The effect of a non-aligned unit on double-screen frequency-selective surface transmission characteristics*

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Double-screen frequency-selective surfaces (FSSs) can bring about a better flattened effect and a rapidly declining edge. They are therefore an effective means to achieve outer-zone stealth of the radar cabin to detect radar waves. In this article, a double-screen wide-bandpass FSS structure is designed and the transmission characteristics of the units under alignment and non-alignment are simulated by means of the spectral domain approach. Meanwhile, the experimental parts fabricated by vacuum evaporation and lithography are tested in a microwave chamber. The results show that the aligned unit structure has good incident angle stability and can achieve high transmittance when the bandwidth is 3.3 GHz, and the transmission loss is less than −1 dB. When the units have a non-aligned structure, the bandwidth decreases and transmission loss increases with increasing incident angle.

Keywords: frequency-selective surface, spectral domain approach, bandwidth

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1. Introduction

A frequency-selective surface (FSS) is a two-dimensional structure composed of a periodic array of metal-patched or periodic opening units on a metallic screen, which shows bandstop or bandpass optional features.[1] FSS has been widely applied in microwave, infrared wave, and visible wavebands, and is the optimum selection, in particular for radar cabin stealth.[2,3] In recent years, FSS has been the hot topic in the microwave and optical fields.[4−6]

With the advances in numerical analysis and design technology, research into single-screen FSS has been developed intensively. Comparatively, the frequency response curve of the double-screen FSS has been characterized as flattened, with a rapidly declining frequency edge, and better bandpass filtering, because the double-screen FSS's frequency response characteristics can be changed by the variation in the near-field coupling between the screens. Meanwhile, the coupling degree can be adjusted by the geometric and physical parameters of the medium. Therefore, for many applications, double-screen FSS is the optimum selection.[7] Double-screen or multiscreen FSS theory has been fully developed and applied in engineering overseas. However, the double-screen or multiscreen research results have seldom been discussed, and only the multiscreen theoretical analysis method has been discussed in the literature since military technology has been involved. In China, some researchers have extended preliminary studies on the numerical simulation technology of double-screen FSSs and transmission characteristics, respectively.[8−12] Under ideal conditions, in double-screen FSS theoretical design, the geometric centres of the first screen FSS units and the second screen units do not deviate from each other. However, in practical design and manufacture, centre deviation is hard to avoid. At present, research into the influence of double-screen wide bandpass FSS unit alignment on the frequency response characteristics have not been reported in the literature.

In this paper, a double-screen FSS is designed and the influence of the non-aligned unit on its frequency response characteristics is studied at different TE wave incident angles by means of the spectral domain approach. Meanwhile, the corresponding experimental parts are prepared by means of coating and lithography techniques and measured in a microwave anechoic chamber. The theoretical and experimental design results are compared and analysed, which pro-

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vides reliable evidence for the application of double-screen FSS in practical engineering projects.

2. Analysis method

Among the various FSS analysis methods, the spectral domain approach is adopted in this paper to analyse the double-screen FSS.

Suppose that $\boldsymbol{M}$ is the equivalent magnetic current density induced by incident electromagnetic field in the units, then the scattering magnetic field at field point r can be expressed as

$$\boldsymbol{H}^{\mathrm{s}} = -\mathrm{j}\omega\varepsilon_0\boldsymbol{F} + \frac{1}{\mathrm{j}\omega\mu_0}\nabla\left(\nabla\cdot\boldsymbol{F}\right), \tag{1}$$

where

$$\boldsymbol{F}(\boldsymbol{r}) = \int \boldsymbol{G}(\boldsymbol{r},\boldsymbol{r}')\boldsymbol{M}(\boldsymbol{r}')\mathrm{d}\boldsymbol{r}' = \boldsymbol{G} * \boldsymbol{M}, \tag{2}$$

$\boldsymbol{G}(\boldsymbol{r},\boldsymbol{r}')$ is the free-space Green's function expressed as

$$\boldsymbol{G}(\boldsymbol{r},\boldsymbol{r}') = \frac{\exp(-\mathrm{j}k_0|\boldsymbol{r}-\boldsymbol{r}'|)}{4\pi|\boldsymbol{r}-\boldsymbol{r}'|}, \tag{3}$$

$\boldsymbol{r}'$ is the source point, the asterisk denotes the convolution operation, and k_0 is the free-space wavenumber.

