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SPATIAL FILTER WITH MULTIPLE EXTRACTED POLES

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We present the numerical simulation results of the scattering of a plane linearly polarized wave at a multi-aperture frequency-selective surface and two design examples for a spatial band-pass filter with multiple extracted poles. Filters are formed by three consecutively placed perforated screens. Shown, that the screens, elementary cell of which contains a number of different rectangular apertures, provide the appearance of extracted poles on the frequency response of the filter.

Keywords: *REFLECTION RESONANCE, SPATIAL FILTER, FREQUENCY-SELECTIVE SURFACE.*

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1. INTRODUCTION

Frequency-selective surfaces are widely used in signal separators in the frequency range from 1 GHz to 1 THz. They are usually realized as the sets of metal dipoles, periodically placed on a dielectric substrate or as the periodic perforated screens [1]. Frequency-selective surfaces (FSS) of the first type provide reflection of the incident plane linearly polarized wave in the vicinity of the given wavelength, which is approximately equal to the dipole half-length. Perforated screens form the total transmission resonance on the wavelength, which is approximately equal to the slot half-length. More complex, for example, the band-pass frequency response is usually realized by some consecutively placed FSS [1, 2]. Moreover, recently there is a tendency of use of the so-called multi-element FSS, periodic cells of which contain some resonance elements that allows to realize the complex frequency response using the single-layer structure. As a rule, such structures provide the multi-resonant response. Dipole lattices form response with some reflection resonances [3, 4], and multi-element screens provide the resonance transmission of an incident wave on some frequencies simultaneously [5]. The present paper investigates precisely these perforated screens with some apertures on a periodic cell. However, this structure is considered here as the FSS, which can form the narrow-band cut-off response – the property typical for a dipole lattice, not for a perforated screen. In fact, the question is the effect of the total reflection, which was discovered for the multi-aperture resonant irises in waveguides [6] and was used as the new realization technique of the method of appeared extracted poles while designing the waveguide band-pass filters [7]. Based on the similar structure of electromagnetic fields in diffraction problems by the iris in a waveguide and on a perforated screen, it is naturally to expect the similar results too, the more so as the waveguide simulation of antenna arrays is the standard test method of numerical calculations [8]. The present paper is devoted to investigation of formability of just the total reflection resonance by the multi-aperture perforated screens. Shown, that varying the number of apertures and their geometrical sizes it is possible to form the frequency response not only with one but also with some reflection resonances. Perforated screens with such properties are used in this paper as the structural components of the band-pass filters, and in this case precisely they provide the formation of quasi-elliptic frequency response. The focus of the present paper is the spatial filter, which consists of three consecutively placed perforated screens. Within the framework of the classical approach each perforated screen provides the total transmission of an incident wave in the vicinity of the given frequency f_c. Being located at the distance $\lambda_c/4$ on the frequency f_c such filter provides the band-pass response. The gain slope of such a filter can be essentially increased if use the perforated screen with some different apertures over the elementary period instead of the classical perforated screen. Additional slots provide the appearance of a couple of extracted poles placed on $f_c - \Delta$ or $f_c + \Delta$, where Δ is the given frequency shift. As a result, the frequency response of three-layer filter takes the quasi-elliptic form. The typical response of such a filter is given in Fig. 1.

