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A Breaching of Electromagnetic Shielding by Narrow Aperture in Metal Film

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We report a theoretical research for the condition of electromagnetic shield breaching when a narrow aperture is punctured in thin metal film. To calculate electromagnetic field transmission through a narrow slit, a Rayleigh wave expansion has been applied for free standing, thin metal film. We found that the DC electric field allows perfect transmission when the length of the slit is infinite, regardless of the other geometrical factors such as slitwidth and thickness. Slitwidth dependent transmission spectra as a function of frequency shows a cutoff frequency that decreases almost linearly to the slitwidth, giving that almost successful shielding is only possible when the slitwidth is smaller than 1 micron.

Keywords : Electromagnetic shielding, Diffraction and scattering, Edge and boundary effects
OCIS codes : (050.1960) Diffractions theory; (120.7000) Transmission; (310.6628) Subwavelength structures, nanostructures

I. INTRODUCTION

An electromagnetic interface (EMI) shielding is a practically important phenomena which prevents high intensity electromagnetic fields from affecting the human body or sensitive electronic devices. Nowadays, highly conductive materials such as metal film, conducting polymer [1], or carbon-based nanomaterials [2] are widely studied or applied as EMI shielding materials.

When designing EMI shielding gear or a room for safety, in principle successful shielding is only available when such materials completely surround human or protecting device without any holes or slits, however, this is not technically possible because the construction process definitely allows small discontinuity of shielding materials: during the stitching process of EMI shielding gear or installation of doors or windows or EMI shielding room, narrow slit-like discontinuities may occur. Hence, determining what is the allowed shape and dimension without breaching EMI shielding has a practical importance.

In this report, we simulate how narrow the slit should be, not to break EMI shielding effectiveness of thin metal film. By applying Rayleigh wave diffraction theory, we calculated transmission amplitude spectra of single slits having infinite length and various widths. We found that the cutoff frequency, where transmission amplitude becomes less than 0.5, is critically dependent on the slitwidth. Additionally, we found that the slitwidth should be smaller than 1 micron for successful shielding for the entire frequency region.

II. THEORY MODEL AND EMI SHIELDING BREACHING IN DC LIMIT

Our theory model starts from the Rayleigh wave expansion applied to the periodic 1 dimensional slit array (see Fig. 1(a)) [3-5]. Here, both reflected wave and transmitted wave are assumed as a summation of diffracted waves, and the electromagnetic field inside the slit is expanded following a cavity mode with open boundary condition. Solving the boundary value problem, we obtain transmission amplitude

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for each diffraction order as follows:

$$T_n = \frac{ikQ_n}{\chi_n}(\frac{k}{\chi_0}+1)P_0 \frac{1}{\sin kh} \frac{1}{1+k^2W^2+2ikW\cot kh}. \quad (1)$$

Here, T_n denotes transmission amplitude for nth diffraction order, h is thickness of the film, $\alpha_n = 2\pi n/d$ is grating vector where d is the period of the slit, and $\chi_n = \sqrt{k^2-\alpha_n^2}$ is wavevector of nth diffracted wave through propagation direction, and k is wavevector of incident EM field. P_n and Q_n are Fourier integrals of rectangular slit and overlap integral of waves which have forms of

$$P_n = \frac{1}{a}\int_0^a e^{i\alpha_n x}dx,\ Q_n = \frac{1}{d}\int_0^a e^{-i\alpha_n x}dx, \quad (2)$$

with a being slitwidth. W is given as a summation of those integrals as

$$W = \sum \frac{Q_n P_n}{\chi_n}. \quad (3)$$

For calculating transmission spectra for a single slit, it is sufficient to extend period as infinite, as depicted in Fig. 1(b). In this case, grating vector α_n approaches zero, which results in P_n and Q_n being unity and a/d, respectively, and W approaches to a/dk. Hence, transmission amplitude for zeroth order diffraction, which only transmits to the far field in our case, can be approximated as

$$T_0 = 2i\varepsilon \frac{1}{(1+\varepsilon^2)\sin kh + 2i\varepsilon\cos kh}. \quad (4)$$

