Study on electromagnetic dynamic tunability of composite structure based on plasma periodic structure loading frequency selective surface

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Abstract. The plasma periodic structure has dynamic reconstruction characteristics having important practical significance in electromagnetic engineering applications. In this paper, a composite electromagnetic structure consisting of plasmas which are periodically arranged and frequency selective surface is proposed and researched. Based on the periodically arranged plasma columns, the frequency selective surface is introduced to study whether a photon-like effect will occur on EM waves propagation in the composite structure even a stronger dynamic tuning ability. The reflectivity between 1~2GHz and 8~12GHz was tested in a microwave dark room to study the influence of periodic plasma and frequency selective surface on incident electromagnetic waves with the free space method. A commercial electromagnetic software also was used to calculate the electric field at different frequency points, and study the mechanism of its interaction with electromagnetic waves.

1. Introduction

In the 1880s, E Yabolnovitch and S John proposed the concept of photonic crystals. John believed that in a superlattice of carefully designed dielectric materials, photons exhibit a strong Anderson locality [1]. When the photonic crystal is ideally free of defects, there is no attenuation mode of light depending on the periodicity of its boundary conditions. If the periodicity of the photonic crystal is destroyed, a strong local state or defect mode will appear at the defect location, and only light of a specific frequency can appear in this defect. The photonic local characteristics of photonic crystals has been studied to conduct many applications such as photonic crystal waveguides [2], photonic crystal fibers [3], optical switches, optical amplification filters, etc. [4, 5].

Plasma photonic crystal is a new research hotspot in photonic crystals. In 2004, Hojo and Mase first proposed the concept of plasma photonic crystal (PPC), including plasma and dielectric periodic placed or plasma with periodic distribution density [6]. The technological applications of PPC are now expanding widely, for example, in plasma lens [7], plasma antenna [8], and plasma stealth aircraft [9]. And there reflectionless transmission due to the Fabry-Pérot resonance in PPC can be applied to frequency filters [10] and interferometers [11]. These periodic plasma structures, which are controllable by external parameters, can create more new possibilities in photonic crystals.

A frequency selective surface (FSS) often consists of an array of periodic metallic patches or a conducting sheet periodically perforated with apertures. FSS has been intensively studied since the 1960s [7]. FSS has been applied to many fields including microwave absorption, radar cross section.
(RCS) reduction, electromagnetic interference (EMI) reduction, millimeter and terahertz wave applications, etc. [12,13,14]. The FSS has adjustable electromagnetic characteristics, which can realize the movement of the filtering frequency band, and the control of the filtering strength [15, 16].

However, the bottlenecks of PPC and FSS research also have been discovered. a narrow dynamic tuning band and a troubled thickness restriction happen frequently on FSS research. when it comes to PPC, On the one hand, most of the current researches are in the theoretical stage, with high time consumption under computer condition, and it is difficult to study into the multidimensional. On the other hand, plasma itself is a very complex medium, which can produce non-uniformity even in the absence of an external field, thus affecting the wave propagation behavior in plasma-filled devices; even if the plasma is at a sufficiently high electron density, it is also impossible to have the same cut-off characteristics and forbidden band structure as the metal.

In response to the above problems, a composite electromagnetic structure is prepared in this paper. Based on the periodically arranged plasma columns, the frequency selective surface is introduced to study whether a PPC-like effect will occur on EM waves propagation in the composite structure even a stronger dynamic tuning ability. The reflectivity between 1~2GHz and 8~12GHz was tested in a microwave dark room to study the influence of periodic plasma and frequency selective surface on incident electromagnetic waves with the free space method. Commercial electromagnetic software also was used to calculate the electric field at different frequency points, and study the mechanism of its interaction with electromagnetic waves.

2. Experiment

2.1. Microwave darkroom reflectivity test system

The main working principle of the microwave darkroom is based on the law that the electromagnetic wave propagates from the low magnetic to the high magnetic permeability in the medium. The high magnetic permeability absorbing material absorbs the radiant energy of the electromagnetic wave in large quantities, and then converts the energy of the electromagnetic wave into heat energy through coupling.