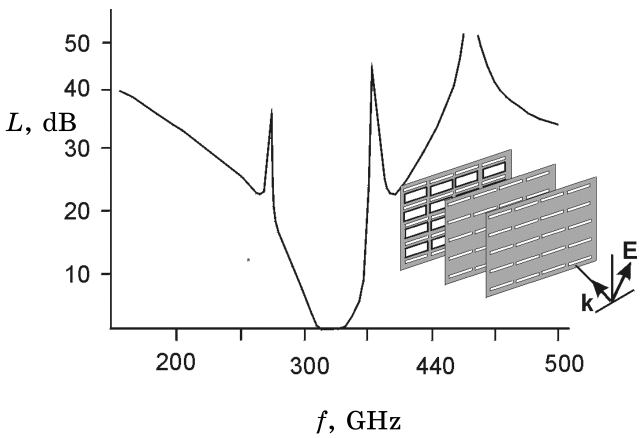

***Fig. 1** – Frequency response of three-layer FSS with two additional extracted poles*

2. MATHEMATICAL MODEL

The investigated structure represents a thin metal screen of the thickness t. Its elementary cell is shown in Fig. 2. Cell size is $L_x \times L_y$. In the simplest case this cell contains two rectangular slots of different sizes ($a_1 \times b_1$ and $a_2 \times b_2$). A plane linearly polarized wave H_{00}, the electric field vector of which in the xy plane is oriented perpendicularly to the slots (i.e., along the y-axis), is incident on a screen.

The partial area method (PAM-II) and the method of generalized scattering matrices were used for numerical investigation of the FSS scattering characteristics. While developing the mathematical model, the investigated multi-aperture screen was represented as two elementary heterogeneities, which are placed at some distance from each other. Planar connection of the Floquet waveguide channel (its cross-section coincides with the elementary cell cross-section of a perforated screen) and two rectangular waveguides of smaller cross-section is the elementary heterogeneity here. Elementary heterogeneities are connected in such a way that connection between them is realized over the rectangular waveguides. The scattering matrix of the elementary heterogeneity is obtained solving the correspon-ding boundary problem by the PAM. Obtained as the result of solving the wave diffraction problems (waves are incident from all the channels conse-cutively) the conversion coefficients are the elements of scattering matrix of elementary heterogeneity. In turn, the total scattering matrix of a resonant iris is calculated using the obtained scattering matrices of the simplest planar connections. Number of modes, taken into account in numerical realization of the projective algorithm, is chosen in such a way that the maximal transverse wave numbers of the highest H- and E-modes (in all the waveguide channels) were equal. 250-300 Floquet waves were considered for the stated below data.

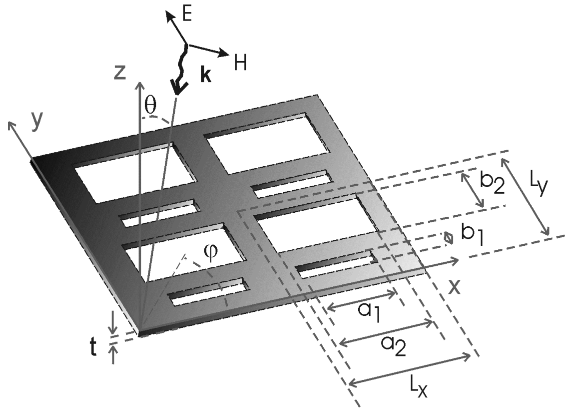

Fig. 2 *– Two-aperture FSS and its elementary cell*

3. NUMERICAL RESULTS AND INTERPRETATION

Based on the mathematical model described above we have investigated the scattering characteristics of multi-aperture screens under normal incidence of the H_{00}-wave, the electric field vector of which is oriented across the slots. Periodic cell of a screen contained from two to four rectangular slots of different sizes. Obtained results can be generalized as follows. FSS, periodic cell of which contains the equal slots only, forms the resonant response of the total transmission typical for classical perforated screens. Position of this total transmission resonance is mainly determined by the length (wide size) of a couple of slots, and its Q-factor is defined by the slot height. Shape of the frequency response is fundamentally changed if slots cease to be equal. In particular, as shown in [9] for two-aperture screen the pair "resonance - high-Q antiresonance" occurs on the frequency response when sizes of two slots (for example, a_1 and a_2) begin to differ. Anti-resonance, i.e., the total reflection resonance, has lesser Q-factor and its frequency changes while difference $|a_1 - a_2|$ growths. In the limiting case two total transmission resonances, which are separated by the wide band-stop, are formed on the frequency response. They are precisely those multiple transmission resonances investigated in [5]. The present investigation is focused on the reflection properties of multi-aperture screens. Established, that it is possible to achieve the formation of pronounced narrow-band total reflection resonance (as well as for multi-aperture irises in rectangular waveguide [6]), which is always placed between two total transmission resonances, by choice of the geometric parameters of the task. Frequency response example of such two-aperture screen with two slots of different sizes is presented in Fig. 3. Size of the screen periodic cell is $L_x \times L_y = 23{,}0 \times 10{,}0$ mm^2, the screen thickness is $t = 0{,}5$ mm. Slot sizes are $a_1 \times b_1 = 13{,}5 \times 1{,}0$ mm^2 and $a_2 \times b_2 = 22{,}95 \times 7{,}0$ mm^2.

