Investigation of combining dipole antennas with three dimensional photonic crystals

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Abstract. The combination of dipole antennas and 3D diamond-structure photonic crystals is investigated by simulating method in this paper. The radiation frequency point of dipole antennas was selected to correspond to the reflection frequency point of the strongest energy in band gap. The results show that there is a good resonance performance in the range of band gap, which also indicate that in all direction the surface waves which propagate along the surface of the photonic crystals substrate can be suppressed because of the reflection the band gap. Moreover, coupling antenna has low return loss and improves the directionality compared to common dipole antenna. The EM waves are reflected and a high gain is attained, improving from 2.76 dB to 7.14 dB. Due to these merits of photonic crystals substrate, coupling antennas exhibit the excellent radiation performance, which will be widely utilized in communication field.

1. Introduction

The concept of “photonic crystal” was proposed by Yablonovitch and John in 1980s [1-2]. It is a new type of optical micro-structure material, which has a periodic variation of permittivity (or refractivity) in space and has a band structure. The photonic bandgap properties are the most fundamental performance of photonic crystal, which refers that the electromagnetic wave of some certain bands is forbidden to propagate in the photonic crystal structure and reflected in the space [3]. Based on these properties of photonic crystal, photonic crystals can be utilized in many fields, such as waveguide, target stealth, especially in microwave antennas, which are used as the excellent material based on their reflection properties [4-5].

Recently, many scholars have taken on the investigation of the antennas based on photonic crystal substrate. Pooja Sharma and Akanksha Singh proposed a monopole antenna with 2D photonic crystal structure as substrate for ultrawide band application with dual band notched characteristics, and studied and measured the performance of a single patch on a photonic crystal substrate [6]. Ting-gen Shen et al. analyzed the common patch antennas and the patch antennas with crossed idiosyncratic 2D photonic band-gap structure, and found that patch antennas with crossed idiosyncratic PBG structure have a lower return loss, a higher gain [7]. N.D. Lu attained performance parameters of the composite 2D PBG patch antennas by simulation, and he found that it has a lower return loss and a higher gain.
Dadras et al. presented a new monopole antenna using 2D photonic crystal substrate (PCs) structure as substrate and investigated four improved prototype of the proposed antenna, and the structure can operate in Wireless LAN in the U-NII-2/2e bands (channel 52-140, frequency range 5.260-5.725) for first the band and X-band for second band [9].

However, band-gap of 2D photonic crystal only exists in the specific direction of the space, namely incomplete band gap. While 3D photonic crystal can achieve photonic band-gap in any direction of space, namely complete band gap. Therefore, compared with 2D photonic crystal, the application of 3D photonic crystal in antenna has higher efficiency of the reflection and greater gain. Glenn S. Smith et al. prepared a monopole antenna device based on 3D woodpile structure of photonic crystals, and using woodpile structure of photonic crystal as the reflector of a monopole antenna increased the gain of the antenna and improved the radiation performance of the antenna [10-11]. While some studies show that 3D PCs with diamond structure and 3D PCs with beam structure are compared, PCs with diamond structure had wider band gap and greater attenuation of electromagnetic wave.

In this paper, a three-dimensional photonic crystal is proposed as an antenna substrate. Firstly, 3D photonic crystals with diamond-structure were designed and simulated; Secondly, dipole antennas were designed and simulated according to the reflection performance of photonic crystals; Finally, the structure of combining dipole antennas with three dimensional photonic crystals was simulated and analyzed its radiation performance and gain.

2. Designing and computing models of 3D photonic crystals and dipole antennas

All of the macroscopic electromagnetism, including the propagation of electromagnetic wave in a PBG structure, is governed by the four macroscopic Maxwell equations. The four Maxwell equations can be expressed as a single differential equation [12],

\[
\nabla \times \left( \frac{1}{\varepsilon(r)} \nabla \times H(r) \right) = \left( \frac{\omega^2}{c^2} \right) H(r)
\]

It has been known that the Bloch theorem in solid-state physics can be generalized to this equation. Therefore, the solution of equation (1) has the form of Bloch wave:

\[
H_k(r) = e^{i(k \cdot r)} u_k(r)
\]

Ansoft HFSS based on FEM was used in this study to compute the band structure and the radiation performances. By the numerical computing, the range of the band-gap for EBGs and the radiation performances for dipole antenna can obtain [13].

![Figure 1](image1.png) **Figure 1.** Diamond-structure photonic crystals substrate.

![Figure 2](image2.png) **Figure 2.** The structure of dipole antenna.
Figure 3. Structure combining dipole antennas with three dimensional photonic crystals.