According to electromagnetic field boundary conditions, i.e. the tangential magnetic field continued in the units, the integral equation of the magnetic field in a single unit can be obtained by means of Fourier transform. FSS is a two-dimensional infinite array structure which meets the Floquet theorem, therefore the incident tangential field of FSS can be obtained as

$$-\begin{vmatrix} H_x^{\mathrm{inc}}(x,y) \\ H_y^{\mathrm{inc}}(x,y) \end{vmatrix} = \frac{4\pi}{\mathrm{j}\omega\mu_0 D_x D_y}\sum_{m=-\infty}^{m=\infty}\sum_{m=-\infty}^{m=\infty}\begin{bmatrix} k_0^2-\alpha_{mn}^2 & -\alpha_{mn}\beta_{mn} \\ -\alpha_{mn}\beta_{mn} & k_0^2-\beta_{mn}^2 \end{bmatrix} \times \tilde{\boldsymbol{G}}(\alpha_{mn},\beta_{mn})\begin{bmatrix} \tilde{M}_x(\alpha_{mn},\beta_{mn}) \\ \tilde{M}_y(\alpha_{mn},\beta_{mn}) \end{bmatrix}\mathrm{e}^{\mathrm{j}\alpha_{mn}x}\,\mathrm{e}^{\mathrm{j}\beta_{mn}y}, \tag{4}$$

where

$$\alpha_{mn} = \frac{2m\pi}{D_x} + k_x^{\mathrm{inc}},$$
$$\beta_{mn} = \frac{2n\pi}{D_y\sin\Omega} - \frac{2m\pi}{D_x}\cot\Omega + k_y^{\mathrm{inc}},$$

Ω is the angle between the two directions of the FSS two-dimensional periods, D_x and D_y are the periods of FSS, respectively; and α_{mn} and β_{mn} are the tangential wavenumbers of the two-dimensional directions.

Solving Eq. (4) by the moment method, the equivalent magnetic current $\boldsymbol{M}$ can be obtained. Furthermore, the reflecting field and transmission field can be obtained by $\boldsymbol{M}$. By replacing the free-space wavenumber in Green's function (3) by the wavenumber in the medium, the tangential field of the FSS with the substrate can also be obtained.

3. Simulation results

3.1. FSS structure

The frequency response characteristics of the FSS can be determined by the unit structure, and the unit arrangement mode of FSS has a direct influence on FSS frequency response characteristics. To obtain the wide bandpass, a double-screen FSS structure is designed in this paper (see Fig. 1). The structure is composed of two dielectric layers (the thickness of each is 0.5 mm, with the dielectric constant being 4.2, and the loss angle tangent value 0.023) and three keriotheca layers (the thickness of each is 4 mm, with the dielectric constant being 1.07). The FSS screen is sandwiched between two keriotheca layers (see Fig. 1). The units designed in this paper have unique unit form characteristics, which make them most suitable for a square arrangement. The unit period is $T = 8$ mm, and suppose $w = 0.5$ mm, $a = 3$ mm, $b = 1.5$ mm, $c = 0.5$ mm, $d = 0.5$ mm, $e = 3$ mm, and $f = 3.5$ mm.

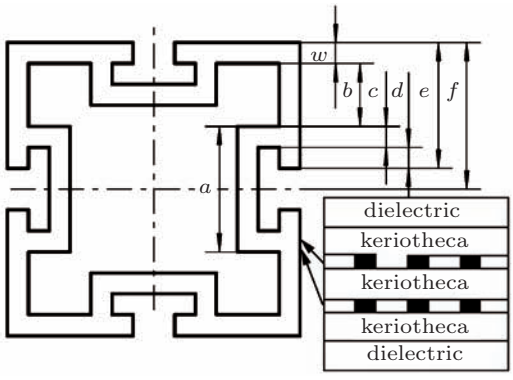


Fig. 1. The structure and unit size of the FSS.

3.2. Frequency response characteristics under unit alignment

For the FSS of the wide bandpass, we focus on the bandwidth and the bandpass transmittance. Therefore, the influence of the structure on them under the condition of unit non-alignment is the research subject.

Under the condition of the unit centre being aligned, the TE waves incident at 0°, 30°, 45°, and 60° irradiate on the FSS. The frequency response curve (see Fig. 2) and characteristics comparison table (see Table 1) are obtained by means of simulation calculation.

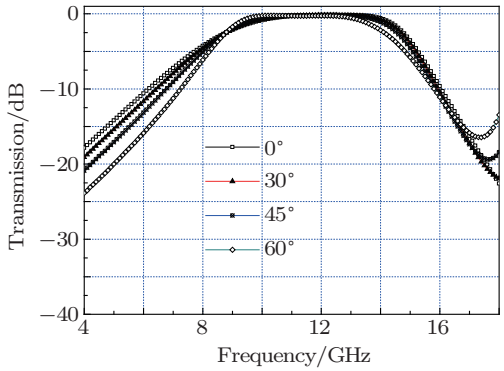


Fig. 2. (colour online) The FSS frequency response characteristic curves for different incident angles.

