Wave Penetration Through Slits on Stacked Thick Plates

Jean-Fu Kiang, *Member, IEEE*

***Abstract*—Wave penetration through slits on single and stacked metal plates of finite thickness is studied by using the Galerkin method. The limiting case of slits on infinitesimally thin plates are also formulated to compare the shielding effectiveness of metal plates with slits against incident plane waves. It is observed that the wave penetrating through slits on stacked plates with a proper separation is much less than that through a single slit on a plate with twice the thickness.**

***Index Terms*—Galerkin's method, shielding, slits.**

I. Introduction

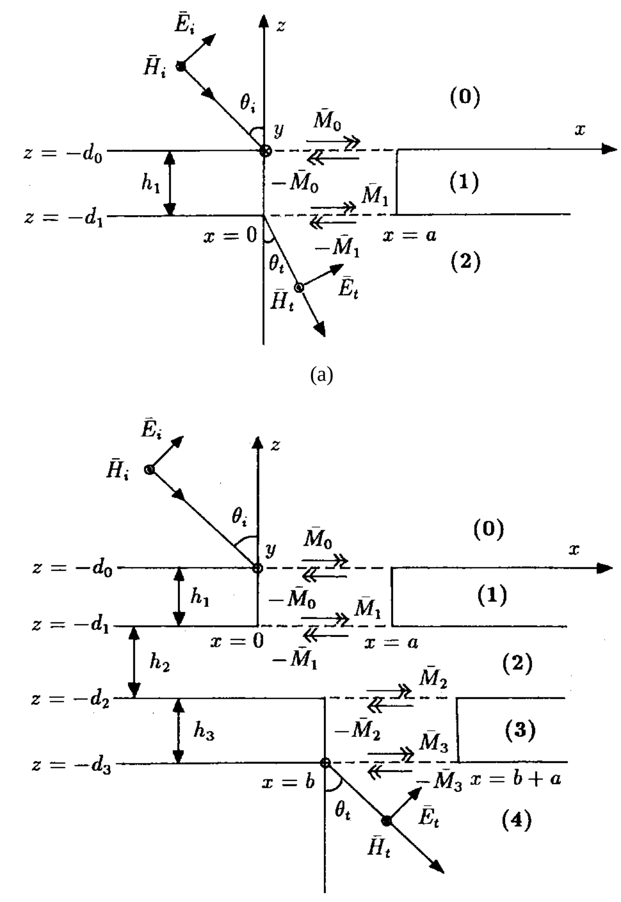
ELECTROMAGNETIC-WAVE penetration through slots or holes on metal screens is an important subject in electromagnetic compatibility [1]. For small holes of regular shape on a plate of zero thickness, the scattering properties can be described by using equivalent electric and magnetic dipoles [2]. As the slot size or plate thickness increases, the detailed field distributions in and around the slot need to be considered. The problem of wave penetration through slits on a single plate has been studied extensively. Some previous studies will be briefly described in this section, and more information can be obtained from the reference lists of these papers. In [3], the characteristic modes of a finite-length slot on a metal screen of zero thickness are obtained by using a method of moments. In [4], Gaussian elementary beams are used to expand the equivalent magnetic surface current across a slot on a ground plane of zero thickness, where the field distribution away from the slot can be obtained directly from these beams.

For slits on thick plates, the finite-difference time-domain (FDTD) method has been proposed to explore the properties of lapped joints and slots at junctions of metal surfaces [5] and narrow apertures of finite depth [6]. Moment methods have also been used to calculate the transmission through a filled slot in a thick conducting screen [7], and the characteristic modes in the slot [8]. In [9], a mode-matching technique combined with Fourier transform is proposed to study the scattering and transmission properties of a slit in a thick conducting screen. In [10], a finite-element and boundary integral method is used to study the scattering and transmission properties of an inhomogeneously filled slot of irregular shape. The resonance depth of slits has been discussed in [5], and it can be used to detect the presence of narrow slits [11].

Manuscript received May 5, 1996; revised April 7, 1998. This work was supported by the National Science Council, Taiwan, R.O.C., under Contract NSC86-2221-E005-011.

The author is with the Department of Electrical Engineering, National Chung-Hsing University, Taichung, Taiwan 402, R.O.C.

Publisher Item Identifier S 0018-9480(98)04965-5.



(a)

(b)

Fig. 1. Configurations of slits on single and stacked plates of finite thickness.

