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Design and Performance Research of Artificial Electromagnetic Structure with Transmission and Absorption Characteristics

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Abstract

A 'sandwish' artificial electromagnetic structure is proposed for meeting the stealth satellite radome's requirements to realize the high-transmission and reduce the radar cross section (RCS) of antennas. This structure is implemented by synthetically utilizing the transmission functional layer and absorbing functional layer. Simulating calculation indicate the proposed structure has less-than 3dB insertion loss in the range of 1GHz-8.5GHz and more-than 0.8 absorptivity in the range of 11.5GHz-18GHz, while keeping incident-angle stability. The proposed artificial electromagnetic structure has important application values of engineering.

Keywords: radome; artificial electromagnetic structure; transmission; absorption

1. General Introduction

With the development of all kinds of advanced space detection equipment, the survivability of satellites has been greatly threatened. Satellite stealth technology is to take corresponding measures against the detection threats of satellites in orbit, so as to achieve the purpose that satellites are difficult to be found, difficult to be hit and difficult to be destroyed. It is an important means of satellite security protection and survival ability improvement [1].

As a functional part of electromagnetic window, the radome of satellite must meet the technical requirements of radar antenna on transmission efficiency and other indicators. At the same time, as one of the main electromagnetic scattering sources of satellite, the stealth effect of radome plays an important role in reducing the RCS of the whole satellite. Therefore, in order to reduce the RCS value of radome, stealth measures must be taken.

The traditional methods to realize the stealth performance of satellite radome are to adopt absorbing materials and frequency selection stealth technology [2]. Absorbing materials are used to absorb electromagnetic waves, namely coating the surface of the radome with absorbent coating and absorbent adhesive layer, etc. However, there are disadvantages such as great influence on the pass-band transmission efficiency, poor design ability of absorbing frequency, and large weight [3]. The frequency selection stealth technology is to make use of the selection characteristics of artificial electromagnetic structures for electromagnetic waves, so that the electromagnetic waves in the working frequency band can almost pass through the radome without loss, and play a role in the suppression and reflection of out-of-band signals [4-8]. This stealth technology must rely on the large curvature shape of the radome to achieve the stealth performance in the key airspace. For the radome structure with small curvature, its RCS reduction performance is greatly limited.

In view of the technical requirements of stealth satellite radome, as well as the limitations of absorbing materials and frequency selection stealth technology, this paper carried out research on the design of artificial electromagnetic structure with transmission and absorption characteristics, and designed a 'sandwich' artificial electromagnetic structure. By using the transmission functional layer and absorbing functional layer, the electromagnetic wave in the working frequency band is lossless and the signal outside the band can be absorbed, so as to realize the function of stealth. The angle stability, wave transmission and absorption mechanism of the structure are analyzed. The simulation results show that the designed structure can give consideration to wave transmission performance at the low frequency and wave absorption performance at the high frequency, and has good angle and polarization stability.

2. Working Mechanism

In order to realize transmission outside the absorbing frequency band, this paper intends to adopt the ‘sandwich’ structure as shown in Figure 1. The upper layer of the structure is absorbing functional layer, the middle layer is the dielectric layer, and the lower layer is the transmission functional layer. Among them, the periodic metal array of the transmission functional layer can achieve good transmission performance at low frequency and good reflection performance at high frequency. Its frequency response characteristic curve is shown in Figure 2(a). The periodic metal array of the absorbing functional layer can achieve good absorbing function at high frequency and good transmission performance at low frequency. Its frequency response characteristic curve is shown in Figure 2(b). Through reasonable matching and optimization design, in high frequency band, the reflection characteristic of the transmission functional layer acts as the metal reflection plate of the absorbing functional layer, so as to realizes the absorption characteristic of the out-of-band signal with the coordination of the absorbing functional layer. In the low frequency band, the absorbing functional layer has good bandpass performance and does not affect the high transmission performance of the whole artificial electromagnetic structure, so as to realize the integrated design of the artificial electromagnetic structure with transmission and absorption characteristics.