Table 1. The variation in frequency response characteristics with incident angle when the units are aligned.

Incident angle/(°)	Frequency at −1 dB/GHz	Bandwidth at −1 dB/GHz
0	9.9–14.2	4.3
30	9.8–14.1	4.3
45	9.6–13.9	4.3
60	9.3–13.4	4.1

The simulation results show that when the power decreases to −1 dB, the working frequency drifts to the low frequency side with the increase in incident TE wave angle, i.e., it drifts from 9.9 GHz–14.2 GHz at normal incidence to 9.3 GHz–13.4 GHz at an incident angle of 60°. However, the designed structure still has good bandpass performance and the working bandwidth still remains at 4.3 GHz.

3.3. Frequency response characteristics under unit non-alignment

According to the actual error due to unit non-alignment in the experimental process, the data analysis model of the unit alignment error is shown in Fig. 3. Figure 3 (a) shows the first screen periodic unit, and figure 3(b) shows the deviations X and Y in the axial directions between the second and the first screens. Suppose that the first screen centre point O is the origin, then the coordinates of it are (0, 0); if the second screen corresponding unit centre point is O', the coordinates are (X, Y), then the offset distance is $L = \sqrt{X^2 + Y^2}$.

Changing the relative positions of the two FSS screens makes the unit centres deviate $L = 2$ mm $(T/4)$, 4 mm $(T/2)$, and 5.656 mm $(\sqrt{2}T/2)$ distances along the horizontal direction of the screen, which forms a unit non-alignment structure. In this structure, the frequency response characteristic curve (see Fig. 4) and the characteristics contrast table (see Table 2) were obtained by simulation at a TE wave normal incident on the double-screen FSS.

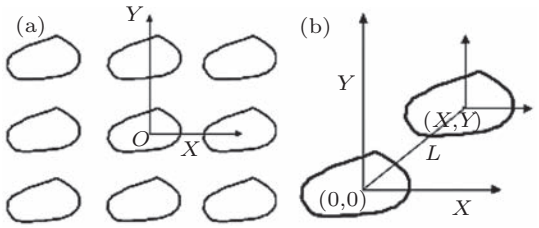


Fig. 3. A schematic diagram of the unit non-alignment model.

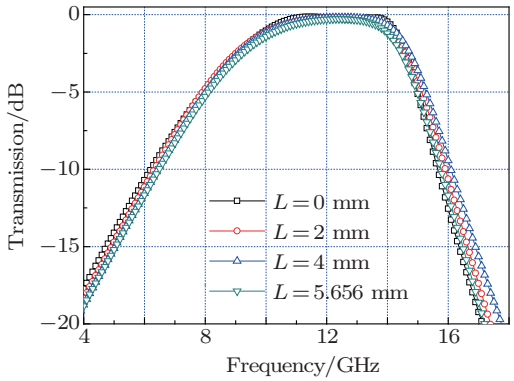


Fig. 4. (colour online) The correlation curves of the frequency response characteristics for different alignment accuracies.

Table 2. The variation in frequency response characteristics with alignment accuracy when the units are non-aligned.

Alignment accuracy/mm	Frequency at −1 dB/GHz	Transmittance/dB
0	9.9–14.2	–0.1409
2	10.2–14.1	–0.1853
4	10.2–14.0	–0.2793
5.656	10.4–13.8	–0.3425

Figure 4 shows that at normal incidence and unit non-alignment, the frequency band of the double-screen FSS drifts towards the high frequency side with the change in offset-length L. The bandwidth narrows down and transmittance decreases slightly, with the offset-length L changing from 0 to 5.656 mm, the frequency band at −1 dB narrowing from 9.9 GHz–14.2 GHz down to 10.4 GHz–13.8 GHz, and the transmittance decreasing from −0.1409 dB to −0.3425 dB. The bandwidth decreases 0.9 GHz and the transmittance decreases 0.2016 dB. Therefore, the offset-length, i.e. the unit alignment accuracy, should be controlled according to the actual needs.

Under the conditions where the double-screen FSS structure remains unchanged and the offset length is $L = 4$ mm, the frequency response characteristics curve (see Fig. 5) and the characteristics league table (see Table 3) were obtained by simulation for the TE wave incident on the FSS at angles of 0°, 30°, 45°, and 60°.