In most of these studies, less attention has been paid to the shielding effectiveness of narrow slits existing in almost all equipment cabinets. In this paper, we will study the shielding effectiveness of single and stacked plates against an incident transverse magnetic (TM) plane wave when slits exist. A Galerkin's method will be developed to calculate both the scattering and the transmission cross sections of slits on thick plates. The limiting case of zero-thickness plates are also formulated for checking purposes.

II. Formulation

The cross section of slits on single and stacked thick-metal plates are shown in Fig. 1. All slits are assumed to be infinitely long in the y-direction, hence, the transverse electromagnetic (TEM) mode may propagate through these slits to the other

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side of the plate. A plane wave is incident upon the plate with an angle θ_i, and an equivalent problem is formed in each region. The gap in the boundary between two adjacent regions is replaced by a perfect electric conductor and a magnetic surface current associated with the tangential electric field. The field distribution in each region can be expressed in terms of these equivalent magnetic surface currents, and then, one can impose the boundary condition that the tangential magnetic fields are continuous across the gaps. The resulting equations are then solved by using the Galerkin method.

A. Slit on Single Plate

A TM wave is incident upon the slit with an angle θ_i. The field components are $\bar{E}^i = E_o(\hat{x}\cos\theta_i + \hat{z}\sin\theta_i)e^{ik_0(x\sin\theta_i - z_0\cos\theta_i)}$ and $\bar{H}^i = -\hat{y}(E_o/\eta_o)e^{ik_0(x\sin\theta_i - z_0\cos\theta_i)}$ where $k_0 = \omega\sqrt{\mu_o\epsilon_o}$, $\eta_o = \sqrt{\mu_o/\epsilon_o}$, and $z_0 = z + d_0$. Both the TEM mode and the higher order TM modes are induced inside the slit. The fields in each region can be expressed as

$$\begin{aligned}
E_{0x} =& E_o\cos\theta_i \\
&\cdot\left[e^{ik_0(x\sin\theta_i - z_0\cos\theta_i)} - e^{ik_0(x\sin\theta_i + z_0\cos\theta_i)}\right] \\
&+\int_{-\infty}^{\infty} dk_x e^{ik_x x + ik_{0z}z_0}\frac{k_{0z}}{\omega\epsilon_0}h_0(k_x) \\
H_{0y} =& -(E_o/\eta_o) \\
&\cdot\left[e^{ik_0(x\sin\theta_i - z_0\cos\theta_i)} + e^{ik_0(x\sin\theta_i + z_0\cos\theta_i)}\right] \\
&+\int_{-\infty}^{\infty} dk_x e^{ik_x x + ik_{0z}z_0}h_0(k_x) \\
E_{1x} =& -\sum_{n=0}^{\infty}\cos\alpha_n x\frac{\gamma_n}{i\omega\epsilon_1} \\
&\cdot\left[h_n^{(1a)}\sin\gamma_n z_1 + h_n^{(1b)}\sin\gamma_n(z_1 - h_1)\right] \\
H_{1y} =& \sum_{n=0}^{\infty}\cos\alpha_n x\left[h_n^{(1a)}\cos\gamma_n z_1 + h_n^{(1b)}\cos\gamma_n(z_1 - h_1)\right] \\
E_{2x} =& -\int_{-\infty}^{\infty} dk_x e^{ik_x x - ik_{2z}z_2}\frac{k_{2z}}{\omega\epsilon_2}h_2(k_x) \\
H_{2y} =& \int_{-\infty}^{\infty} dk_x e^{ik_x x - ik_{2z}z_2}h_2(k_x)
\end{aligned} \tag{1}$$

where $z_1 = z + d_1$, $z_2 = z + d_1$, $h_1 = d_1 - d_0$ is the thickness of the plate, $\alpha_n = n\pi/a$, $\alpha_n^2 + \gamma_n^2 = \omega^2\mu_o\epsilon_1$, and $k_{iz} = \sqrt{k_0^2 - k_x^2}$ for $i = 0, 2$. The first term in the E_{0x} and H_{0y} expressions is the incident and the reflected TM wave, the integral in the E_{0x} and H_{0y} expressions is the contribution by the induced magnetic surface current $\bar{M}_0$. By using the equivalence $\bar{M} = \bar{E}\times\hat{n}$ at the gaps, we obtain the relations between the unknown coefficients in (1) and the Fourier transform of the magnetic surface current. The magnetic fields can then be expressed in terms of the Fourier transform of these magnetic surface currents.