Here, ε is slitwidth-period ratio given as a/d. To examine shielding effectiveness for a DC field in the vicinity of such slit, additional approximation is made for vanishing wavevector, $k \to 0$; $\lambda \to \infty$. In such case, sinkh approaches zero and coskh approaches unity, hence we have

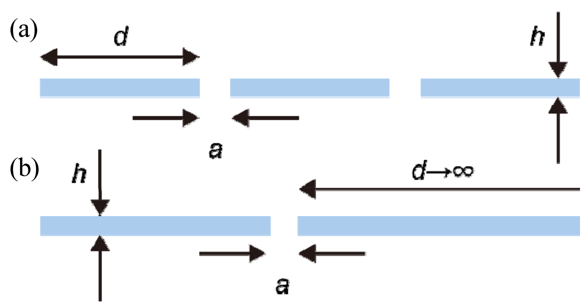

FIG. 1. Sample structures used in the simulation (a) slit array (b) single slit as an array having infinite period.

$$T_0 \approx 2i\varepsilon \frac{1}{(1+\varepsilon^2)\times 0 + 2i\varepsilon \times 1} = 1 \quad (5)$$

Surprisingly, this results indicates that the DC electric field perfectly transmits through the infinitely long slit, regardless of the slitwidth and film thickness: in other words, EMI shielding for DC field completely breaches even though ultra-narrow slit is made. In reality, of course, such breaching is not available because there should be no such infinitely long slit. However, this result still gives an implication that a rather narrow scratch in EMI shielding may cause serious problems.

III. EMI SHIELDING BREACHING IN AC FIELD

To investigate the breaching of EMI shielding for ordinary AC EM field, we calculated transmission spectra for a single slit by using Eq. 1 with large period, i.e. d = 1 m, with film thickness of 100 μm. Slitwidth was varied from 2.2 mm to 1 nm to observe how transmission is affected by it. Shown in Fig. 2 is transmission spectrum as a function of frequency of the incident wave when slitwidth was set as 1 mm. As shown in Fig. 2, transmission is almost suppressed at the high frequency region, however, increases significantly at around 1 kHz, reaching unity in the low frequency region, which is consistent with our approximation calculated in the DC limit. This frequency is relatively low compared to radio frequency or microwave frequency, which indicates that EMI shielding is still valid for microwave applications or electronics safety. However, unity transmission below 1 kHz implies that high intensity fluctuation of an EM field such as a spark or lightning cannot be perfectly protected when such a slit is present.

To examine the critical slitwidth which guarantees marginal shielding for the entire frequency including the DC limit, we have calculated transmission spectra, while varying slitwidth

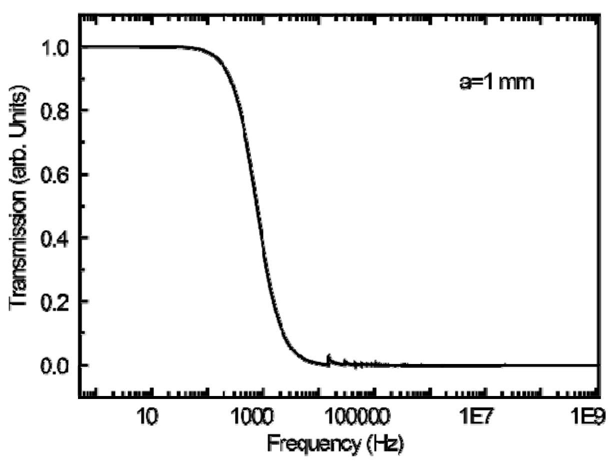

FIG. 2. Calculated transmission spectrum as a function of frequency when slitwidth was 1 mm.

