Basic research on reflection characteristics of coupled artificial electromagnetic structures

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Abstract. This paper presents a composite artificial electromagnetic structure that couples a plasma photonic crystal (PPC) with frequency selective surface (FSS). Plasma photonic crystals, as an artificial electromagnetic structure, have the effects of photon band gap and photon locality, but their cut-off frequency is affected by their characteristic scale, so we couple another artificial electromagnetic structure FSS, and expect it to have better electromagnetic properties and tuning capabilities. The S-parameters of this coupled artificial electromagnetic structure in the 6-18GHz frequency band were simulated and measured in a microwave darkroom, which proved that the structure has excellent electromagnetic characteristics.

1. Introduction
In 2004, Hojo H and Mase A proposed the concept of plasma photonic crystal (PPC) [1], which is a periodic structure formed by the periodic distribution of the plasma's own density or staggered arrangement with other dielectric materials. It has a photonic bandgap structure, which can prevent electromagnetic waves whose frequency falls within the forbidden band from being propagated, and at the same time it can be externally driven to change the size and spatial distribution of parameters such as plasma density and temperature [2]. Plasma photonic crystals can control electromagnetic wave propagation in different frequency bands in time and space. Based on the above characteristics, the basic research value and broad application prospects of plasma photonic crystals have become hot cross-cutting topics across the field of plasma and electromagnetic wave control, and are expected to be applied to filters, optical switches, plasma lenses, and plasma stealth weapons for military development [3]. However, the plasma itself is a very complicated medium, and it will produce non-uniformity even in the absence of an external field, which will affect the propagation of electromagnetic waves in the plasma photonic crystal, and even if the plasma has a sufficiently high electron density, May have the same cut-off characteristics and band gap structure as metal. Due to the complexity and limitation of the plasma adjustment, we introduce another artificial electromagnetic structure which is the frequency selective surface (FSS). We hope to couple the influence of the two on the electromagnetic wave transmission characteristics, thereby broadening the electromagnetic characteristics of the periodic structure.

FSS is a two-dimensional periodic structure proposed by the U.S. Munk et al. [4]. The surface is composed of conductive patches or aperture elements. These conductive patches or aperture elements are usually designed to reflect, transmit or absorb electromagnetic waves. When the electromagnetic...
wave is irradiated on the FSS, a surface current is generated on the structure surface, thereby generating a scattering field, so the FSS can pass or block electromagnetic waves of certain frequencies in free space. The FSS structure is loaded on the radome, and according to the equipment requirements, a frequency selective structure with various performances can be flexibly formed to achieve the filter characteristics of in-band transmission and out-of-band high reflection. FSS is mainly used in the radome of an aircraft or a ship. It can conform to the radome geometry without changing the mechanical structure and performance of the radome. At the same time, the signal is filtered to reduce the influence of out-of-band interference and stray radiation [5].

The upper layer of this coupled composite electromagnetic structure is FSS, and the bottom layer is a plasma cylinder arranged at the same period as the FSS surface patch. We tested its S-parameters from 6 to 18 GHz in the microwave darkroom, studied its electromagnetic characteristics, and simulated this coupled artificial electromagnetic structure using CST commercial software. Finally, the results were analyzed for error.

2. Experiment

2.1. Model design

The design of the FSS is shown in Figure 1 (a). The total size is 192mm×192mm. The top layer is a metal patch with a thickness of 0.05mm. The bottom layer is a FR4 dielectric layer with a thickness of 0.5mm. The original cell of the FSS is made of 8 square metal patches, and the length of a single patch is 3mm. The entire FSS board is formed from the original cells in a periodic 8 × 8 array and is produced by the PCB process.

