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Feasibility Study of Square, Circular, Rectangular and Greek Cross Aperture Shapes for the Band-Pass Frequency Selective Surface Design

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ABSTRACT

The first step in the frequency selective surface (FSS) spatial filter design is to choose the rightFSS element. The performance of FSS elements is influenced by the element shape, its dimension, spacing between the elements, incidence angle and polarization angle. In this paper, band-pass free-standing FSS filter is designed for the 15.5 GHz pass band, so the above FSS elements' structural parameters will be tuned to resonate around 15 GHz band. The feasibility of aperture shapes like square, circular, rectangular and Greek cross for the spatial band-pass frequency selective filtering isstudied. The study will be useful in choosing the right FSS element for the right application and also to shape the curve for the desired response. The FSS surface designed can be used in any spatial filtering application.

Keywords:Band-Pass Filter, Frequency Selective Surface,Greek Crossaperture, Spatial Filter.

I. INTRODUCTION

Frequency selective surface (FSS) is a periodic structure of conductive elements printed on the substrate or apertures made on the conductive sheet in either one or two dimensions to perform a filter operation when they are illuminated by electromagnetic wave as shown in Fig.1. When illuminated, FSS exhibits total transmission or total reflection around the resonant frequency. Several elements, starting from basic dipole to complex structured elements can be used. But each element has its own merits and demerits. The spatial filter behaviour of the FSS allows to achievelow-pass, high-pass, band-pass, band-stop response. The FSS elements are broadly categorized into four groups as (i) Center-connected elements or N-Pole elements (ii) Loop-type (iii) Solid-interior type and (iv) Combinations[1].

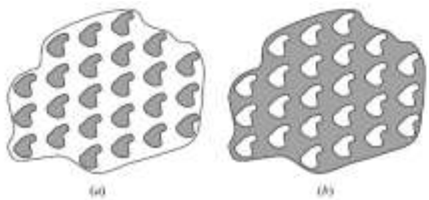

Fig. 1 2D array structures of (a) metallic elements and (b) apertures in a conducting plane

Even the analysisand design of FSS elements are well established by researchers, the understanding of basic shapes will be useful to design any derived elements which are categorized as above [2-5]. In this paper, the feasibility of the basic aperture shapes like square, circular, rectangular and Greek cross for the spatial band-pass frequency selective filtering isstudied. In detail the influenceof dimension, spacing between the elements, incidence angle and polarization angle on each element will be studied.The FSS elements are modelled using the CST microwave studio [6] a full wave solver, with unit cell boundary condition which repeats the modelled structure periodically in two directions up to infinity.

II.SQUARE APERTURE

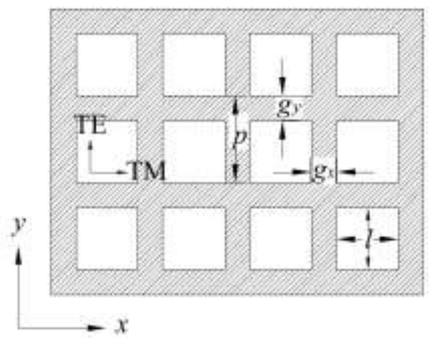

Fig. 2 Square FSS geometry

The geometry of square aperture FSS array and its length, gap, periodicity is shown in Figure 2. The length of the square element *(l)* is varied from 0.6 cm to 1.4 cm. Assume wave incident normally at an angle *(ϕ)* with transverse electric (TE) polarization. In TE polarization the electric field is perpendicular to the plane of incidence.

