Study of X-Band Plasma Devices for Shielding Applications

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Abstract — This study presents novel switchable frequency selective surface (FSS) structures using encapsulated gas plasma elements. Simulations of geometric parameter sweeps show passband performance effects, and second-order model performance is compared with measured results. Average switchable attenuation can be increased from 24 dB for a second-order structure to 44 dB by adding another FSS and plasma element layer. These results suggest that switchable large-area plasma-based structures are practical for electromagnetic shielding applications in extreme environments.

Index Terms — Band-pass filters, electromagnetic radiation, electromagnetic shielding, frequency selective surfaces, plasma devices.

I. Introduction

Large-scale plasma attenuates microwave energy and reduces radar backscatter [1]. The ability to rapidly switch large-scale plasma volumes is highly desirable for the creation of large-area electromagnetic (EM) devices with controllable transmission/reflection/absorption characteristics. Examples include radomes, low radar cross section (RCS) surfaces, and high-power microwave (HPM) and electromagnetic pulse (EMP) shielding [2]. Theory for plasma absorbers has existed for decades [3], but demonstrations have only been conducted with laboratory devices that are either not scalable or impractical for use on mobile platforms [4], [5]. A plasma-based structure suitable for large-area, light-weight, conformal apertures has recently been demonstrated [6] and this device exhibits a switchable bandpass response in X-band (8–12 GHz), however, switchable attenuation must be considerably increased for use in practical applications.

To accomplish this, a parametric study of an array shown in Fig. 1(a) will be investigated. The structure is a conventional second-order frequency selective surface (FSS) with outer dielectric slabs [7]. Switchable attenuation is accomplished using plasma that can be ionized within plasma-shells by applying voltage across FSS layers [8]. Plasma-shells, depicted in Fig. 1(b) with the front face sectioned to show internal plasma, are hollow ceramic shells encapsulating a controlled-pressure gas that can be ionized to plasma. Unit cell geometric degrees of freedom shown in Fig. 1(c) will be investigated to achieve higher attenuation. Details of the simulation model will be presented in Section II, and parametric sweep results are presented in Section III. Measured results of a second-order device are presented in Section IV. Finally, a third-order structure is analyzed in Section V that demonstrates the effectiveness of stacking additional plasma-shell/FSS layers. Results of this work are summarized in Section VI.

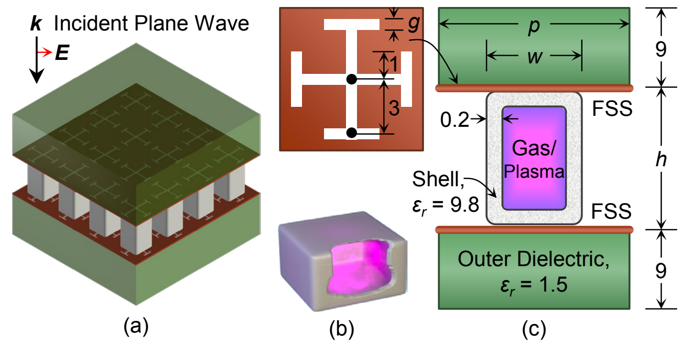

Fig. 1. (a) Proposed second-order array; (b) plasma-shell cutaway showing internal plasma; and (c) unit cell geometry (all units in mm).

II. Model Analysis

The symmetric second-order structure cross section in Fig. 1(c) consists of two dielectric-clad conductive FSS sheets in direct contact with an array of shells. Dielectric slabs stabilize the response center frequency and bandwidth across scan angle and provide structural support. Jerusalem cross elements are etched from the FSS sheet, providing large conductor area in contact with plasma-shells. Thin alumina shells ac-couple EM energy to the fill gas with nearly no loss.

