Transmission through thick metallic structures with subwavelength annular holes from the enhancement and slow-wave perspectives

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Abstract

In this paper, we systematically study transmission through the thick metallic structures with the periodic subwavelength hole arrays, with the aim to show how replacing circular holes with annular ones affects the transmission. In particular, it will be demonstrated that the transmission can be strongly enhanced in certain frequency ranges due to such a modification that leads to the downshifting of the lowest-frequency passband, or the creating of a new one. Structures of three types are compared, for which strong enhancement and a relatively large equivalent (group) index of refraction can be obtained.

1. Introduction

The interest to the optical and microwave transmission through subwavelength holes has been growing since the phenomenon of extraordinary transmission was demonstrated by Ebessen et al. [1]. Among the structures with a rather large total thickness, passbands located below a cutoff are well known to occur in the stacked hole arrays [2]. While arrays with circular and square holes have been the focus of most of the studies, more complicated shapes might lead to the downshifting of the lowest-frequency passband. In this concern, the transmission mechanism associated with the electroinductive waves as those arising in the stacked arrays of complimentary SRRs [3] should be mentioned.

Thick solid metallic screens with the arrays of annular holes represent one more class of the thick structures, where subwavelength transmission is possible [4]. In many cases, the lowest passband is connected with the localized resonance arising due to mode TE_{11} of the coaxial waveguide. Accordingly, strong transmission can appear within wide ranges of geometrical parameters and frequency, where the extraordinary transmission is still impossible for the corresponding circular hole arrays. Up to now, the screens of a small and intermediate thickness ($D<1.5\,\lambda$) have mainly been studied. Being interpretable in terms of the Fabry-Perot type axial resonances, this mechanism is expected to lead to high transmittance also in thicker structures. It is worth noting that the effect of thickness has not yet been systematically studied.

Modification of the circular hole shape leading to a strong field *confinement* within certain regions of an "old" hole volume is expected to be an efficient tool for downshifting the lowest-frequency passband, or creating a new passband. The annular topology is the *simplest* one that might be appropriate. In this paper, we study such passbands and the corresponding microwave transmission enhancement that occur owing to the re-shaping of circular holes in the thick structures of three types – periodically stacked arrays of annular holes, stacked arrays of circular holes with the long circular inserts, and thick solid metallic screens with arrays of annular holes. The near-edge transmission peaks will be demonstrated, which correspond to rather small group velocity. All simulation results are obtained by using CST Microwave Studio at normal incidence and plane-wave illumination.

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2. Stacked annular hole arrays

Figure 1 presents the geometry and transmission results for the stack of the five hole arrays. The following parameters are used: axial period - L_z=1.05 mm, transversal period – L_x= L_y=4.8 mm, outer hole radius – R_o=1.2 mm, and thickness of a metallic (PEC) plate – d=50 µm. The lowest passband appears here at smaller frequencies than in the circular hole case while the disks of radius R_i=1.1 mm are placed concentrically within every circular hole. The enhancement of the transmitted electric field due to this modification can be larger than 50 dBV/m, at least in the frequency band from 40 to 52 GHz. To compare, the lower-frequency passband edge in the circular hole case (R_i=0) is approximately shown by the gray rectangle, while the arrow indicates direction, toward which the passband is extended. As expected, Fabry-Perot type, (nearly) total transmission peaks are observed. According to their location, the equivalent (group) index of refraction, n_{eq}, can exceed 20, so that this structure may support slow electromagnetic waves. Dispersion results (not shown) are in agreement with the transmission ones.

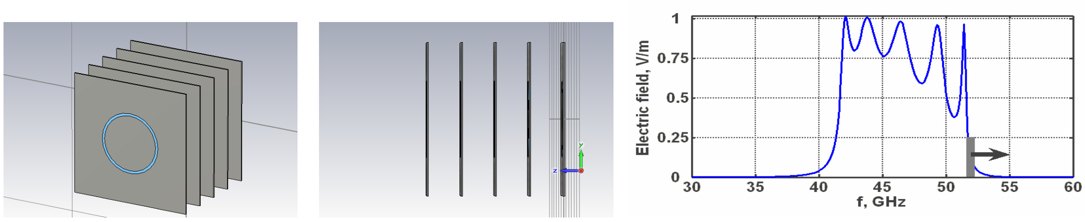

Fig. 1: Geometry of a cell of the stacked array of annular holes (left and middle) and magnitude of the transmitted electric field (right).