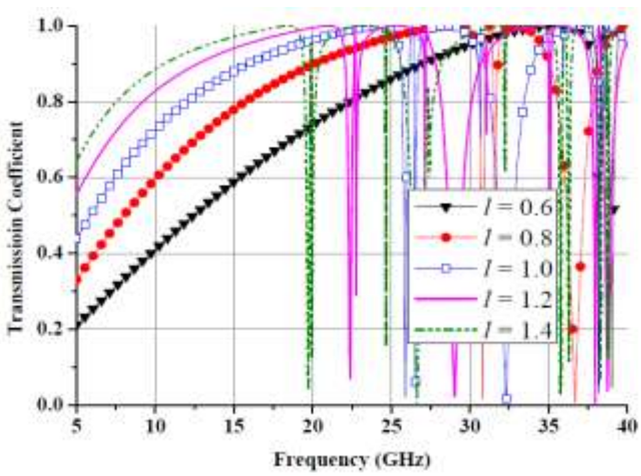

Fig.3 Transmission coefficient of square aperture array for l= 0.6 to 1.4 cm, g_x = g_y = 0.2 cm

In the Fig. 3, high-pass behaviour is observed and cutoff frequency shifts down with an increase in the aperture length. The band - pass response is not observed since the element does not resonate. To understand the high-

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pass behaviour of the square FSS of the specific dimension, let us first consider high-pass FSS consisting of a periodic arrangement of infinitely long conducting elements [7] shown in Fig. 4. This FSS screen behaves as a shunt inductance for the incident plane waves with the electric field polarized along the conductive elements (*y*-direction) inducing an electric current on the strip and the field gets scattered.

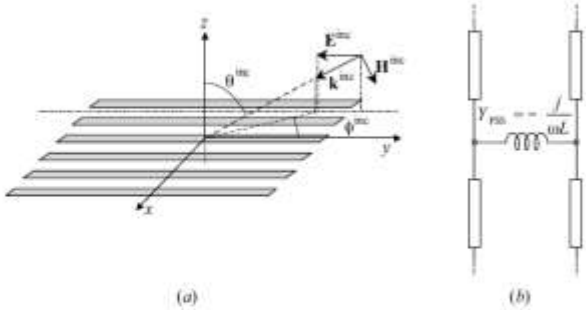

Fig. 4(a) Periodical arrangement of infinitely long conducting elements under TEz plane-wave incidence (b) and its equivalent circuit

So, at sufficiently low frequencies, the strip grating reflects y-polarized uniform plane wave, whereas at high frequencies almost no reflection occurs. Vice versa, if the incident field is TM polarized (E field directed along z-direction), the screen acts as a low-pass filter.

Now consider the strip grating present in two dimension, ie.,*x* and *y*-direction as shown Fig. 5, which is a conducting screen periodically perforated with square apertures. The equivalent network representations consist of a capacitance in parallel with the inductor, for both orthogonal polarizations. Now the screen acts as a band-pass filter when the LC resonates. But for the square aperture array shown in Fig. 2, the aperture length is large that the equivalent capacitance is too small to produce a resonance. So, it acts as a high pass filter and is called as an inductive FSS filter. To achieve the band pass behaviour the capacitance value should be increased by reducing the length of the aperture (then aperture becomes rectangular shape). The aperture length should be half the wavelength of the resonance frequency interested (1 cm for 15 GHz case). Reducing the aperture length further will increase the resonance frequency.

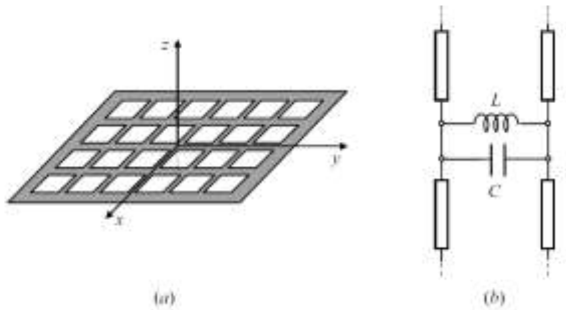

Fig. 5 (a) Square aperture array and (b) its equivalent circuit

Since the square aperture behaves as spatial high pass filter, and as the objective of the paper is to design band-pass filter, further study of square aperture array will not performed.

III.CIRCULAR APERTURE

Circular aperture with area equal to square aperture have a same transmission profile with a difference that the bandwidth of the circular aperture is narrow compared to square aperture.

