Two-dimensional plasma photonic crystal structure transmission characteristics

Junyi Zhang*
School of Electronic, Information and Electrical Engineering, Shanghai Jiao Tong University, Shanghai, China
*Corresponding author e-mail: 498910223@qq.com

Abstract. This paper use the finite difference time domain (FDTD) algorithm to study the forbidden band characteristics of two-dimensional non-magnetized plasma photonic crystals. We analyse the obtained S-parameter from the perspective of frequency domain, and discuss the influence of the interlayer angle and distance of the photonic crystal, the polarization mode of the antenna and the plasma parameters on the band gap characteristics. The results show that when the photonic crystal has a certain plasma filling rate, different angles and distances between layers and different polarization modes can achieve modulation of transmission characteristics.

1. Introduction
Since the 1980s, John [1], Yablonovitch [2], etc. first proposed the concept of photonic crystal (PC), and photonic crystal has become one of the hot research topics in the world. A photonic crystal is an artificial dielectric structure composed of a multi-media material and periodically distributed in space. The photonic crystal can be divided into one-dimensional, two-dimensional and three-dimensional photonic crystals through different spatial distributions. These structures can generate a spectral region of the forbidden band frequency called the photonic band gap (PBG). These characteristics of PBG lead to PCs leading to many potential applications, such as narrow filters, omnidirectional mirrors, photodiodes and optoelectronics [3], [4], [5].

In 2004, Hojo and Mase [6] proposed that plasma photonic crystal (PPC) is also a kind of photonic crystal. It consists of artificial periodic structure of plasma and medium or vacuum, which proves that PBG is also present in plasma photonic crystal. And pointed out that as the plasma density or plasma width increases, the frequency gap will become larger. Plasma is a medium with dispersive and dissipative properties that makes plasma photonic crystals have photon band gap properties not found in conventional dielectric photonic crystals [7]. At present, the research work on plasma photonic crystals is mainly concentrated on one-dimensional plasma photonic crystals. Shiveshwari and Mahto [8] studied the photonic band gap effect in one-dimensional plasma dielectric photonic crystals. Fukaya and Tominaga [9] studied the propagation of electromagnetic waves in periodic multilayers. Naumov and Zheltikev [10] studied the ability of ternary one-dimensional photonic crystals to simultaneously phase match, and compared several light fields with different frequencies to propagate in the dispersion medium.

In this paper, a novel two-dimensional plasma photonic crystal is designed. The finite difference time domain algorithm (FDTD) is used to study the forbidden band characteristics of uniform non-time-
varying two-dimensional non-magnetized plasma photonic crystals. The simulation was performed in the case. We calculated the forbidden modulation characteristics of the two-dimensional plasma photonic crystal by calculating the S-parameter of the electromagnetic wave. Then, we analysed the influence of the angle and distance between the layers, the polarization mode of the antenna, and the plasma parameters on the transmission characteristics of the photonic crystal.

2. FDTD algorithm for simulation calculations

This paper use the finite difference time domain algorithm to perform simulation calculation. The process of the FDTD algorithm is first calculated in the time domain—using a wide-spectrum excitation signal to excite the model, and after completing the time domain calculation, the data is inverted to the frequency domain. The network parameters and field parameters of the system are basically obtained after inversion, and a considerable bandwidth result can be calculated.

In the absence of a current source and a magnetic current source (current density and magnetic flux density are zero), the Maxwell curl equation can be expanded into three directions: x, y, and z in a Cartesian coordinate system:

\[
\begin{align*}
\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} &= \varepsilon \frac{\partial E_x}{\partial t} + \sigma E_x \\
\frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z} &= -\mu \frac{\partial H_x}{\partial t} - \sigma_m H_x \\
\frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z} &= -\mu \frac{\partial H_y}{\partial t} - \sigma_m H_y \\
\frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y} &= -\mu \frac{\partial H_z}{\partial t} - \sigma_m H_z
\end{align*}
\]  

(1)

where E is the electric field strength component, H is the magnetic field strength, \(\varepsilon\) is the dielectric constant in vacuum, \(\mu\) is the magnetic permeability, and \(\Delta t\) is the time step.