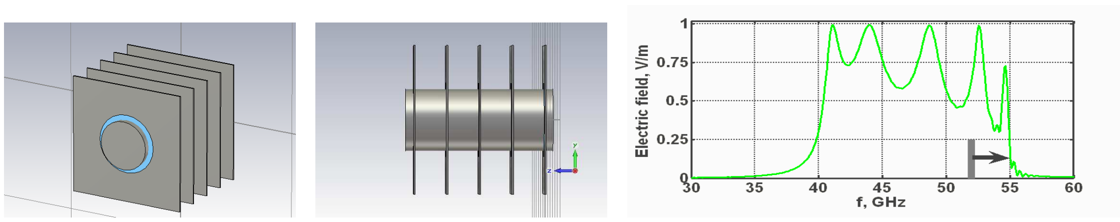

Fig. 2: Geometry of a cell of the stacked array of circular holes with the long solid circular insert (left and middle) and magnitude of the transmitted electric field (right).

Furthermore, adding the solid metallic rod of the radius R_i=1.1 mm and length l=4.75 mm to the stacked circular hole array is sufficient for shifting the lowest passband, which is now even wider than in Fig. 1 for the expenses of smaller n_{eq}, see Fig. 2. Comparing to the circular hole case, transmission enhancement is close to that in Fig. 1. The passbands shown in Fig. 1 and Fig. 2 are expected to be explainable in terms of transmission line theory. Their nature is similar in some sense to that of the effects studied in [3]. To illustrate the electrical sizes, $D/\lambda = l/\lambda = 0.59$ where D is the total thickness of the structure, and $2R_o/\lambda$=0.33, at f=41.5 GHz.

3. Annular hole array in thick solid screen

In this section, we consider transmission through the solid screens with annular holes, which are up to 4λ thick. An example is presented in Fig. 3. Here, the same values of L_x, L_y, R_o and R_i are used as in Fig. 1, while D=24 mm. The enhancement due to adding the rod can be stronger than 80 dBV/m, while n_{eq}=13 corresponds to the locations of the two lowest Fabry-Perot type transmission peaks. The incident-wave energy at the peaks is *squeezed* into very narrow waveguide channels, e.g., $(R_o-R_i)/\lambda$=0.014. The observed features indicate the similarity with the waveguide cutoff based squeezing mechanism, which has recently been studied for a rectangular plasmonic waveguide [5]. The low-frequency edge of the passband is associated in the considered case with the TE_{11}–mode cutoff in the coaxial waveguide [4], so that the lowest-frequency peak appears in its vicinity.

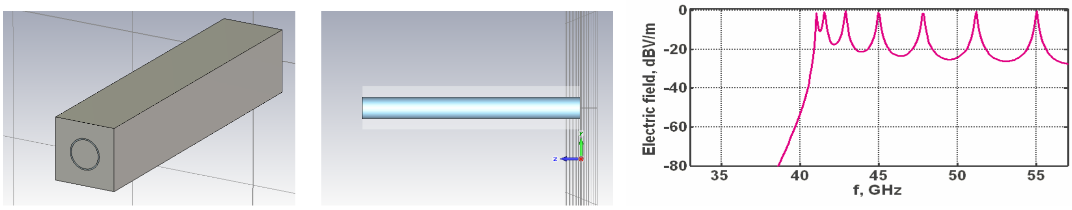

Fig. 3: Geometry of a cell of the annular hole array in a thick metallic screen (left and middle) and magnitude of the transmitted electric field (right).

Location of this peak is not scalable with *D*. Rather, it remains nearly the same within a wide range of variation of *D*. It varies with increasing *D* as in the case of adding a new layer to a periodic stack, e.g., a one-dimensional photonic crystal. In the other words, the larger *D*, the closer the lowest peak to the band edge is, and the larger n_{eq} can be. For example, n_{eq} is nearly equal to 1.9, 4.9, 5.6, 6, 11.2, and 13 for *D*=6, 8, 9.5, 12, 21, and 24 mm, respectively. Strong sensitivity of the transmission to the permittivity and permeability of a medium that partially or completely fills a coaxial waveguide can be noticed, making these structures promising for sensing applications. It is worth noting that the lower-frequency edge is located in the vicinity of the TE_{11}-mode cutoff also for the structures in Figs. 1 and 2.

4. Conclusion

To summarize, the comparative study of transmission through the thick metallic structures containing subwavelength holes is carried out with the focus on the enhancement and slow-wave features. It is shown that the transmitted field may be enhanced by 80dBV/m, due to placing a circular rod or disk into the circular hole(s) of a larger radius. For the considered parameter sets, rather large values of the equivalent (group) index of refraction can be obtained at the passband edge. Choosing type and parameters of the structure, one can obtain the desired width of the new passband and index of refraction, both in a wide range of variation. Presently, several thick metallic structures are under study, which are designed for the use at the optical frequencies.

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