Electromagnetic scattering by a two-dimensional periodic array of small resonant apertures

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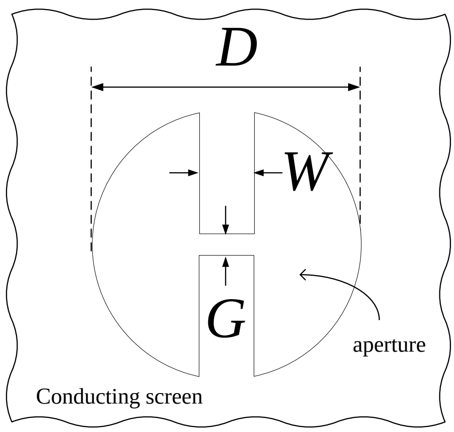
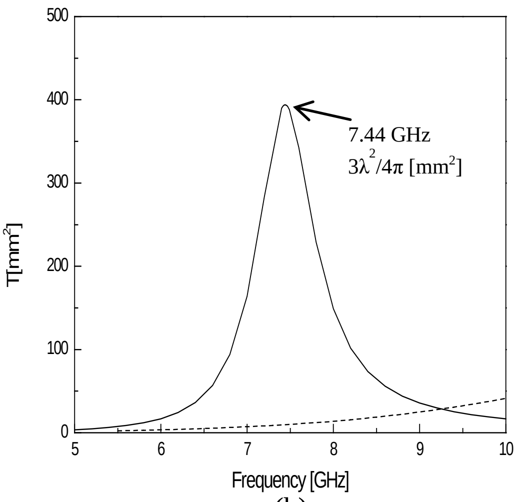
I. Introduction

Since H. A. Bethe reported his work [1] on the electromagnetic coupling through a small hole in the conducting plane, it has been well known that the transmission efficiency is very poor, in more detail the transmittance normalized to the hole area scales as $(a/\lambda)^4$ where a is the hole radius much smaller than the wavelength λ.

Recently lots of researches have been done with a view of enhancing transmission efficiency of small (sub-wavelength) aperture for the applications such as optical data storage, nano-lithography and nano-microscopy. Through these researches, it has been found that the poor transmittance through small hole can be made to be significantly enhanced by modifying the small aperture in shape [2, 3] as shown in Fig.1 (a).



(a)



(b)

Fig. 1 (a) Geometry of a small (sub-wavelength) aperture with a ridge. (D=10 mm, W=3 mm, and G=0.5 mm) (b) Comparison of transmission area T versus frequency between the ridged circular aperture solid line and the circular aperture with no ridge (dotted line).

Fig. 1 (a) shows a ridged aperture as a representative aperture in which the transmission resonance phenomena occur. Here the transmission resonance means the phenomena in which the transmission efficiency is made to become maximum. In this case the power incident upon the area corresponding to $3\lambda^2/4\pi$ [m^2] in the incident side is transmitted through the ridged aperture as discussed in [4].

For reference, the transmission area T [m^2] of the ridged circular aperture is illustrated as a function of frequency in Fig. 1 (b), where the solid curve represents the transmission area T for the ridged aperture (D=10 mm, W=3 mm, and G=0.5 mm) and the dotted line represents the circular aperture

(D=10mm). Here the transmission area T is defined as a ratio of the transmitted power [Watts] through the aperture to the incident power density [Watts/m^2] when the incident power density is assumed to be 1 Watt/m^2.

It is observed from the figure that the transmission efficiency can be made to be remarkably increased by modifying the aperture in shape as in the ridged aperture.
It seems to be rare that researches have been reported on the two dimensional (FSS: Frequency Selective Surface) structure composed of the above small resonant apertures, i.e., the ridged aperture. For this reason it would be interesting to compare this transmission characteristics with that of the periodic array of the circular aperture with no ridge. So the aim of this paper is to investigate the transmission characteristics for the above two case.

II. Transmission Characteristics of the two dimensional array of the ridged circular aperture.

Here we investigate the transmission characteristics of the periodic array (FSS: Frequency Selective Surface) structure of the ridged circular aperture. The basic procedure is to expand the unknown electric field distribution near the conducting screen in a set of Floquet mode functions and relate the unknown magnetic fields on the two sides of the screen to the corresponding modal admittances in these two regions. By appropriately matching the tangential field components at the screen, an integral equation is obtained for the unknown electric field (magnetic surface current densities) in each aperture. To simplify the computations, the unknown aperture field distribution is then expanded into a new set of rooftop basis functions over the aperture itself.