The diamond-structure photonic crystal having 3D band gap with a midgap frequency about 16 GHz in our study was designed. The lattice constant of the PCs was designed as 5 mm since its band gap lies at X-band of microwave frequency range. The dimension of the PCs was set as 80 mm*80mm*60 mm (length*width*height), as shown in figure 1. The length of the dipole antenna corresponds to a quarter wavelength of EM wave at a frequency of 16GHz, which is close to the band gap of 3D photonic crystal substrate. The length of dipole antenna is approximately 5mm according to the calculation, as show in figure 2. The coupling structure of photonic crystal and dipole antenna was shown in figure 3. The spacing between photonic crystal and dipole antenna is 5mm.

3. Simulation results and discussion of combining 3D photonic crystals with dipole antennas
Their microwave transmission properties should firstly be matched when 3D photonic crystals with diamond structure were selected as reflection substrate. According to the above the designing structure parameters of photonic crystals, the lattice constant of the PCs is 7 mm and the aspect ratio (the radius of skeleton rod to the lattice constant) is 0.37. In simulation, the dielectric constant of the high dielectric material was set as 45, and we can obtain the transmission properties of photonic crystals substrate, as shown in figure 4. The figure 4 shows that the range of band gap is between 12.9 GHz and 19 GHz, and the midgap frequency is 15.92 GHz, which is almost equal to the designed result (16GHz). Moreover, the transmission loss in band gap is high, especially between 14.2 GHz and 16 GHz, and the value of the transmission loss is under -30dB, which indicates that the photonic crystals substrate can generate strong the property of reflecting microwave and is suit to be used as antennas substrate.

Figure 4. The transmission properties of photonic crystals substrate.  
Figure 5. The return loss of dipole antenna.
According to the reflection properties of 3D photonic crystals, the dipoles were designed and simulated. We simulated these dipole antennas, and the return loss (S11) is shown in figure 5. It can be seen from figure 5 that the radiation band width of the dipole antenna is between 13.9 GHz and 19.2GHz, and the radiation frequency point (16GHz) is included in band width. Moreover, it also can be seen from figure 5 that about 16GHz for the dipoles have the best return loss. The band width and the radiation frequency point of the dipole antenna perfectly correspond to these dates of 3D photonic crystals, which will provide a basis for combining 3D photonic crystals with dipole antennas.

Figure 6 shows that the return loss of composite photonic crystals dipole antenna is excellent between 12.3GHz and 19.2GHz, corresponding to the band gap of photonic crystals, which also indicates that 3D photonic crystals fit to be used as the reflection substrate. Moreover, it can be seen from figure 6 that composite photonic crystals dipole antenna has a better return loss compared to the common dipole antenna. The maximum value of the transmission for the common dipole can get about -16dB, and the maximum value of the transmission for the common dipole can get about -35dB, which show that combining 3D photonic crystals with dipole antennas can obviously improve the value of the return loss. Theoretically, 3D photonic crystals can be used as substrate to improve the return loss and the gain of the dipole.

**Figure 6.** The return loss of composite photonic crystals dipole antenna.

In order to further explain its merits, the radiation of common dipole antenna and photonic crystals dipole antenna were simulated, as shown in figure 7 and figure 8. It can be seen from figure 7 that dipole antenna belongs to an omnidirectional antenna, and the maximum value of the gain can reach 2.76 dB. Figure 8 shows that it is no radiation in back when 3D photonic crystals with diamond structure were combined with dipole antenna. In contrast, the radiation of another side is added and the value reaches 7.14 dB, 4.38 dB improved, indicating that composite photonic crystals dipole antenna can obviously increase dipole antennas’ gain. Figure 8 also shows that EM waves absorbed by the substrate will be reduced, and more energy reflected into the free space will be increased. Moreover, more interference wave will be shield in arbitrary direction due to the band gap properties of in all directions 3D photonic crystals by comparing the 2D photonic crystals substrates. Meanwhile, compared else 3D structures, diamond-structure photonic crystals have more the advantage of controlling band gap, which can realize more perfect combination of antennas and photonic crystals.
4. Conclusions
In this paper, the radiation performances of dipole antennas based on 3D photonic crystals with diamond structure in X-band of microwave frequency range were designed and simulated by FEM method. The results indicated that the chosen radiation frequency point of the dipole antenna corresponds to the strongest reflection frequency point at band gap of photonic crystals, which can make coupling antenna have a lower return loss compared to the common dipole antenna. Moreover, it can obviously improve the gain, improved by almost 2 times, which also can improve the directionality and avoid the interference of else EM microwave.

Acknowledgements
This work is supported by National Natural Science Foundation of China (No. 51508031), China Postdoctoral Science Foundation (No.2015M582583), Shaanxi Natural Science Foundation (No. 2017JM5020 and 2017JM5105) and Fundamental Research Funds for the Central Universities of China (No.300102258202, 300102258104, 300102258106).

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