
Original Research Article

Simulation design and analysis of energy selection surface based on RF front-end field protection

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Abstract: Designed an Energy Selective Surface (ESS) for field protection of RF front-end. Through in-depth research on the working mechanism, the structural parameters that affect the performance of ESS were simulated and optimized, achieving efficient transmission of low-power signals and effective protection of high-power signals. Field circuit joint simulation was also conducted. The results indicate that when the signal power is low, the -3 dB bandwidth of ESS is 504 MHz, and the insertion loss at the center frequency of 5.698 GHz is low, demonstrating good transmission performance; When the signal power is high, the -10 dB bandwidth of ESS is 9.296 GHz, indicating that the surface has good protective characteristics. Meanwhile, the protective performance of the surface in complex electromagnetic environments was verified through joint simulation.

Keywords: RF front-end; frequency selective surface; insertion loss; equivalent circuit

1. Introduction

With the development of high-power microwave technology, the electromagnetic threats faced by RF front-end are becoming increasingly severe. As the "front door" channel for electromagnetic energy to enter the system, antennas are difficult to protect with traditional shielding methods, and high-power limiters have inherent contradictions between response speed, recovery time, and power capacity, making it difficult to meet the protection requirements in complex electromagnetic environments^[1-3].

Energy Selective Surface (ESS) achieves adaptive protection based on nonlinear impedance transients: Diode cutoff at low power incidence, ESS wave transmission, ensuring normal communication; When high-power is incident, the diode conducts, causing a sudden change in ESS impedance, resulting in strong reflection or absorption, blocking high-power microwaves from entering the receiver, thus possessing both transceiver compatibility and adaptive protection capabilities^[4-6].

At present, ESS research still faces challenges such as balancing low insertion loss and high protection efficiency, expanding working bandwidth, precise control of threshold field strength, and consistency between simulation and actual measurement. This article studies the influence of structural parameters on the transmission characteristics and protection effectiveness of ESS through simulation design and optimization. The results show that the -3 dB bandwidth of ESS at low power is 504 MHz, and the insertion loss is low at the center frequency of 5.698 GHz; At high power, the bandwidth of -10 dB is 9.296 GHz, and the protection characteristics are good. The protection performance in complex electromagnetic environments has been verified through field circuit joint simulation.

2. Structural design and analysis

This article designs an energy selective surface based on RF front-end field protection, consisting of a metal outer ring, a metal inner ring rotated 90°, and a Jerusalem cross structure. The structural parameters are: Period $p=12$ mm, outer ring width $w_1=2$ mm, cross width $w_2=0.6$ mm, length $L=5.5$ mm, inner ring

width $w_3=1$ mm, and the dielectric substrate uses Rogers RT5880 with a thickness $h=0.3$ mm ($\epsilon_r=2.20$, $\tan \delta=0.0009$). By loading PIN diodes into the gap between the metal inner square ring and the cross structure, the ESS adaptive conversion function is achieved, as shown in **Figure 1**.

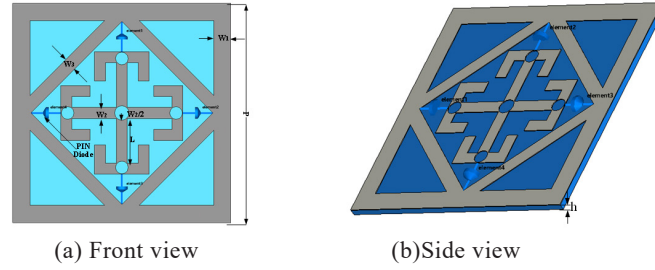


Figure 1. ESS structural unit structure diagram.

The low-pass characteristics of energy selective surfaces mainly rely on the electrical properties of nonlinear components such as PIN diodes, and adaptive protection is achieved by regulating the equivalent impedance changes in their cutoff and conduction states. At low power, the PIN diode turns off with high impedance, equivalent to a small capacitor, and the ESS is similar to a bandpass frequency selective surface; At high power, induced current causes the PIN diode to conduct, reducing impedance. When connecting the metal square ring and cross structure, the surface impedance rapidly decreases, reflecting strong electromagnetic pulses and achieving protection.

