THE CHARACTERISTICS OF A THREE-DIMENSIONAL EBG STRUCTURE *

Xiu-Juan LI[1.2]   Wen-Xun ZHANG[1]   Long-Gen ZHENG[1]   Peng LU[1]

1. State Key Laboratory of Millimeter Waves, Southeast University

2. Department of Physics, Nanjing Xiaozhuang College

State Key Laboratory of Millimeter Waves, Southeast University, Nanjing 210096,CHINA

E-mail lxjxiao@Yahoo.com.cn

1. Introduction

The electromagnetic band-gap (EBG) structure possesses the common forbidden frequency bands to electromagnetic waves with arbitrary polarization and arbitrary propagation direction[1]. The two-dimensional EBG structures (such as: the air holes drilled in dielectric substrate, holes etched on ground plate etc.) have wide application in microwave integrated circuit, which can availably suppress surface waves. But if using EBG in the antenna, the three-dimensional EBG structure must be adopted. In this paper, the three-dimensional periodic EBG structure is composed of dielectric gratings non-orthogonally arranged alternately along the third dimension. It is easy to manufacture layer by layer. Though the complete band-gap for electromagnetic waves with arbitrary polarization and in arbitrary propagation direction does not exist, a common polarization-independent broad band-gap in the normal dimension is found. So this structure can be used as the substrate for printed or low-profile antennas. Not only can it suppress the surface waves, but also improve the radiation pattern.

2. Analysis of the dispersion characteristic

In practical structure, a set of parallel grooves are cut along one basic vector $\vec{a}_1$ in the upper side of a dielectric slab, and another set of grooves along the basic vector $\vec{a}_2$ in the lower side (Fig. 1). The angle between $\vec{a}_1$ and $\vec{a}_2$ is ψ. Then a series of those slabs are stratified to form a periodicity in z direction.

Denote a is the period of groove, b is the depth of groove which equals to a half of the slab thickness, ($a-d$) is the width of groove. So the unit of EBG lattice is a rhombic prism involving two crossed dielectric rods (Fig. 2). Because of the symmetry of unit geometry and the first Brillouin zone, the first Brillouin zone (Fig. 3) can be abstracted to a irreducible symmetric sub-zone as an hexahedron surrounded by eight vertices {Γ, Z, U, Y, K, X, V, W}. Only wave vectors in this irreducible zone are necessary to obtain the dispersive curves. By using MIT Photonic-Bands (MPB) software[2] which is based on the method of plane wave spectrum expansion, a magnetic field wave equation described in terms of Bloch waves is solved iteratively .
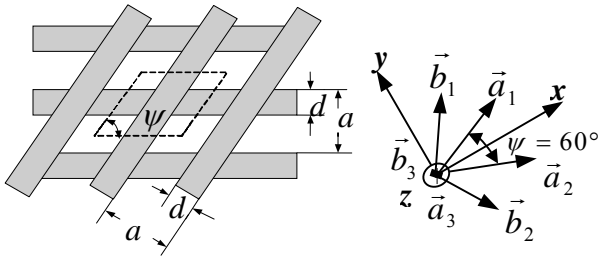

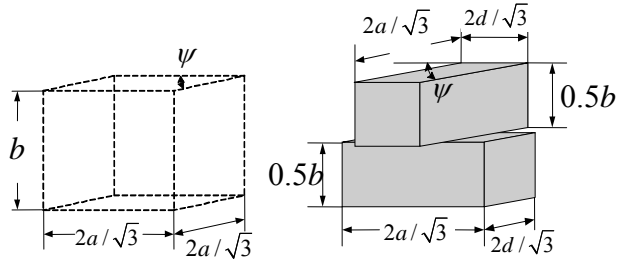Figure1 the EBG structure of non-orthogonal stratified dielectric gratings.

Figure 2 the periodic unit of EBG structure of non-orthogonal stratified dielectric gratings.