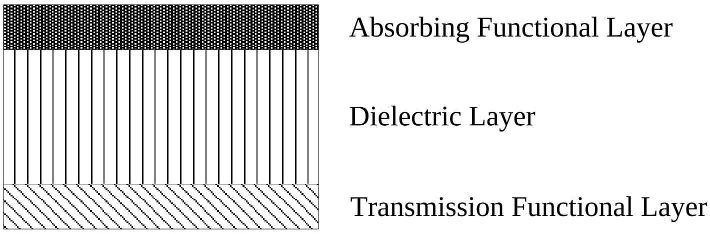
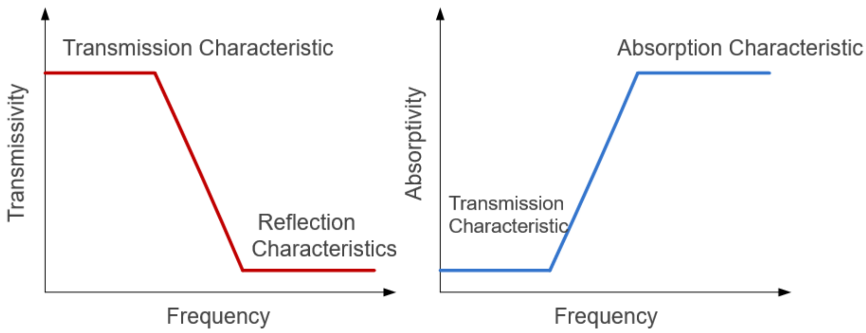


Figure 1 – Topology of the ‘sandwich’ structure.



(a) Transmission functional layer (b) Absorbing functional layer
Figure 2 –The frequency response characteristic curves.

It is worth noting that, due to the requirement of wave transmission in the low frequency band, the bottom plate cannot be covered with all metal, and the transmission is not all 0. Therefore, the influence of S_{11} and S_{21} parameters should be taken into account in the calculation of the absorption rate, so the absorptivity calculation formula is:

$$A(\omega) = 1 - |S_{11}|^2 - |S_{21}|^2 \tag{1}$$

3. Structure Design

According to the above design ideas and considering the strength and stiffness required by the actual use of the radome, the artificial electromagnetic structure with transmission and absorption characteristics as shown in Figure 3 is designed. The thickness of the inner skin is 0.4mm, and the thickness of the outer skin is 0.6mm. The skin is made of composite materials with dielectric constant of 3.3 and the loss angle tangent of 0.02. The thickness of the core layer is 3.0mm. The core layer is made of honeycomb material with dielectric constant of 1.2 and the loss angle tangent of 0.007. The transmission functional layer is loaded between the inner skin and the core layer, and the absorbing functional layer is loaded between the outer skin and the core layer.

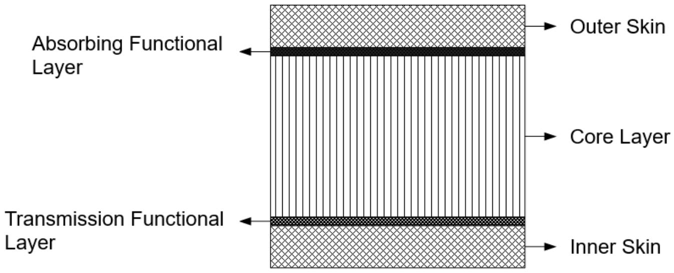


Figure 3 –Topology of the proposed artificial electromagnetic structure.

The structure of the transmission functional layer is a periodic metal element array, and the diagram of the element is shown in Figure 4. After optimization design, the outer length of the square frame is l_1 =8mm, the inner length of the square frame is l_2 =4mm, the width of the cross line inside the square is w =0.1mm, the diameter of the circular aperture on the square frame is d =1.8mm, and the period of the element is 12.5mm. The frequency response characteristic curve of the composite structure composed of the transmission functional layer, skin and core layer is shown in Figure 5. It can be seen from the figure that the transmission functional layer has good wave-transmission characteristic at low frequency and good reflection characteristic at high frequency, which can meet the construction requirements of the artificial electromagnetic structure with transmission and absorption characteristics.

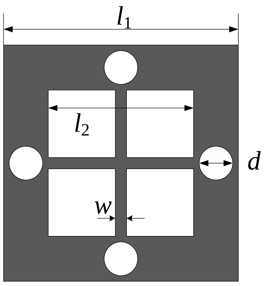


Figure 4 –Topology of the transmission functional layer.

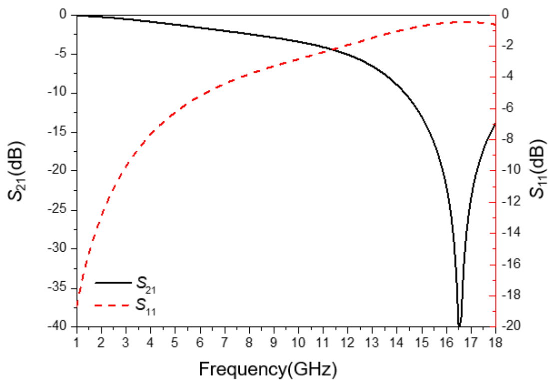


Figure 5 –The frequency response characteristic curves of the transmission functional layer.