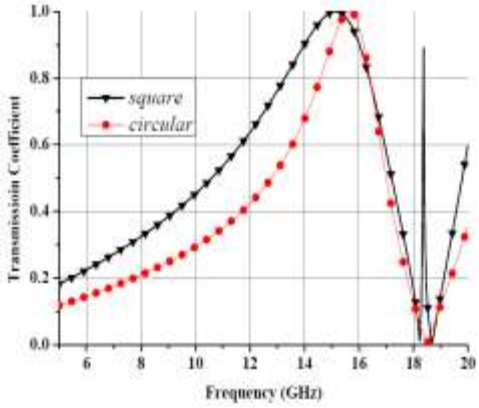

Fig. 7Comparison of square (l = 1 cm, g = 0.8 cm) and circular (r = 0.5046 cm, g = 0.8 cm) aperture of same area for ϕ = 0°, TE

IV.RECTANGULAR SLOT

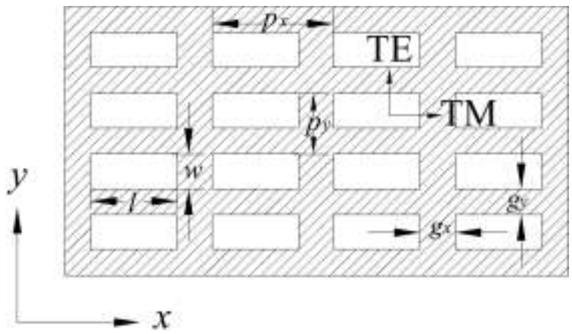

Fig. 8 Rectangular aperture array

The capacitance is increased in the equivalent circuit since the width of an element is small compared to the length. Fig. 7 shows the rectangular aperture array and its structural details.Fig. 10 shows the reflection curve in the above case. From here onwards, reflection curves will be plotted since the stop band and cutoff frequency is visible clearly.With the increase in width of the rectangular aperture the cut-off frequency of the high-pass response shifts slightly downward. Also for the l = 1 cm and w = 1 cm, the response is high pass. But for l = 1cm and w = 0.1 cm, the response is like band-pass. But it should be verified with varying inter-element spacing and incidence angle, since it could be the grating lobe.

The grating lobe formula is:

$$f = \frac{mc}{(1 \pm \sin\phi_i)(l+g)} \tag{1}$$

Where m = 1, 2, etc., (m = 0 gives no grating lobes), ϕ_i is the incident plane wave excitation angle and l, g are length and inter-element spacing of FSS element.The disadvantages of increasing the inter-element spacing are that the packing density will be reduced and is very sensitive to incidence angle. A general rule for preventing grating lobes is to keep the element size and spacing less than one wavelength at 0°incidence. For large oblique incident angles, it should be kept less than one-half of a wavelength. The criterion for suppressing grating lobe is to ensure the condition $p\,(1 + \sin\,\phi) < \lambda$.

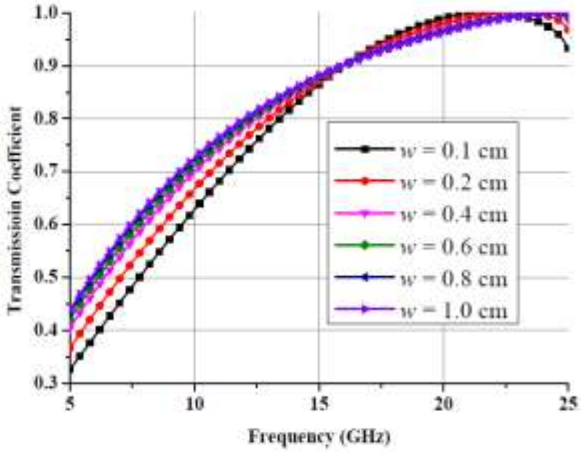

Fig. 9Transmission curve of rectangular aperture array for varying width (w), l = 1 cm, g = 0.2 cm, ϕ = 0°, TE incidence