![Figure 1](image)

Figure 1. The Schematic diagram of coupled electromagnetic structure; (a) FSS schematic; (b) Front view of the structure; (c) Top view of the structure

Figures 1 (b) and 1 (c) are the front and top views of the proposed coupled artificial electromagnetic structure, respectively. The top layer is FSS, the middle is a T4 fluorescent lamp with the same cycle as the FSS patch, and the bottom layer is a metal back plate. The T4 fluorescent lamp is 32cm in length and about 12mm in diameter, which is slightly larger than the diagonal width of the metal patch. A total of 15 lamps are placed on the bottom of the FSS. During the measurement, we will place the same area of absorbing foam on the four corners of the FSS to avoid the reflection effect of the fluorescent tube from affecting the measurement result.
2.2. Experiment environment

1987 Ghodgaonkar et al. [6] proposed the free space method to measure the electromagnetic parameters of materials in free space. Since then, the free space method has developed rapidly. This method has high flexibility and can be used when the polarization direction and incident angle of electromagnetic waves change. It is suitable for measuring the electromagnetic parameters of composite materials, and the sample preparation of the free space method is simple, so we apply this method for experiment.

The test system is shown in Figure 2. It consists of two horn antennas, a vector network analyzer, a test bench, a microwave darkroom, and an absorbing material. The transmitting antenna and the receiving antenna are connected to the network analyzer through a coaxial cable, and the electromagnetic waves sent are TEM waves. We placed the test sample on a horizontal test stand, and the sample was about 1100 mm from the transceiver antenna. In order to reduce the experimental error, a 600 × 600 × 700mm apex type absorbing material was placed around the entire dark room.

![Figure 2. Test system diagram](image)

2.3. Experiment method

First, all T4 fluorescent tubes are periodically fixed on the bottom metal plate, and then the FSS is placed above the fluorescent tube. The placement method is shown in Figure 2. The absorbing material is completely blocked. We named the different states of the samples separately, where the state of “FSS + closed PPC + metal plate” is called FSS-PPC-OFF, and the state of “FSS + opened PPC + metal plate” is called FSS-PPC-ON. At the same time, as a comparison experiment, we intercepted a pp foam with the same size as the plasma photonic crystal array and a thickness of 12mm instead of PPC. In other cases, the test conditions were unchanged to compare the effect of PPC on the FSS test results. This state is called FSS. The state where only the metal plate is placed is called the basic state, and it is recorded as BASE.
2.4. Experiment result

Figure 3. Experiment result; (a) 6-18GHz experiment results; (b) 8-12GHz experiment results.

The experiment frequency band is 6-18GHz, and the experiment results are shown in Figure 3 (a). As can be seen from Figure 3(a), compared with the BASE state, this coupled artificial electromagnetic structure has a strong suppression effect on electromagnetic wave reflection. When there is only FSS, the reflectance of the metal plate is reduced by about 6dB at 6-12GHz. The FSS-PPC-OFF state of the coupled artificial electromagnetic structure without turning on the fluorescent lamp has approximately 2dB attenuation in the 6-12GHz frequency band. In this state, the suppression effect of electromagnetic waves is not as good as that of FSS, so we need to turn on the fluorescent lamp to compare the effect of the sample under the plasma excitation state. We can obviously find that the FSS-PPC-ON state has a very obvious attenuation effect in the entire 6-18GHz frequency band compared to the BASE state, and the overall attenuation is close to 7dB. Compared with the FSS state, the attenuation in the 8-12GHz frequency band is also greater than 3dB, which can explain that this coupled artificial electromagnetic structure has relatively good attenuation characteristics for electromagnetic waves.

Figure 3 (a) shows that the frequency band with the best performance of this coupled artificial electromagnetic structure is probably in the 8-12GHz band, so we accurately measured the 8-12GHz band and verified its electromagnetic characteristics again, as shown in Figure 4 (b). We can see that the FSS-PPC-ON state has the best performance at 8-12GHz, compared to the BASE state and the FSS-PPC-OFF state, the attenuation of electromagnetic waves is above 5dB. Only in the frequency bands of 8-8.5GHz and 11.9 ~ 12GHz, the performance is slightly weaker than FSS, which is contrary to Figure 4 (a). This is because the time-domain characteristics of electromagnetic waves are more complicated. The network analyzer's measurement results may differ in different frequency bands. These errors are subject to Fourier transform, which leads to differences in the final results in certain frequency bands. This error range is acceptable.

