Study on the reflection characteristics of the composite structure coupled with periodic plasma and frequency selective surface

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Abstract. This paper proposes and prepares a composite structure composed of periodic plasma structure and three-dimensional (three-layer) metal period structure. The printed circuit board (PCB)-based frequency selective surface (FSS) is a double-layer conjugate structure. The periodic plasma structure consists of six horizontally aligned T8 fluorescent tubes. The composite structure exhibits some characteristics of plasma photonic crystal. The effects of periodic plasma structure, metal grids above periodic plasma and polarization angle on the reflection of metal periodic structure are studied in this paper. Experimental results show that FSS of the composite structure causes the reflection of electromagnetic wave to drop by 6.3 dB at 2.0 GHz compared with the composite structure without FSS. When the polarization angle is 30 degrees, the metal grids above the periodic plasma can further reduce electromagnetic wave reflection, and the reflection of a composite structure with metal grids is about 14dB lower than that of structure without metal grids at 1.89GHz. In addition, when the polarization angle changes from 0 degree to 30 degrees, the reflection of electromagnetic wave drops by 9.3 dB at the absorption peak.

1. Introduction

The concept of plasma photonic crystal is proposed by Hojo H and Mase A in 2004, plasma photonic crystal is a new class of photonic crystals composed of alternating plasma and other medium [1]. Plasma photonic crystal not only has the characteristics of reflection of a general photonic crystal, but also has the physical properties of plasma, the reflection characteristics of plasma photonic crystal can be controlled by changing the parameters of the plasma or by changing external parameters such as pressure, temperature and applied magnetic field [2], [3]. The reflection characteristics of plasma photonic crystal have very important research and application value. With this characteristic, tunable plasma photonic devices can be fabricated [4], [5], etc., plasma lens [6] and plasma antenna [7]. Due to the large instability of the control of external environmental parameters, it becomes more difficult to dynamically adjust the reflection of the plasma photonic crystal. Moreover, since the transmittance of the plasma photonic crystal is relatively high, the application of the plasma photonic crystal is limited.

Frequency selective surface is a periodic surface structure, which refers to as an infinite array of exactly the same cells arranged in one- or two-dimensional directions [8]. Frequency selective surface is a kind of spatial filter. Through reasonable design, the frequency selective surface has good frequency selection characteristics, which can be applied to the design of specific bandpass filters [9]. In this paper,
a periodic plasma structure coupled with a three-dimension metallic periodic structure is proposed, which is not reported in the literatures. With good cut-off frequency characteristic of FSS, it is hoped that the composite structure can solve the problem of excessive transmittance of periodic plasma structure and reduce the reflection of electromagnetic wave, thus the effects of FSS, metal grids above the periodic plasma structure and polarization angle on the reflection of the composite structure are studied.

2. Experimental

2.1. Experimental set up
A schematic diagram of the measurement system is shown in Figure 1(a), Figure 1(b) is an image of the test chamber environment:

Figure 1. The measurement system:(a) schematic diagram of the measurement system; (b) the test chamber environment and sample.

The test system consists of a vector network analyzer, two horn antennas, a test stand, test samples arranged in a dark-room. The transmitter and receiver antennas are connected by coaxial cable to the receive and transmit ports of the network analyzer. The test sample is placed on a horizontal test rack. To reduce the experimental error, the level of the sample is checked with a level tester before each test. In the frequency range of 0.4-2.2 GHz, test results show that the frequency point of the absorption peak (maximum - minimum)/average is 0.02%.

Figure 2 is the schematic of the composite structure, which is coupled by periodic plasma structure and three-dimensional (three-layer) metal periodic structure that is composed of the FSS and periodic metal grids. On the right is the top layer and on the left is the bottom layer in Figure 2(b)

The composite structure includes FSS, metal grids, periodic plasma structure and metal plate. The first layer is the FSS, the overall size is 159.94mm × 159.94mm × 2mm, which is processed by PCB process. The unit cell of FSS is 10.66mm × 10.66mm × 2mm, it is shown in Figure 3.