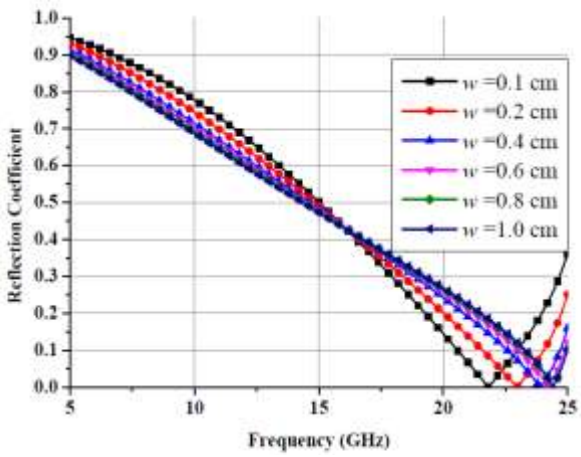

Fig. 10Reflection curve of rectangular aperture array for varying width (w), l = 1 cm, g = 0.2 cm, ϕ = 0°, TE incidence

For FSS with different periodicity along x and y-direction, the grating lobe formula is [1]:

$$\lambda_x = m(1 \pm \sin\phi_i) p_x \quad (2)$$

$$\lambda_y = m(1 \pm \sin\phi_i) p_y \quad (3)$$

$$\lambda_{grate} = \max(\lambda_x, \lambda_y) \quad (4)$$

where λ_x, λ_y is the grating lobe wavelength in x and y direction respectively. p_x and p_y are the periodicity along the x and y-axis respectively. Early grating lobe occurrence will be decided by the highest periodicity in x or y direction. From the Table 1, it is observed that, irrespective of the aperture width, the maximum periodicity is along x-axis.So, the grating lobe starts at 25 GHz as per grating formula. So in Fig. 10, for l = 1 cm and w = 0.1 cm the band-pass looking response is due to the grating lobe. The band-pass response at 25 GHz is due to the grating lobe which is undesired. As with the rectangular aperture spatial high pass filter cannot be attained, and as the objective of the paper is to design band-pass filter, further study of rectangular aperture array will not performed.

Table 1Varying the width of rectangular aperture and the grating lobe

Length (l) in cm	Width (w) in cm	Inter-element spacing $g_x = g_y = g$ in cm	Periodicity along x-axis (p_x) in cm	Periodicity along y-axis (p_y) in cm	f at which grating lobe start for ϕ = 0° (GHz)
1	0.2	0.2	1.2	0.4	25
	0.4			0.6	25
	0.6			0.8	25
	0.8			1	25
	1			1.2	25

V.GREEK CROSS SLOT

Greek cross is the combination of un-rotated rectangular aperture and its 90˚ rotated version as shown in Fig. 12. With rectangular aperture, band-pass response could be only observed for TE polarization. To get the same response for the TM polarization, if 90˚ rotated rectangular aperture is present, then band-pass response could be obtained for both polarizations.

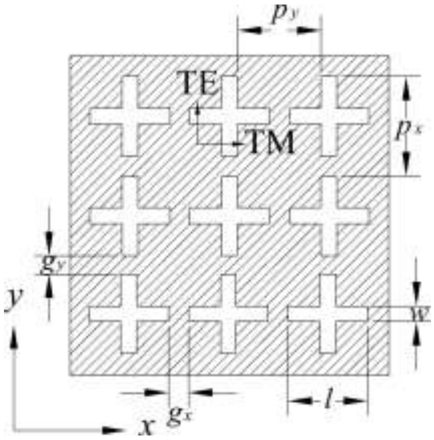

Fig. 12 Greek cross aperture array

VI. VARYING APERTURE LENGTH AND WIDTH

Fig. 13, shows the reflection coefficient for varying length of Greek cross. Cross dipole resonates when the largest tip to tip length is approximately equal to $\lambda/2$, which is evident from different lengths shown in Fig. 13. The resonant frequency shifts down with an increase in the length.