Next, impose the boundary conditions that the tangential magnetic fields are continuous across the gaps at $z = -d_0$ and $z = -d_1$ to obtain two equations with the magnetic surface currents as unknowns. The two equations are solved by applying the Galerkin method where Chebyshev polynomials are chosen for both the basis and the weighting functions. The limiting case with zero plate thickness can be solved in a similar manner.

B. Slits on Stacked Plates

For slits on stacked thick plates, shown in Fig. 1, the magnetic fields in each region can be expressed in terms of the Fourier transform of the equivalent magnetic surface currents as

$$\begin{aligned}
H_{0y} =& -(E_o/\eta_o) \\
&\cdot\left[e^{ik_0(x\sin\theta_i - z_0\cos\theta_i)} + e^{ik_0(x\sin\theta_i + z_0\cos\theta_i)}\right] \\
&-\int_{-\infty}^{\infty} dk_x e^{ik_x x + ik_{0z}z_0}\frac{\omega\epsilon_0}{k_{0z}}M_{0y}(k_x) \\
H_{1y} =& \sum_{n=0}^{\infty}\cos\alpha_n x\frac{i\omega\epsilon_1}{\gamma_{1n}} \\
&\cdot\left[\frac{\cos\gamma_{1n}z_1}{\sin\gamma_{1n}h_1}M_{0n} - \frac{\cos\gamma_{1n}(z_1 - h_1)}{\sin\gamma_{1n}h_1}M_{1n}\right] \\
H_{2y} =& \int_{-\infty}^{\infty} dk_x e^{ik_x x}\frac{i\omega\epsilon_2}{k_{2z}} \\
&\cdot\left[\frac{\cos k_{2z}z_2}{\sin k_{2z}h_2}M_{1y}(k_x) - \frac{\cos k_{2z}(z_2 - h_2)}{\sin k_{2z}h_2}M_{2y}(k_x)\right] \\
H_{3y} =& \sum_{n=0}^{\infty}\cos\alpha_n(x - b)\frac{i\omega\epsilon_3}{\gamma_{3n}} \\
&\cdot\left[\frac{\cos\gamma_{3n}z_3}{\sin\gamma_{3n}h_3}M_{2n} - \frac{\cos\gamma_{3n}(z_3 - h_3)}{\sin\gamma_{3n}h_3}M_{3n}\right] \\
H_{4y} =& \int_{-\infty}^{\infty} dk_x e^{ik_x x - ik_{4z}z_4}\frac{\omega\epsilon_4}{k_{4z}}M_{3y}(k_x)
\end{aligned} \tag{2}$$

where $\alpha_n = n\pi/a$, $\alpha_n^2 + \gamma_{in}^2 = \omega^2\mu\epsilon_i$ with $i = 1, 3$, $k_x^2 + k_{iz}^2 = \omega^2\mu\epsilon_i$ with $i = 0, 2, 4$. The Fourier transform of the magnetic surface currents are defined as

$$\begin{aligned}
M_{iy}(k_x) &= \frac{1}{2\pi}\int_{-\infty}^{\infty} dx e^{-ik_x x}M_{iy}(x) \\
M_{in} &= \frac{\varepsilon_n}{a}\int_0^a dx_i\cos\alpha_n x_i M_{iy}(x), \qquad 0 \le i \le 3
\end{aligned} \tag{3}$$

where $\varepsilon_n = 1$ when $n = 0$ and $\varepsilon_n = 2$ when $n > 0$, $x_0 = x_1 = x$, and $x_2 = x_3 = x - b$. Expand the magnetic surface currents in terms of the basis functions as

$$M_{iy}(x) = \sum_{p=1}^{N_i} u_{ip}f_{ip}(x), \qquad 0 \le i \le 3 \tag{4}$$

where u_{ip}'s are the unknown coefficients, and $f_{ip}(x)$'s are the basis functions, which are chosen to be Chebyshev polynomials. When the plate thickness is zero, the electric field near the edge of the slit varies approximately as $\rho^{-1/2}$ where ρ is the distance to the slit edge. With a thick plate, the electric field near the edge varies as $\rho^{-1/3}$, which is smoother than with the zero-thickness plate. Incorporating no edge condition in the basis functions may incur less accurate field distribution near the edge, but should have less effect on the far field.

