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PRACTICABILITY ANALYSIS AND APPLICATION OF PBG STRUCTURES ON CYLINDRICAL CONFORMAL MICROSTRIP ANTENNA AND ARRAY

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Abstract—An antenna and an array with photonic bandgap (PBG) structures, which are cylindrical conformal microstrip antennas, both operating in X-band (10.2 GHz) are proposed. As shown in the simulation, PBG structures could suppress the surface wave propagating on substrate and balance the influence of cylindrical curvature at resonance frequency on antennas. The simulation results indicate that they have a higher gain and better directivity over the conventional antenna without PBG structure. Both of the antenna and the array are designed and manufactured, and the measurement results agree well with the simulations.

1. INTRODUCTION

The conformal microstrip antennas have received significant attention for their advantages of simple structure, easy manufacture, low cost, convenient integration with other microwave components and fabrication of their feeding network together with antennas. Many researchers have been studying these antennas for years [1–5], and developed a structure conformal to the surface of missiles and satellites. However, conformal microstrip antennas still have disadvantages of lower efficiency and narrow band width due to the effects of surface waves, feeder loss and dielectric loss. Therefore, how to adapt antennas to the machine shape better without reducing its performance has become a new mission.

At present, various numerical algorithms are used for the analysis and calculation of conformal antennas to reduce the cost and shorten

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the design period. Full-wave analysis method can accurately simulate the performance of antennas, typically, such as using method of moments (MoM) to analyze radiation and scattering characteristics of array antenna accurately [6–9], finite difference time domain (FDTD) method to dual-frequency microstrip patch antenna [10], and finite element method (FEM) to radiation characteristics of cylindrical conformal antenna [11, 12]. All these researches above are doing these based on traditional conformal antennas, no respect from media substrate is concerned to improve the inherent disadvantage such as low efficiency and dielectric loss due to the surface wave losses.

There has been an increasing interest in microwave applications of photonic bandgap (PBG) structures. Due to properly designing the lattice periodicity on space, the PBG structures can be used to suppress the surface wave and improve the performance of the patch antenna [13–18], the efficiency of suppressing the high order harmonics and surface waves have been compared with that of normal structures. However, the application of PBG structures is mainly to plane structure [19, 20]. Being theoretical analysis, numerical simulation and small in number, most of the reports about curved conformal antennas are given without enough attention to the development of the array antenna and the feasibility of designing structures experimentally.

In this paper, by employing PBG structures, the cylindrical microstrip antenna and antenna array are implemented actually and measured in practice. The simulations are carried out using Ansoft HFSS. The measurement results indicate that compared with the antenna without PBG structure, proper PBG structures can increase the forward radiation gain, directivity and suppress side-lobe radiation strongly. In addition, considering about its stability and durability, new requirements are proposed on the design of cylindrical conformal microstrip array antenna.

2. DESIGN OF CYLINDRICAL CONFORMAL MICROSTRIP ANTENNA

Each proposed antenna below is constructed with PBG structure, which shows its unique ability to suppress the surface wave propagation on the substrate and lower the influence of cylindrical curvature at resonance frequency on antennas.

2.1. Configuration of Cylindrical Microstrip Antennas

The main criterions for choosing the substrate are the thickness h and the loss tangent $\tan\delta$. A thick substrate could help to increase the

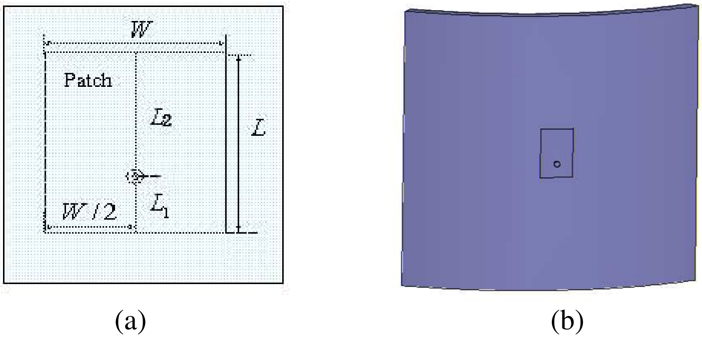


Figure 1. The structure of the probe-fed cylindrical patch antenna: (a) the metallic patch, (b) the cylindrical structure.

