Influence of substrate process tolerances on transmission characteristics of frequency-selective surface

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Received August 30, 2007

Frequency-selective surface (FSS) is a two-dimensional periodic structure consisting of a dielectric substrate and the metal units (or apertures) arranged periodically on it. When manufacturing the substrate, its thickness and dielectric constant suffer process tolerances. This may induce the center frequency of the FSS to shift, and consequently influence its characteristics. In this paper, a bandpass FSS structure is designed. The units are the Jerusalem crosses arranged squarely. The mode-matching technique is used for simulation. The influence of the tolerances of the substrate's thickness and dielectric constant on the center frequency is analyzed. Results show that the tolerances of thickness and dielectric constant have different influences on the center frequency of the FSS. It is necessary to ensure the process tolerance of the dielectric constant in the design and manufacturing of the substrate in order to stabilize the center frequency.

OCIS codes: 160.0160, 260.2110, 310.0310.

Frequency-selective surface (FSS) is a periodic structure. On it, ideal conductor patches (or apertures on an ideal conductor) with special shape are arranged periodically along two directions[1]. FSSs own frequency-selective reflectance or transmission and are widely applied in microwave antennae and radomes[2].

Usually, a FSS consists of metal units (or apertures) and a substrate[3]. Many elements influence the characteristics of FSS, such as the shape, size, and arrangement of the units, the polarization and the incident angle of the incident wave, the thickness and dielectric constant of the substrate. When manufacturing the substrate, its thickness and dielectric constant suffer process tolerances. This will induce the center frequency of the FSS to shift, and consequently influence its performance. In this paper, a bandpass FSS structure is designed. The units are the Jerusalem crosses arranged squarely. The mode-matching technique[4] is used for simulation. The influence of the thickness and dielectric constant of the substrate on characteristics of the FSS is analyzed.

Mode-matching technique is a common and important method for analyzing FSSs[4]. The main procedures of this technique include: expanding the electromagnetic field in free space or dielectric outside the planar periodic array into Floquet spatial harmonic waves, expanding the field on the periodic surface into a series of complete orthogonal modes, matching the two fields on the periodic surface and getting an integral equation of the unknown electric field (or electric current) on the surface, and at last solving the transmission and reflection coefficients of the FSS structure.

The mode-matching equations are

$$[Y_{ij}]\,[F_j] = 2\,[I_i]\,, \tag{1}$$

$$Y_{ij} = \sum_m (\xi_m + Y_m) \int_s E_i^* \cdot R_m \mathrm{d}s \int_s E_j \cdot R_m^* \mathrm{d}s, \tag{2}$$

$$I_i = \sum_r A_r \xi \int_s E_i^* \cdot R_r \mathrm{d}s, \qquad (r = 1, 2), \tag{3}$$

where R_m is the electric field of the m-th order Floquet mode, R_m^* is its complex conjugate, ξ_m is the output field's admittance, E_i is the mode field of the waveguide, E_i^* is its complex conjugate, and A_r is the incident electric field.

According to the mode-matching technique, we expand the electric field in the units into the guided modes of the waveguide. The fields in the waveguide are two-dimensional parameters and can be solved using the finite element method. Substituting the guided modes into Eq. (3), the coupling integration can be given as

$$I_i = \sum_r \sum_{e=1}^{N} \sum_{j=1}^{3} A_r \xi_r \frac{\left(c_j^e \phi_j^e \beta_i + b_j^e \phi_j^e \alpha_i\right) \cdot S_e}{\left(\sqrt{\alpha_i^2 + \beta_i^2}\right) \left(2\Delta_e \sqrt{d_1 d_2 \sin\theta}\right)}, \tag{4}$$

where

$$\alpha = k \sin\alpha \cos\phi + \frac{2\pi p}{d_1},$$

$$\beta = k \sin\alpha \sin\phi + \frac{2\pi q}{d_2} - \frac{2\pi p}{d_1 \tan\theta},$$

$$p, q = 0, \pm 1, \pm 2, \pm K.$$

For the meaning of α and β please see Ref. [5].

For transverse electric (TE) modes,

$$S_e(\alpha, \beta) = \int \mathrm{e}^{j\left(\alpha x + \beta y + \frac{\pi}{2}\right)} \mathrm{d}x\mathrm{d}y,$$

for transverse magnetic (TM) modes

$$S_e(\alpha, \beta) = \int \mathrm{e}^{j(\alpha x + \beta y)} \mathrm{d}x\mathrm{d}y,$$

where d_1 and d_2 are the periods of the units along the x and y directions, respectively, θ is the angle between them. For the meaning of Δ_e and ϕ_j^e, see Ref. [6]. We can get the reflection and transmission coefficients after solving the coupling integration.

We choose the Jerusalem crosses as the resonating

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units of our FSS. They are arranged squarely and the period is $T = 8$ mm. The designed structure parameters, as shown in Fig. 1, are $W = 0.5$ mm, $D = P = 3$ mm, $H = 0.5$ mm, and $L = 7.5$ mm.