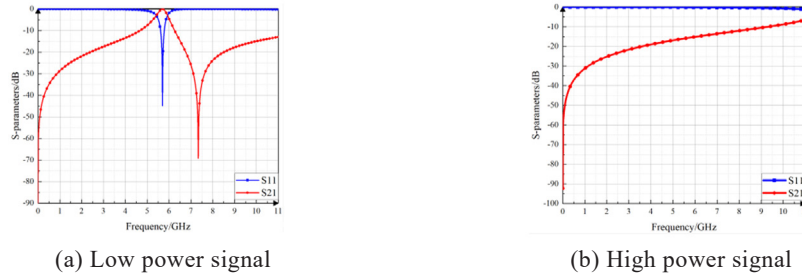


Figure 2. ESS response curve.

Under vertical incidence of electromagnetic waves, **Figure 2** (a) shows that at low power, the -3 dB bandwidth of the structure is 504 MHz (5.418-5.922 GHz), and the insertion loss at the center frequency of 5.698 GHz is only 0.0002 dB. The transmission performance is good and can meet normal signal transmission and reception; The transmission zero at 7.336 GHz enhances the out of band selectivity of the high-frequency end, which can suppress high-frequency signals outside the passband. **Figure 2** (b) shows that at high power, the -10 dB bandwidth is between 0-9.296 GHz, which effectively suppresses high-power signals and protects the system from strong electromagnetic pulse interference.

3. Analysis of factors affecting ESS transmission performance

This section focuses on the simulation analysis and parameter optimization research of ESS. Based on Floquet theory, an infinite periodic array can be simplified into a single unit for analysis. In the study, SMP1340 diode was used as a nonlinear component, which can be equivalent to a parallel circuit of 0.1 pF capacitor and 0.5 nH inductor in the cut-off state; When in a conducting state, its equivalent circuit can be simplified to a 3Ω resistance model.

3.1. The influence of substrate thickness h on ESS performance

At low power, the PIN diode is turned off. According to **Figure 3** (a), the increase in substrate thickness reduces the center frequency f_0 from 4.02 GHz to 3.888 GHz, and the transmission zero point f_1 from 4.92 GHz to 4.74 GHz. This is due to the increase in effective dielectric constant, propagation path extension, and equivalent capacitance, which lowers the resonant frequency. At high power, as shown in **Figure 3** (b), the -10 dB bandwidth decreases from 8.592 GHz to 7.068 GHz; The thickening of the substrate enhances the control of propagation paths and phase delays, resulting in a weakened ESS protection capability. The

thickness of the ESS substrate in this article is taken as $h=0.5$ mm.

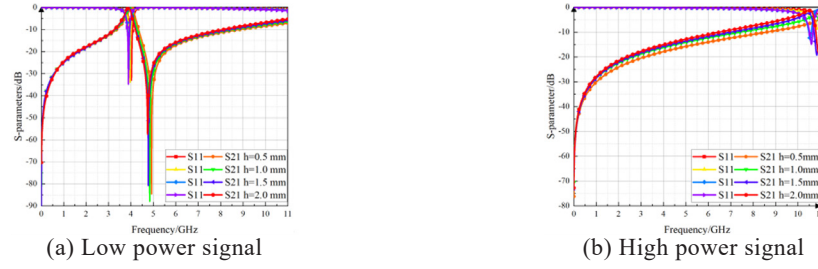


Figure 3. Influence of substrate thickness h on ESS performance.

3.2. The influence of metal ring width w_1 on ESS performance

At low power, the PIN diode exhibits high impedance and has little impact on electromagnetic wave transmission. As shown in **Figure 4** (a), when the width w_1 of the metal outer ring increases, the center frequency f_0 remains almost unchanged, and the transmission zero point f_1 increases from 4.68 GHz to 4.944 GHz. The reason is that the increase in the width of the outer ring reduces the equivalent inductance, increases the resonant frequency, and shifts the transmission zero point towards higher frequencies. At high power, the PIN diode conducts with low impedance. From **Figure 4** (b), the -10 dB bandwidth has increased from 6.048 GHz to 9.06 GHz, enhancing the ESS protection performance. The width of the ESS metal outer ring designed in this article is taken as $w_1=2$ mm.