![Figure 1. Darkroom test system.](image1)

![Figure 2. Topology structure.](image2)

The schematic diagram of the microwave darkroom reflectance test system used in this paper is shown in Figure 1. The transceiver device is a vector network analyzer, and the transmitting and receiving antennas are 1~18 GHz double-ridged horn antennas, which are installed at the same height of the microwave darkroom. The sample is about 900mm away from the antenna placed on the foam sample stage in the middle of the darkroom. 600×600×700 pyramidal absorbing materials are placed in the whole space. The microwave signal is output from port 1, received from port 2 of the vector network analyzer, with coaxial lines as the transmission line, and the transmitted electromagnetic wave is a TEM wave.
Table 1. Topology unit size parameter.

| Variant name | Value            |
|--------------|------------------|
| cc           | 19.2~20.5        |
| nee          | 0.10~0.18        |
| dd           | 0.19~0.21        |
| ddz          | 0.5~0.55         |
| ff           | cc×sin(π/4~π/3)  |
| bb           | cc×sin(π/6~π/4)  |
| b            | cc×3             |

2.2. Introduction to test methods
Since 1987, Cullen proposed an effective inversion method based on Fresnel's law of reflection to obtain the electromagnetic parameters of materials in free space [17], and the free space method began to develop rapidly. The free space method has a high flexibility, which can be used when polarization direction and incident angle of the electromagnetic wave change, and is suitable for measuring the electromagnetic parameters of the composite material. The sample of the free space method is simple to make, only requiring a flat, double-sided parallel sample with a large enough area to ensure that the electromagnetic wave can be totally incident, avoiding the influence of electromagnetic wave diffraction. The method also has been used to test the reflectivity of the samples in this paper.

2.3. Experimental steps
First, the metal patch shown in Figure 2 is produced on the FR4 substrate by PCB technology. The unit patch size parameters shown in Table 1, the units are periodically distributed on the two sides of the FR4 (thickness of 0.4mm) as a 7×4 arrangement. Then, the various elements are loaded to the FSS according to the position of Figure 3(d). The kinds and parameters of the components are shown in Table 2. Then, six T8 fluorescent lamps with a diameter 23.75 mm and a length of 235 mm are closely arranged, made to be a plasma generator. The lamps are connected to 220V, 50Hz AC through a ballast, fixed above the metal plate of 240×280×5mm. Finally, the metal grid strips with a width of 9.2mm are fixed between the fluorescent lamps, the five metal grid bars spaced at 25.7mm distance periodically arranged above the plasma generator. Figure 3 is a schematic diagram of the sample prepared well, and Figure 4 shows that the sample has different test conditions, such as metal plate (abbreviated as METAL) in Figure 4(a), an off lamp placed on the metal plate (abbreviated as LOFFM), an on lamp placed on the metal plate (abbreviated as LONM), an off lamp and FSS with metal grids placed on the metal plate (abbreviated as LOFFM-FSS) in Figure 4(b), and an on lamp and FSS with metal grids placed on the metal plate (abbreviated as LONM-FSS) in Figure 4(c).

Table 2. Electronic component parameter value.

| Variant name | Value            |
|--------------|------------------|
| C1           | 4~4.7uF          |
| L1           | 0.7~1uH          |
| R1           | 790~820Ω         |
| R2           | 1450~1520Ω       |

In order to improve the accuracy and stability of the test, the vector network analyzer is preheated for 30 minutes before the start of the experiment. After calibration, the background calibration of the static field is performed. Repeated tests show that the maximum deviation of the darkroom background is 0.0162dB when taking 1601 test points in the range of 1~18 GHz, and the metal reflectivity is 10dB higher comparing with background. The darkroom environment meets the test requirements and has good repeatability. The number of tests of the vector network analyzer is
increased to reduce the influence of noise on the test results. At the same time, in order to overcome the influence causing by infinite reflection happening between the signal source and the measured samples in the test, the time domain gate technique is used in data processing to effectively improve the test accuracy.

![Figure 3.](image)

**Figure 3.** Schematic diagram of the sample after construction. (a): side view; (b): top view; (c): left view; (d): local structure enlargement view.

![Figure 4.](image)

**Figure 4.** Different samples in darkroom test system at 90° polarization angle. (a): METAL; (b): LOFFM-FSS; (c): LONM-FSS.

### 2.4. Results

We tested the different states of the composite structure at 1~2GHz and 8~12GHz, as shown in Figure 4. The test results have been shown in Figure 5 and Figure 6 respectively. At the same time, we also studied the influence of polarization angle on reflectivity. The test results are shown in Figure 7 and Figure 8. It can be seen from Figure 5(a) that the periodic plasma has a strong tuning ability to the incident electromagnetic wave, compared with the metal, a strong absorption peak appearing near 1.65
GHz, and the reflectance decreases 2~5dB in the whole frequency range of 1 to 2 GHz. The LOFFM-FSS exists an absorption peak of -15.5 dB depth around 1.24 GHz, and the reflectance is higher at other frequencies, as shown in Figure 5(b). The composite structure LONM-FSS has a resonance peak of -20.7dB near 1.26GHz, and the reflectivity also decreases in the whole frequency band, indicating that the coupling absorption enhancement effect occurs in the composite structure, as shown in Figure 5(c). The specific data has been shown in Table 3.