Using \(f(x, y, z, t)\) to represent the component of the electric field or magnetic field in the Cartesian coordinate system in a certain direction, and discretizing them in the time domain and the spatial domain respectively, the following formula can be obtained.

\[
f(x, y, z, t) = f(i\Delta x, j\Delta y, k\Delta z, n\Delta t) = f^n(i, j, k)
\]  

(3)

The FDTD algorithm uses the frog leaping method to alternately sample the time step, assuming that the time step is \(\Delta t\), the electric field is sampled at the integer time \(n\Delta t\) (\(n=0, 1, 2, 3...\)), and the magnetic field is at a half integer time \((n+1)\Delta t\) (\(n=0, 1, 2, 3...\)) is sampled, so the sampling time of the electric field and the magnetic field differ by half a time step. The new value of the field on each grid point is dependent on the value of the point at the previous time step and the value of the other field at the adjacent point around the point at the first half of the time step. Therefore, one point can be calculated at a time, and the parallel algorithm can calculate multiple points. Through these operations, the values of the electric field magnetic field at each time step can be alternately calculated.

In the calculation, the time discrete step size \(\Delta t\) and the spatial discrete step size \(\Delta x, \Delta y, \Delta z\) must satisfy the Courant-Friedrichs-Levy (CFL) stability condition: \(\Delta t \leq \frac{\sqrt{\varepsilon \mu}}{\sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2}}\).
3. Physical model and simulation calculation

Figure 1 shows a two-dimensional non-magnetized plasma photonic crystal formed by a cylindrically arranged cylinder filled with a plasma as a medium in a quartz tube. The TM wave is incident in the positive direction of the x-axis, and the incident frequency ranges from 6 to 18 GHz. Let a denote the diameter of each cylinder in the plasma photonic crystal, and b denote the diameter of the cylindrical cylinder of the plasma medium filled in the original cylinder. Let d1 denote the distance between the cylinders of the same layer, d2 denote the distance between the layers of the cylindrical array, and denote the angle between the layers of the cylindrical array by α.

![Figure 1](image)

**Figure 1.** This figure is a schematic diagram of the physical model. (a) model perspective view of the angle between layers $\alpha = 0^\circ$, (b) model front view with angle $\alpha = 45^\circ$ between layers, (c) model front view with angle $\alpha = 90^\circ$ between layers, (d) model top view of the angle between layers $\alpha = 0^\circ$

The initial parameters of the simulation calculation are set as follows: single cylinder diameter $a = 8$ mm, plasma cylinder diameter $b = 6$ mm, column spacing $d_1 = 6$ mm, layer spacing $d_2 = 7$ mm, layer angle $\alpha = 0^\circ$, plasma frequency $\omega_P = 4.5 \times 10^9 \text{rad/s}$, collision frequency $\nu = 1.45 \times 10^{11} \text{rad/s}$, and polarization.

To obtain the transmission characteristics of two-dimensional plasma photonic crystals, after the simulation calculation, the electric field component obtained in the time domain is converted into the frequency domain by Fourier transform, and then the S parameter is calculated in the frequency domain.

In the following, the transmission characteristics of the photonic crystal are measured using the angle and distance between the layers and the polarization of the antenna as parameters.
4. Transmission Characteristics of Plasma Photonic Crystals

4.1. Influence of the interlayer angle of photonic crystal on transmission characteristics

Figure 2 shows the relationship between the layer angle $\alpha = 0^\circ$ and $90^\circ$ and the S21 parameter under the initial conditions. It can be seen from the figure that with the increase of $\alpha$, the center frequency of S21’s forbidden band gradually moves towards the low frequency (shifted from 16GHz to 14GHz), and the transmittance gradually decreases; as $\alpha$ continues to increase, the center frequency of the forbidden band gradually moves toward the high frequency (shifted from 14GHz to 15GHz), and the transmittance gradually increases.