3. Simulation and discussion

3.1. Parameter design

Plasma is usually described by $\nu_c$ and $\omega_{pe}$ \cite{7}, where $\omega_{pe}$ is the plasma frequency, and $\nu_c$ is the collision frequency. $S_{11}$ can be expressed as following (1):

$$S_{11} = \frac{T(1-\Gamma^2)}{1-\Gamma^2T^2}$$ (1)
Where $\Gamma$ is the single reflection coefficient, $T$ is the transmission coefficient and the refractive index $n$ has relationship with $S11$ (2):

$$n = \mu - j\chi$$  \hspace{1cm} (2)

Then

$$\mu = \sqrt{\frac{1}{2} \left( 1 - \frac{\omega_{pe}^2}{\omega^2 + v_e^2} \right) + \frac{1}{2} \sqrt{\left( 1 - \frac{\omega_{pe}^2}{\omega^2 + v_e^2} \right) + \frac{v_e^2}{\omega^2} \left( \frac{\omega_{pe}^2}{\omega^2 + v_e^2} \right)}}$$  \hspace{1cm} (3)

And

$$\chi = \sqrt{-\frac{1}{2} \left( 1 - \frac{\omega_{pe}^2}{\omega^2 + v_e^2} \right) + \frac{1}{2} \sqrt{\left( 1 - \frac{\omega_{pe}^2}{\omega^2 + v_e^2} \right) + \frac{v_e^2}{\omega^2} \left( \frac{\omega_{pe}^2}{\omega^2 + v_e^2} \right)}}$$  \hspace{1cm} (4)

After the experimental results are substituted into the above formula [7], the plasma collision frequency and plasma frequency can be calculated, which are about $5.3 \times 10^9 Hz$ and $3.7 \times 10^{10} Hz$, which can be brought into the simulation.

3.2. Simulation analysis

We model our experimental model through commercial simulation software CST, and verify the accuracy of the experimental results through simulation. We set the settings in CST as shown in Figure 4. We set the Zmax direction as the open boundary, and the Zmin direction as the electric wall boundary. The time-domain solver was used for simulation. The CST software's time-domain solver algorithm uses the FDTD algorithm to solve, and it is widely used in the field of periodic structure analysis algorithms with high accuracy. We simulate the FSS-PPC-ON state, and the simulation results are shown in Figure 5.

![Figure 4. CST model side view](image1)

![Figure 5. CST simulation results](image2)

It can be seen from Figure 5 that FSS-PPC-ON basically has an attenuation of nearly 10dB in the whole range in the frequency band of 6-18GHz, and even 20dB attenuation near 10GHz. The simulation results are in good agreement with the overall trend of experimental results. However, there is a certain
error in the attenuation amplitude of electromagnetic waves, which mainly comes from the following aspects:

1. The actual plasma density distribution is not uniform. We use a T4 fluorescent tube array to simulate a PPC array, but the plasma distribution in the fluorescent tube is non-uniform, and the thickness of the tube wall also affects the transmission of electromagnetic waves. These problems cannot be simulated cause errors.

2. We generally use the Drude model to analyze the plasma system, but the model itself is relatively rough, causing errors in the plasma frequency and collision frequency we designed;

3. The nonlinear calculation of FDTD itself has errors.

Taking these factors into consideration, we believe that this error range is within our acceptance range, so the actual electromagnetic characteristics of this coupled artificial electromagnetic structure are excellent, indicating that our design has great value and potential in the study of periodic electromagnetic structures.

4. Conclusion
In this paper, the reflectivity of the artificial electromagnetic structure coupled by FSS and PPC is tested and simulated, and the error analysis is performed systematically. On the one hand, we have verified that the coupling structure has a strong suppression effect on electromagnetic waves in the 6-18GHz frequency band. After adjusting and optimizing the structure, it can be used as high-frequency filtering. On the other hand, we modeled and simulated the model in CST to verify the accuracy of its electromagnetic characteristics. This paper proposes a new type of coupled artificial electromagnetic structure, which provides a new idea for the study of periodic electromagnetic structure, which is of great significance in the field of electromagnetic field.

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