![Figure 5](image-url)

**Figure 5.** Characteristic reflectivity of different samples between 1~2GHz at polarization angle 90°.

| Experiment results of different samples in 1~2GHz. |
|-------------------------------------------|
| Samples | Absorbing frequency (GHz) | Absorbing depth(dB) |
|---------|--------------------------|---------------------|
| LONM    | 1.65                     | -15.2               |
| LOFFM-FSS | 1.24                    | -15.5               |
| LONM-FSS | 1.26                     | -20.7               |

At 8~12GHz, we can also find that the periodic plasma structure reduces the reflectivity of the metal by 2~7dB and changes the waveform, as shown in Figure 6(a). It is shown in Figure 6(b) that although the LOFFM-FSS do not change the peak position of the metal sample, the reflectivity amplitude metal sample is shifted downward comparing to metal; as shown in Figure 6(c), the LONM-FSS strongly absorbs at 11.7 GHz, with -21.1 dB depth, and the waveform is flattened at high

![Figure 6](image-url)

**Figure 6.** Characteristic reflectivity of different samples between 8~12GHz at polarization angle 90°.
reflectivity, showing good broadband absorbing effect. Numerical results have been listed in the Table 4.

**Table 4.** Experiment results of different samples in 8–12GHz.

| Samples       | Absorbing frequency (GHz) | Absorbing depth(dB) |
|---------------|---------------------------|---------------------|
| LONM          | 8.2                       | -23.5               |
| LOFFM-FSS     | 11.3                      | -20.4               |
| LONM-FSS      | 11.7                      | -21.5               |

It can be seen from Figure 7 and Figure 8 that changing the polarization angle also have influence on the dynamic adjustment of the composite structure. As can be seen from Figure 7, the periodic plasma exhibits polarization stability at 1-2 GHz, and FSS shows the deepest absorption peak at 45°, while the composite structure has the deepest resonance peak at 90° polarization angle. It can be seen from Figure 8 that the three samples exhibit different polarization angle dependence in the range of 8-12 GHz, worth to make deeper research.

**Figure 7.** Characteristic reflectivity of different samples between 1~2GHz at 0°, 45°,90° polarization angle. (a): LONM; (b): LOFFM-FSS; (c): LONM-FSS.

**Figure 8.** Characteristic reflectivity of different samples between 8~12GHz at 0°, 45°,90° polarization angle. (a): LONM; (b): LOFFM-FSS; (c): LONM-FSS.
3. Discussion

3.1. How to express the composite structure in theory?

There are many parameters to describe plasma, and two electromagnetic parameters $v_e$ and $\omega_{pe}$ have been diagnosed from experiment. $S_{21}$ can be expressed as following:

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

where $\Gamma$ is the single reflection coefficient and $T$ is the transmission coefficient, and the refractive index $n$ has relationship to $S_{21}$ and is also related to the plasma frequency $\omega_{pe}$ and collision frequency $v_e$[18], and can be expressed as:

$$n = \mu - j\chi,$$

where

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

and

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

after substituting values into formula calculations, the plasma collision frequency, the plasma frequency the plasma density of the T8 lamp is diagnosed as $5 \times 10^{10}/s$, $3 \times 10^{10}$Hz, consistent of the values from literature [19].

Figure 9. The equivalent circuit model of composite structure.

Meanwhile, an equivalent circuit method combined with the theory of transmission line theory [20, 21], has been used to describe and analyze the composite structure. The FSS formed by the periodic patch array can be equivalent to a series connection between a capacitor FSS_X and an inductor FSS_B. At the resonance point, since the input impedance is zero, total reflection phenomenon occurs; at the non-resonant point, the FSS appearing to be capacitive, will exist high absorption and low reflection properties. The role of the plasma can be qualitatively expressed in two aspects: one is the effect of the uneven distribution of charged particles on the system reactance modulation, which can be equivalent to the coupled capacitive load Plasma_X for the non-magnetized plasma herein; The second is the modulation effect of the absorbing property on the resistance, which can be equivalent to the coupled resistive load Plasma_absorb. Therefore, the equivalent circuit model of the system under coupled plasma conditions is as shown in Figure 9.