Features of the unit cell are as follows. Period p sets inter-element spacing. Element patterns have uniform gap width g, and monopole leg and hat lengths are fixed to 3 and 1 mm, respectively. Shells of width w and height h have wall thickness of 0.2 mm. Dielectric thickness is 9 mm. The proposed structure was modeled with COMSOL Multiphysics, a finite element method tool. The lossless model uses Floquet periodic boundary conditions to simulate an infinite array illuminated by a uniform plane wave at normal incidence.

The plasma volume within each shell was modeled as a lossy homogenous dielectric medium. Frequency-dependent complex permittivity of a cold, collisional, weakly ionized plasma is

$$\varepsilon = \varepsilon_0 \left(1 - \frac{\omega_p^2}{\omega^2 + \nu^2} - j\frac{\omega_p^2 \, \nu/\omega}{\omega^2 + \nu^2}\right) \qquad (1)$$

as a function of plasma frequency (ω_p, in rad/s), microwave drive frequency (ω, in rad/s), and electron collision frequency (ν, in rad/s) [1]. Frequency-invariant plasma parameters at

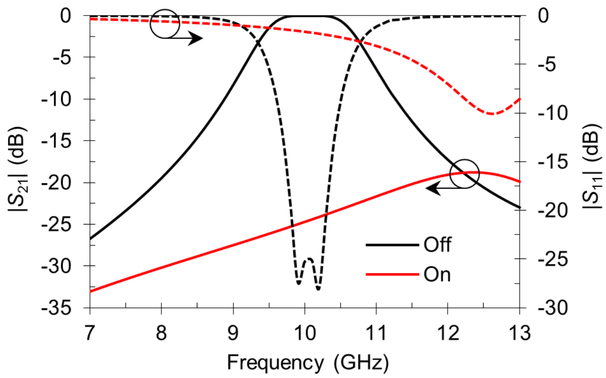

Fig. 2. Simulated performance of nominal second-order structure.

10 GHz were calculated from previous work to be $\varepsilon = \varepsilon_0(-1.88 - j\,0.20)$ and conductivity $\sigma = 0.45$ S/m (for $\omega_p = 1.07 \times 10^{11}$ rad/s, electron density $n_e = 3.6 \times 10^{12}$ cm^{-3}, and $\nu = 4.3 \times 10^9$ rad/s) [6].

Nominal parameter dimensions used for parametric sweeps in Section III are: $w = 4.4$; $h = 8.4$; $p = 8$; and $g = 0.5$. These values are varied over a wide range to study the performance effects, and values correspond to a device with good switchable X-band performance. The nominal structure passband response in Fig. 2 has center frequency of 10.0 GHz, bandwidth of 1.4 GHz, and average switchable attenuation in the passband of 24.5 dB.

III. Model Results

A. Effect of Shell Height

Fig. 3(a) shows the effect of increasing h up to ~0.3 wavelengths at 10 GHz. Attenuation increases significantly from 1.4 to 5.4 mm, then marginally increases another 4.7 dB with another 5 mm. Center frequency decreases by 10% across this range, and bandwidth remains similar above 3.4 mm. Shell height should be dictated by proper FSS design constraints, and h = 8.4 mm is an appropriate value located midway in the attenuation plateau.

B. Effect of Shell Width

Increasing w increases the percentage of space between FSS layers filled with plasma. Width is varied from a small 1-mm-wide plasma column until adjacent shells nearly touch. Fig. 3(b) shows that the fill factor has a significant effect on switchable attenuation. Increasing w from 4.4 to 7.4 mm yields an additional 8.4 dB of attenuation. Center frequency and bandwidth are relatively unaffected by such an increase.