radiation power, reduce conductor loss and improve the impedance bandwidth. Generally the thickness of substrate is less than one-tenth of the wavelength λ_0. Meanwhile, the dielectric constant ε_r of the substrate plays the same role in increasing edge field and its radiation power [21, 22]. The configuration parameters of the patch antenna as is shown in Fig. 1 are $\varepsilon_r = 2.25$, $\tan\delta = 0.001$, $h = 2.6\,\text{mm}$, and the inner radius of the cylindrical substrate is $R = 50\,\text{mm}$. The length of the cylindrical surface is 51 mm, the curving angle is 55.6 degree, and the size of the patch is $L \times W = 9\,\text{mm} \times 6\,\text{mm}$. While based on the transmission line theory of rectangular patch antennas, the feed point is located at $L_1 = 2.5\,\text{mm}$.

2.2. Effect of Different Curvature on Cylindrical Antenna at the Resonance Frequency

To detect the influence of different curvature radius R on cylindrical antennas at the resonance frequency, the return loss of the antenna with $R = 50\,\text{mm}$, $R = 65\,\text{mm}$ and $R = \infty$ (plan antenna) are drawn in Fig. 2, respectively. The reduction in the curvature radius will increase the resonance bandwidth. However, for the radius is larger than the wavelength here, the curvature of the antenna has some impact on input impedance.

2.3. Arranging PBG Structure in Cylindrical Antenna

In terms of the Bragg reflect condition [13–16], the period of the PBG structure T is half of the guide wavelength of a general microwave strip

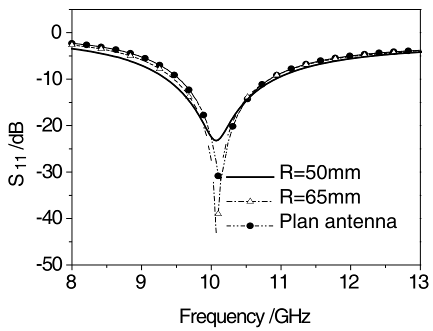


Figure 2. Return loss with different curvature radius.

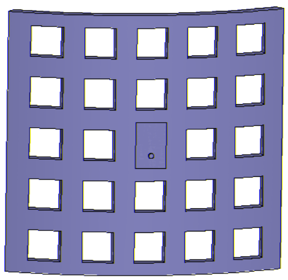


Figure 3. Prototype of PBG structure in cylindrical antenna.

λ_g,

$$T = \lambda_g/2, \tag{1}$$

where,

$$\lambda_g = \frac{c}{f\sqrt{\varepsilon_e}} \tag{2}$$

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{12h}{W}\right)^{-\frac{1}{2}} \tag{3}$$

c, f, W and h are the velocity of light, resonance frequency, width and the height of the patch, respectively. Here, the cylindrical patch antenna is designed in a conventional fashion by itself and then surrounded properly by the PBG lattice structure shown in Fig. 3, the period of PBG with square lattice is $T = 10\,\text{mm}$. Several cases of return loss with different cell size a relative to the period T are simulated, and an optimum size of the hole $a/T = 3/5$ is obtained.

By the application of PBG structure to patch antenna, as is shown in Fig. 4, we find that the PBG patch antenna proposed here exhibits the peak return loss $-19.2\,\text{dB}$ at $10.2\,\text{GHz}$ and a bandwidth of 14.2 percent, which is as good as the reference patch antenna without PBG structure, while the resonance frequency is increased.

Moreover, Fig. 5 shows the simulated H-plane radiation patterns of the cylindrical antennas with different cell size, including $a/T = 3/5$, $a/T = 1/3$ and $a/T = 0$ (without PBG). For $a/T = 3/5$ the Gain of the PBG patch antenna is $7.2\,\text{dB}$, that is $0.7\,\text{dB}$ higher than the reference antenna, while the main lobe of the reference antenna's gain has a split head caused by surface wave losses, indicating that PBG can increase the gain and suppress the effect of the surface wave.

