Study on reflection characteristics of plasma and metallic periodic structure composite frequency selective device

Xuefeng Zhu\textsuperscript{1,2} and Zhongyu Hou\textsuperscript{1,2,3}

\textsuperscript{1}School of Electronic information and Electrical Engineering, Shanghai JiaoTong University, Shanghai 200030, P.R. China
\textsuperscript{2}The National Key Laboratory of Micro/Nano Fabrication Technology
\textsuperscript{3}Email: zhyhou@sjtu.edu.cn

Abstract. Plasma technology is widely used in the electromagnetic field. In this work, a novel composite frequency selection (CFS) device composed of plasma and metallic periodic structure is proposed. This paper demonstrates the reflection coefficient of the proposed CFS at 12-18 GHz. The dispersion of absorption effect in the frequency domain is also mentioned. A simulation result of the electric field distribution of CFS device is presented to give a tentative explanation.

1. Introduction
The application of plasma technical in the electromagnetic field is expanding widely, such as frequency filters, frequency converters [1], plasma antenna [2-5], etc. A plasma periodic structure is composed of plasma and other medium or vacuum. There are a few known plasma periodic structure applications, for instance, the plasma lens [6] and the plasma antenna [7]. However, one of the problems that limit the application of plasma periodic structure is the excessive transmission of plasma. When the frequency of electromagnetic waves is higher than the plasma frequency, the electromagnetic waves can propagate in the plasma. Therefore, for the higher frequency range of incoming electromagnetic field (EMF), the periodic structure of the plasma does not completely prevent electromagnetic waves from transmitting except for sustaining higher electron density with higher energy consumption and even unacceptable higher temperature. Consequently, the basic idea of this paper is to incorporate the cut-off characteristics of Frequency Selective Surface (FSS) with metallic periodic structures to increase the stopband feature of the combined system with more limited side-effects and remain the active reconfigurability of plasma periodic structure.

The Frequency Selective Surface (FSS) is generally composed of periodic conductive patches or aperture elements for reflecting, transmitting or absorbing electromagnetic waves. FSS is widely used in the electromagnetic field, such as radome [8-11], interference suppression in WLAN communication [12], electromagnetic shielding rooms [13], information security [14], etc. In this work, electromagnetic waves that pass through the FSS interact with the plasma. This may change the frequency selection characteristics of the frequency selective device. The passband and stopband of the FSS can be changed by changing the geometry of the periodic structure of the metallic pads on the FSS. Therefore, the FSS absorb electromagnetic waves in some specific frequency bands, making it possible to solve the problem of excessive transmission of plasma periodic structure to some extent. To our best knowledge, there are few reports on combining plasma periodic structure with FSS, which makes it worth exploring.
In order to study the coupling characteristics of the plasma periodic structure and the metallic periodic structure, we do experiments on a three-layer composite frequency selection (CFS) device composed of FSS, plasma and metallic plate. A reflectivity experiment was performed in a microwave dark chamber. The background reflectivity is 20 to 30dB lower than the averaged reflectivity of the device under test (DUT). The experimental results show that the coupling effect of plasma and FSS in the three-layer structure cause a significant change in the reflection characteristics of the DUT. It produces a -15dB absorption peak at 17.2 GHz, which is not available for plasma or metallic periodic structure alone. The dispersion of absorption effect at 8.33GHz is also found. To study the mechanism of the coupling of plasma with FSS, a model is built which is consistent with the DUT. It is expected to explain the relationship between electric field distribution and resonance characteristics.

