

Study on transmission and scattering characteristics of conformal double layer frequency selective surface

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Abstract. This paper presents a three-medium, double-layer Frequency Selective Surface (FSS) structure that exhibits stable filtering characteristics, including stability with respect to incident angle and stability of filtering performance under misalignment conditions. The resonant frequency remains unchanged even when the elements are misaligned. The Radar Cross Section (RCS) of this structure has been tested, and the results indicate high transmittance within the passband and an RCS reduction of up to 20 dB outside the passband. These features render the structure highly significant for applications in conformal radome designs.

Keywords: FSS / non-aligned / curved surface / conformal

1 Introduction

In the contemporary era of highly advanced electromagnetic technology, the precise control and efficient utilization of electromagnetic waves have become critical demands across diverse scientific research endeavors and engineering applications. Frequency Selective Surfaces (FSS), a class of electromagnetic structures capable of selectively transmitting or reflecting electromagnetic waves within specific frequency bands, have been extensively studied and applied over the past few decades. However, with increasing practical demands, single-layer planar FSS have proven inadequate for specialized requirements in complex environments. This has led to the development of curved structures and multi-layer designs.

Curved structures have endowed FSS with greater design flexibility and adaptability, enabling better conformity to curved surfaces in practical applications, such as aircraft exteriors and communication radomes. Furthermore, double-layer or multi-layer designs have expanded the frequency-selective properties and functionalities of FSS, allowing for more precise and diversified control of electromagnetic waves. However, an inevitable challenge arises: the issue of interlayer unit cell alignment [1–3]. During the actual fabrication process, misalignment between the layers of multi-layer FSS can lead to problems such as resonant frequency shifts and reduced transmittance [4,5]. Consequently, achieving consistent alignment between curved surfaces while maintaining agreement

between experimental and simulation results has become a critical research direction that scientists are actively striving to address.

In 2012, Wang Jianbo et al. [6] proposed a novel unit cell, the aligned unit cell structure has good incident angle stability and can achieve a wide bandwidth of 3.3 GHz. The non-aligned unit cell, the bandwidth narrows down and transmission loss increases with increasing incident angle. However, the research on conformal dual-layer FSS had not been extensively conducted. In 2018, Wang Xiangfeng et al., based on the electromagnetic transmission characteristics of a two-dimensional infinite FSS with a Y-shaped unit cell structure, proposed an integrated processing scheme for conformal curved thick-screen FSS radomes using a multi-degree-of-freedom laser robot in conjunction with a rotating table [7]. Test results from the microwave anechoic chamber indicated that the fabricated conformal curved FSS radome exhibited excellent electromagnetic filtering characteristics. In 2019, Shi Xiangzhu introduced methods for conformal modeling on two types of non-developable surfaces [8]. However, research on conformal curved structures for multilayer designs had not been conducted. In 2021, Fule Kang et al. designed an ultra-wideband bandpass FSS with a three-layer structure [9]. They employed a multilayer coupling method to design the metallic patches and layered Jerusalem cross metallic grids. Full-wave simulation results indicated that the -3 dB bandwidth of this structure extended from 8.9 GHz to 36.1 GHz, with an absolute bandwidth of 27.2 GHz and a relative bandwidth of 121%. Additionally, this FSS featured a low profile, a flat passband, and stable performance at different incident angles. Within the

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ultra-wideband operating range, when the incident angle was 40° , the maximum loss of the electromagnetic wave within the passband was less than 0.6 dB, and the bandwidth remained virtually unchanged, demonstrating excellent angular and polarization stability. In 2021, Kanishka Katoch et al. proposed structure manifests polarization independent characteristics and provides a stable frequency response for normal and oblique angles under both transverse electric (TE) and transverse magnetic (TM) incident polarization [10]. The angular stability for various polarization angles is also obtained. This structure provides a -10 dB wide impedance bandwidth of 110.79%. In 2025, Naveena Meka et al. presented a miniaturized angularly stable wideband FSS for shielding applications [11]. The structure exhibits wide band stop characteristics from 3.7 GHz to 15.5 GHz with Shield effectiveness of 67 dB. The designed FSS provides good angular and polarization stability up to 75 degrees for both planar and conformal structure.