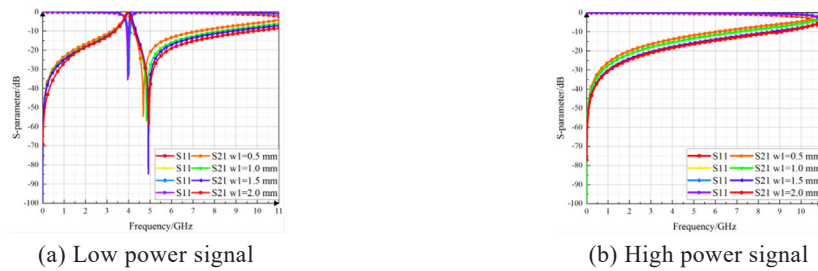


Figure 4. The effect of metal square ring width w_1 on ESS performance.

3.3. The influence of structure width w_2 on ESS performance

At low power, the PIN diode exhibits high impedance and has little impact on electromagnetic wave transmission. According to **Figure 5** (a), increasing the cross width w_2 causes f_0 to rise from 3.816 GHz to 4.02 GHz, and f_1 to rise from 4.428 GHz to 4.92 GHz. As the cross width increases, the equivalent inductance decreases, the resonant frequency increases, and the transmission zero shifts towards higher frequencies. At high power, the PIN diode conducts with low impedance. From **Figure 5** (b), the -10 dB bandwidth increased from 6.948 GHz to 8.592 GHz, significantly enhancing the protective function. It can be seen that adjusting the cross width can effectively adjust the ESS response characteristics and adapt to different power requirements. The width of the ESS cross structure in this article is taken as $w_2=0.8$ mm.

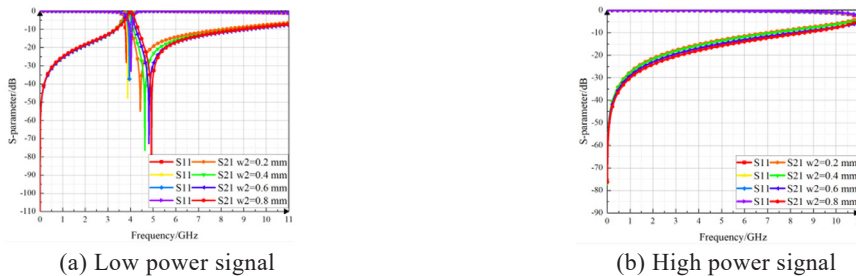


Figure 5. The effect of cross structure width w_2 on ESS performance.

3.4. The influence of incident angle on ESS performance

Under TE polarization, as shown in **Figure 6** (a), the protection bandwidth increases with the increase of incident angle. As the TE wave electric field is perpendicular to the incident surface, the angle increases,

which enhances the interaction between the electric field and matter. The vertical component of the electric field is projected more at the interface, making electromagnetic waves more easily absorbed or scattered. Under TM polarization, as shown in **Figure 6** (b), the protection bandwidth decreases with increasing incident angle. As the TM wave magnetic field is in the incident plane, the angle increases, resulting in a decrease in the efficiency of the interaction between the magnetic field and the material. The vertical component of the magnetic field is projected less at the interface, leading to a decrease in absorption or scattering efficiency.



Figure 6. The influence of incident angle on ESS performance.

4. Field road joint simulation analysis

The relationship between time-domain response and incident wave field strength can provide a more intuitive understanding of ESS performance. The incident wave is a 1.0 GHz sine plane wave, and CST is used for field circuit joint simulation. The SMP1340 diode SPICE model is loaded to simulate its time-domain response. **Figure 7** (a) shows the simulation model, and **Figure 7** (b) shows the variation of input-output over time under low-power incidence. As shown in the figure, when the incident field strength is 10 V/m, the PIN diode is not conducting, and the ESS is in a transparent state, with most of the energy smoothly passing through the surface.

Figures 7 (c) and (d) show the field strength and voltage across the diode under high-power incidence. When the incident field strength increases to 2000 V/m, the PIN diode conducts and the ESS enters protection mode. The field strength is about 120 V/m, and the peak leakage is about 150 V/m, with significant attenuation and good protection effect; The leakage voltage at both ends of the diode is less than 2.5 V, which is basically harmless.