The structure of the absorbing functional layer is a periodic array of resistive film elements. The diagram of the element is shown in Figure 6. After optimized design, the length of the inner square side is l_3 =5mm, the length of the inner cross is l_4=8mm, and its width is w_1 =2mm, the length of the surrounding rectangle is l_5 =3.5mm, and its width is w_2 =1mm, and the period of the element is 12.5mm. Square resistance is 50Ω/sq. The frequency response characteristic curve of the composite structure composed of the absorbing functional layer, skin, core layer and metal bottom plate is shown in Figure 7. It can be seen from the figure that the absorbing functional layer has good wave-transmission characteristic at low frequency and good wave-absorption characteristic at high frequency when combined with the metal base plate, which can meet the requirements of the artificial electromagnetic structure with transmission and absorption characteristics.

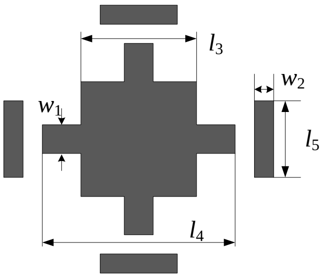


Figure 6 –Topology of the absorbing functional layer.

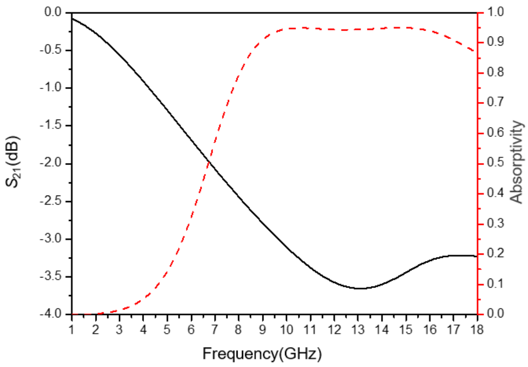


Figure 7 –The frequency response characteristic curves of the absorbing functional layer.

The transmission functional layer, the absorbing functional layer and the dielectric support layer are combined together to construct the artificial electromagnetic structure with transmission and absorption characteristics, as shown in Figure 3, and its frequency response characteristic curve is shown in Figure 8. As can be seen from the figure, the insertion loss of this structure is less than 3dB in the frequency range of 1GHz~8.5GHz, and the absorptivity is all greater than 0.8 in the frequency range of 11.5GHz~18GHz. That is to say, this structure has good transmission performance at low frequency and good absorption performance at high frequency.

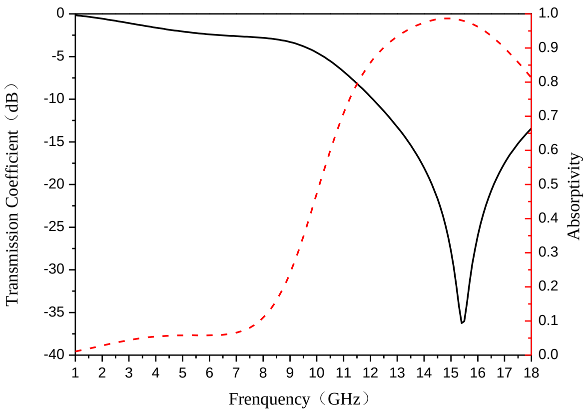
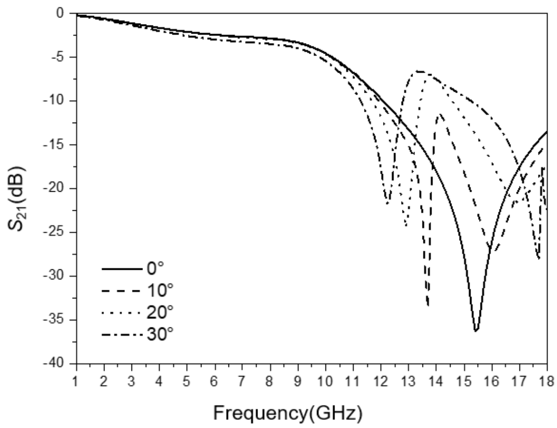


Figure 8 –The frequency response characteristic curves of the artificial electromagnetic structure.