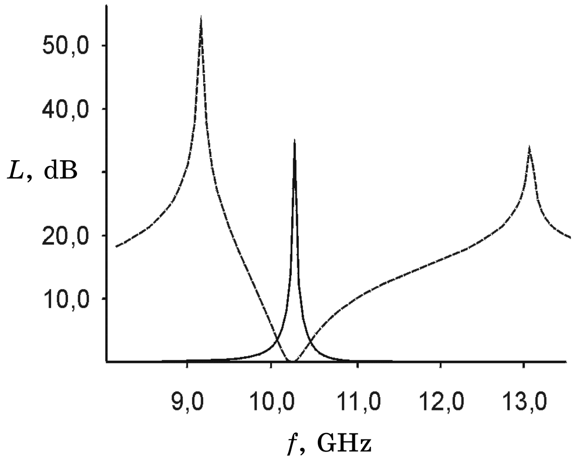

Fig. 3 *– Frequency response of two-aperture FSS (solid line – the insertion losses, dotted line – the reverse losses)*

As seen from the figure, the investigated FSS forms the response with a total cut-off point of an incident wave. At the same time such a response is not typical for perforated screens, which usually form the transmission response. That is in this case multi-aperture FSS exhibits properties, which are distinctive for a lattice of half-wave dipoles, not for a perforated screen.

Non-trivial property of multi-aperture FSS to form the rejection frequency response has the same physical interpretation that the total reflection effect of multi-slot irises in rectangular waveguide [6]. The physical basis of this resonance is the excitation of a couple of natural oscillations with a complex frequency and different Q-factor in FSS, which is considered as an open waveguide resonator. Thus, for example, the frequency response of two-aperture FSS obtained by solving the diffraction problem (solid line) is represented in Fig. 4. The dotted line is the frequency response renewed by a couple of complex natural frequencies using the analytic expression [10] for frequency responses of the scattering matrix elements of a waveguide-type open system in the complex frequency domain. Size of the FSS periodic cell is $L_x \times L_y = 18{,}1 \times 14{,}3$ mm^2, the screen thickness is $t = 0{,}3$ mm. Slot sizes are $a_1 \times b_1 = 11{,}0 \times 1{,}1$ mm^2 and $a_2 \times b_2 = 12{,}1 \times 1{,}2$ mm^2.

As seen from the figure, the approximation curve wholly satisfactorily describes the frequency response both in the resonant and non-resonant regions.

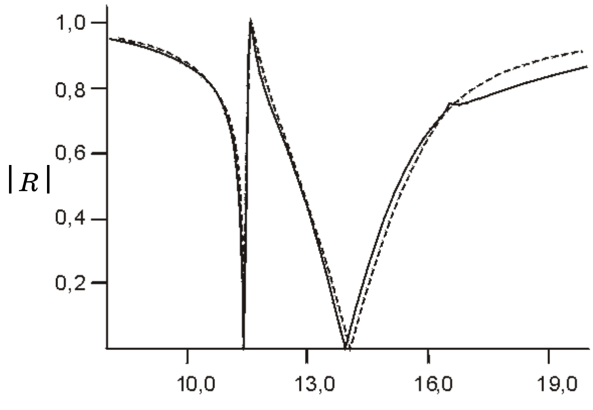

***Fig. 4** – Frequency response of two-aperture FSS plotted on the basis of the rigorous solution – the diffraction problem (solid line) and its approximation subject to two complex natural oscillations – the spectral problem solution (dotted line)*