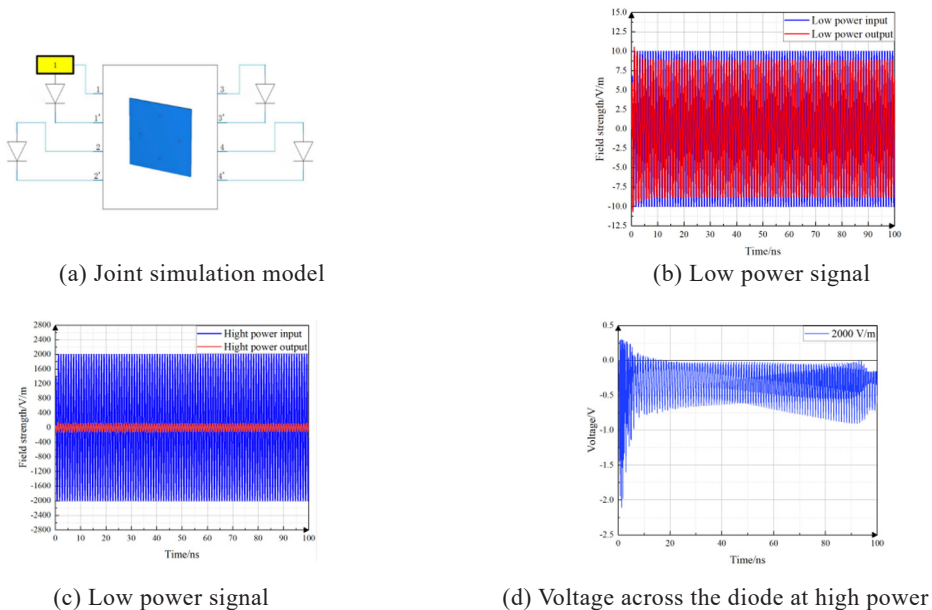


Figure 7. Joint simulation model and results.

5. Conclusion

This article designs an energy selective surface for loading PIN diodes, which achieves efficient transmission of low-power signals and effective protection of high-power signals through theoretical analysis, parameter optimization, and field circuit joint simulation. Simulation results show that at low power, the -3 dB bandwidth is 504 MHz and the insertion loss at the center frequency of 5.698 GHz is only 0.0002 dB. At high power, the -10 dB bandwidth reaches 9.296 GHz. When the incident field strength is 2000 V/m, the diode conducts, the field strength drops to 120 V/m, the peak leakage is about 150 V/m, and the leakage voltage at both ends of the diode is less than 2.5 V. The structural parameters and PIN diode characteristics have a significant impact on the performance of ESS, and after optimization, the center frequency, bandwidth, and protection capability can be effectively adjusted.

References

- [1] Kocyigit A ,Karadeniz B M ,Celik B , et al.Energy-selective surface superstrate for gain enhancement and HPM protection of patch antennas[J].AEUE-International Journal of Electronics and Communications,2026,217-156574156574.DOI:10.1016/J.AEUE.2026.156574.
- [2] Zhang H ,Zhang J ,Zha S , et al.Design of an Energy Selective Surface Employing Dual-Resonant Circuit Topology[J].Electronics,2025,14(15):3029-3029.DOI:10.3390/ELECTRONICS14153029.
- [3] Lv J ,Luo C ,Zhao J , et al.Development of Energy-Selective Surface for Electromagnetic Protection[J].Micro machines,2025,16(5):555-555.DOI:10.3390/MI16050555.
- [4] Kim H Y ,Bae G Y ,Sohn Y W .Uncovering Energetic Positions of Surface Trap States in α -Fe₂O₃ Treated with Cobalt Phosphate (Co-Pi) Using Charge Carrier-Selective Heterodyne Transient Grating Technique.[J].Chemphyschem : a European journal of chemical physics and physical chemistry,2024,25(9):e202300894-e202300894. DOI:10.1002/CPHC.202300894.
- [5] Li Z ,Yuan H ,Li W , et al.A Novel Energy-Selective Surface Endowed with High Shielding Effectiveness by Using a Shape Memory Alloy[J].Technologies,2026,14(4):242-242.DOI:10.3390/TECHNOLOGIES14040242.
- [6] Zhang H ,Zhang J ,Zha S , et al.Design of an Energy Selective Surface Employing Dual-Resonant Circuit Topology[J].Electronics,2025,14(15):3029-3029.DOI:10.3390/ELECTRONICS14153029.