Based on the previous research of the research group, this work examines the use of an FSS structure on curved surfaces that is unaffected by the degree of alignment. The interaction between FSS layers is confirmed by comparing the electric field conditions of double-layer FSS with varying degrees of misalignment. The transmittance stays at a good level when the misalignment is less than $T/4$, which is relatively simple to do in real processing. When the misalignment value is at its maximum $T/2$, the transmittance decreases within -2.9 dB. The test curve and the simulation curve show good agreement when a double-layer FSS screen is processed on a genuine curved radar antenna cover and tested using the free space technique, with the increase of incident angle, the filter characteristic curve does not produce a large deviation because of non-alignment, these values are within the acceptable range in engineering.

2 Material and methods

2.1 FSS structure model

Figure 1 shows the unit cell structure of the FSS. To achieve better bandwidth performance, a multi-layer ceramic/FSS composite structure design is adopted. The layers are supported by honeycomb material as the spacer layer, and the base material is a ceramic with a dielectric constant of 3. In addition to the unit cell shape, size, and arrangement being important, the coupling effect of the dielectric layers cannot be ignored. Therefore, after optimizing the relevant structural parameters, a structure consisting of three dielectric layers and two FSS layers was designed, as shown in Figure 1b. As can be seen from Figure 2, as the incident angle (The incident angle is the angle between the incident electromagnetic wave and the normal) increases, this structure exhibits excellent filtering stability. For normal incidence, the -3 dB bandwidth is 3.95 GHz. When the incident angle increases to 70° , the -3 dB bandwidth narrows to 2.8 GHz.

After aligning with a specific point in the FSS layer, due to the varying curvature, there will naturally be a misalignment between the two layers, with the outer

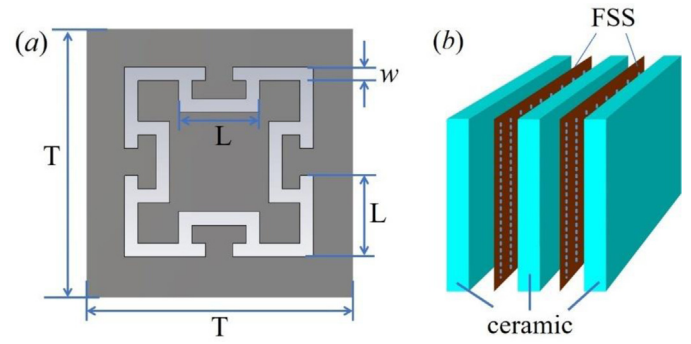


Fig. 1. The schematic of FSS. (a) The schematic of unit cell. (b) Exploded view.

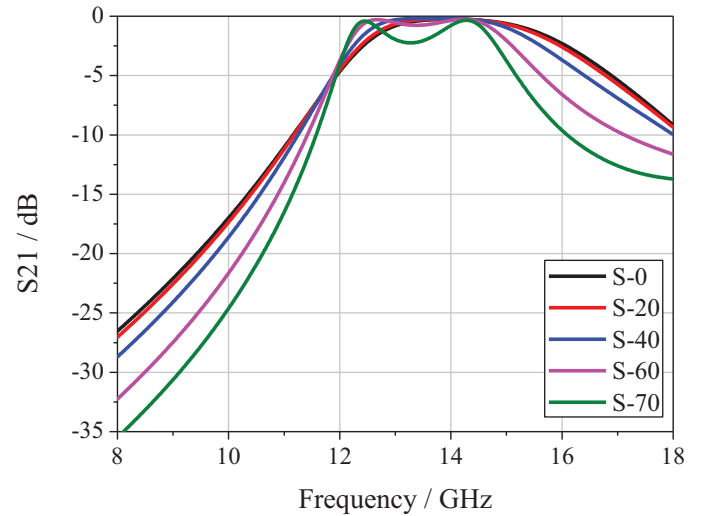


Fig. 2. The propagation characteristics of different incident angles.

radius labeled as r_1 and the inner radius as r_2 , as shown in Figure 3a. Therefore, the dislocation value caused by different curvature is $\Delta T = (\theta_2 - \theta_1) r_2$, where, $d = r_1 - r_2$. And because $T = r_1 \theta_1 = r_2 \theta_2$, so $\Delta T = \frac{d}{r_1} T$. The radius of the radome is $r_1 = 20$ mm. Therefore, when a unit is fully aligned, the natural misalignment value is $1/8 T$. In this case, the FSS unit cell has better stability, as shown in Figure 3b. In the ideal flat plate alignment and curved surface alignment, the curve is almost the same. When there are errors in the alignment process, our structure still has good frequency stability, with reducing of the transmission rate. The reason for the reduce in transmission rate is given in the subsequent electric field analysis.