Substitute the magnetic surface-current expansion into (2), then impose the boundary conditions that the tangential magnetic fields are continuous across the gaps. Applying the Galerkin procedure, we obtain the matrix equation (5), shown at the bottom of this page, where

$$f_{ip}(k_x) = \frac{1}{2\pi}\int_{-\infty}^{\infty} dx e^{-ik_x x} f_{ip}(x)$$
$$f_{ip,n} = \frac{\varepsilon_n}{a}\int_0^a dx \cos\alpha_n x_i f_{ip}(x), \qquad 0 \le i \le 3;\ 1 \le p \le N_i. \tag{6}$$

Consider the limiting case where the plate thickness is infinitesimal. The magnetic fields in regions (0), (1), and (2) can be expressed in terms of the Fourier transform of the magnetic surface currents as

$$\begin{aligned}H_{0y} &= -(E_o/\eta_o)\\ &\quad\cdot\left[e^{ik_0(x\sin\theta_i - z_0\cos\theta_i)} + e^{ik_0(x\sin\theta_i + z_0\cos\theta_i)}\right]\\ &\quad - \int_{-\infty}^{\infty} dk_x e^{ik_x x + ik_{0z}z_0}\frac{\omega\epsilon_0}{k_{0z}} M_{0y}(k_x)\\ H_{1y} &= \int_{-\infty}^{\infty} dk_x e^{ik_x x}\frac{i\omega\epsilon_1}{k_{1z}}\\ &\quad\cdot\left[\frac{\cos k_{1z}z_1}{\sin k_{1z}h_1}M_{0y}(k_x) - \frac{\cos k_{1z}(z_1 - h_1)}{\sin k_{1z}h_1}M_{1y}(k_x)\right]\\ H_{2y} &= \int_{-\infty}^{\infty} dk_x e^{ik_x x - ik_{2z}z_2}\frac{\omega\epsilon_2}{k_{2z}} M_{1y}(k_x)\end{aligned} \tag{7}$$

where $M_{iy}(k_x)$'s are defined in (3).

By imposing the boundary condition that the tangential magnetic fields are continuous across the gaps at $z = -d_0$ and $z = -d_1$, and applying the Galerkin procedure, we have (8), shown at the bottom of the following page, where $f_{ip}(k_x)$'s are defined in (6).

III. Numerical Results

Fig. 2 shows the backscattering cross section of a plane wave incident upon the slit, which is defined as

$$\sigma_b(\theta_i) = 10\log_{10}\left(2\pi\rho\frac{|H_{0y}^s(\bar{\rho})|^2}{|E_o/\eta_o|^2}\right)\text{dB} \tag{9}$$

where $H_{0y}^s(\bar{\rho})$ is the scattering magnetic field in the backward direction due to the induced magnetic surface current. Our results with $a = 2.2\lambda_0$ match reasonably well with those of [9] in $0 \le \theta_i \le 65°$. In the range $\theta_i > 65°$, the difference between our results and the exact solution of [9] is of the order of 5 dB. This may be due to the different numerical integration schemes used. Also note that when using the stationary phase approximation, the far field near the grazing angle is usually less accurate. However, the absolute value of the backscattering cross section near the grazing angle is about 20 dB lower than that in the normal incidence. Thus, the calculated results are fairly useful for practical purposes.

In all the cases considered, the number of basis functions is incremented to obtain convergent results, usually five to seven is sufficient.

A mode-matching method has also been derived, and the results (also shown as a dashed curve) are very close to those

