

Reconfigurable Plasma Frequency Selective Surface

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Abstract

This paper presents single- and double-layer reconfigurable frequency selective surfaces (FSS) for high-power microwave (HPM) shielding, utilizing plasma as an active element. Unlike conventional FSS, plasma-based design enables tunable filtering by adjusting plasma density or shape, reducing the need for extensive structural modifications. Plasma elements enhance shielding, offer reconfigurability (ON mode), and can be rendered transparent when the plasma is deactivated (OFF mode). The proposed FSS utilizes plasma formation, induced by HPM-generated electric fields, to selectively absorb electromagnetic (EM) energy. Simulation results indicate excellent isolation, with insertion loss exceeding 10 dB across the target frequency band as input power increases. This approach offers promising capabilities for dynamic EM power reception control and equipment shielding in high-power environments.

1 Introduction

Wireless communication systems rely on highly sensitive components that are specifically designed to detect and process weak signals, which are typically only slightly stronger than the thermal and shot noise floor, and this is the case across a broad range of frequencies. Within the receiver chain, key active components such as low-noise amplifiers (LNAs) and mixers are optimized to handle low-power signals with minimal distortion [1]. However, due to their high sensitivity, these components are particularly susceptible to external electromagnetic (EM) interference, potential damage or operational failure when subjected to high-power microwave (HPM) signals [2].

HPM signals pose a significant threat to wireless receivers, as they originate from various high-energy radio frequency (RF) sources. These sources can introduce excessive energy into the receiver circuitry, which can overwhelm its delicate RF electronics. The effects of such interference may range from temporary performance degradation, such as increased noise levels or signal distortion, to permanent damage that renders the system inoperable [1]. Given the critical role of these receiver components in maintaining effective communication, it is essential to understand and

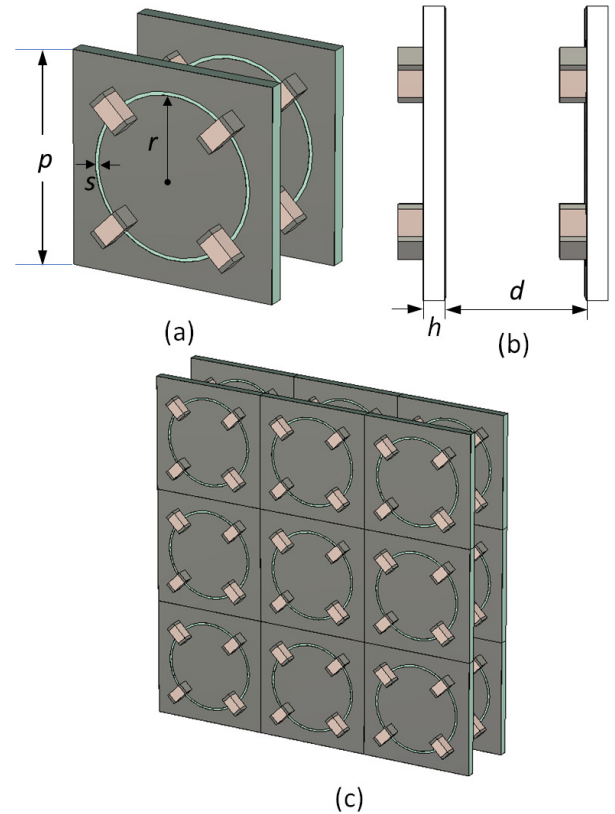


Figure 1. Design of the reconfigurable plasma FSS: (a) perspective view and (b) side view and (c) 3×3 array representation.

mitigate the risks posed by HPM signals to ensure the reliability, resilience, and safety of wireless systems [3].

A fundamental protection method is metallic shielding. However, while it effectively blocks HPM, it also attenuates all signals, thus disrupting communication. A more effective approach is adaptive shielding, which selectively filters HPM signals while allowing low-power signals to pass [4] [5]. Frequency selective surfaces (FSS) using p-i-n and varactor diodes are widely studied for reconfigurable and multifunctional protection of sensitive electronics [6], [7], [8]. These structures selectively filter frequency signals while allowing normal communication. However, conventional semiconductor devices have limited power handling