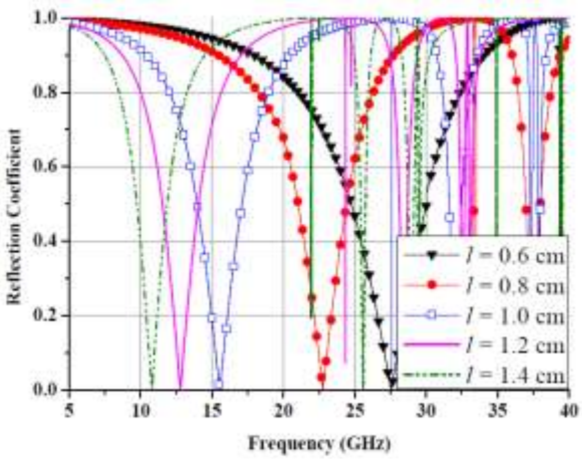

Fig. 13 Reflection curve of Greek cross aperture array (l = 0.6, 0.8, 1, 1.2, 1.4, w = 0.2, gx= gy= 0.2 cm, ϕ = 0°, TE

VII. VARYING THE POLARIZATION

As the Greek cross is symmetric under 90° rotation both components of polarization will see the same grid geometry. This means that both components have the same transmission and reflection coefficients, and the overall transmission coefficient is therefore not a function of the polarization angle. For the normal incident wave, reflection curve is plotted for TE and TM polarization in Fig. 14 of the Greek cross with l = 1 cm, $g_x = g_y$= 0.2 cm, w = 0.2 cm. As TE and TM polarization are orthogonal, Greek cross has the same response.

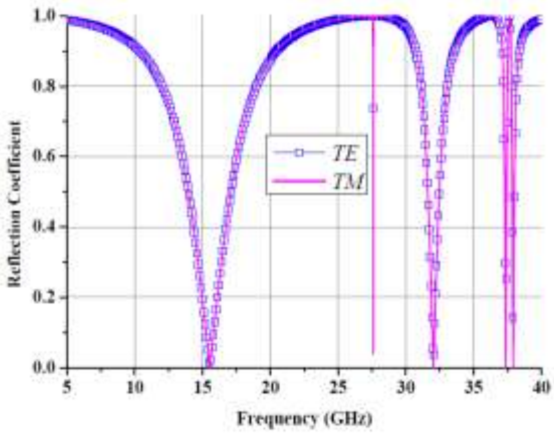

Fig. 14Comparison of TE and TM polarization of Greek cross aperture array for l = 1, w = 0.2,gx= gy= 0.2 cm,ϕ = 0°

VIII.VARYING THE INTER-ELEMENT SPACING

As inter-element space increases the resonance curve narrows, and shifts down. With the increase in the inter-element spacing, periodicity increases and so the occurrence of first grating lobes shifts to a lower frequency. Also, spacing is varied along *y*-axis, *x*-axis as shown in Fig. 15 and Fig. 16 respectively, where resonance behaviour is not same for both above cases.

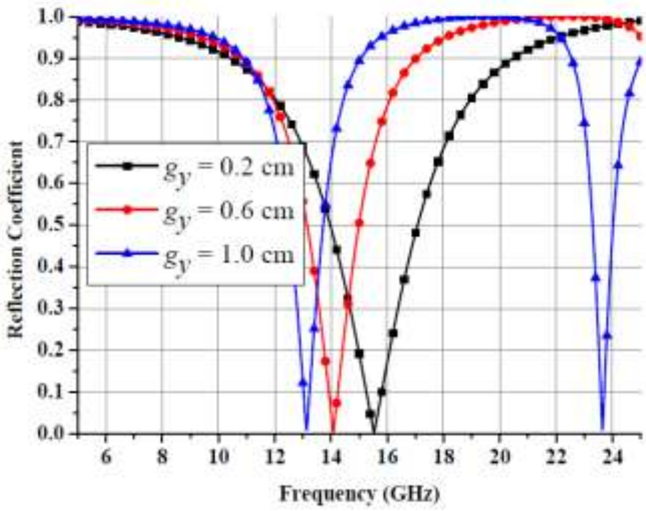

Fig. 15Reflection curve of Greek cross aperture array for l = 1, w = 0.2, gx= 0.2, gy=0.2, 0.6, 1 cm, ϕ = 0°, TE