Meanwhile, there are specific structural factors principally affect the resonant frequency and bandwidth stability in the double-layer FSS. As shown in Figure 4a, the influence of the ceramic-based thickness on the passband is not obvious. The influence of the unit cell's parameters is shown in Figures 4b–4d. The influence of parameter L is the most significant, followed by W , and finally T . Select the structural parameter as the period is $T = 6$ mm, the width $w = 0.3$ mm, and the length $L = 1.5$ mm according to requirements.

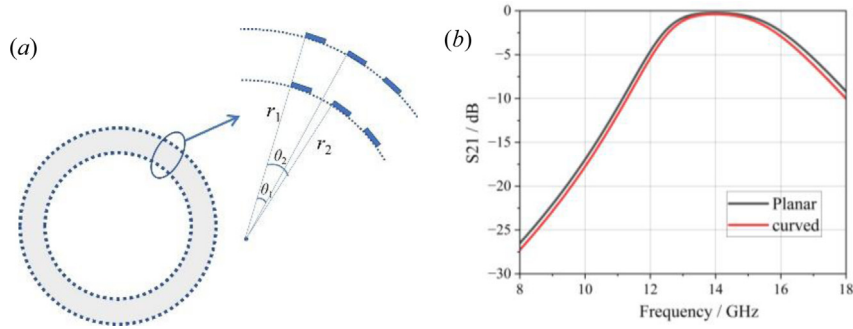


Fig. 3. (a) Double layers FSS. (b) Influence of bending on filtering characteristics.

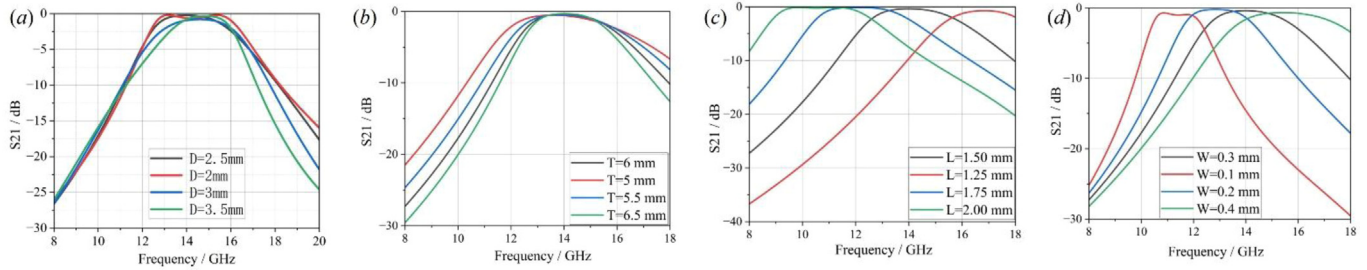


Fig. 4. The influence of the unit cell's parameters.

2.2 Theoretical of transmission mechanism

The double-layer FSS is usually composed of two layers of periodic metal patterns, such as cruciform, annular or square annular. The two layers are separated by a dielectric layer, which is sandwiched between the two substrates as a whole.

Assuming that when the electromagnetic wave is incident on the FSS from left to right, the electric field on the FSS generates a force on the electron to make it oscillate, and the electron will absorb the energy of the electromagnetic wave and radiate it out again, thus forming a reflected wave, which is characterized by high reflectivity.

Assuming that when the incident electromagnetic wave is incident on the FSS from left to right, and the frequency of the incident wave is not the resonant frequency, the incident electromagnetic wave cannot drive the electron to oscillate, and the energy of the incident electromagnetic wave will not be absorbed by the electron, and will be transmitted completely, showing high transmittance.

