Analysis of Microwave Transmission Characteristics of Toroidal Plasma Array Photonic Crystal

Can Xu
School of Electronic Information and Electrical Engineering, Shanghai Jiao Tong University, Shanghai, China
a1561294819@sjtu.edu.cn

Abstract. In this paper, a new type of ring-shaped plasma photonic crystal structure is proposed. The influence of the structure parameters on the photonic band gap is calculated by simulation. At the same time, the application possibility of the structure change transmission mechanism is discussed. The use of photonic crystals to achieve tunable forbidden bands is the focus of current research in the field of electromagnetics, and plasmas have been widely used in photonic crystal structures in recent years because of their special electromagnetic properties, density changes with frequency. In addition to studying the band gap regulation of photonic crystals by plasma frequency, it is also an important direction to explore the effects of different plasma photonic crystal shapes and periodic structure parameters on the mechanism of microwave transmission.

1. Introduction
Photonic crystal is an extremely hot concept in the field of electromagnetic research. Because of its special ability to control electromagnetic waves, it has been widely studied since its inception [1]-[2]. Special electromagnetic property of photonic crystals is that it presents a "forbidden" effect on electromagnetic waves at a specific frequency, that is, it generates a photonic band gap, and this is the focus of research on photonic crystals [3]. For conventional photonic crystals, it is difficult to adjust the band gap. Up to now, some people have proposed some methods to achieve the regulation of the photon band gap, but they are somewhat limited by the method's own defects and environmental factors, and cannot achieve the expected results [4]-[5]. Plasma is also a hot topic in the field because of its special dielectric properties. With the deepening of plasma research, it has been found that after introducing plasma into photonic crystals, the propagation characteristics of electromagnetic waves in it will change greatly due to changes in plasma parameters [6]-[7]. The dielectric parameter of the plasma is closely related to the frequency of the incident electromagnetic wave and the plasma density. It is a dispersive medium. Photonic crystals containing plasma are called plasma photonic crystals (p pc). Plasma density has a large effect on the photonic band gap of PPC.

In 2007, Saki et al. pioneered the construction of photonic crystals using gaseous plasma as an element [8]. Due to the ability to change the plasma density, the tenability of the band gap and the passband of the defect state is relatively high compared to a structured metal dielectric. These rates are limited by the plasma's ionization or recombination time, and may be significantly higher than those limited by mechanical, thermal, or fluid time scales. Experimentally, it is possible to control the plasma frequency by changing the operating frequency of the gaseous plasma device. Through modeling and
simulation, and through experimental tests, we explored plasma-based bandgap devices [9]. Owing to surface plasmon wave excitation, the band gap mode. B. wang. Designed a two-dimensional periodic array composed of circular discharge quartz tubes as shown in Figure 1[10]. It was proved through simulation and experiment that the photonic band gap of the plasma photonic crystal was caused by the existence of a plasma with positive and negative dielectric constants.

![Figure 1](image1.png)

**Figure 1.** (a) Schematic diagram of a 7 × 7 plasma photonic crystal array and lattice constant a = 38.1mm. (b) Experimental scene graph.

In this paper, we have designed a plasma photonic crystal structure model in which the plasma rings are periodically arrayed in one dimension. The design concept diagram of the structure is shown below. The CST simulation software was used to simulate the microwave transmission characteristics of the plasma photonic crystal under different structural parameters. The result is that the change of the structural parameters has a regulating effect on the photonic band gap of the designed plasma photonic crystal.

![Figure 2](image2.png)

**Figure 2.** (a) Conceptual diagram of one-dimensional array of toroidal plasma. (b) Schematic cross-section of a circular array structure, the cross-section is parallel to the wave vector direction.
2. Theory of electromagnetic propagation in plasma

For microwave electromagnetic waves, the Helmholtz equation \( \nabla^2 E + k^2 E = 0 \), where \( k^2 = k_0^2 \epsilon_r \), can obtain the propagation factor \( e^{j(kr - \omega t)} \) of the plane wave. Where \( k = nk_0 \) is the wave number of the microwave in the plasma, \( k_0 \) is the wave number in the vacuum, and \( \epsilon_r \) is the relative permittivity of the plasma. In this paper, the plasma permittivity is described by the Drude model.

\[
\epsilon_r(w) = 1 - \frac{w_p^2}{w^2 - i\nu}
\]

Among them, \( \nu \) is the total momentum transfer collision frequency of the plasma electrons, and \( w_p \) is the natural oscillation frequency of the plasma. In the Drude model, based on the basic assumptions of classical electrodynamics, through the continuity equation and Poisson's equation, the oscillation frequency of the "free electron gas" can be derived as:

\[
w_p = \sqrt{\frac{n_e e^2}{m_e \epsilon_0} (2)}
\]

In the above formula, \( e \) is the electronic charge, \( n_e \) is the plasma density, \( m_e \) is the electron mass, and \( \epsilon_0 \) is the vacuum dielectric constant. Maxwell's equation describes the propagation of electromagnetic waves in photonic crystals. In photonic crystals, the dielectric constant and magnetic permeability of a medium are distributed periodically. With the development of photonic crystals, related calculation methods are also continuously improved. Since plasma is a frequency-change medium, the calculation technology of plasma photonic crystals needs to be adjusted accordingly on the basis of the original. Common plasma photonic crystal analysis algorithms include TMM, WKB, PWE and FDTD.