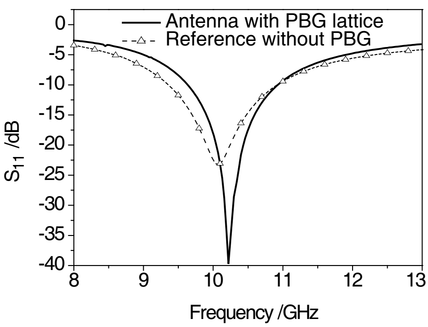


Figure 4. Comparison of S_{11} of the PBG microstrip antenna with that of reference antenna.

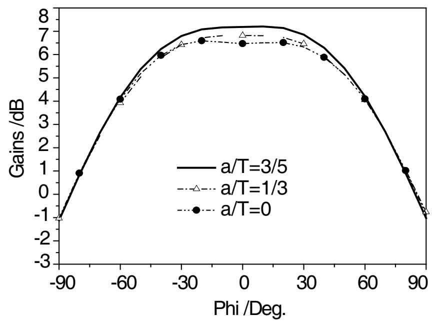


Figure 5. Comparison of the H-plane radiation patterns of PBG patch antenna with reference antenna at 10.2 GHz.

Figure 6. Fabricated cylindrical microstrip antenna with PBG lattice.

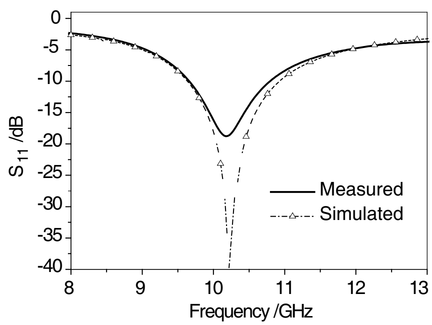
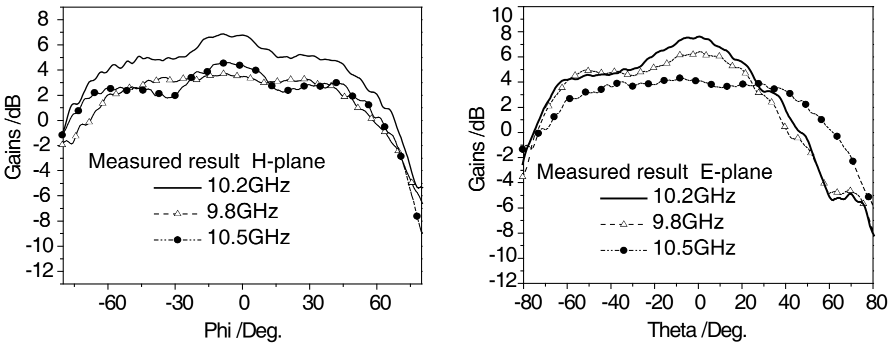


Figure 7. Return loss of the fabricated antenna with PBG lattice.

3. MEASUREMENT ANALYSIS OF CYLINDRICAL MICROSTRIP ANTENNA WITH PBG LATTICE

Once the proper PBG lattice for surface wave suppression is determined, the cylindrical antenna fabrication is straight forward as is shown in Fig. 6.

Figure 7 shows the return loss of the fabricated antenna. Compared with the simulated PBG patch antenna, the peak return loss is -18.77 dB at 10.175 GHz, and a bandwidth of 11.0 percent, which is in good agreement with the designed antenna.



(a) (b)

Figure 8. Radiation pattern of the PBG cylindrical conformal antenna. (a) H-plane, (b) E-plane.

Radiation gain of the antenna is obtained by comparing with the standard gain of horn antenna. $G = (G_T - G_L) + G_B$, where G is practical gain of antenna; G_T is measurement gain of antenna; G_L is measured gain of horn antenna; G_B is standard gain of horn antenna [23].

Figure 8 shows the measurement of E/H-plane radiation gains at the frequencies of 9.8 GHz, 10.2 GHz and 10.5 GHz. Measurement and simulation results are well-matched, and the radiation gain reaches its maximum at the frequency of 10.2 GHz with the peak gains of H-plane and E-plane being 6.9 dB and 7.6 dB respectively. The fact that gains of the proposed antenna are obviously higher than the conventional antenna indicates that cylindrical PBG structure can improve the performance of conformal antennas.