Let d and ε represent the thickness and the dielectric constant of the substrate, respectively. Using the mode-matching technique we analyze the influence of the process tolerances of them on the center frequency of the FSS.

In Figs. 2(a) and (b), we plot the FSS transmission spectra at different dielectric constants for $d = 4$ mm and at 0° and 45° incident angles respectively. The center frequencies at different situations are listed in Table 1. It can be seen that the center frequency decreases as the dielectric constant increases, and the incident angle has no influence on the center frequency.

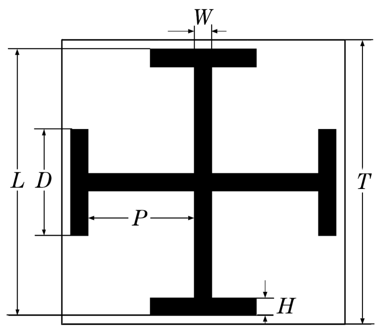

Fig. 1. Jerusalem cross.

Figure 3 plots the transmission spectra at different substrate thicknesses for $\varepsilon = 3.5$ and at 0° and 45° incident angles respectively. The center frequencies at different situations are listed in Table 2. We can see that the center frequency keeps unchanged for different thicknesses and incident angles. So the FSS with the Jerusalem cross units is insensitive to the thickness and the incident angle of the substrate.

To simulate the designed bandpass FSS structure, the mode-matching technique is used. Results show that when the substrate's dielectric constant increases, center frequency of the FSS shifts rapidly toward lower frequency. While, when keeping the dielectric constant unchanged, and the substrate's thickness increases by the same ratio, the center frequency does not change significantly. So, the thickness and dielectric constant of the substrate have different effects on the FSS's center frequency. The influence of the dielectric constant on the center frequency is greater than the thickness. Thus, it is necessary to ensure the process tolerance of the dielectric constant in the design and manufacturing

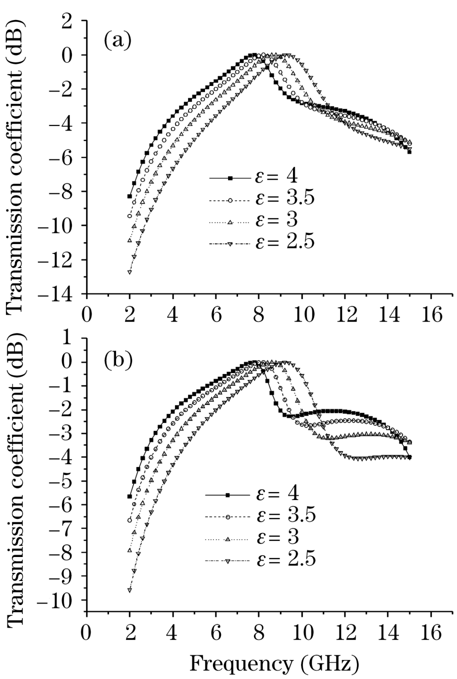

Fig. 2. Transmission coefficient spectra for different dielectric constants at incident angles of (a) 0° and (b) 45°.

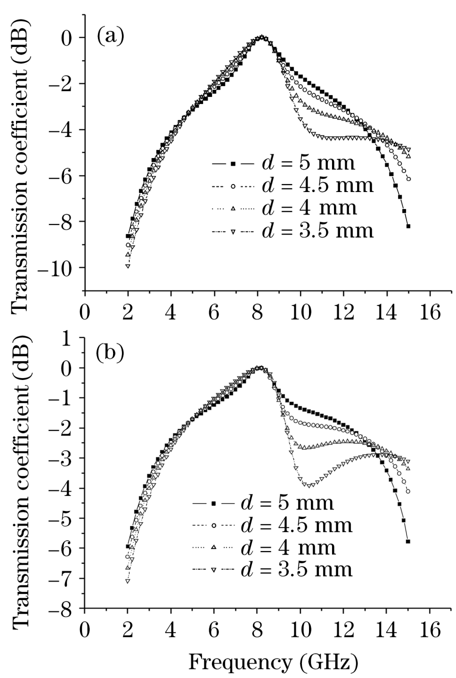

Fig. 3. Transmission coefficient spectra for different substrate thicknesses at incident angles of (a) 0° and (b) 45°.

Table 1. Center Frequencies for Different Dielectric Constants

ε	f_0 (GHz)	
	0°	45°
2.5	9.2	9.2
3.0	8.6	8.6
3.5	8.2	8.2
4.0	7.8	7.8

Table 2. Center Frequencies for Different Substrate Thicknesses

d (mm)	f_0 (GHz)	
	0°	45°
5.0	8.2	8.2
4.5		
4.0		
3.5		

of the substrate in order to stabilize the center frequency.

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