![Figure 2. Relationship with S21 parameters when $\alpha = 0^\circ$, $\alpha = 45^\circ$, $\alpha = 90^\circ$](image)

4.2. Influence of interlayer distance of photonic crystal on transmission characteristics

Figure 3 shows the simulation calculations of different layer spacings for the three layer angle models under the initial conditions. The layer spacing d2 is 7 mm and 14 mm (1/4 and 1/2 of the center frequency wavelength), respectively. It can be seen from the figure that in each case, the change in the layer spacing causes a change in the transmission characteristics. With the increase of d2, the center frequency of the forbidden band of S21 in the three models has gradually moved toward the high frequency. This shows that controlling the layer spacing can control the transmission characteristics of the two-dimensional plasma photonic crystal to a certain extent.
4.3. Influence of antenna polarization mode on transmission characteristics

Figure 4 shows the results of simulation calculations for the three models under different polarization modes under the initial conditions. It can be seen from the figure that the simulation results of the same model under horizontal polarization and vertical polarization are different. When $\alpha = 0^\circ$, the center frequency of S21's forbidden band gradually moves to the high frequency direction; $\alpha = 45^\circ$ at $90^\circ$, the center frequency of the forbidden band of S21 gradually moves to the low frequency direction. This shows that the polarization mode also has an effect on the transmission characteristics. On the other hand, it can be seen from Figures 1 and 3 that under the same polarization mode, the S21 parameters of the two models of $\alpha = 0^\circ$ and $90^\circ$ are almost the same.
5. Conclusion

In this paper, the FDTD algorithm is used to simulate the two-dimensional plasma photonic crystal without considering the external magnetic field. The transmission characteristics of the new plasma photonic crystal structure are analyzed by the angle and distance between the layers and the antenna polarization mode. And other factors. The calculation results show that the modulation of the transmission characteristics of the plasma photonic crystal structure can be achieved to some extent by changing the behaviors such as the angle and distance between the layers of the plasma photonic crystal structure and the polarization mode of the antenna. Therefore, a reasonable selection of the angle and distance between layers and the polarization of the antenna can be used to obtain plasma photonic crystals with specific transmission characteristics, which provides a reference for the design of two-dimensional non-magnetized plasma photonic crystal microwave devices.

References

[1] S. John Physical Review Letters 1987 58 (23) pp 2486 ~ 2489
[2] E. Yablonovitch Physical Review Letter 1987 58 (20) pp s2059 ~ 2061
[3] Gu X, Chen X, Chen Y, et al. Narrowband multiple wavelengths filter in aperiodic optical superlattice [J]. Optics Communications, 2004, 237 (1-3): 53 - 58.
[4] Srivastava S K, Ojha S P. Omnidirectional reflection bands in one-dimensional photonic crystal
structure using fullerene films [J]. Progress In Electromagnetics Research, 2007, 74: 181 - 194.

[5] Knight, J. C. Photonic Band Gap Guidance in Optical Fibers [J]. Science, 1998, 282 (5393): 1476 - 1478.

[6] Hojo H , Mase A. Dispersion Relation of Electromagnetic Waves in One-Dimensional Plasma Photonic Crystals [J]. Journal of Plasma and Fusion Research, 2004, 80 (2): 89 - 90.

[7] Liu Shaobin, Zhu Chuanxi, Yuan Naichang. FDTD analysis of plasma photonic crystals [J]. Acta Phys. Sin., 2005 (06): 348 - 352.

[8] Shiveshwari L, Mahto P. Photonic band gap effect in one-dimensional plasma dielectric photonic crystals [J]. Solid State Communications, 2006, 138 (3): 160 - 164.

[9] Fukaya T, Tominaga J. Slab lens with restrained light propagation in periodic multilayer [J]. Journal of the Optical Society of America B, 2004, 21 (7): 1280 - 1288.

[10] Naumov A N, Zheltikov A M. Ternary one-dimensional photonic band-gap structures: Dispersion relation, extended phase-matching abilities, and attosecond outlook [J]. Laser Physics, 2001, 11 (7): 879 - 884.