Journal of Zhejiang University SCIENCE
ISSN 1009-3095
http://www.zju.edu.cn/jzus
E-mail: jzus@zju.edu.cn

A new photonic bandgap cover for a patch antenna with a photonic bandgap substrate*

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Received Apr. 16, 2003; revision accepted June 20, 2003

Abstract: A new photonic bandgap (PBG) cover for a patch antenna with a photonic bandgap substrate is introduced. The plane wave expansion method and the FDTD method were used to calculate such an antenna system. Numerical results for the input return loss, radiation pattern, surface wave, and the directivity of the antennas are presented. A comparison between the conventional patch antenna and the new PBG antenna is given. It is shown that the new PBG cover is very efficient for improving the radiation directivity. The physical reasons for the improvement are also given.

Key words: Photonic bandgap cover, Patch antenna, FDTD, Plane wave expansion method

Document code: A **CLC number:** TN82; O73

INTRODUCTION

Investigation of photonic bandgap (PBG) materials is currently one of the most active frontiers in engineering and physics. PBG materials have recently emerged as a new multidisciplinary field of study (Kesler *et al.*, 1996; Yablonovitch, 1994; Simovski and He, 2001). A PBG structure can have a bandgap within which electromagnetic (EM) wave propagation is prevented in all directions (Joannopoulos *et al.*, 1997; Ozbay *et al.*, 1994). For a two-dimensional PBG material, the propagation of an EM wave within its bandgap is prevented in all directions within the X-Y plane (Fig.1).

PBG materials had been used to improve the performance of various antennas, such as patch antennas (Gonzalo *et al.*, 1999) and resonant antennas (Lin *et al.*, 2002). In such applications, PBGs were used to replace the usual dielectric or metallic materials in order to improve the performance of the antennas. Patch antennas are very useful in many applications, such as satellites, aircrafts, spacecrafts, missiles, and mobile radios, due to their advantages such as low profile, conformity to planar and nonplanar surfaces, simplicity, inexpensive manufacture, and mechanically robustness (Balanis, 1997; Ying and Kidal, 1996).

In this paper, we introduce a new cover (acting as a lens or passive array) of a two-dimensional PBG structure, to improve the directivity of patch antennas (Thèvenot *et al.*, 1999). A PBG substrate is used in our patch antenna to improve its directivity further by suppressing the surface wave (Brown *et al.*, 1993). The plane wave expansion method (Plihal *et al.*, 1991; Qiu and He, 2000) was used to calculate the photonic band structure of the PBG structure. The input return loss, radia-

* Project supported by the National Natural Science Foundation of China (No. 90101024) and the Science and Technologies of Zhejiang Provinc (No. ZD0002)

input return loss, radiation pattern, surface wave, and the directivity of such a patch antenna were computed by the finite-difference time-domain method (Taflove, 1995), in combination with boundary treatment of the perfectly matched layer (PML) (Berenger, 1994).

In our FDTD computations, the antenna was excited with a Gaussian sinusoidal voltage source. Computations were run for enough steps to ensure that a steady state (all the fields in our computation domain were nearly zero) was achieved. Yee cell sizes of 0.006λ−0.009λ (λ is the working wavelength) were used in the computations. The Fourier transform method was used in the calculations of the radiation patterns.

DESIGN AND RESULTS

The schematic diagram of our PBG patch antenna is shown in Fig.1. The dielectric constants for the substrate and the cover was ε_r=12. The rectangular patch antenna was 27.8 mm wide and 17.8 mm long, and had a 4 mm ($h_{\text{substrate}}$) thick substrate. The central working frequency for such a conventional patch antenna (without any PBG structure) is 2.303 GHz. The TM_0 mode has no cutoff frequency in such a substrate. The cutoff frequency for the first TE_1 mode is $f_c = c_0/(4\, h_{\text{substrate}}\sqrt{\varepsilon_r - 1}) = 5.65$ GHz, which is safely away from the working frequency.

Thus, one only needs to eliminate the TM_0 mode. So we only have to consider the TM mode band structure.