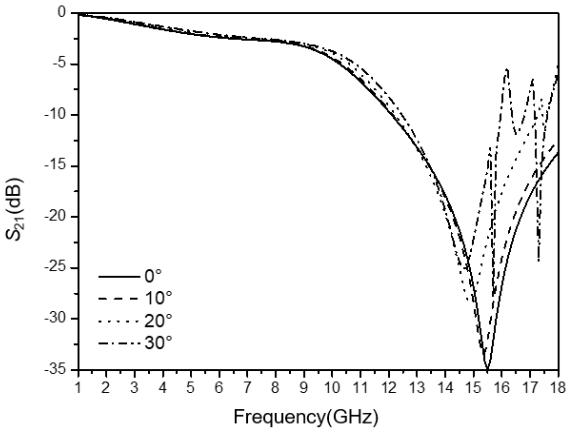
4. Performance Analysis

4.1 Stability Analysis

The angle stability of the designed artificial electromagnetic structure is analyzed. The transmission characteristic curves of vertical polarization and horizontal polarization and in the incidence angle range of 0°~30° are shown in Figure 9. It can be seen from the figure that the insertion loss of the structure is less than 3dB in the vertical polarization and 1.0GHz~8.5GHz frequency band, and less than 3dB in the horizontal polarization and 1.0GHz~6GHz frequency band. Both polarizations have good angle stability. The absorption characteristic curves are shown in Figure 10. As can be seen from the figure, when the incident angle increases, the absorptivity in the absorbing frequency band decreases. The main reason is that the transmission functional layer will produce grating-lobe at high frequency with the increase of the incident angle, and its reflection characteristics are difficult to match with the absorbing functional layer.

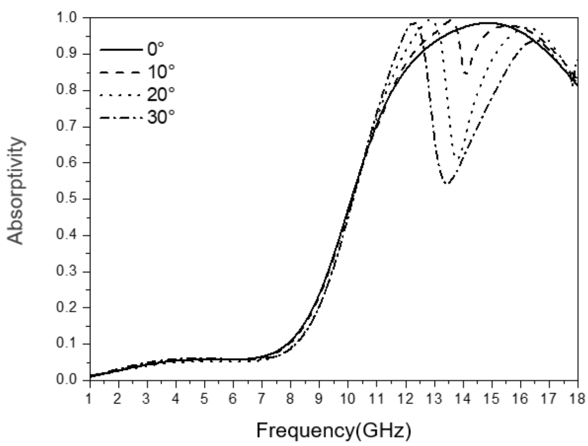


(a) Vertical polarization

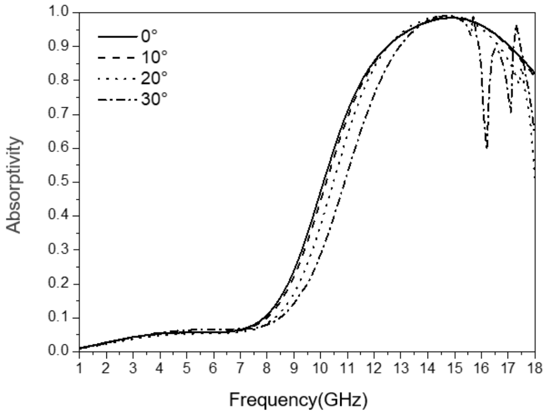


(b) Horizontal polarization

Figure 9 –The transmission characteristic curves.



(a) Vertical polarization



(b) Horizontal polarization

Figure 10 –The absorption characteristic curves.

4.2 Analysis of Transmission Mechanism

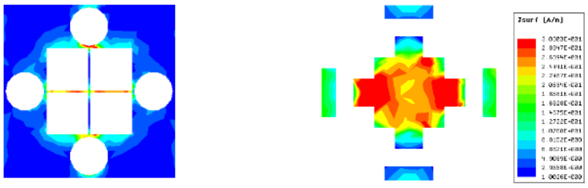
The frequency point of 2.0GHz is selected in the low frequency band for transmission mechanism analysis. The surface current distribution of the transmission functional layer and the absorbing functional layer at this frequency point is shown in Figure 11. As can be seen from the figure, the surface current at this frequency point is mainly distributed in the transmission functional layer. That is to say, the resonance at the transmission frequency point is mainly caused by the transmission functional layer, and the ohmic loss caused by the absorbing functional layer is very small. Therefore, it shows good wave-transmission performance at this frequency point.