By employing the Galerkin scheme, the integral equation is reduced to a set of linear algebraic equations, from which the desired transmission (and reflection) coefficient can be obtained. The periodic array of the ridged circular aperture which is to be analyzed is shown in Fig. 2.

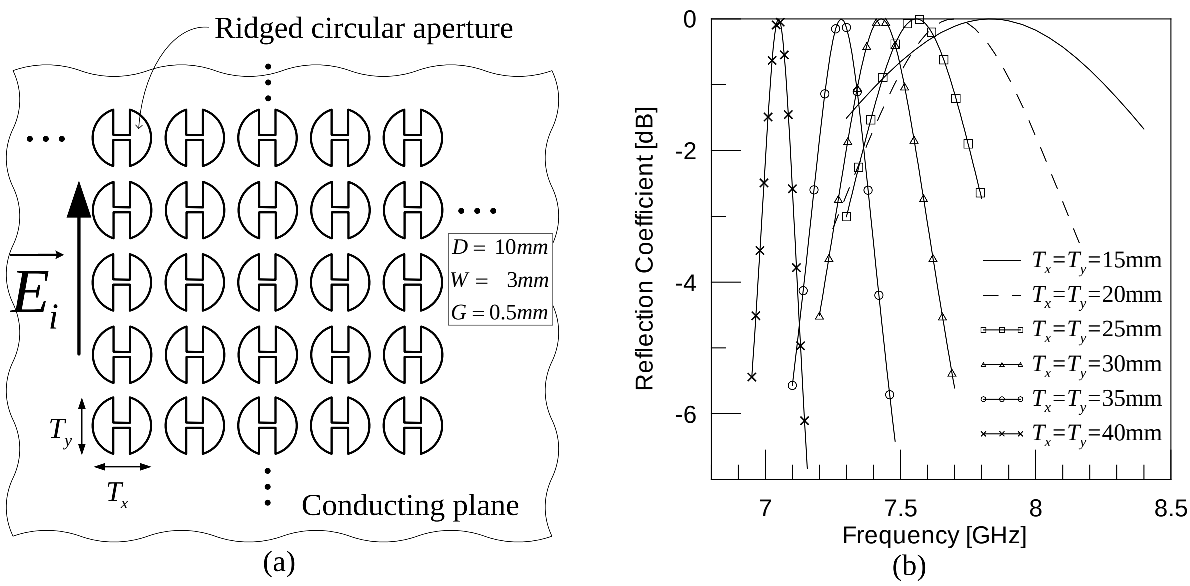


Fig. 2 (a) Periodic array composed of ridged circular aperture. [T_x(T_y): period along x(y) axis.]
(b) Transmission coefficients for six cases for which T_x=T_y=15mm, T_x=T_y=20mm, T_x=T_y=25mm, T_x=T_y=30mm, T_x=T_y=35mm, and T_x=T_y=40mm.

In the problem of Fig. 2 (a), it is assumed that the plane wave whose electric field has only the y-component be normally incident upon the screen.

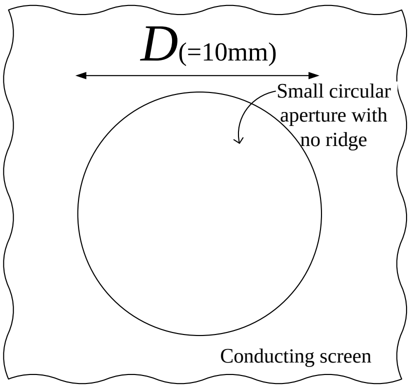
Fig. 2 (b) shows the transmission coefficients for six cases for which T_x=T_y=15mm, T_x=T_y=20mm, T_x=T_y=25mm, T_x=T_y=30mm, T_x=T_y=35mm, and T_x=T_y=40mm.

The frequencies for which the transmission coefficient becomes zero [dB] for each case are given respectively as 7.825 GHz, 7.7 GHz, 7.56 GHz, 7.43 GHz, 7.28 GHz, and 7.05 GHz.

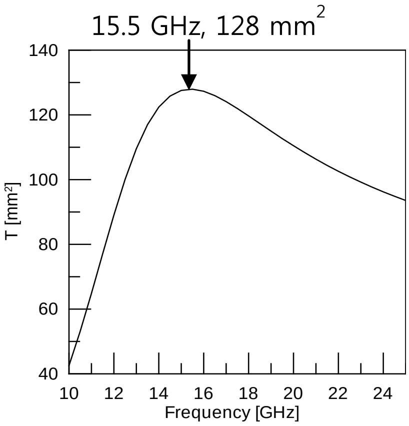
If we calculate the smallest ratio of the actual perforated aperture area to the unit cell area for the zero reflection (or total transmission) case, it is found to be approximately 3.22% for the case that T_x=T_y=40mm. It is interesting to note that this ratio is very small in comparision with that for the periodic array composed of the circular aperture with no ridge as will be seen later.