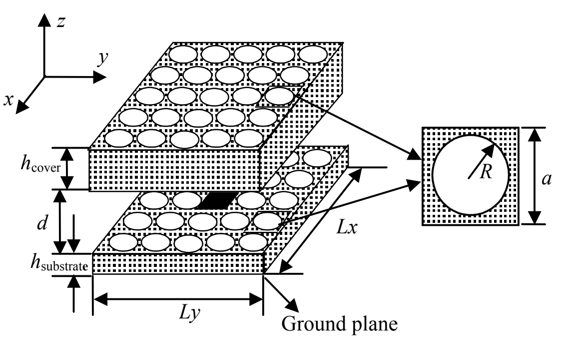

Fig.1 Schematic diagram of the PBG patch antenna

In the present paper, all the PBG structures were formed with a square lattice of air holes in a dielectric host medium (as shown in Fig.1). We chose $R/a = 0.4$ and ε_r=12. The TM mode band structure of this infinite two-dimensional PBG structure was computed with the plane wave expansion method and the result is shown in Fig.2, showing that the TM mode has a bandgap between 0.214 and 0.250 (the normalized working frequency $\omega a/2\pi c_0$. We chose the lattice period a =29 mm. Thus, the PBG structure had a TM mode bandgap between 2.21 and 2.58 GHz.

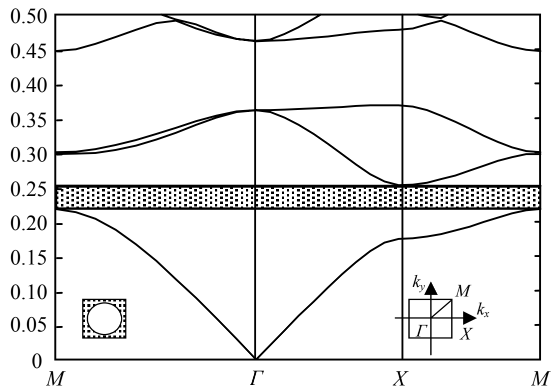

Fig.2 TM mode band structure of the PBG structure with a square array of air columns in a dielectric (ε_r=12) host medium

The substrate was 145 mm×145 mm ($L_x \times L_y$), and consisted of 5×5 unit cells, with the middle air hole unpunched to support the patch antenna. The PBG cover had the same geometrical structure (except for thickness) as the PBG substrate (this can make the fabrication of the whole antenna system easier and cheaper). The PBG cover had a thickness of 30 mm. The distance between the substrate and the cover was chosen to be d = 30 mm.

The input return loss (S_{11}) for the PBG patch antennas and the conventional patch antennas are shown in Fig.3, indicating that the working frequency of the patch antenna shifts slightly in the presence of the PBG substrate and the PBG cover, and that S_{11} has a roughly similar value for all of the configurations at a frequency of f_0 =2.317 GHz, so the radiation patterns, surface waves and the directivities were compared at this frequency.

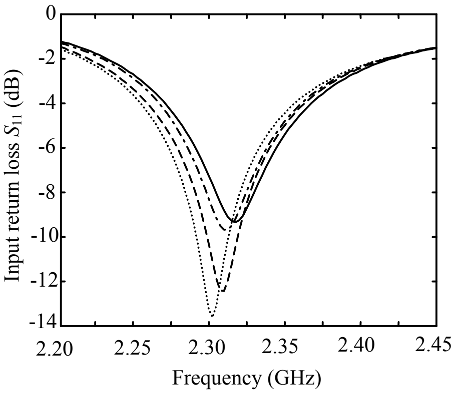

Fig.3 Input return loss (S_{11}) for the conventional patch antenna and PBG patch antennas
—— PBG substrate and PBG cover; ---- PBG cover; -·-·- PBG substrate; ········ Conventional

Fig.4 is a surface plot of the electric field on the surface of the substrate for the cases of (a) the conventional patch antenna and (b) the PBG substrate patch antenna. The figure clearly shows the surface wave suppressed considerably by the PBG substrate.

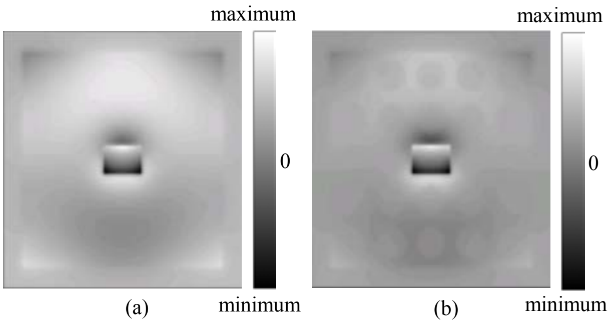

Fig.4 Distribution of the electric field on the surface of the substrate (a) without PBG substrate; (b) with PBG substrate