The equivalent circuit method is one of the methods often used to analyze FSS. For normal incidence, the patch structure can be equivalent to a series LC circuit. Therefore, the double-layer FSS in this paper can be modeled as a two-level filter structure, as shown in Figure 5, which is composed of two series LC circuits separated by a transmission line simulated dielectric layer.

The transmission matrix of the dielectric layer simulated by the transmission line is:

$$T_d = \begin{bmatrix} \cos(\beta d) & jZ \sin(\beta d) \\ j\frac{\sin(\beta d)}{Z} & \cos(\beta d) \end{bmatrix} \quad (1)$$

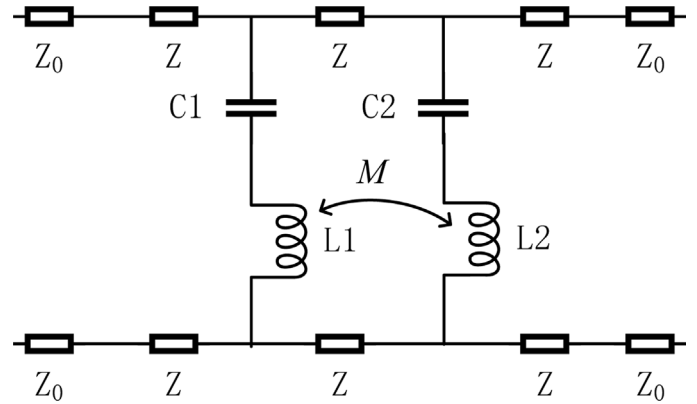


Fig. 5. FSS equivalent circuit model.

where $\omega = 2\pi f$, f is the frequency. $\theta = \beta d = 2\pi n d / \lambda$, where n is the refractive index of the medium and d is the thickness of the medium layer.

For each FSS layer, its impedance is:

$$Z_{FSS1} = j\omega L_1 + \frac{1}{j\omega C_1}, \quad Z_{FSS2} = j\omega L_2 + \frac{1}{j\omega C_2}. \quad (2)$$

For one of the equivalent impedance Z , it can be modeled as a transmission matrix:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix}. \quad (3)$$

For any two ports network, the conversion relationship between ABCD matrix and S parameter is:

$$\begin{aligned} S_{11} &= \frac{A + \frac{B}{Z_0} - CZ_0 - D}{A + \frac{B}{Z_0} + CZ_0 + D}, \\ S_{21} &= \frac{2}{A + \frac{B}{Z_0} + CZ_0 + D}. \end{aligned} \quad (4)$$

According to the transmission line theory, the approximate formula of inductance and capacitance of metal chip unit is:

$$\begin{cases} L = -\mu_0 \frac{D}{2\pi} \log\left(\sin\left(\frac{\pi w}{2D}\right)\right) \\ C = -\epsilon_0 \epsilon_{eff} \frac{2D}{\pi} \log\left(\sin\left(\frac{\pi s}{2D}\right)\right) \end{cases} \quad (5)$$

where D , w and s are the length, width and spacing of the structure capacitance and inductance respectively. Where μ_0 and ϵ_0 are the permeability and permittivity of air. And ϵ_{eff} is the effective relative permittivity of the dielectric layer.

Equation (5) is more suitable for two-dimensional grid structure. Through a large number of simulation experiments, it is confirmed that the capacitance and inductance values calculated by this equation in FSS array deviate greatly from the actual situation. Therefore, equation (5) can only be used for qualitative analysis but not for quantitative calculation.

Since the beginning of the 20th century, many scholars have been committed to establishing accurate formulas to calculate the LC value of structures to accurately obtain the frequency response characteristics of FSS [12]. In references [13,14], the first resonance of simple patterns such as grid structures can be calculated more accurately by introducing semi empirical relations. Langley et al. gave the analytical formula for calculating more complex structures in the 1980s [15]. However, the application scope of these formulas is narrow, and with the increase of the complexity of FSS structure, these formulas become more and more lengthy and complicated, which has deviated from the original intention of simplicity and convenience.