(a) Transmission functional layer (b) Absorbing functional layer

Figure 11 –The surface current distribution. (2GHz)

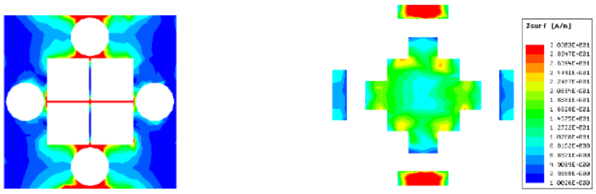
4.3 Analysis of Absorption Mechanism

The frequency points of 11.5GHz and 18.0GHz are selected in the high frequency band to analyze the absorption mechanism, and the current distribution on the surface of the transmission functional layer and the absorbing functional layer under these frequency points are shown in Figure 12 and 13. It can be seen from the figure that, at the absorbing frequency point, there is a large current distribution on both the transmission functional layer and the absorbing functional layer. That is, the absorption performance of the absorbing frequency band is mainly formed by the coordination of the transmission functional layer and the absorbing functional layer. The absorption performance of the lower frequency (11.5GHz) depends on the combined action of the inner cross of the transmission functional layer and the inner square and cross of the absorbing functional layer. The absorption performance of the higher frequency (18.0GHz) depends on the combined action of the circular aperture on the square frame of the transmission functional layer and the rectangle around the absorbing functional layer. In other words, both the transmission functional layer and the absorbing functional layer are composed of composite elements. Different frequencies resonate at different positions of the composite element, and multiple resonances together constitute the whole absorbing frequency band.



(a) Transmission functional layer (b) Absorbing functional layer

Figure 12 –The surface current distribution. (11.5GHz)



(a) Transmission functional layer (b) Absorbing functional layer

Figure 13 –The surface current distribution. (18.0GHz)

In order to further study the energy loss of the artificial electromagnetic structure, the dielectric loss of the skin and core layer is increased by 10 times, and the absorbing performance is compared with the original absorbing performance, as shown in Figure 14. As can be seen from the figure, when the loss of dielectric layer increases substantially, the change of absorptivity in the absorbing frequency band is no more than 0.03. That is, the dielectric loss caused by the skin and core layer of the whole structure is very small, and its energy is mainly consumed by the ohmic loss of t the absorbing functional layer.

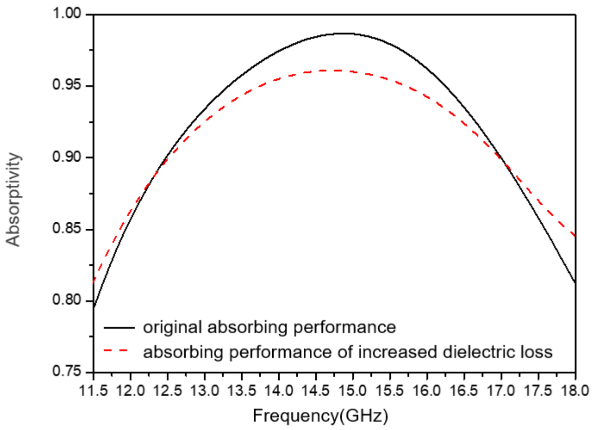


Figure 14 –Contrast curves of absorbing performance

5. Conclusion

In this paper, a ‘sandwich’ artificial electromagnetic structure with transmission and absorption characteristics is proposed, which makes comprehensive use of the transmission functional layer and the absorption functional layer. The proposed structure has less-than 3dB insertion loss in the range of 1GHz-8.5GHz and more-than 0.8 absorptivity in the range of 11.5GHz-18GHz, while keeping incident-angle stability. Operating principle and loss mechanisms of the proposed structure are analyzed through surface current distribution. Analyses results show that the resonance in low frequency is mainly caused by the transmission functional layer. Meanwhile that in high frequency is caused by combined action of both functional layers. Energy loss of the proposed structure largely depends on ohmic loss of the absorbing functional layer. The proposed artificial electromagnetic structure has important project application values for stealth satellites.

6. Copyright Statement

References

[1] Huang H W. Research on the concept of satellite stealth [J]. Aerospace Electronic Warfare, 2010, 26(6): 22-24.

[2] Ruan Y Z. Radar cross section and stealth technology [M]. Beijing: National Defense Industry Press, 2001.

[3] Lai K, Chen M Y, Sun R J, Yin F F. Application of absorbing materials in radar stealth field [J]. Journal of Xi'an Polytechnic University, 29(6): 655-662.

[4] Wahid M. The development of a conical frequency selective radome [J]. GEC J.Res, 1995, 12(2): 95-96.

[5] Chui C, Chang C. A novel miniaturized-element frequency selective surface having a stable resonance[J]. IEEE Antenna and Wireless Propagation Letter, 2009, 8: 1175-1177.

[6] Sarabandi K, Behdad N. A frequency selective surfaces with miniaturized elements[J]. IEEE Transactions on Antennas and Propagation, 2007, 55(5): 1239-1224.

[7] Yang G, Zhang T, Li W, et al. A novel stable miniaturized frequency selective surfaces[J]. IEEE Antenna and Wireless Propagation Letters, 2010, 9: 1018-1021.

[8] Munk B A. Frequency selective surface: theory and design[M]. New York: A Wiley Interscience Publication, 2000.