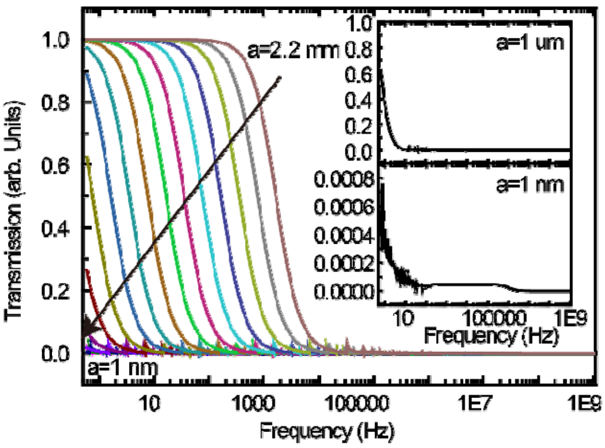

FIG. 3. Calculated transmission spectrum as a function of frequency when slitwidth was varied from 2.2 mm to 1 nm. (Upper inset) Transmission spectrum for 1 μm slitwidth. (Lower inset) Transmission spectrum for 1 nm slitwidth.

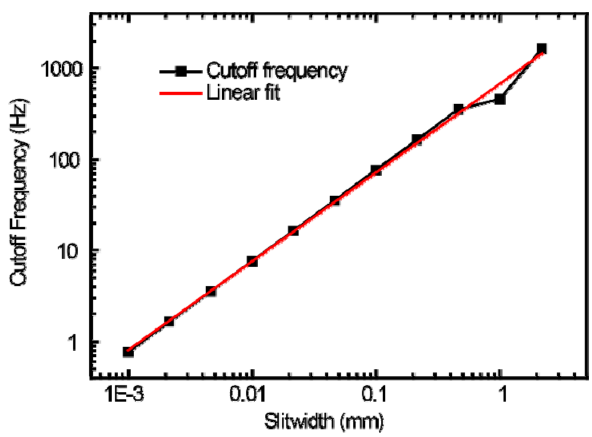

FIG. 4. Cutoff frequency as a function of slitwidth (black square), together with linear fit (red straight line).

from 2.2 mm to 1 nm, which is shown in Fig. 3. As shown in this figure, the frequency region with unity transmission decreases with decreasing slitwidth. Specifically, when slitwidth becomes 1 μm, transmission becomes less than 0.6 for the entire observing spectral region. Of course, if we zoom in more into the low frequency region, perfect transmission is still observed, however, such a region is limited below 0.6 Hz. When the slitwidth becomes narrower than 1 μm (see upper inset figure in Fig. 3), transmission is successfully suppressed, and for 1 nm slitwidth, transmission almost vanishes to less than 0.1% for the entire frequency range (see lower inset figure in Fig. 3).

To quantitatively examine EMI shielding effectiveness in the vicinity of a narrow slit, we have calculated a cutoff frequency as a function of slit width. Here, cutoff frequency was obtained by extracting the frequency where the transmission start to be lower than 0.5. This result is depicted in Fig. 4 in the form of a log-log plot. The extracted cutoff frequency was surprisingly linear as can be seen in the figure. The linear fit confirmed our observation, which gives unity in slope. This results suggests to us that the cutoff frequency is linearly dependent on the slitwidth, with a form of

$$f_c = ra\,, \tag{6}$$

where f_c is the cutoff frequency, a is the slitwidth, and r is a constant which is obtained as 0.7 Hz/μm in our case. This result would helpful in determining a safety margin when designing EMI shielding systems which may contain a certain kind of slit-like openings.

IV. CONCLUSION

In conclusion, we theoretically studied a breaching of EMI shielding in the vicinity of a narrow slit on metal film. We found that an infinitely long slit seriously damages the EMI shielding effectiveness. Specifically, EMI shielding may be completely breached in the DC limit, regardless of its width. From transmission calculation through the narrow slit while varying the slitwidth, we found that the maximum allowed width was 1 μm for considerable shielding for the entire frequency region. Also, we found a linear relationship between slitwidth and cutoff frequency which gives an indication for designing safe EMI shielding systems.

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