3 Results

3.1 Simulation results

When in the non-aligned situation, under normal incidence, the center resonance frequency f_0 and transmittance T for different non-alignment conditions are shown in Figure 6. When the lateral offset $H = T/4$ and the vertical offsets are $V = 0, T/4, L/2$, respectively, the three curves essentially coincide. Upon further increasing the non-alignment, when the lateral offset $H = T/2$ and the vertical offsets are $V = 0, T/2$, a significant drop in transmittance can be observed. The specific numerical values are presented in Table 1. Since the FSS unit cell is a symmetric shape, the results are symmetric when the lateral and vertical offsets are the same. The simulation data indicates

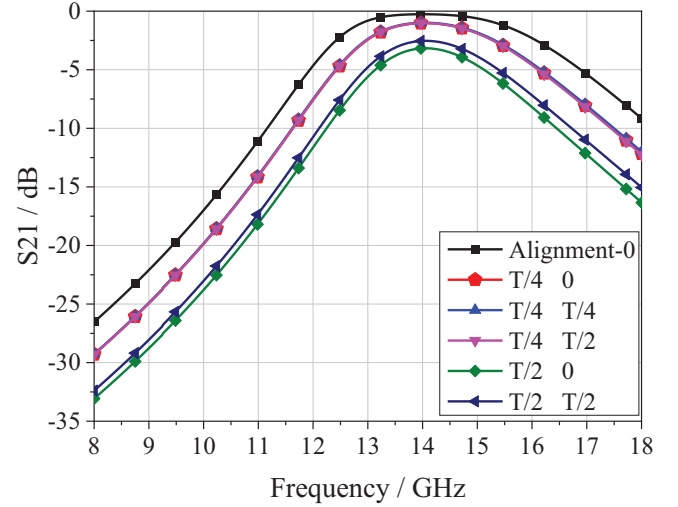


Fig. 6. Filtering characteristics of different alignment conditions.

that when the second layer of elements is misaligned with respect to the first layer, the drift of the center resonant frequency is within 0.06 GHz. Similarly, as the degree of misalignment increases, the -3 dB bandwidth narrows from 3.95 GHz to 2.05 GHz. The greater the misalignment, the more pronounced the decrease in transmittance, which can be explained by the distribution of the electric field.