2. Experimental

The three-layer CFS device is shown in Figure 1(b), including FSS, plasma, and metallic plane. The FSS is made of a printed circuit board (PCB) with a size of 0.4 mm × 250 mm × 170 mm. Each periodic unit contains four metallic pads, and the geometry of the pad is shown in Figure 1(a). It consists of a trapezoid merged with four crescent shapes at each boundary. The periodical metallic pads are used to generate the interference wave to couple with the backscattering EMF from the structured plasma reflector below the FSS. The basic consideration of the FSS unit structure is to form a typical cross-shape with crescent borders to enhance the electric field convergence effect in the exterior region of every pad. In the following, the electric field distribution on the surface of the FSS unit and the plasma region have been investigated based on the Drude’s description of the plasma. Each crescent shape is determined by two arcs, whose distance from the center to the trapezoidal side is shown in Figure 1(a). A periodic unit consists of these pads in a definite orientation, as shown in Figure 1(c). The arrangement of the lumped component is also shown in Figure 1(c). As shown in figure 1(b), six lamps in the middle layer of the device are used to generate plasma. The diameter of the lamp tube is 25.72 mm. The third layer is a metallic plate of the same size as the FSS.

Figure 1. The schematic diagram of DUT design. (a: size of a pad, b: assembly structure of the FSS, lamps and metallic plate, where plasma means the lamps, c: position of small cells in a periodic structure and arrangement of the lumped component).
The reflectivity experiment system is shown in Figure 2. The reflectivity experiment is conducted in a microwave dark chamber. Two standard gain horn antennas are connected to the two ports of the network analyzer respectively. One of the horn antennas emits electromagnetic waves, which are reflected by the DUT and received by another horn antenna. The reflectivity of the DUT is obtained by a network analyzer. The DUT is placed on a well leveled platform, the distance between the platform and the horn is 1 m, and the horn is aligned with the center of the DUT. The DUT is shown in Figure 2. Since the lamps are longer than the FSS, the part in excess are covered with absorbing material. The boundary of absorbing material dose not conflict with the boundary of FSS unit to keep its periodicity. The reflectivity of microwave dark chamber background and the metallic plate at the same location with the DUT is also measured. Therefore, the experiment results shown below are the relative values with the metal plate.

The reflectivity of the plasma periodic structure in the 12-18 GHz band is measured. The array of 6 lamps is placed on a metallic plate (equal to the size of the FSS). The experiment results are shown in the black curve of Figure 3 (right). It can be seen that the DUT combing of the lamps and the metallic plate show a strong reflectivity, which is almost equivalent to a metal plate. We believe that this is because the transmittance of electromagnetic waves is high in the plasma, electromagnetic waves are less affected.

The reflection of the three-layer CFS device is also measured. Figure 3 shows the reflectivity curves of the DUT when the lamps is turned on and off (red and blue curve). When there is no plasma, the DUT shows an absorption peak at 17.2 GHz, but with a shallow depth. When the lamps are turned on, the absorption peak depth is significantly increased, the deepest point reaching -21dB. A similar resonance phenomenon did not occur when the plasma and FSS were measured separately. We believe that it is because the coupling between the plasma and the FSS causes the deepening of the absorption peak. It is believed that the plasma enhances the propagation of electromagnetic waves between the FSS and the metallic plate. More energy of the electromagnetic wave is dissipated on the FSS and the plasma, affecting the reflection characteristics of the DUT.

A similar experiment at 8-12GHz is also performed. In Figure 3(left), the black line shows the reflection curve of the two-layer structure of plasma and metallic plate. It has an absorption peak of about -18dB at 8.33GHz. This is the performance of the plasma periodic structure. In the experiment of the three-layer DUT, the absorption peak at this frequency was reduced to -15dB, but the bandwidth was increased. The experiment results of the DUT did not show strong frequency selection characteristics, but a dispersion of the absorption effect.

As can be seen in Figure 3, the curves in the Ku band and the X band are not connected. This may be due to the complexity of the time domain features near the peak with a different performance of the two
test bands. Therefore, when doing the Fourier transform, the resulting curves do not match exactly at the junction (12GHz).

Figure 3. Reflectivity test results. (plasma: array of 6 lamps on a metallic plate, FSS with plasma: the three-layer CFS device with lamps turned on, FSS: the three-layer CFS device with lamps turned off).