The PBG cover is illuminated by the EM fields radiated from the patch antenna, which can suppress the propagation of EM wave parallel to the upper surface of the cover. The role of the PBG cover is to control the distribution of the EM fields. No wave can propagate in the cover. Fig.5 on the distribution of the electric field on the upper surface of the cover shows that almost all of the dielectric elements of the cover are excited. Thus,

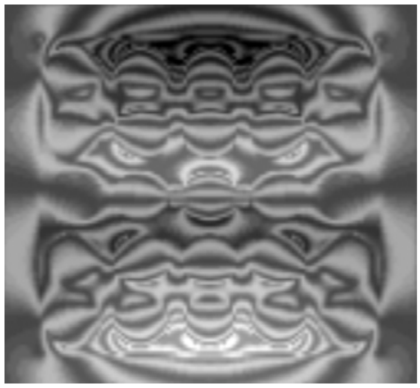

Fig.5 Distribution of the electric field on the upper surface of the cover

the field distribution on the cover surface is quite uniform. So the PBG cover is excited to act as an aperture antenna.

The improvement of the directivity is shown in Fig.6. The directivity of the conventional patch antenna is 4.3 dB, which the PBG substrate can increase to 5.0 dB. The PBG cover can increase the directivity significantly to 10.4 dB. When both the PBG substrate and the PBG cover are used, the directivity of the patch antenna can be increased to 11.2 dB. Theoretically, the maximum directivity of an aperture antenna is $D_{max}=4\pi A/\lambda^2$. Since the area of the aperture is A=145 mm×145 mm, and $\lambda=c_0/f_0$=129.5 mm, one has D_{max}=12.0 dB. The directivity of the designed patch antenna with both the PBG substrate and the PBG cover is very close to the maximum directivity (12.0 dB) physically possible for this size and type of antenna.

CONCLUSION

In conclusion, we have introduced a new PBG cover for a patch antenna with a PBG substrate. The PBG cover has the same geometrical structure (except for thickness) as that of the PBG substrate. This can make the fabrication of the whole antenna system easier and cheaper. The PBG structure was analyzed with the plane wave expansion method. The FDTD method was used to calculate such an antenna system. The input return loss, rad-