The plasma density can be calculated by the following formula (5):

$$n_e = \frac{\omega_{pe}^2 m_e e_0}{e^2},$$

where $e_0$ and $m_e$ is vacuum dielectric constant, and electron mass respectively. And the plasma temperature can be analyzed from formula (6) [22]:

$$v_e = \frac{4}{3} \pi \eta \sigma^2 \left( \frac{kT}{m_e} \right)^{\frac{1}{2}},$$
in which $\left(\frac{8kT}{\pi m_e}\right)^{\frac{1}{2}}$ is the mean of thermal velocity of electrons at temperature $T$, $\pi \sigma^2$ is a constant or a suitable mean value, corresponding to a diffusion cross section [23]. There have been some formulas to expressed the relationship between plasma impedance and $n_e, T$ as formulas (7), (8) [24]:

$$\text{Plasma}_X = \frac{A(u_c^2 - \omega_{pe}^2)}{\nu_c^2},$$  \hspace{1cm} (7)

$$\text{Plasma}_{\text{absorb}} = \frac{B u_c^2}{\omega_{pe}^2 \nu_c^2},$$  \hspace{1cm} (8)

in which $A$ and $B$ both are constants. The formulas (5) ~ (8) can be used to derive the impedance value of the plasma. In the future, the equivalent model and the formula relationship can be used to further analyze the impedance characteristics of the system, characterize the mismatch level, and calculate the plasma parameters $n_e$ and $T$ corresponding to the impedance matching state, which will be the key breakthrough direction.

3.2. Why does the experiments have such results with different samples?

In order to study the mechanism of interaction between composite structures and electromagnetic waves, commercial electromagnetic software (CST) has been chosen to simulate the electric field distributions of different samples by the frequency domain algorithm.

Figure 10. Simulation map of electric field distribution with open boundary. b1, b2 and b3 is result of the LONM, LOFF-FSS and LONM-FSS at frequency 1.2GHz respectively; c1, c2 and c3 is result of the LONM(a1), LOFF-FSS(a2) and LONM-FSS(a3) at frequency 1.8GHz respectively.
According to the experimental results, discuss the electric field distribution on the three samples at the 1.2GHz, 1.8GHz frequency points, which are the points corresponding to the highest and lowest reflectivity values of the LONM-FSS reflection curve. The composite structure by introducing the hexagonal units, control the electric field to be distributed along the crescent of the FSS, superiority of the design reflecting here and a flexible tuning ability obtained and it can be seen in Figure 10, that the electric field is weaker at 1.2GHz than 1.8GHz, which exists in all three samples at the same time. Comparing Figure 10(b3) to Figure 10(b2), find that electric field strength of LONM-FSS shows a lower maximum and a better continuous uniformity in color than LOFFM-FSS, consistent with the experimental results, illustrating that the periodic plasma and FSS have a coupling effect. Meanwhile at 1.8GHz, Figure 10(c2) and Figure 10(c3) both exist high electric field concentration distribution at the edge of samples, showing a great discontinuity, which may be the reason why LOFFM-FSS and LONM-FSS have a high reflectivity at the frequency.

In order to study the edge distribution effect of the electric field shown from Figure 10, the model of LONM-FSS has been simulated under unit cell boundary. The electric field distribution changes from the edge concentration to the periodic distribution in which high electric field is evenly dispersed along FSS units shown from Figure 11. At the same time, the electric field strength value at the periodic boundary is about 20 times that of the open boundary. This shows that the boundary problem is in great value and potential of the periodic electromagnetic structure.

![Figure 11. Simulation map of electric field distribution with unit cell boundary. a, b is result of the LONM-FSS at 1.2GHz and 1.8GHz.](image)

### 4. Conclusions

In this paper, the reflectivity of the composite structure composed of FSS and periodic plasma has been tested by free space method, and the electric field distribution of the composite structure also has been calculated by electromagnetic software. On the one hand, the composite structure has presented a flexible ability to modulate electromagnetic waves through experiment, which can be controlled by plasma switch and polarization angle. On the other hand, the electric field exhibits a periodic distribution along the FSS, and the high electric field concentrates on edge under the open boundary is the result of the interaction of the plasma and FSS in the composite structure. Finally, an equivalent circuit model has been proposed to explain the reasons of combination between FSS and periodic plasma in theory. This work illustrates the composite structure also exists a PPC-like phenomenon, providing a new idea for the study of artificial electromagnetic materials and is of great significance in EM field. However, the lamp with the same electromagnetic parameters as the plasma generator was selected in the paper. The response of the composite structure can be studied when changing the plasma parameters or the plasma arrangement in the future, and how to break through the edge effect is also an important direction.
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