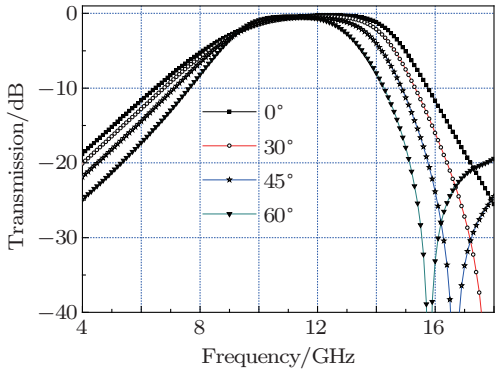


Fig. 5. (colour online) The non-aligned FSS frequency response characteristics curves at different incident angles.

Table 3. The variation in frequency response characteristics with incident angle when the units are non-aligned.

Incident angle/(°)	Frequency at −1 dB/GHz	Bandwidth at −1 dB/GHz
0	10.4–13.8	3.4
30	10.4–13.4	3.0
45	10.3–12.8	2.5
60	9.9–12.2	2.3

Figure 5 shows that when the unit is non-aligned, the bandwidth of the working frequency band (at a power loss less than −1 dB) reduces obviously from 4.3 GHz to lower than 3.4 GHz. The transmission loss within the working frequency band increases from 0.17 dB to 0.28 dB under the condition of the aligned unit. When the centres of the units are non-aligned, the response characteristics of the double-screen FSS change greatly with the variation in incident angle. With increasing incident angle, the working frequency band drifts towards the low frequency side, and the working bandwidth reduces. Meanwhile, with increasing incident angle, the FSS transmission characteristics become less stable and grating lobes can easily occur. The main reason for this phenomenon is that the non-aligned structure will change the electrical size, which has an effect on the near-field coupling between the screens, and therefore the resonance region decreases and grating lobes occur.

4. Experimental results and comparisons

In this paper, the double-screen FSS samples are fabricated by gluing the keriotheca layer with the FSS screen (copper film). The copper film is directly prepared on the substrate by vacuum evaporation, and then the FSS unit is obtained by lithography on the film. The samples fabricated by the above method

match the theoretical model perfectly. The two fabricated 500 mm×500 mm samples (the offset length L of one is 0 and the other is 4 mm) are tested for their transmission characteristics in a microwave chamber. Figure 6 shows picture of the prepared experimental samples and the measurement system. Figures 7 and 8 are testing curves under the conditions of aligned and non-aligned units, respectively. The results show that the measured value is in accordance with the calculated result.



Fig. 6. The experimental sample and testing system.

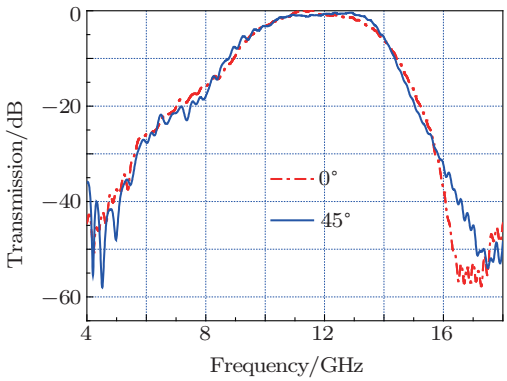


Fig. 7. (colour online) The FSS frequency response characteristics testing curves under the aligned unit.

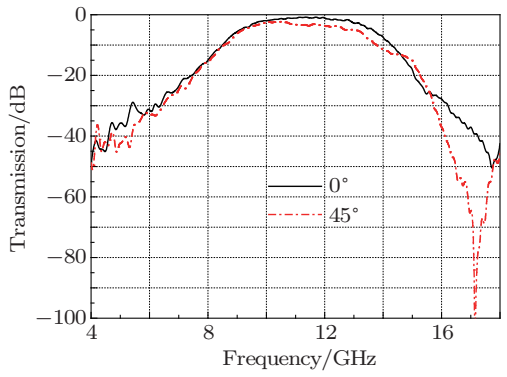


Fig. 8. (colour online) The FSS frequency response characteristics testing curves for the non-aligned unit.

5. Conclusion

Compared with single-screen FSS, the electromagnetic transmission characteristics of double-screen FSS have been greatly improved. In this paper, a wide bandpass double-screen FSS (bandwidth larger than 3 GHz) has been designed. The effect of unit alignment and incident angle on the frequency response characteristics have been studied; meanwhile, the experimental samples prepared by vacuum evaporation and lithography are tested in a microwave chamber. The results show that the testing value obtained is in agreement with the calculation, i.e., the aligned unit structure has good incident angle stability and can achieve a wide bandwidth of 3.3 GHz. When the unit is non-aligned, the bandwidth narrows down and transmission loss increases with increasing incident angle. As a result, the frequency response characteristics change greatly and grating lobes occur frequently with the variation in incident angle. To meet the engineering requirements of filtering characteristics, the unit alignment accuracy should be controlled strictly.

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