C. Effect of Element Period

Increasing p decreases inter-element coupling and therefore bandwidth. Attenuation increases as bandwidth decreases and more energy is stored within the lossy plasma medium. Fig. 3(c) shows attenuation increasing steadily with p by a total of 17.0 dB. Bandwidth decreases over a range of 4.7:1 and

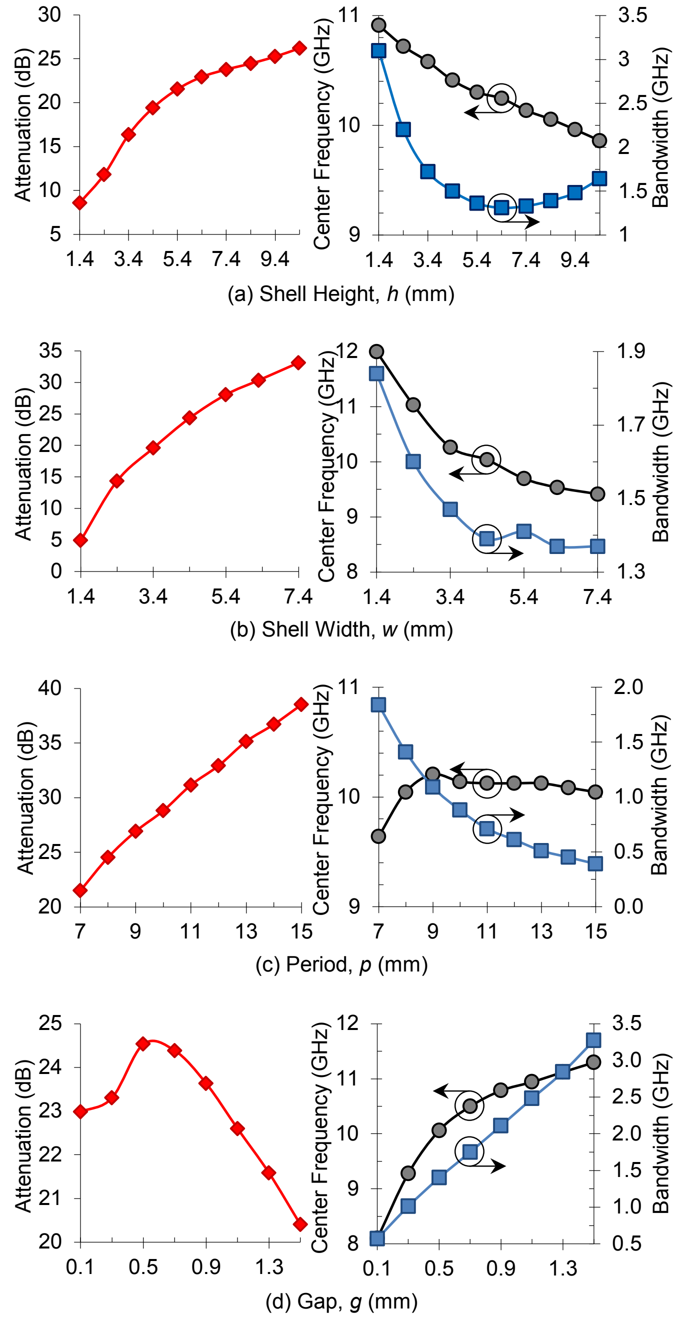

Fig. 3. Parametric sweep results of: (a) h; (b) w; (c) p; and (d) g.

frequency remains fairly stable (above 7 mm). Although increasing p may effectively increase attenuation, this is not recommended because closely spaced elements stabilize performance across scan angle.

D. Effect of Element Gap

Varying g over a large range of 0.1–1.5 mm has little effect on attenuation. Fig. 3(d) shows attenuation within 22.5 ±2.1 dB while bandwidth increases over a 5.7:1 range, and center frequency increases by 40%. One possible explanation is that as gap increases (and bandwidth with it), so

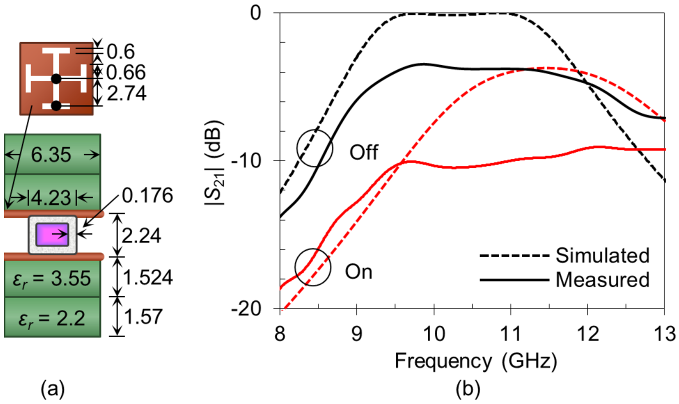

Fig. 4. (a) Fabricated device geometry; and (b) comparison of simulated and measured results.