When choosing $b = a$, $\varepsilon_r = 4$ and $d = 0.4a$, the results of calculation show that there is no common band gap for electromagnetic waves with arbitrary polarization in arbitrary propagation direction, but there is specific stop band for the waves propagating in some particular direction (Fig. 4). The normalized frequency $\bar{f} = (a/c)f$ is defined, c is the velocity in free space.
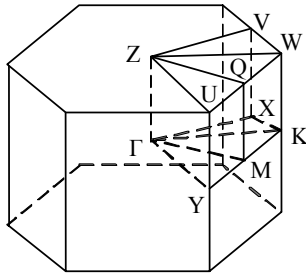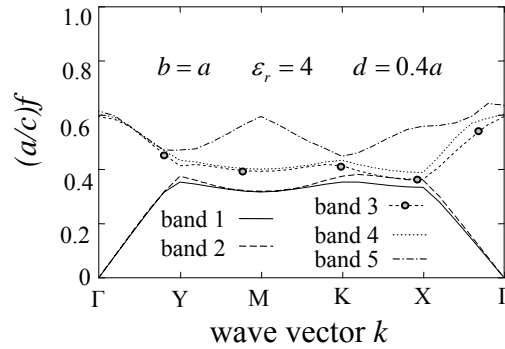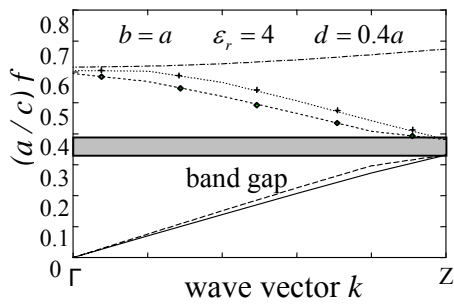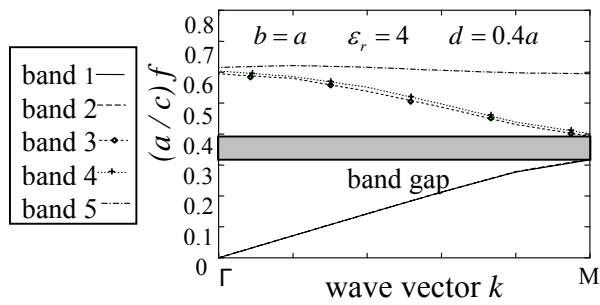

Figure 3 the first Brillouin zone and irreducible Brillouin sub-zone.

a. the dispersion curve of two-dimension xoy plane.

b. stop band along the direction Γ-Z.

c. stop band along the direction Γ-M.

Figure 4 the dispersion curves of rhombic cube ($\varepsilon_r = 4$, $b = a$, $d = 0.4a$).

3.The relative stop bandwith

Further study on the relative stop bandwidth vs. geometric parameters are listed below:

(1) Depending on the permittivity of dielectric substrate (Fig. 5 for $b = a$ and $d = 0.4a$)------

Increasing the permittivity of dielectric substrate can widen the relative stop bandwidth. The relative stop bandwidth for wave propagating along z direction (Γ-Z) is about 13.9% when $\varepsilon_r = 4$, it can approach 27.4% when $\varepsilon_r = 10$. Simultaneously, the center frequency of stop

band will decrease. The absolute stop bandwidth would change little when permittivity is higher.

(2) Depending on the dielectric filled ratio (Fig. 6 for $b = a$)------

Denote the dielectric filled ratio as $q = d/a$. The maximum of relative stop bandwidth occurs at $q \approx 0.4$ for $\varepsilon_r = 4$, or $q \approx 0.3$ for $\varepsilon_r = 10$. On the other hand, the normalized center frequency of stop band $\overline{f_0}$ is down vs. q rise, thus $q = 0.4$ is always chosen.

(3) Depending on the height/width ratio of periodic unit (Fig. 7 for $d = 0.4a$)------

Denote the height/width ratio of periodic unit as $t = b/a$, and let $q = 0.4$. The maximum of relative stop bandwidth occurs at about $t = 0.9 - 1.1$ whatever $\varepsilon_r = 4$ or $\varepsilon_r = 10$, and also the $\overline{f_0}$ are same when $t = 1.0$ in either Γ-Z or Γ-M direction (Fig. 8). So, choosing $t = 1.0$ is reasonable.
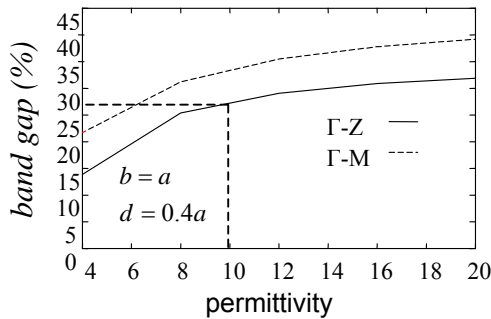

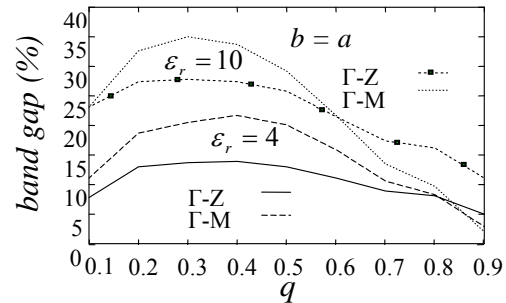Figure 5 the relation of relative stop bandwidth vs. permittivity.