As can be seen from Fig. 4 and Fig. 7 that the measured resonance frequency is almost the same as simulated. However, the tendency that the Gain is increased by PBG structure is obviously as is shown in Fig. 5.

4. DESIGN OF CYLINDRICAL CONFORMAL MICROSTRIP ARRAY WITH PBG LATTICE

A new four-cell cylindrical array antenna is presented based on the analysis of the previous example. The parameters of the substrate such as cylindrical radius, dielectric coefficient and element size are identical to the single patch antenna above.

4.1. Designing Process of Cylindrical Array Antenna

The mutual coupling among cylindrical conformal microstrip antenna elements and interconnection feeding scheme should be figured out in the design process. As is shown in Fig. 9, where the distance between elements of proposed array is 18.2 mm, integrated with groove loaded microstrip feeding with the depth l_{slot}, for the matching of input impedance with the antenna [24, 25], calculated by

$$l_{slot} = \arccos\left(\sqrt{Z_c/R_a}\right)\frac{L}{\pi}, \tag{4}$$

where, Z_c is characteristic impedance of the microstrip, $R_a = (120\lambda_0 hQ)/\varepsilon_r LW$, Q is the quality factor of all the loss accounted. When rectangle microstrip antenna working at TM_{01} pattern, Q is

$$Q = \left[\frac{120\lambda_0 hG_r}{\varepsilon_r LW(1-3.4H_e)} + \frac{1}{\pi h\sqrt{\frac{\lambda_0}{120\sigma_e}}} + \tan\delta\right]^{-1} \tag{5}$$

while, $H_e = \sqrt{\varepsilon_r - 1}h/\lambda_0$, σ_e is specific conductance; $\tan\delta$ is tangent loss. G_r is radiation conductance of rectangle patch, $G_r = \frac{1}{45}[\frac{L}{\lambda_0}]^2$ in our case.

Due to the width of the feeding line is $w = 1.603$ mm, in terms of the Equation (5), the depth of rectangle groove is $l_{slot} = 2.38$ mm and width $w_{slot} = 2.603$ mm. Thus our proposed array antenna has the same resonance frequency at $f = 10.2$ GHz. Additional, the array is also placed on proposed substrate with the same PBG structure in

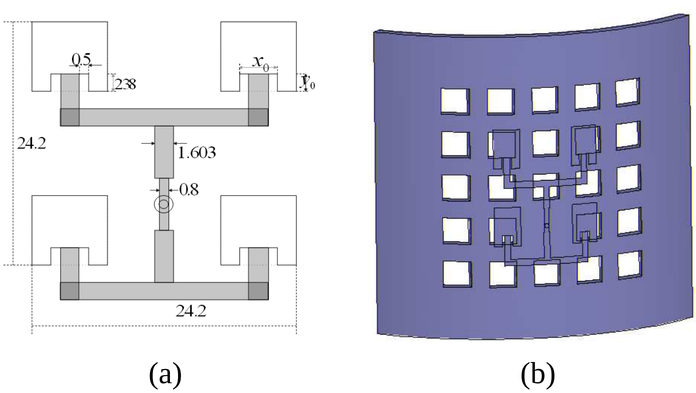


Figure 9. Prototype of cylindrical array with PBG lattice: (a) The patch array, (b) the cylindrical structure.

previous single patch antenna, as is shown in Fig. 9. The distance of the reflection plane's edge to the radiation patch is larger than $\lambda/4$.

4.2. Measurement and Analysis of Proposed Cylindrical Array Antenna

The proposed conformal PBG cylindrical array antenna has been fabricated and measured, as is shown in Fig. 10. Return losses of the cylindrical microstrip array with PBG structure are figured in Fig. 11, the peak return loss is -12.27 dB at 10.2 GHz and a bandwidth of 6.4%, which indicates that the measurement results are in good agreement

Figure 10. Fabricated cylindrical conformal array antenna with PBG lattice.