Multi-aperture screen can be used for a cut-off of an incident wave on some frequencies simultaneously. Periodic cell of such a screen contains larger (than two) number of rectangular slots. Thus, for example, a screen with three different slots over a period forms the frequency response with two total reflection resonances. The example of such a response is represented in Fig. 5. Position of each reflection resonance is mainly defined by the length of one of the slots. I.e., dependence of the resonance position on geometrical parameters is almost the same that for FSS with two different slots over the elementary period. Thus, the size changes of the larger-length slot at the other fixed parameters lead mainly to repositioning of the low-frequency total reflection resonance. When this slot length increases, the low-frequency resonance is shifted to the low-frequency region, and vice versa. That is true for the high-frequency reflection resonance, too. Its position is mainly defined by the smaller-size slot. Simultaneous frequency change of the total reflection resonances is possible as well. The typical dependences of the position change of two resonances at the simultaneous length change of two slots (all the other geometric parameters are fixed) are represented in Fig. 5. Size of the periodic cell of three-aperture FSS is $L_x \times L_y = 23 \times 16$ mm^2, the screen thickness is $t = 0{,}3$ mm. Unchangeable slot sizes are $a_2 \times b_2 = 22{,}8 \times 10{,}0$ mm^2, $b_1 = 1$ mm, $b_3 = 1$ mm. Changeable slot sizes are $a_1 = 13$; 11; 10 mm and $a_3 = 16$; 14; 13 mm (solid, dotted, and long-dotted lines, respectively, in Fig. 5).

FSS described above can be used not only as the single-layer screens, providing reflection of an incident wave on one or some frequencies, but also as the elements of spatial band-pass filters (BPF). In this case multi-aperture FSS will create the additional extracted poles into BPF frequency response. We have to note here, that earlier the only known way to create extracted poles on the frequency response of a filter, which was realized on classical one-element FSS, was such fitting of the periodic cell sizes that the frequency range of the highest space harmonic generation forms the natural band-stop in required frequency range [11, 12]. In this case the single extracted pole is always placed on the right of the band-pass. Filter with such a frequency response allows to perform the effective signal separation. However, here the signal, which should pass through a screen with minimal losses, should always have the smaller frequency than the signal, which should be reflected.

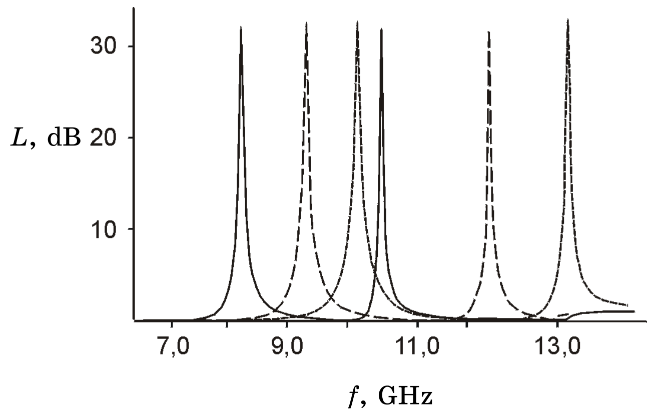

***Fig. 5** – Shifting of the total reflection resonances at simultaneous change of the slot width*

Multi-aperture FSS considered in the paper allow to realize the new creation method of additional extracted poles, providing in this case both the arbitrary pole position and the pole number itself. This method is applied not only for signal separation with close frequencies but also for increase of out-of-band cut-off [13]. Design of the band-pass filters with quasi-elliptic response, providing essential increase of the gain slope, is one more possible application.