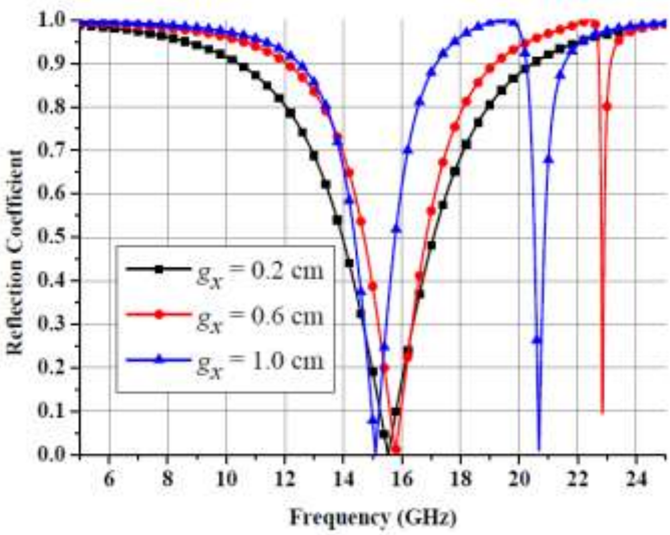

Fig. 16 Reflection curve of Greek cross aperture array for l = 1, w = 0.2, gy= 0.2, gx= 0.2, 0.6, 1 cm, ϕ = 0°, TE

IX.VARYING THE INCIDENCE ANGLE

When a signal arrives at an oblique angle to an FSS with conducting strips periodically separated by *g*, the projected effective separation between each strip will be reduced by a factor of $\cos\phi$. So, the current induced differs from the scenario with oblique incidence angles [8].As the incidence angle increases, the resonance frequency shifts down, shown in Fig. 17. Since the spacing is larger than $\lambda/2$, grating lobe push the fundamental resonance downward with angle of incidence. For oblique incidence angles TE and TM polarization won't have the same current distribution. Angular stability can be improved by adding a dielectric substrate to the FSS aperture array. Also, by further reducing the inter-element spacing angular stability can be improved.

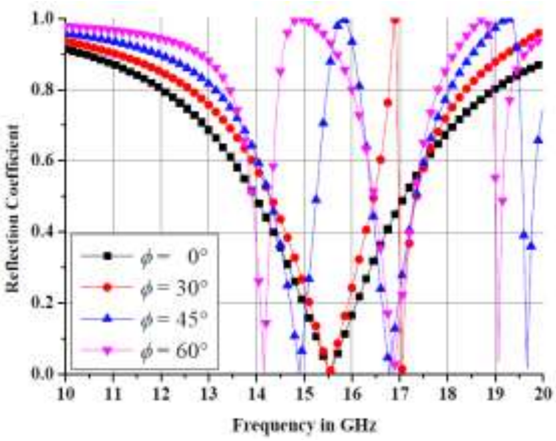

Fig. 17Reflection curve of Greek cross aperture array for l = 1, w = 0.2, gx= gy= 0.2 cm, ϕ = 0, 30, 45, 60°, TE

X.CONCLUSION

In this paper square, circular, and rectangular apertures are studied since they are the most commonly used apertures in the electronic enclosures. It is shown that they are not suitable for band-pass filter design. But the observation will be useful to understand the physics behind the filtering capability of simple FSS elements like Greek cross. The factors that influence the performance of FSS such as the FSS elements' dimensions, inter-element spacing, and wave incident / polarization angles are discussed.

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