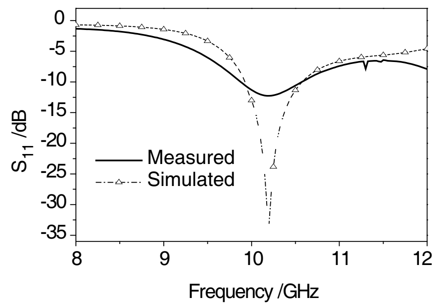


Figure 11. Return loss of cylindrical microstrip array antenna with PBG lattice.

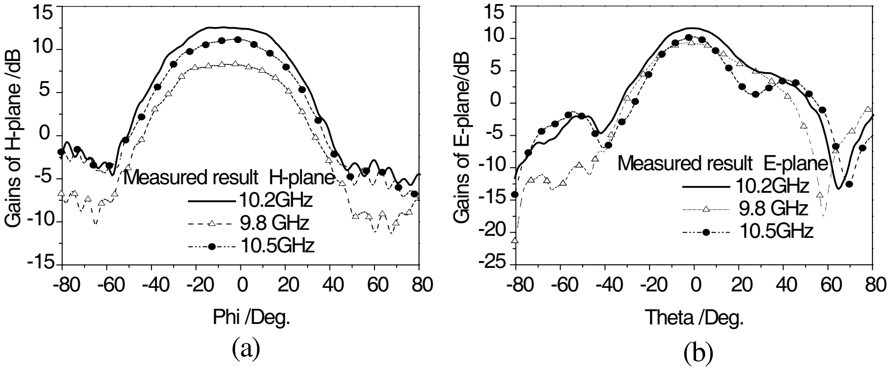


Figure 12. Measured radiation pattern of cylindrical array antenna with PBG lattice at different frequencies: (a) H-plane, (b) E-plane.

with the simulation.

Figure 12 shows the measured H-plane and E-plane radiation patterns of array antenna at 9.8 GHz, 10.2 GHz and 10.5 GHz respectively. It is obvious that the peak of the gain in H-plane at the resonance frequency of $f = 10.2$ GHz reaches 12.85 dB with a peak gain of 11.58 dB in E-plane, a very notable increase in antenna gain.

The results at the resonance frequency 10.2 GHz indicate that the cylindrical PBG structure, both simulated and measured, shown in Fig. 13, could enhance the gain of array antenna and suppress the broadside radiation.

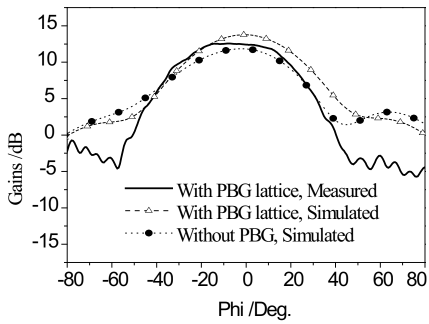


Figure 13. Radiation pattern of cylindrical array antenna with PBG structure.

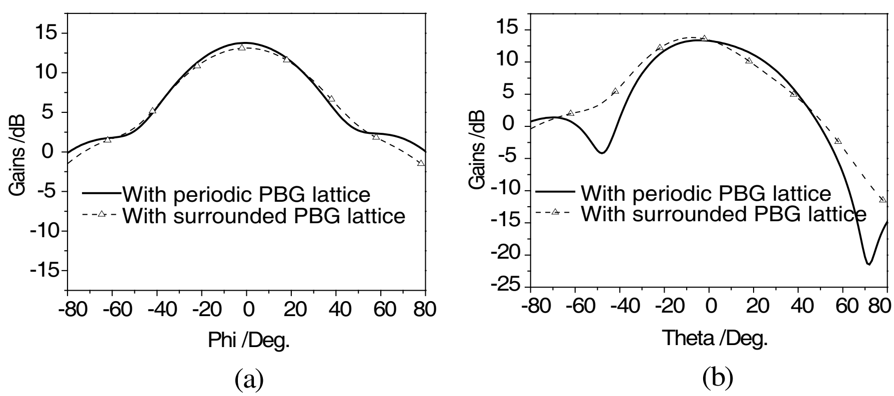


Figure 14. Radiation pattern of cylindrical array antenna with surrounded PBG lattice: (a) H-plane, (b) E-plane.