3. Discussion
Two phenomena were found in reflectivity experiment in Figure 3. In Ku band, plasma periodic structure does not show frequency selective characteristic. While it changes significantly when FSS added, a deep absorption peak appears at 17.2 GHz. In the X band, plasma periodic structure shows a strong frequency selective characteristic. But it presents a dispersion of the absorption peak when covering it with the FSS.

To better understand the experiment phenomena, a simulation model is built and whose structure is same as the actual DUT. It is found that the characteristics of the plasma have a great influence on the propagation of electromagnetic waves therein. The physical parameters of the plasma may vary widely, which causes a problem in accurately analyzing the propagation of electromagnetic waves in the plasma in this field. In addition, the plasma has a considerable of frequency dispersion, and electromagnetic waves of different frequencies would propagate differently. Moreover, the plasma is generally non-uniform, which also affects the propagation of electromagnetic waves therein. Although it is difficult to characterize plasma with a complete precise numerical model, this method is commonly used for qualitative mechanism analysis in the field. To simplify the calculation, it is assumed that the plasma is uniform and can be characterized by the Drude’s model. Besides, the plasma parameters have also been diagnosed through microwave diagnostic method, with a result of electron density from 0.9E+17 to 7.1E+17, the plasma frequency from 1.6E+10 to 4.8E+10, and the collision frequency from 2E+10 to 8E+10. The Drude’s model is used to describe the interaction between the EMF and the plasma. According to the diagnosis, the plasma frequency is set to 2E+10, and collision frequency is set to 5E+10. The diameter of the cylinder is 25.72 mm.

Figure 4 shows the electric field distribution of FSS at 16 GHz, 17 GHz and 18 GHz in a CFS device. At 16 GHz and 18 GHz, the FSS electric field is stronger on average, and the electric field intensity at the junction of the lumped elements in the same periodic cell is high. At the absorption peak of 17 GHz, the electric field on the FSS is weak, but the electric field intensity between the periodic units is higher than that of interior region of periodic unit. According to the transmission line theory, some of the roles of the FSS have been understood as the behavior of an impedance matching network. The role of the plasma could be interoperated as a parallel connection of capacitance and resistance. The value of the capacitance and resistance are related to plasma electron density. The input impedance has changed significantly compared to the case with FSS only. The impedance matching characteristics may change. It results in an absorption peak at a frequency point where the impedance well matches. At 17 GHz, the
scattering field of the plasma coupled with the electromagnetic waves improves the impedance matching characteristics of the FSS, resulting in an absorption peak.

For small size FSS, the boundary effect caused by the cut-off of the periodic structure in the real-world approximation is not negligible. It can be seen that at all three frequencies, the electric field strength at the edge of FSS is greater than that at the center of the FSS. The scattering of FSS edges are mainly caused by the radiation generated by surface current. When the current reaches the edge, the mismatched radiation occurs, which is manifested due to the boundary effect of the FSS. [15] In addition, it is worth noting that at some frequencies, the electric field distributions of the upper-lower edges and the left-right edges of the FSS are not the same. It may be related to the arrangement of the lumped elements.

Figure 4. Electric field distribution of FSS in a CFS device at 16 GHz, 17 GHz and 18 GHz from top to bottom, respectively.
The scene of turning off the lamps is also calculated, as shown in Figure 5. The results at 16 GHz and 18 GHz are not shown because they are similar with the scene of turning on the lamps. At 17 GHz, the intensity of the electric field on the FSS without plasma is greater than the case with plasma, which is consistent with the experiment. By comparing the cases with or without plasma, we found that plasma can significantly reduce the electric field intensity at the center of the FSS but have a weaker effect on the boundaries of the DUT. This may be explained by reason that the traveling wave and boundary diffraction is not much affected by plasma.