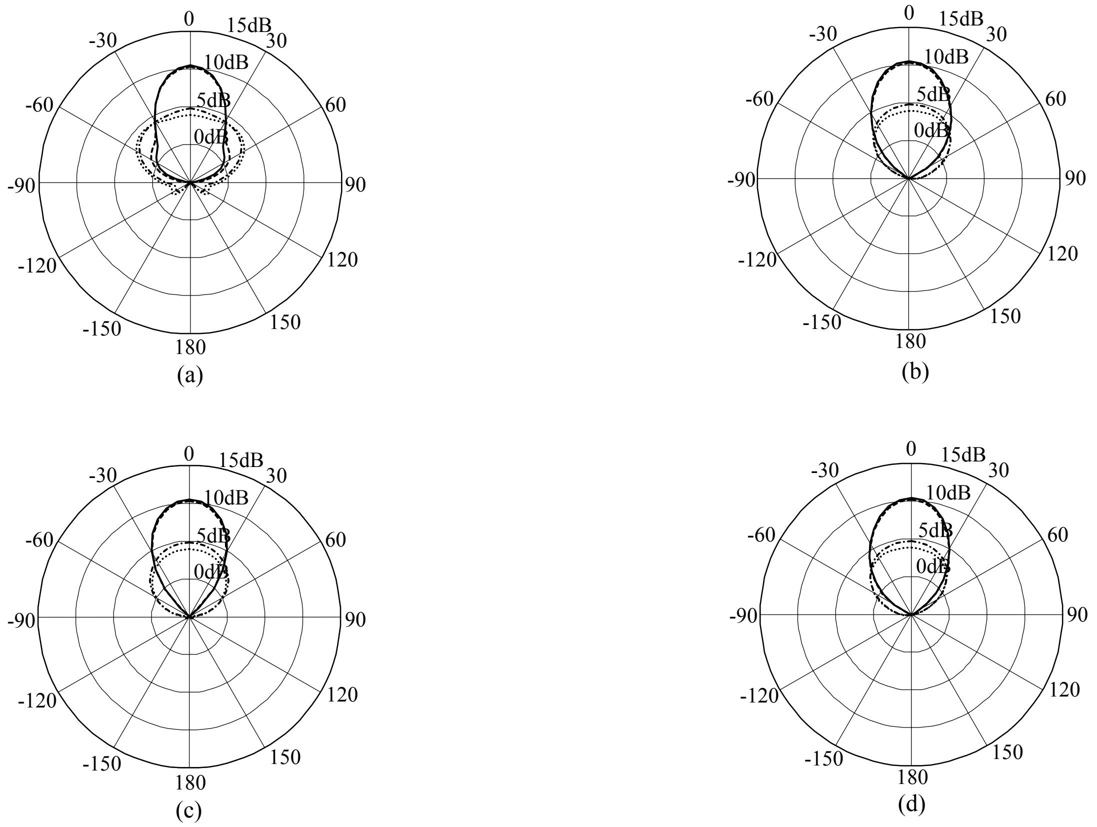

Fig.6 Radiation patterns at a frequency of 2.317 GHz for the conventional patch antennas and PBG patch antennas. (a) the *E*-plane cut; (b) the 45° plane cut; (c) the *H*-plane cut; (d) the 135° plane cut

—— PBG substrate and PBG cover; ---- PBG cover; -·-·- PBG substrate; ········ Conventional

iation pattern, surface wave, and the directivity of the antennas were calculated. The numerical results showed that the radiation directivity of the designed PBG patch antenna was improved significantly.

References

Balanis, C.A., 1997. Antenna Theory: Analysis and Design, Second Edition. John Wiley & Sons Inc., New York.

Berenger, J.P., 1994. A perfectly matched layer for the adsorption of electromagnetic waves. *J. Comput. Phys.*, **114**:185-200.

Brown, E.R., Parker, C.D., Yablonovitch, E., 1993. Radiation properties if a planar antenna on a photonic crystal substrate. *J. Opt. Soc. Am.:B*, **10**:404.

Gonzalo, R., Martinez, B., De Maagt, P., Sorolla, M., 1999. Improved patch antenna performance by using photonic bandgap substrates. *Microwave Opt. Technol. Lett.*, **24**: 213-215.

Joannopoulos, J.D., Villeneuve, P.R., Fan, S., 1997. Photonic crystals: putting a new twist on light. *Nature*, **386**:143.

Kesler, M.P., Maloney, J.G., Shirley, B.L., Smith, G.S., 1996. Antenna design with the use of photonic bandgap materials as all-dielectric planar reflectors. *Microwave Opt. Technol. Lett.*, **11**:169-174.

Lin, Q.C., Fu, J., He, S.L., Zhang, J.W., 2002. Metallic photonic bandgap resonant antennas with high directivity and high radiation resistance. *Chin. Phys. Lett.*, **19**:804-806.

Ozbay, E., Abeyta, A., Tuttle, G., Tringides, M., Biswas, R., Chan, C.T., Soukoulis, C.M., Ho, K.M., 1994. Measurement of athree-dimensional photonic band gap in a crystal structure made of dielectric rods. *Phys. Rev.:B*, **50**:1945-1948.

Plihal, M., Maradudin, A.A., 1991. Photonic band structure of two-dimensional systems: the triangular lattice. *Phys. Rev.:B*, **44**:8565-571.

Qiu, M., He, S.L., 2000. Numerical method for computing defect modes in two-dimensional photonic crystals with dielectric or metallic inclusions. *Phys. Rev.:B*, **61**:12871-2876.

Simovski, C.R., He, S.L., 2001. Antennas based on modified metallic photonic bandgap structures consisting of capacitively loaded wires. *Microw Opt. Technol. Lett.*, **31**:214-221.

Taflove, A., 1995. Computational Electrodynamics: The Finite-Difference Time-Domain Method. Boston-London: Artech House, chap 3.

Thèvenot, M., Denis, M.S., Reineix, A., Jecko, B., 1999. Design of a new photonic cover to increase antenna directivity. *Microwave Opt. Technol. Lett.*, **22**:136-139.

Yablonovitch, E., 1994. Photonic crystals. *J. Modern Opt.*, **41**:173-194.

Ying, Z., Kildal, P.S., 1996. Improvements of dipole, helix, spiral, microstrip patch and aperture antennas with ground planes by using corrugated soft surfaces. *IEEE Process−Microwave Antennas Propagation*, **143**:244-248.