Table 1. Design Parameters of the Unit cells

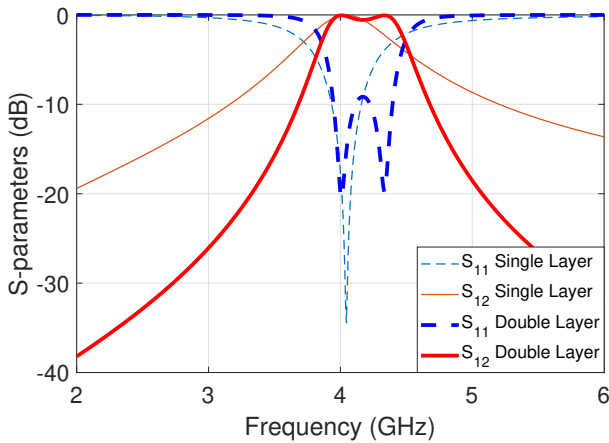
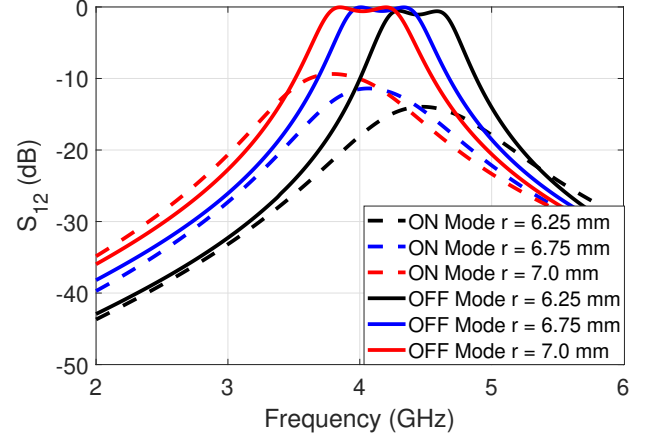
Parameter	p	r	s	h	d
Value (λ)	0.24	0.09	0.004	0.0168	0.133
Value (mm)	18	6.75	0.3	1.26	10

capabilities and are prone to electrical breakdown under intense HPM exposure, leading to performance degradation or even failure [1]. On the other hand, plasma-based RF circuits are gaining interest for high-power applications due to their high power handling capabilities [9]. As an example, the plasma-based FSS structures reported in [10], [11] [12] show the possibility of developing such surfaces to cater for the high power requirements.

In this paper, the application of plasma as a sensing element for HPM signals is presented and studied to develop a reconfigurable FSS. The detailed design methodology and the design simulation procedure are explained. In section II the design and simulation of reconfigurable FSS is described. The properties of plasma medium, modeling and its material properties are discussed in section III. Finally, the conclusions are drawn in section IV.

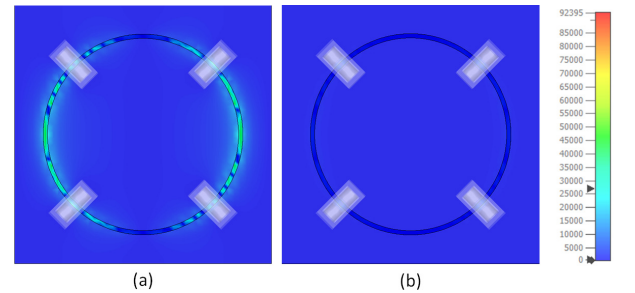
2 Design and Simulation of Reconfigurable Plasma FSS

A power-dependent reconfigurable FSS is designed based on plasma technology with a wide band response. The structural arrangement of the proposed double-layer FSS with plasma-enabled gas discharge tubes (GDT) is shown in Figure 1. The design consists of a circular ring resonator with a radius of $r = 6.75$ mm and a slot width of $s = 0.3$ mm, etched onto a Rogers TMM6 dielectric substrate with $\epsilon_r = 6$ and $\tan\delta = 0.0023$, and having a thickness of $h = 1.26$ mm. The design dimensions of the unit cell are shown in Table 1. At first, a single-layer structure is designed following the design dimensions. Further, to achieve the wide

**Figure 2.** Frequency response of the unit cell.**Figure 3.** ON and OFF mode response of the reconfigurable plasma FSS as a function of ring radius.

band response a second-order structure is designed by replicating the single layer. The top and bottom layers are separated by an air spacer with a separation distance, d , for second-order response. Four GDTs are loaded diagonally on the top and bottom layers as shown in Figure 1a and 1b. The array representation of the unit cell is shown in Figure 1c. The unit cell is simulated using a full-wave EM simulation tool, CST Microwave Studio, with periodic boundary conditions along x - and y -directions. A plane wave excitation is used along the z -direction using the Floquet mode. The plasma OFF and ON mode simulations are carried out with an assumption of electron number density (N_e) values on 1 and 1×10^{18} respectively [9], [11].

The reflection and transmission coefficients of the unit cell in single-layer and double-layer forms are shown in Figure 2. The structure is designed to operate at 4 GHz [14]. The single-layer structure shows the bandpass response at 4 GHz with a transmission bandwidth (BW) of 0.35 GHz and a low insertion loss (IL) of 0.1 dB. The double-layer structure shows a wide flat-top response with an IL of 0.5 dB and a BW of 0.5 GHz in the OFF mode of the GDT. Next, an instance of high incoming power stimulates the ions in the GDT and switches them to the ON state. The frequency response of the double layer FSS for OFF and ON modes is shown in Figure 3. The ON mode response shows the

**Figure 4.** E -field distribution on the unit cell: (a) at 4 GHz and (b) 5 GHz. The colorbar denotes the E -field strength.

isolation of up to -10 dB as an effect of the rise of N_e in the GDT.

Also, the E -field distribution on the unit cell can be seen in Figures 4(a) and 4(b) at 4 GHz and 5 GHz, respectively, to show the plasma generation implication at these frequencies. A uniform field distribution is observed at 4 GHz, evidence of the plasma creation as a function of high E -field. In contrast, the structure is non-resonant at 5 GHz and has no field above the surface, which confirms that the GDT will remain in an OFF state beyond the operating frequency region.