4. Conclusions
In summary, a novel composite frequency selection device incorporated with plasma and metallic periodic structure is proposed. This paper shows the reflectivity of the CFS device in the reflectivity experiment, a -21dB absorption peak at 17.2 GHz, which is not available for plasma or metallic periodic structure alone. When the plasma itself has an absorption peak, FSS causes the dispersion of absorption effect in the frequency domain. The distribution of the electric field on the FSS in a CFS device is also revealed by numerical calculations. At the absorption peak of 17 GHz, where the impedance well matches, the electric field on the FSS is weak, while it is strong at 16 GHz and 18 GHz. The boundary effect significantly affects the electric field distribution of FSS too. The application of plasma in the electromagnetic field is increasingly valued [16]. However, there is a problem about the cutoff characteristics. This paper presents a new possibility to improve the cut-off characteristics of plasma-based parodic structures. It is also possible to dynamically change the resonance characteristics of the CFS device. The relationship between the electric field distribution in different component of the CFS and their reflectivity is also discussed. In the future, we will optimize the design through transmission line theory.

Acknowledgments
This work was financially supported by the National Natural Science Foundation of China (60906053, 61204069, 61274118, 61306144, 61504079, and 11605112), Shanghai Science Innovation Project (15DZ1160800 and 17XD1702400), China Postdoctoral Science Foundation (2016M601595).

References
[1] Hojo H and Mase A 2004 Dispersion Relation of Electromagnetic Waves in One-Dimensional Plasma Photonic Crystals Journal of Plasma & Fusion Research 80(2) 89-90
[2] Rayner J P, Whichello A P and Cheetham A D 2004 Physical Characteristics of Plasma Antennas IEEE Transactions on Plasma Science 32(1) 269-281
[3] Kumar R and Bora D 2011 Wireless communication capability of a reconfigurable plasma antenna Journal of Applied Physics 109(6) 1228

[4] Alexeff I, et al. 2008 Recent results for plasma antennas Physics of Plasmas 15.5 057104

[5] Alexeff I, et al. 2006 Experimental and Theoretical Results With Plasma Antennas IEEE Transactions on Plasma Science 34(2) 166-172

[6] Goncharov A A, et al. 1993 High-current plasma lens IEEE Transactions on Plasma Science 21(5) 573-577

[7] Dwyer T, et al. 1984 On the feasibility of using an atmospheric discharge plasma as an RF antenna IEEE Transactions on Antennas & Propagation 32(2) 141-146

[8] Costa F and Monorchio A 2012 A Frequency Selective Radome With Wideband Absorbing Properties IEEE Transactions on Antennas & Propagation 60(6) 2740-2747

[9] Kim J H, et al. 2014 Analysis of FSS Radomes Based on Physical Optics Method and Ray Tracing Technique IEEE Antennas and Wireless Propagation Letters 13(1933) 868-871

[10] Kim P C, et al. 2008 Nanocomposite stealth radomes with frequency selective surfaces Composite Structures 86(1) 299-305

[11] Li H Y 2016 Design and analysis of a frequency selective radome (FSR) with wideband absorbing properties IEEE International Workshop on Electromagnetics: Applications & Student Innovation Competition

[12] Yan M B, et al. 2014 A Miniaturized Dual-Band FSS With Stable Resonance Frequencies of 2.4 GHz/5 GHz for WLAN Applications IEEE Antennas & Wireless Propagation Letters 13(1933) 895-898

[13] Parker E A, et al. 2010 Frequency selectively screened office incorporating convoluted FSS window Electronics Letters 46(5) 317-318

[14] Taylor P S, Parker E A and Batchelor J C 2010 Experimental phase plate employing a phase modulated active frequency selective surface Microwave & Optical Technology Letters 52(10) 2300-2302

[15] Munk B A, et al. 2001 Scattering from surface waves on finite FSS IEEE Transactions on Antennas and Propagation 49(12) 1782-1793

[16] Sakai O and Tachibana K 2012 Plasmas as metamaterials a review Plasma Sources Science Technology 21(1) 013001