3. Simulation calculation and analysis

Using CST software to model the annular plasma array, the model picture is as follows. The annular is the plasma, which is under the background of air. The plasma studied in this paper is a low-temperature plasma, and its density is on the order of \( 10^{12}/cm^3 \), so the Drude model is selected in the CST, and the angular frequency of the plasma is set to \( \omega_p = 2\pi \times 7.48 \times 10^9 \text{rad/s} \), the collision frequency is \( \nu_p = 1.45 \times 10^{10} \text{s}^{-1} \). The outer ring radius \( R \) of the plasma ring is set to 4mm, and the inner ring radius is 1mm, in other words, the cross-sectional size of the plasma is 3mm. Let the plasma ring be periodically arranged at an interval \( D \) (adjustable) in the propagation direction of the electromagnetic wave (z), and the dielectric environment is air.

Set different periodic intervals, and calculate the transmission of electromagnetic waves in the annular plasma array at different incident wavelengths. As shown in the Fig4, \( S_{21} \) graphs with \( D \) of 3mm,
4.5mm and 6mm are obtained. It can be seen from the observation results that the structure generates photonic band gaps in certain frequency bands at different pitches. As the distance increases, the band gaps shift to lower frequency bands, and the depth of the band gaps increases. Therefore, the periodic array formed by annular plasma and air also has the selective transmission characteristics of electromagnetic waves. In addition, changing the structural parameters of the array can play a role in regulating the band gap. Calculate the electric field distribution at the resonance point, and the obtained distribution map corresponds to the $S_{21}$ curve.

![Figure 4. S21 graphs of different spacings and cross-section electric field graphs of resonance frequency calculated by simulation.](image)

The plane wave is selected and the electric field distribution is calculated. The electric field distribution diagrams at three pitches are obtained as follows. As the distance changes, the transmission mode of the electromagnetic wave in the annular plasma photonic crystal changes. When the distance is smaller, the electromagnetic wave is more distributed on the plasma ring, and when the distance is relatively long, the structure has a lower influence on the electromagnetic wave transmission path. Combined with the figure above, the analysis of the electric field distribution shows that under different structural parameters, the effect of the ring plasma array on the frequency selection of electromagnetic waves is inconsistent, and the influence on the transmission distribution of electromagnetic waves is also different. Therefore, in order to meet the filtering and field distribution requirements in different scenarios, the research results of such a toroidal plasma photonic crystal designed in this article will provide some directions for considering.
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Figure 5. Simulation calculation of X-section electric field distribution of three pitch parameters at 8GHz.

4. Conclusion
In this paper, a new photonic crystal based on a ring cryogenic plasma array is designed in conjunction with CST software simulation. This structure is different from the general plasma cylindrical array, which is an array structure formed by the plasma ring and air periodically alternately arranged in the wave vector direction. By adjusting the periodic arrangement pitch of the plasma photonic crystal, the $S_{21}$ parameters and electric field distribution are calculated by simulation, and it is proved that the change of the periodic pitch will affect the photonic band gap of the photonic crystal. The band-gap resonance points under different structural parameters produce frequency shifts, and the band-gap depth also changes. The calculation result of the electric field distribution reflects the change of the electromagnetic wave transmission mechanism under different structures.

In order to generate electromagnetic grating fringes at specific locations, the plasma photonic crystal structure designed in this article provides a new direction for discussing. In regions where the frequency is lower than the cut-off frequency, there is a transverse electrical (TE) mode band gap due to the surface mode. Above the cutoff frequency, the dielectric constant band gap of the mode is the result of the periodic distribution of the dielectric constant in the plasma and the background medium. Subsequent research can explore more ways to adjust the photonic band gap in combination with changes in plasma frequency.

References
[1] Yablonovitch E. Inhibited Spontaneous Emission in Solid-State Physics and Electronics [J]. Physical Review Letters, 1987, 58 (20): 2059 - 2062.
[2] Knight J C. Photonic crystal fibres [J]. Nature, 2003, 424 (6950): 847 - 851.
[3] Joannopoulos J D, Villeneuve P R, Fan S. Photonic crystals: putting a new twist on light [J]. Nature, 1997, 386 (6621): 143 - 149.
[4] Kitagawa J, Kodama M, Koya S, et al. THz wave propagation in two-dimensional metallic photonic crystal with mechanically tunable photonic-bands [J]. Optics Express, 2012, 20 (16): 17271.
[5] Chong H M H, Rue R M D L. Tuning of photonic crystal waveguide microcavity by thermooptic effect [J]. IEEE Photonics Technology Letters, 2004, 16 (6): 1528 - 1530.
[6] Sakai O, Sakaguchi T, Tachibana K. Plasma Photonic Crystals in Two-Dimensional Arrays of Microplasmas [J]. 2007, 47 (1-2): 96 - 102.
[7] Sakaguchi T, Sakai O, Tachibana K. Photonic bands in two-dimensional microplasma arrays. II.
Band gaps observed in millimeter and subterahertz ranges [J]. JOURNAL OF APPLIED PHYSICS, 2007, 101 (7): 73305 - 0.

[8] O. Sakai, T. Sakaguchi, Y. Ito, and K. Tachibana, “Interaction and control of millimetre-waves with microplasma arrays,” Plasma Phys. Controlled Fusion 47, B617 – B627 (2005).

[9] Sakai O, Sakaguchi T, Tachibana K. Photonic bands in two-dimensional microplasma arrays. I. Theoretical derivation of band structures of electromagnetic waves [J]. J. Appl. Phys, 2007, 101 (7): 73304 - 0.

[10] B. Wang, M. A. Cappelli, "A tunable microwave plasma photonic crystal filter", Appl. Phys. Lett., vol. 107, no. 17, pp. 171107, 2015.