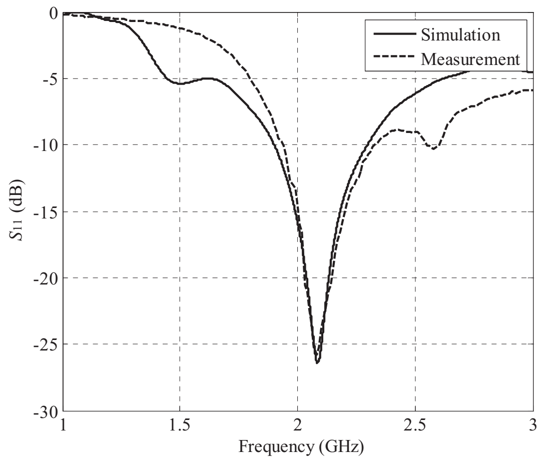

Figure 11. The return loss (S_{11}) of the proposed antenna.

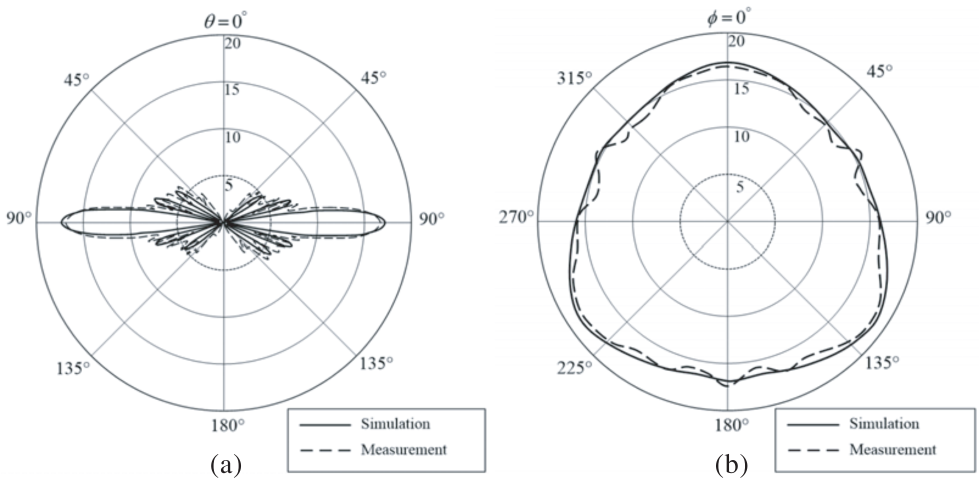

Figure 12. The radiation pattern of the proposed antenna. (a) E-plane. (b) H-plane.

5. CONCLUSIONS

We present a triangular array configuration consisting of three panels of 1×4 slot antenna arrays, containing four slots on each side of the triangle. Each four-element array is developed from an original bidirectional antenna to be the directional one by adding PEC reflector and increasing its gain with the technique of EBG metamaterial. An additional cavity of curved woodpile EBG structures is used to cover an angular sector of 120° of the triangular array. This method obviously demonstrates that the proposed antenna array provides directive gain on each side and increases around 3 dB when the EBG structures are added, while its length of the array is not enlarged. Furthermore, the radiation pattern in the horizontal plane is consistent with our requirement. Finally, a good agreement is obtained between the simulated and experimental results. Therefore, this proposed antenna is certainly appropriate for 3.9 G mobile phone base station, the UMTS band of 2.1 GHz. However, the geometry of this proposed antenna can be easily modified and applied to use in other generations of mobile phone base station in the future.

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