The thickness of the metal structure in the unit cell is 0.025 mm, and the thickness of the FR4 dielectric layer is 1.46 mm. Two metal structures in each layer of the unit cell are connected in series by a resistor and a capacitor, the top layer is R1 and C1, and the bottom layer is R2 and C2. The cells are also connected in series by resistors and capacitors, the top layer is R3 and C3, and the bottom layer is R4 and C4, the resistance of the resistors is between 100Ω to 2000Ω, and the value of the capacitor is between 2.2μF to 47μF.
Figure 2. The schematic diagram of the composite structure: (a) top view of the structure; (b) side view of the structure.

Figure 3. Structure of the unit cell of FSS: (a) top view of a unite cell; (b) side view of a unite cell; (c) perspective view

2.2. Test plan

The polarization angle is defined as the angle at which the composite structure rotates around its center in the X-Y plane, when the antenna is fixed in this paper.

In order to study the dynamic tuneable characteristics of the reflection of the composite structures, the following three schemes are proposed, Table 1 is the combined state of scheme A:

- A: study the effect of the FSS on the tuneable characteristics of the composite structure reflection;
- (1) FLFM, the FSS(F) is at the top, lamp-off(LF) is under the FSS, metal plate(M) is at the bottom;
- (2) LOM, lamp-on(LO) is above metal plate(M);
- (3) FLOM, the FSS(F) is at the top, lamp-on(LO) is behind the FSS, metal plate(M) is under lamp;
- (4) M, there is just a metal plate

| Configuration | FSS | Lamp | Metal grid | Metal plate | Polarization angle |
|---------------|-----|------|------------|-------------|--------------------|
| (1)           | FLFM| Yes  | Off        | No          | Yes               | 0°                 |
| (2)           | LOM | No   | On         | No          | Yes               | 0°                 |
| (3)           | FLOM| Yes  | On         | No          | Yes               | 0°                 |
| (4)           | M   | No   | Off        | No          | Yes               | 0°                 |

Table 1. Each state combination table of plan A.
B: study the effect of metal grids on the tuneable characteristics of the composite structure reflection when polarization angle is 30 degrees, Table 2 is the combined state of scheme B:

1) FLOMM, the FSS(F), which coupled with metal grids(M), is at the top, lamp-on(LO) is under the FSS, and metal plate(M) is under lamp;

2) FLOM, the FSS(F) is at the top, lamp-on(LO) is under the FSS, and metal plate(M) is under lamp;

3) M, there is just a metal plate;

Table 2. Each state combination table of plan B.

| Configuration | FSS | Lamp | Metal grid | Metal plate | Polarization angle |
|---------------|-----|------|------------|-------------|-------------------|
| (1) FLOMM     | Yes | On   | Yes        | Yes         | 30°               |
| (2) FLOM      | Yes | On   | No         | Yes         | 30°               |
| (3) M         | No  | Off  | No         | Yes         | 30°               |

C: study the effect of polarization angle on the tuneable characteristics of the composite structure reflection. Table 3 is the combined state of scheme C:

1) FLOMM, the FSS(F), which coupled with metal grids(M), is at the top, lamp-on(LO) is under the FSS, and metal plate(M) is under lamp (0°);

2) FLOMM, the FSS(F), which coupled with metal grids(M), is at the top, lamp-on(LO) is under the FSS, and metal plate(M) is under lamp (30°);

3) FLOMM, the FSS(F), which coupled with metal grids(M), is at the top, lamp-on(LO) is under the FSS, and metal plate(M) is under lamp (90°);

Table 3. Each state combination table of plan C.

| Configuration | FSS | Lamp | Metal grid | Metal plate | Polarization angle |
|---------------|-----|------|------------|-------------|-------------------|
| (1) FLOMM     | Yes | On   | Yes        | Yes         | 0°                |
| (2) FLOMM     | Yes | On   | Yes        | Yes         | 30°               |
| (3) FLOMM     | Yes | On   | Yes        | Yes         | 90°               |

2.3. Test results
The results of several tests show that the experiment has good stability and repeatability, in the frequency range of 0.4-2.2 GHz, test results show that the frequency point of the absorption peak (maximum - minimum)/average is 0.02%, the following is one of the test results.