Figure 6 the relation of relative stop bandwidth vs. the dielectric filled ratio.
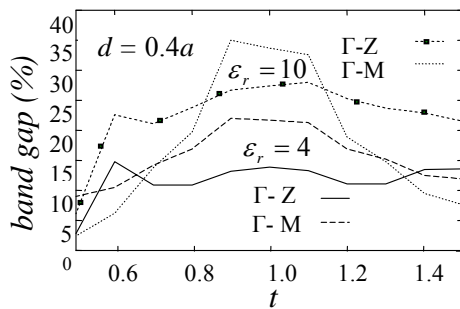

Figure 7 the relation of relative stop bandwidth vs. the height/width ratio of periodic unit.
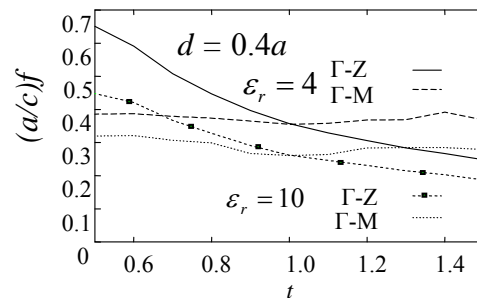

Figure 8 the relation of $\overline{f_0}$ vs. t.

(4) The band-stops in some directions (Fig. 9) ------

There is no common band gap for all cases of polarization and incident angle, but a broad band-gap for normal (z) direction ($\theta = 0°$) exists. There is a common band-gaps existing for specified angular scopes: the smaller angle $\theta < 20°$; and larger angle $\theta > 76°$ and also ϕ in $n \cdot 180° \pm 60°$ $(n = 0,1)$.

Figure 9 the definition of angle θ , ϕ in rhombic lattice.

4. The design data

By synthesizing the above relations between the relative stop bandwidth and the geometric/constitutive

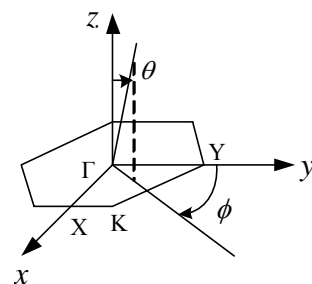parameters, selecting $b = a$ ($t = 1$) and $d = 0.4a$ ($q = 0.4$) in advance. Then the design data are listed in Table 1 (the relation of the center wave-length λ_0 vs. permittivity ε_r, and slab thickness b).

5. The case of finite layers

The dispersion characteristics of infinite layers along z direction are discussed above. However, a practical structure will be constructed by finite layers. How many layers may be considered as approximation of infinite layers, or say, may provide appropriate stop bandwith for the wave propagating along z direction? By using the software HFSS, the 3dB stop bandwidth vs. the number of layer has been simulated, and the results are listed in Table 2, which are also valuable reference data in engineering design.

Table 1 the relation of center wave-length vs. the permittivity and slab thickness.

λ_0 (mm) \ b / ε_r	4 mm	6 mm	8 mm
4.0	11.2	16.8	22.4
8.0	14.0	21.0	28.0
12.0	16.4	24.6	32.9
16.0	18.4	27.6	36.8
20.0	20.2	30.3	40.4

Table 2 the reference data for the engineering design about number of layer and 3dB stop band-width along the normal dimension ($\Gamma - Z$) when $\varepsilon_r = 12$, $a = b$, $d = 0.4a$, $\lambda_0 = 8mm$.

number of layer	3	4	5	∞
thickness of substrate (mm)	5.8	7.8	9.7	∞
Max. of gain (dB)	9.6	14.2	18.7	∞
3dB stop bandwidth (GHz)	11.0	8.5	7.0	10.9
3dB relative stop bandwidth (%)	29.3	22.7	18.7	29.1

6. Conclusion

A common polarization-independent broad band-gap along the normal direction ($\theta < 20°$) is verified, which has also the common band-gap for grazing directions ($\theta \to 90°$) in some azimuth scope. This structure is easy to realize for engineering and can be used as the substrate of low-profile or printed antennas.

In order to design this kind of EBG structure with broader stop bandwidth, (1) to select appropriate structure parameters: making the groove slightly wider than teeth, and the period a equal to the thickness of slab b; (2) to increase the permittivity.

Reference:
[1] J. D. Joannopoulos, R. D. Mead, J. N. Winn, "Photonic Crystals Molding the Flow of Light", Princeton University Press (1995).
[2] S. G. Johnson and J. D. Joannopoulos, "The MIT Photonic-Bands Package", from Internet Homepage http://abinitio.mit.edu/mpb/
[3] S. Satpathy and Z. Zhang, "Theory of Photon Bands in Three-Dimensional Periodic Dielectric Structures", Phys. Rev. Lett. Vol.64, No.11, pp.2646-2649, (1990).
[4] Z. Zhang and S. Satpathy, "Electromagnetic Wave Propagation in Periodic Structures: Bloch Wave Solution of Maxwell's Equation", Phys. Rev. Lett. Vol.65, No.21, pp.2650-2653, (1990).