3 Plasma Medium

As the incident power level increases, the E -field at the resonance frequency intensifies, actuating the GDTs. As a result, the electrons inside the GDT start accelerating with the increased E -field, thus increasing the electron density (N_e in cm^{-3}) and achieving a steady state with a continuous supply of the high power. This increase in N_e improves the conductivity of the plasma, yet decreases the GDT impedance and serves as a very small resistor in the fully turned-on state. This functionality plays a crucial role in the design of the reconfigurable FSS. By utilizing the varying impedance of the GDT, the FSS with a well-designed structure can respond to the incident EM wave, leading to high transmission and strong shielding effectiveness for low- and high-power incidences, respectively. The plasma volume inside the GDT is modeled as a homogeneous conductive dielectric medium whose permittivity (ϵ_p) and bulk conductivity (σ_p) in (S/m) can be expressed by Drude expressions as follows [9]:

$$\epsilon_p(f) = 1 - \frac{e^2 N_e}{\epsilon_0 m (\omega^2 + \nu_m^2)} \quad (1)$$

$$\sigma_p(f) = \frac{e^2 N_e \nu_m}{m (\omega^2 + \nu_m^2)} \quad (2)$$

where m is the mass of electron (kg), e is the charge of electron (C), ω is the angular frequency (rad/s) and ν_m is the collision frequency (Hz). The effect of ϵ_p and conductivity σ_p is plotted over frequency for $N_e = 1$ (OFF mode) and $N_e = 1 \times 10^{18}$ (ON mode), and is shown in Figures 5(a) and (b) respectively. It can be seen that the σ_p value is almost zero at $N_e = 1$ and increases with an increase in N_e . In comparison, ϵ_p becomes negative with an increase in N_e and directly impacts the plasma capacitance C_p due to the GDT. Nevertheless, the values of σ_p and C_p are dependent on the GDT's gas type and pressure [11], [12].

The functionality of reconfigurable FSS is primarily governed by variations in the material properties of the plasma. These properties influence the EM response of the structure, allowing for dynamic tuning and adaptability. Additionally,

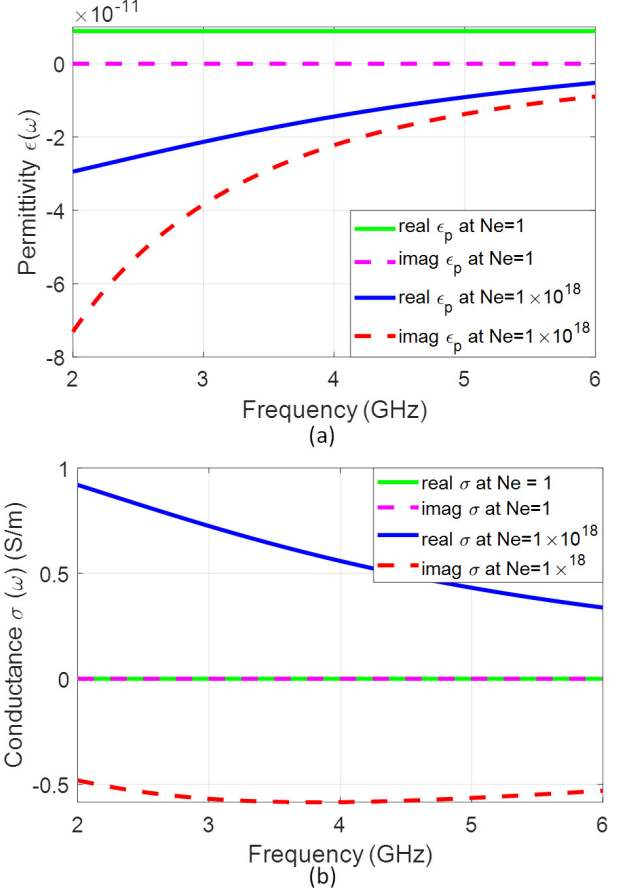


Figure 5. Material properties of plasma for OFF and ON modes: (a) permittivity and (b) conductivity.

the amplitude of the transmission coefficient can be modulated based on the strength of the incoming HPM signal, enabling controlled attenuation or enhancement of wave propagation. Future research will focus on a more comprehensive investigation into the efficacy of plasma properties in influencing FSS performance. Furthermore, experimental validations will be conducted to substantiate theoretical findings and refine practical implementations.

4 Conclusion

This paper presents a reconfigurable plasma-based FSS for HPM shielding. Unlike conventional active FSS designs, the proposed FSS leverages plasma's tunability, enabling dynamic filtering. The ON mode provides over 10 dB isolation, while the OFF mode ensures low insertion loss. Simulation results confirm its effectiveness for protecting sensitive electronics in satellite, aeronautics, and radar applications. The design offers scalability and adaptability, making it a viable alternative to traditional shielding methods. Future work will focus on experimental validation and optimizing plasma parameters for enhanced frequency agility and response time.

Acknowledgement

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