Figure 4. The effect of FSS on the tuneable characteristics of composite structure reflection: (a) with metal plate; (b) subtracting metal plate.
The effect of the FSS on reflection of the composite structure at a polarization angle of 0 degree is shown in Figure 4. The four curves corresponding to the plan A are shown in Figure 4(a), and Figure 4(b) is the curve obtained by subtracting the S21 value of metal plate. It can be seen from the above two figures that in the frequency band of 0.4-2.2 GHz, the FSS can dynamically adjust the reflection of the composite structure, forming a deep absorption peak at 1.2 GHz and 2.0 GHz. At 2.0 GHz, the composite structure with FSS decreased by 6.3 dB over the S21 value of the composite structure without FSS.

The dielectric coefficient of the plasmas is higher than that of the air and distributed in the T8 columns, it is expected that the lateral propagation of the electromagnetic field (EMF) is comparatively significant. Consequently, the idea of cutting the propagation route of the lateral branch of EMF energy and generating new series of periodic back-scattering EMF by inserting the second layer of metal sheets between every two plasma columns have been experimented. Besides, the propagation properties of the EMF in the boundary region of plasma-metallic sheets have been examined by the calculation of the electric field distribution. Based on this idea, metal grids are added to a portion of the periodic plasma structure to study the effect of the metal grids on the dynamic tunable characteristics of the reflection. It is found that the reflection of the composite has good dynamic tunability at a polarization angle of 30 degrees. The test results of scenario B are shown in Figure 5:

![Figure 5](image-url)

**Figure 5.** The effect of metal grid on the tuneable characteristics of the composite structure reflection: (a) metal grid; (b) without metal grid.

It can be seen from Figure 5 that the reflection of the composite structure with metal grids has better dynamic adjustability when the polarization angle is 30 degrees. The reflection of electromagnetic waves is weakened throughout the frequency band, and the S21 curve is moved down as a whole; At the absorption peak of 1.89 GHz, the composite structure with metal grids is 15dB lower than the S21 of the composite structure without metal grids.

It can be seen from Figure 6 that when the polarization angle is increased from 0 degree to 30 degrees, the S21 of the composite structure is reduced by 9.3 dB at the peak than the composite structure at 0 degree, the S21 with 90 degrees is also worse than that with 30 degrees. The polarization angle can significantly improve the dynamic tunability of the reflection of the composite structure.
The effect of polarization angle on the tuneable characteristics of the composite structure reflection: (a) with metal plate; (b) subtracting metal plate.

3. Discussion

The test results for the three scenarios are given in the paper, and we will discuss some interesting issues here.

There is an inevitable connection between plasma density and transmittance, S21 can be expressed as following:

\[ S_{21} = \frac{T(1-\Gamma^2)}{1-\Gamma^2 T^2}, \]  

where T is the transmission coefficient and \( \Gamma \) is the single reflection coefficient. The permittivity \( \varepsilon \) is related to \( S_{21} \) and is also related to the plasma frequency \( \omega_{pe} \) and collision frequency \( \nu_c \) [10], and can be expressed as:

\[ n = \sqrt{\varepsilon}, \] 
\[ n = \mu - j\chi, \]

where

\[ \mu = \sqrt{\frac{1}{2} \left( 1 - \frac{\omega_{pe}^2}{\omega^2 + \nu_c^2} \right) + \frac{1}{2} \sqrt{\left( 1 - \frac{\omega_{pe}^2}{\omega^2 + \nu_c^2} \right)^2 + \frac{\nu_c^2 \left( \omega_{pe}^2 \omega^2 + \nu_c^2 \right)}{\omega^2 \left( \omega^2 + \nu_c^2 \right)}}, \]

and

\[ \chi = \sqrt{-\frac{1}{2} \left( 1 - \frac{\omega_{pe}^2}{\omega^2 + \nu_c^2} \right) + \frac{1}{2} \sqrt{\left( 1 - \frac{\omega_{pe}^2}{\omega^2 + \nu_c^2} \right)^2 + \frac{\nu_c^2 \left( \omega_{pe}^2 \omega^2 + \nu_c^2 \right)}{\omega^2 \left( \omega^2 + \nu_c^2 \right)}}, \]

In this paper, the transmittance is measured by microwave transmission method [10], and then the above expression is used to obtain the plasma frequency and collision frequency. According to the experimental results, the electronic number density of T8 fluorescent lamps ranges from \( 0.8 \times 10^{11}/\text{cm}^3 \) to \( 5.3 \times 10^{11}/\text{cm}^3 \), the collision frequency is \( (2-7) \times 10^{11}\text{Hz} \).