III. Transmission characteristics of the two dimensional array of the circular aperture with no ridge.

In order to investigate the difference in transmission area characteristics as a single element between the ridged circular aperture and the circular aperture with no ridge, we have calculated the transmission area versus frequencies for the original circular aperture with no ridge as shown in Fig. 3 (a). Fig. 3 (b) shows the frequency characteristics of the transmission area for the case of the circular aperture with no ridge in Fig. 3 (a). Comparison shows that, though the resonant frequency is much smaller for the ridged aperture case, the transmission efficiency can be made to be remarkably enhanced.



(a)



(b)

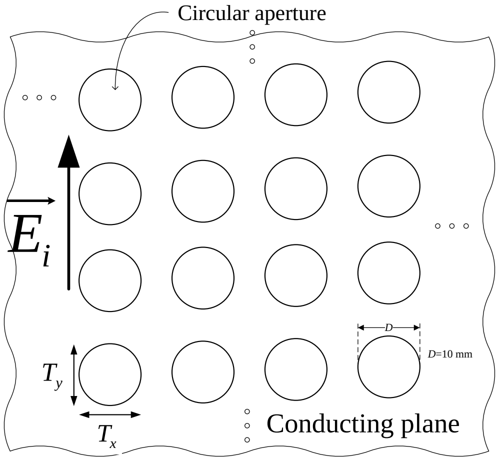
Fig. 3 (a) Structure of the single element of circular aperture with no ridge
(b) its frequency characteristics of the transmission area T [mm^2].

From the Fig. 3, it is seen that the frequency (15.5GHz) at which the transmission area T becomes maximum is significantly increased in comparison with that (7.44 GHz) for the ridged circular aperture. In order to investigate the transmission characteristics of the periodic array (FSS: Frequency Selective Surface) structure of the circular aperture as shown in Fig. 4(a), we have calculated the frequency characteristics of the transmission coefficient for four cases of T_x=T_y=15mm, T_x=T_y=20mm, T_x=T_y=25m, T_x=T_y=30mm.

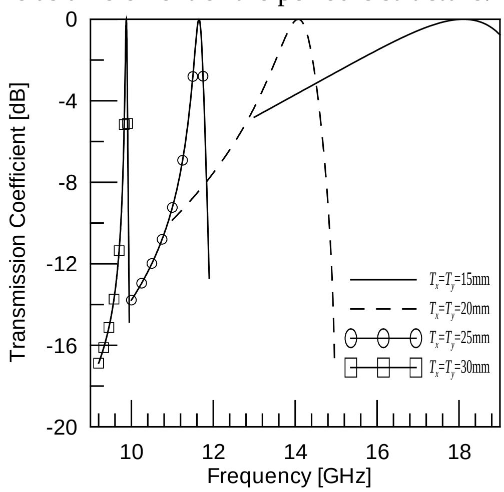
Fig. 4(b) shows the frequency characteristics of the transmission coefficient for the four cases.

Form Fig. 4, it is seen that the total transmission (or zero reflection) occur at frequencies of 9.876 GHz, 11.65GHz, 14.08 GHz, and 18.11 GHz.

For the total transmission (or zero reflection), the smallest ratio of the actual perforated aperture area to the unit cell area is found to be roughly 8.72%, which is larger than that for the previous case composed of the ridged circular aperture. Based upon the above observations, it can be seen that the operating frequency at which total transmission (zero reflection) occurs can be made to be remarkably reduced by employing the ridged circular aperture structure as an element of the periodic structure.



(a)



(b)

Fig. 4 (a) Periodic array composed of circular aperture with no ridge
(b) Its frequency characteristics of transmission coefficient.
[T_x(T_y): period along x(y) axis].

IV. Conclusion

Comparative study on the total transmission (zero reflection) has been done between two FSS structures which are composed of the resonant aperture (i.e., ridged circular aperture) and the nonresonant aperture (i.e., circular aperture with no ridge).

It has been found that, the FSS of the resonant aperture has much smaller ratio of actual aperture area to one cell than that of the FSS of the nonresonant aperture for the total transmission (or zero reflection). For the same reason, also the operating frequency can be made to be significantly reduced by using such a resonant structure. This physical situation is thought to be similar to that of EOT (Extraordinary Optical Transmission) phenomenon [5], in optics area.

Acknowledgments

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Reference

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