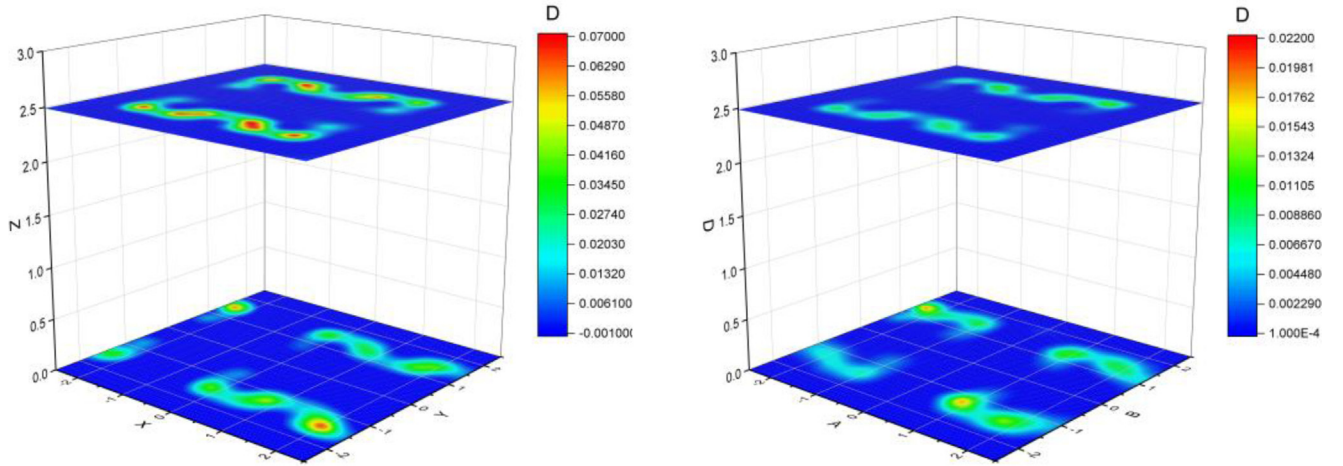
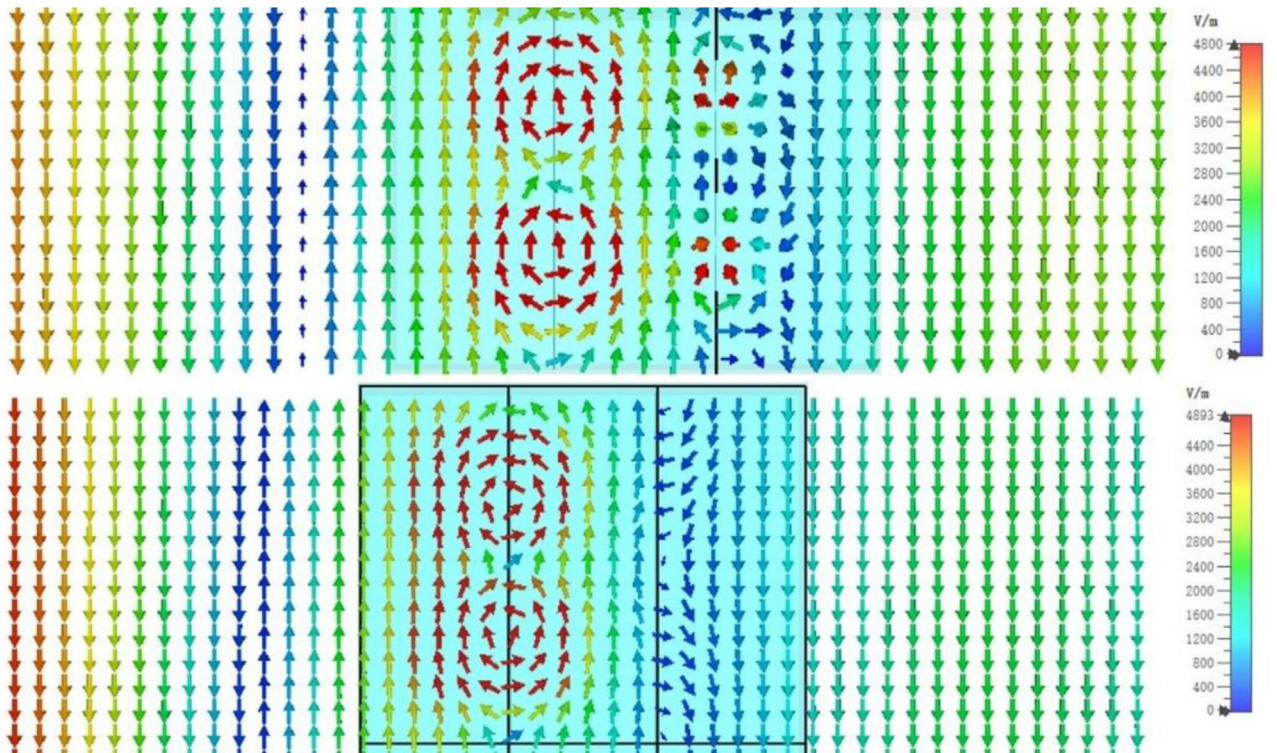
The filtering characteristics are closely related to the interaction of electromagnetic waves within and between periodic structural units. Therefore, to explore the influence of the alignment degree on the electromagnetic wave response in the double-layer misaligned structure, this paper analyzes the electric field distribution within the units and the inter-layer electric field distribution under misalignment, as shown in Figures 7 and 8.

In order to better understand the interactions within the dual-layer FSS unit cells and the effects of layer misalignment, simulations were conducted on the electric field distribution of the structure when the upper layer of FSS unit cells remains stationary and the lower FSS screen is laterally shifted by $T/4$ and $T/2$, respectively. As shown in Figure 7, the comparison of the induced electric fields for the two cases reveals that the FSS units exhibit a significant response to the electric field. This response is precisely why the impact of unit cell misalignment on the filtering characteristics cannot be overlooked. The figure illustrates that when the electromagnetic wave is incident from the upper layer, the lower FSS screen exhibits different electric field responses depending on its position. This occurs because, after the electromagnetic wave interacts with the upper FSS layer, the transmission to the lower layer is affected by the misalignment, leading to a re-response of the electric field and a subsequent decrease in transmittance.