When an electromagnetic wave is incident on the surface of a composite structure, what is the effect of the plasma on the surface electric field of the composite structure? It can be seen from Figure 4 that when the electromagnetic wave is incident on the surface of the structure coupled with FSS and plasma, a strong double absorption peak appears, the resonance is strengthened, and in the frequency band other than 1.3-1.86 GHz, the S-parameter curve is shifted downward. In order to explore the cause of this phenomenon, this paper selects plan A to establish a model, and uses CST to calculate the surface electric field at 2.0GHz before and after coupling of FSS and plasma. The results are shown in the following figures:
Figure 7. The electric field changes of the composite structures before and after plasma and FSS coupling: (a) without coupling plasma; (b) coupling plasma.

It can be seen from Figure 7 that when the electromagnetic wave is incident on the surface of the FSS before coupling, the electric field on the FSS edge surface is weaker, and the surface electric field in the middle region is relatively stronger. When the electromagnetic wave is incident on the surface of the composite structure after the plasma and FSS coupling, the electric field distribution on the surface of the composite structure is more uniform, and the edge effect is strengthened, which may cause the phenomenon of reflection energy ‘dispersion’ in the frequency domain, as shown in Figure 4.

It can be seen from Figure 5 that a deep absorption peak appears at 1.89 GHz and the reflection is the lowest. In order to explore the relationship between this phenomenon and the surface electric field, the article calculates the surface electric field strength at the two frequency points of 0.7GHz and 1.89GHz based on the scheme B. The results are shown in the following Figures:

Figure 8. The distribution of electric field on the surface of the composite structure: (a) 0.7GHz (b) 1.89GHz.

As can be seen from Figure 8, the surface electric field corresponding to 1.89 GHz is weaker, and the surface electric field corresponding to 0.7 GHz is stronger. Since the electric field can store energy, the corresponding electric field at the stronger reflection point should be strong, and the surface electric field at the weaker reflection point should be weaker.

The major effects of the experiments include: (1) The position of the absorption peak of the composite structure after coupling is shifted and significantly reduced; (2) The introduction of the metal grids causes the S21 curve to move down as a whole, and the surface electric field distribution is diffused; (3) The reflection effect of the composite structure on electromagnetic wave is related to the polarization angle.
It is suggested the transmission line theory can be used to shed some light on the underlying mechanisms. The frequency-selective absorbing effect of a FSS could be understood by the impedance matching of the equivalent-circuit of the scattering system of the device under study herewith. Since FSS has impedance matching characteristics, the FSS interacts with the periodic plasma structure to make the impedance match better at the frequency point of the absorption peak, which reduces the reflection of electromagnetic wave, so that the electric field energy at the frequency point corresponding to the absorption peak is consumed a large amount to generate a weak reflection. To quantitively characterize the relationship between the electric field distribution and the reflectivity measurements, the calculation results of the electric field on the surface of the metal sheets have been shown in Figure 7 and 8, the simulation results are consistent with the experimental results.

4. Conclusions
In this paper, the dynamic tunability of the reflection of composite structure in 0.4-2.2GHz is studied, experimental results show: when the polarization angle is 0 degree, the introduction of the FSS in the periodic plasma can cause the composite structure to have two absorption peaks in the 0.4-2.2 GHz band, the composite structure with FSS is reduced by 6.3 dB compared with the composite structure without FSS at 1.89 GHz; The metal grids can reduce the absorption peak of a composite structure by 15 dB at a polarization angle of 30 degrees. Furthermore, the polarization angle also has an effect on the dynamic tunability of the band gap of the composite structure. The surface electric field corresponding to the frequency point of absorption peak is weaker and the periodic plasma structure has a significant effect on the distribution of fringing elective fields. The future works will focus on the coupling mechanisms of different layers of periodic structures and optimize the general effects shown in this tentative study.

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