4.3. Improvement of the Proposed PBG Cylindrical Array

Actually due to the radiation patch of microstrip antenna is only 0.018–0.036 mm in thickness, if the substrate is excavated by uniform PBG lattice, as is shown in Fig. 10, the dangling edge part of patch or feed line is easy to roll up. All these situations would reduce the performance of the antenna. Therefore, we propose an improved cylindrical antenna array surrounded with transformative PBG lattice, shown in Fig. 15, to make sure that the elements of patch and the feed line are sticking on the substrate.

Changing the distance betterments 16.2 mm, the feeding line

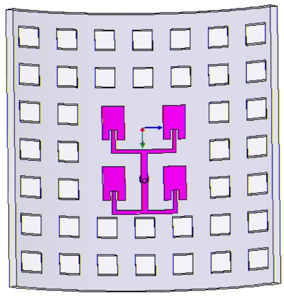


Figure 15. Prototype of improved array with surrounded PBG lattice.

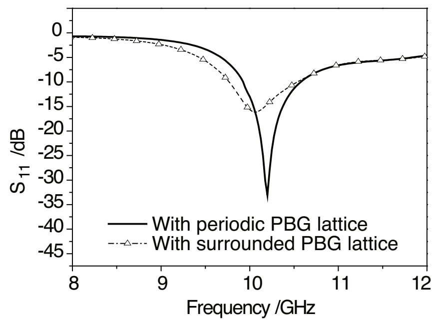


Figure 16. Return loss of cylindrical microstrip array antenna with PBG lattice.

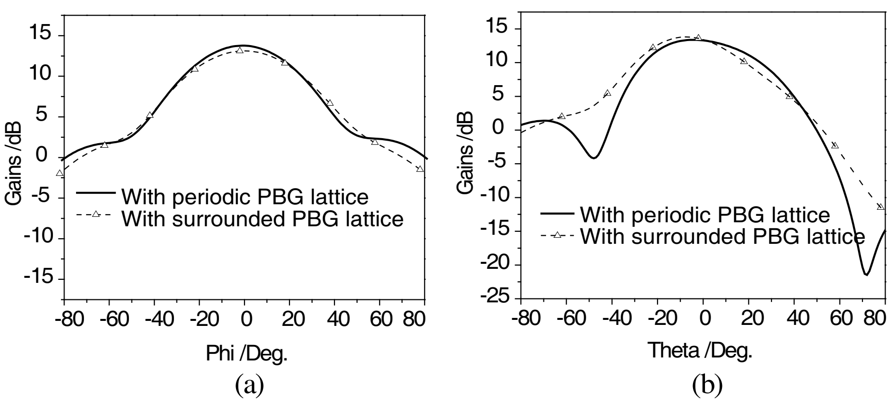


Figure 17. Pattern of cylindrical array antenna with surrounded PBG lattice: (a) H-plane, (b) E-plane.

width $w = 1.0\,\text{mm}$, the depth on cleft rectangle groove $l_{slot} = 1.74\,\text{mm}$ with characteristic impedance $120\,\Omega$. Thus the proposed array antenna is approaching the resonant frequency of $f = 10.1\,\text{GHz}$, shown in Fig. 16. And Fig. 17 indicates that the simulated H-plane and E-plane radiation patterns of improved array are also in good agreement with previous periodic PBG array.

5. CONCLUSION

All the results above show that these new cylindrical conformal antennas with PBG lattice have many advantages over the traditional antennas. The application of PBG lattice to the curved conformal antenna can suppress the surface wave, improve the gain, reduce the side-lobe radiation, and balance the influence of cylindrical curvature at resonance frequency. Furthermore, the proposed cylindrical arrays with PBG structure have a high gain and a small thickness, which make it easy to be mounted on the aircraft surface. In brief, PBG structures are helpful in increasing the performances of antennas and so are these research results in developing practical conformal antennas with BPG structure.

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