Figure 8 shows the electric field distribution between layers, which confirms the above analysis. The proposed unit cell in this paper has a high occupancy rate and a relatively simple structure. Therefore, the internal response of the unit cell is stable, which allows it to maintain good stability

Table 1. The filtering characteristics under different misalignment values.

H V	0			T/4			T/2		
	f_0 (GHz)	T(dB)	-3dB	f_0 (GHz)	T(dB)	-3dB	f_0 (GHz)	T(dB)	-3dB
0	14	-0.262	3.95GHz	14.03	-1.0199	2.65GHz	14.06	-3.1693	—
T/4	14.03	-1.0199	2.65GHz	14.03	-0.98559	2.7GHz	14.03	-1.02189	2.64GHz
T/2	14.06	-3.1693	—	14.03	-1.02189	2.64GHz	14.06	-2.53392	2.05GHz

**Fig. 7.** Comparison of the induced electric fields.**Fig. 8.** The distribution of interlayer electric field.

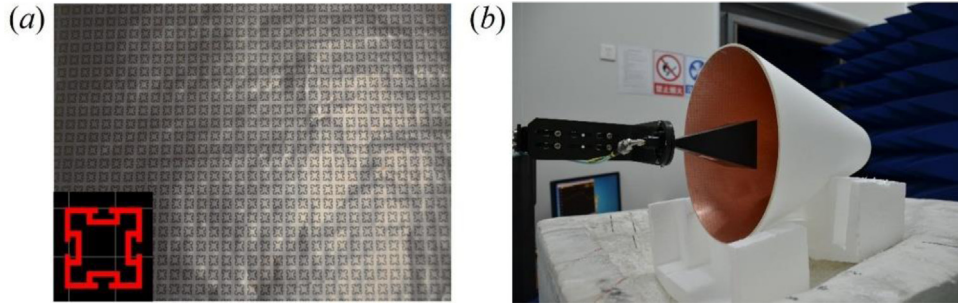


Fig. 9. Fabricated samples and testing environment.

during the misalignment process of the double-layer FSS. When the electromagnetic wave passes through the second layer, it is re-excited. Therefore, the transmittance varies with the magnitude of the misalignment.

3.2 Testing results

The content of this paper is based on our previous studies in which the non-alignment problem of multi-layer flat structure was studied in the early stage. This paper made further research and analyzed the electric field distribution of the misaligned layer. The stability structure is added to the curved radome, and the stability of the non-aligned structure proposed in the paper is verified by testing. The fabricated samples of the proposed structure were carefully processed and prepared for evaluation. For the structure proposed in this thesis, the flexible FSS screen (as shown in Fig. 9a) was attached to the curved antenna radome. The testing environment (as shown in Fig. 9b) was designed to accurately assess the performance of the samples under controlled conditions. And the filtering characteristics were measured using the free-space method which is a type of network parameter method. The setup included precise alignment of the samples within the test chamber, ensuring that all parameters were maintained according to the experimental protocol. This rigorous approach to both fabrication and testing ensured reliable and reproducible results.

The second layer of elements was intentionally misaligned by $T/4$ relative to the first layer. Measurements were taken for different incident angles ranging from 0° to 60° . As shown in Figure 10, the simulation data are in good agreement with the test data. When the incident angle increases to 60° , the misalignment slightly narrows the passband bandwidth, but the resonant frequency remains stable. This structure exhibits excellent angular stability and the advantage of low alignment requirements between the two layers of FSS.

Then, the RCS of the curved ceramic/FSS composite cover sample with three-layer medium and double screen non-aligned FSS is measured at multiple frequency points with an analog antenna (as shown in Fig. 9). It can be seen from the test curve that the addition of FSS does not change the RCS characteristics of the cover and antenna in the working frequency band. As the operating frequency point moves out of band, the out of band filtering baud property of the FSS composite cover is obvious. The antenna reflection at 0° occupation angle at 18 GHz drops