As an example we have synthesized three-layer FSS, which should provide the H_{00}-wave transmission with the incidence angle 45° in the frequency band 316,5-325,5 GHz at the insertion losses in the band not more than 0,05 dB and the out-of-band losses not more than 20 dB. FSS consists of three perforated screens located at the distance $\lambda_c/4$ on the band-pass central frequency f_c. Two screens are the classical one-aperture FSS, sizes of which are chosen in such a way that each of these screens provides total transmission of an incidence wave on the central frequency of the band-pass. The third screen is the multi-aperture FSS, the geometrical sizes of which are chosen in such a way that it creates two extracted poles on the boundary frequencies of the band-passes. As the result, such a filter forms the quasi-elliptic frequency response with larger (in comparison with the classical filters) gain slope and higher out-of-band cut-off. Frequency response of such a filter is represented in Fig. 1. Size of the periodic cell of all the screens is $L_x \times L_y = 0{,}5 \times 0{,}5$ mm^2, the screen thickness is $t = 0{,}01$ mm. Slot sizes of the first and the second classical screens are $a_1 \times b_1 = 0{,}3725 \times 0{,}015$ mm^2 and $a_1 \times b_1 = 0{,}46 \times 0{,}015$ mm^2, respectively. Periodic cell of the multi-aperture screen contains two slots of the sizes $a_1 \times b_1 = 0{,}495 \times 0{,}015$ mm^2 and $a_2 \times b_2 = 0{,}464 \times 0{,}015$ mm^2. Distance between the screens is 0,143 mm.

One more example is the filter design with four extracted poles, placed pairwise on the left and on the right of the band-pass. Such a filter is realized as the consecutively placed classical FSS and two multi-aperture screens. Each multi-aperture screen provides total transmission of an incidence wave on the central frequency of the band-pass and appearance of a couple of extracted poles on the left and on the right of the band-pass on the frequencies $f_c \pm \Delta_1$ and $f_c \pm \Delta_2$, where Δ_1 and Δ_2 are the given frequency shift. Frequency response of such a filter with four extracted poles is represented in Fig. 6.

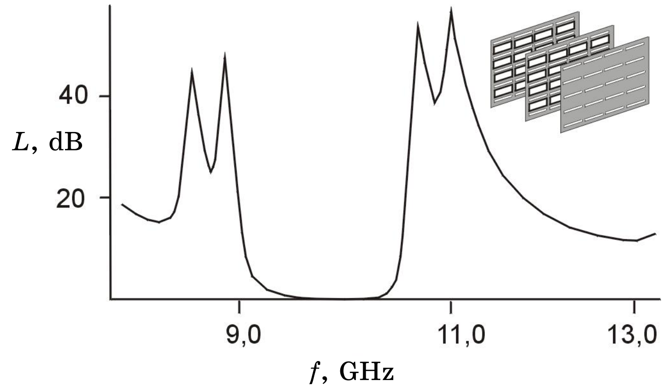

Fig. 6 *– Frequency response of three-layer FSS, H_{00}-wave normal incidence*

Size of the periodic cell of all the screens is $L_x \times L_y = 23 \times 16$ mm^2, the screen thickness is $t = 0,3$ mm. Slot sizes of the first classical screen are $a_1 \times b_1 = 11,5 \times 0,5$ mm^2. Periodic cell of the one multi-aperture screen contains four slots of the sizes $a_1 \times b_1 = 22,8 \times 2,0$ mm^2, $a_2 \times b_2 = 16,0 \times 5,0$ mm^2, $a_3 \times b_3 = 22,8 \times 2,0$ mm^2 and $a_4 \times b_4 = 15,5 \times 1,0$ mm^2. And there are three slots over the period of the third multi-aperture screen with the sizes: $a_1 \times b_1 = 22,8 \times 10,0$ mm^2, $a_2 \times b_2 = 16,0 \times 1,0$ mm^2, $a_3 \times b_3 = 12,0 \times 1,0$ mm^2. Distance between the screens is 7,35 mm.

4. CONCLUSIONS

Obtained results show that use of the multi-aperture perforated screens allows to effectively realize the new method of creation of additional extracted poles while designing the spatial filter. The possibility of appearance of the arbitrary number of extracted poles on the required frequencies is the distinctive feature of this method. It became possible due to the revealed non-trivial feature of multi-aperture screens, namely, the possibility to form the frequency response with some total reflection resonances. The proposed filters are simple-to-construct, fully compatible with the modern process of their production and have the improved characteristics. And, finally, absence of dielectric fill opens the prospects for use of such filters in high-frequency – up to the terahertz one – ranges.

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