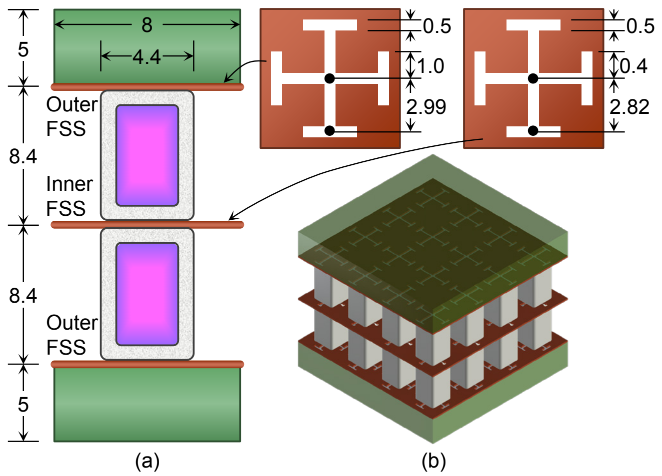

Fig. 5. Third-order structure (a) dimensions; and (b) array render.

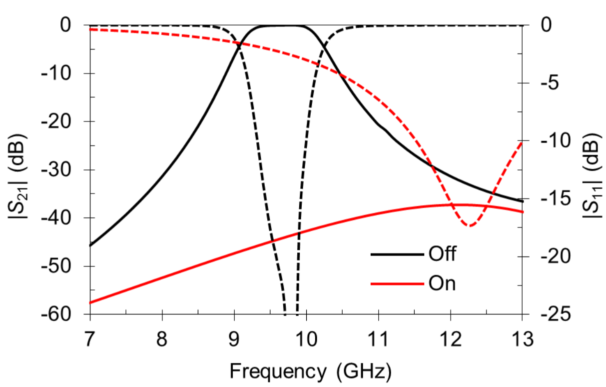

Fig. 6. Simulated third-order response with 44 dB attenuation.

too does the amount of electrical flux that interacts with the plasma volume, cancelling opposing attenuation effects.

IV. Experimental Validation

A second-order structure was fabricated and tested to demonstrate the shielding functionality of a small 12×12 element array with dimensions shown in Fig. 4(a). The array was mounted to a large metal plate with an aperture and the transmission response was measured with a VNA. The plasma-shells were sustained with a 1200 V_{pp} square wave. Fig. 4(b) shows similar trends in simulated and measured performance from off to on state: higher center frequency, and higher average passband insertion loss (6.3 dB simulated and 5.9 dB measured). The fabricated sample has center frequency of 10.7 GHz and bandwidth of 3.6 GHz.

V. Third-Order Structure

Attenuation can be further increased using a third-order structure. With dimensions in Fig. 5(a), the array visualized in Fig. 5(b) has nearly the same overall thickness as Fig. 1(a), and simulated results in Fig. 6 show attenuation of 44.3 dB. Center frequency is 9.7 GHz and bandwidth is 1.1 GHz.

VI. Conclusions

A detailed study of novel plasma-switched FSS structures has been presented. Second- and third-order structures sharing many key dimensions and overall thickness were compared, and the third plasma-shell/FSS layer increased switchable attenuation from 24 to 44 dB. A second-order device was fabricated using conventional photo-etching and surface mount assembly techniques. This device demonstrated the practicability of large-area, low-loss switchable structures that could prove useful for HPM shielding, RCS control, and beam steering applications in extreme environments.

Acknowledgement

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