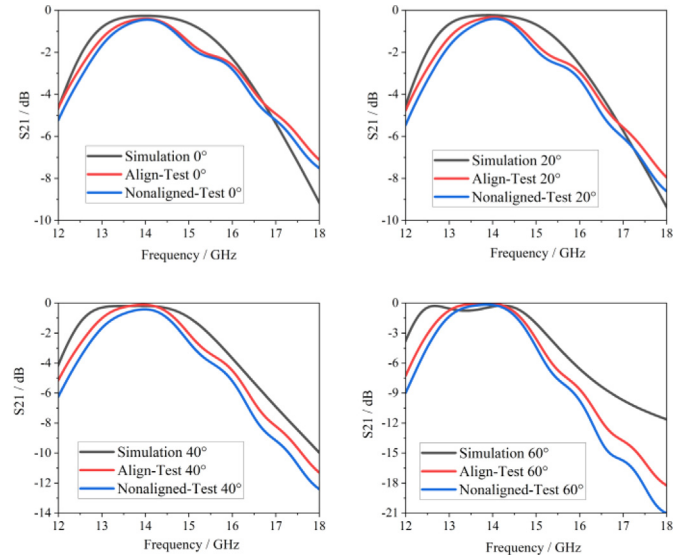


Fig. 10. Comparison diagram of simulation test curve.

from 10 dbm^2 to 12 dbm^2 , and the out of band RCS is reduced by more than 20 dB. In Figure 9, “radome” refers to a radar antenna cover without FSS screen, and “FSS” refers to a radar antenna cover with FSS screen. At the same time, considering the simulation data in the design process (Fig. 11), it can be seen that the out of band transmission transmittance in the low frequency band decreases more rapidly than that in the high frequency band.

4 Conclusion

The filtering characteristics of the traditional curved FSS radome often have a certain drift compared with the plane case. In this paper, the design of three-layer medium + Dual Screen FSS is improved. From the simulation results of the electric field distribution, it can be seen that the FSS unit cell pattern will generate new excitation to the electric field, and the central resonance position has not changed significantly after the dislocation of the FSS. The filtering characteristics of the conformal FSS radome are also simulated and tested in this paper. The structure has stable angular stability, and it still maintains stable filtering characteristics in the case of non-aligned elements between layers, which is confirmed in RCS test.

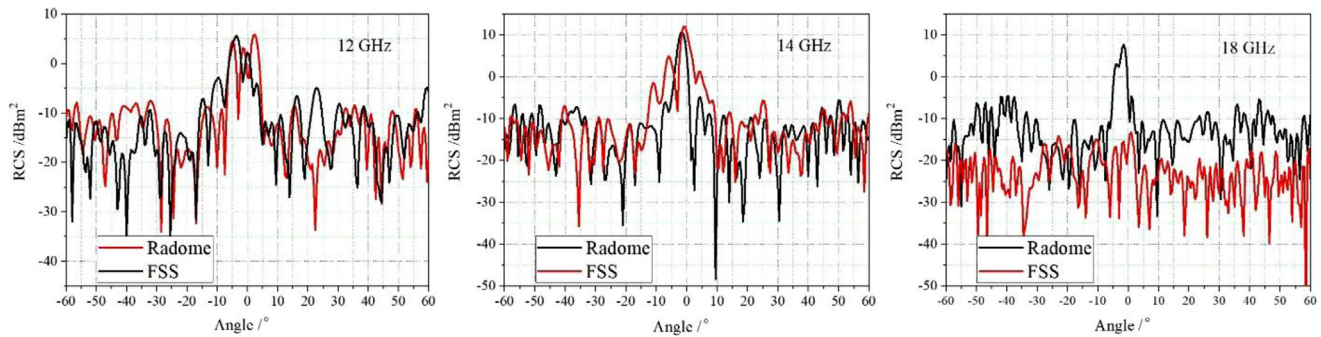


Fig. 11. Comparison diagram of simulation test curve.

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Conflicts of interest

The authors have nothing to disclose.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

Author contribution statement

Conceptualization, M.Y.; Methodology, J.W.; Software, M.Y.; Validation, N.X.; Formal Analysis, M.Y. and N.X.; Investigation, J.W.; Resources, J.W.; Data Curation, J.W.; Writing – Original Draft Preparation, M.Y. and J.W.; Writing – Review & Editing, M.Y. and J.W.; Visualization, M.Y.; Supervision, J.W.; Project Administration, M.Y.; Funding Acquisition, M.Y.

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