$$\begin{aligned}&-\frac{2E_o}{\eta_o}\int_0^a dx e^{ik_0 x\sin\theta_i} f_{0q}(x) - \sum_{p=1}^{N_0} u_{0p} 2\pi\int_{-\infty}^{\infty} dk_x f_{0q}(-k_x)\frac{\omega\epsilon_0}{k_{0z}} f_{0p}(k_x)\\ &\quad= \sum_{p=1}^{N_0} u_{0p}\sum_{n=0}^{\infty}\frac{a}{\varepsilon_n} f_{0q,n}\frac{i\omega\epsilon_1}{\gamma_{1n}}\cot\gamma_{1n}h_1 f_{0p,n} - \sum_{p=1}^{N_1} u_{1p}\sum_{n=0}^{\infty}\frac{a}{\varepsilon_n} f_{0q,n}\frac{i\omega\epsilon_1}{\gamma_{1n}}\csc\gamma_{1n}h_1 f_{1p,n}, \qquad 1 \le q \le N_0\\ &\sum_{p=1}^{N_1} u_{1p}2\pi\int_{-\infty}^{\infty} dk_x f_{1q}(-k_x)\frac{i\omega\epsilon_2}{k_{2z}}\cot k_{2z}h_2 f_{1p}(k_x) - \sum_{p=1}^{N_2} u_{2p}2\pi\int_{-\infty}^{\infty} dk_x f_{1q}(-k_x)\frac{i\omega\epsilon_2}{k_{2z}}\csc k_{2z}h_2 f_{2p}(k_x)\\ &\quad= \sum_{p=1}^{N_0} u_{0p}\sum_{n=0}^{\infty}\frac{a}{\varepsilon_n} f_{1q,n}\frac{i\omega\epsilon_1}{\gamma_{1n}}\csc\gamma_{1n}h_1 f_{0p,n} - \sum_{p=1}^{N_1} u_{1p}\sum_{n=0}^{\infty}\frac{a}{\varepsilon_n} f_{1q,n}\frac{i\omega\epsilon_1}{\gamma_{1n}}\cot\gamma_{1n}h_1 f_{1p,n}, \qquad 1 \le q \le N_1\\ &\sum_{p=1}^{N_1} u_{1p}2\pi\int_{-\infty}^{\infty} dk_x f_{2q}(-k_x)\frac{i\omega\epsilon_2}{k_{2z}}\csc k_{2z}h_2 f_{1p}(k_x) - \sum_{p=1}^{N_2} u_{2p}2\pi\int_{-\infty}^{\infty} dk_x f_{2q}(-k_x)\frac{i\omega\epsilon_2}{k_{2z}}\cot k_{2z}h_2 f_{2p}(k_x)\\ &\quad= \sum_{p=1}^{N_2} u_{2p}\sum_{n=0}^{\infty}\frac{a}{\varepsilon_n} f_{2q,n}\frac{i\omega\epsilon_3}{\gamma_{3n}}\cot\gamma_{3n}h_3 f_{2p,n} - \sum_{p=1}^{N_3} u_{3p}\sum_{n=0}^{\infty}\frac{a}{\varepsilon_n} f_{2q,n}\frac{i\omega\epsilon_3}{\gamma_{3n}}\csc\gamma_{3n}h_3 f_{3p,n}, \qquad 1 \le q \le N_2\\ &\sum_{p=1}^{N_3} u_{3p}2\pi\int_{-\infty}^{\infty} dk_x f_{3q}(-k_x)\frac{\omega\epsilon_4}{k_{4z}} f_{3p}(k_x)\\ &\quad= \sum_{p=1}^{N_2} u_{2p}\sum_{n=0}^{\infty}\frac{a}{\varepsilon_n} f_{3q,n}\frac{i\omega\epsilon_3}{\gamma_{3n}}\csc\gamma_{3n}h_3 f_{2p,n} - \sum_{p=1}^{N_3} u_{3p}\sum_{n=0}^{\infty}\frac{a}{\varepsilon_n} f_{3q,n}\frac{i\omega\epsilon_3}{\gamma_{3n}}\cot\gamma_{3n}h_3 f_{3p,n}, \qquad 1 \le q \le N_3\end{aligned} \tag{5}$$

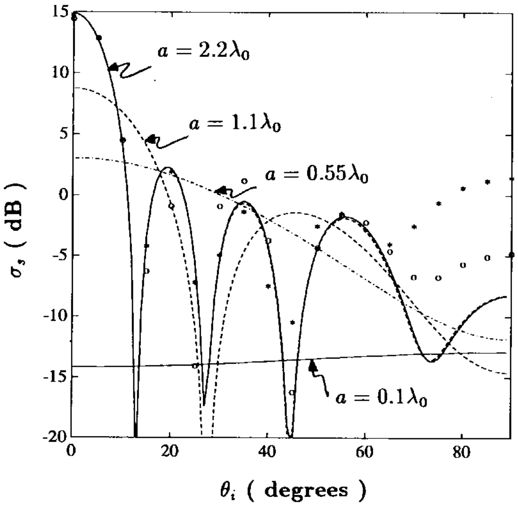

Fig. 2. Backscattering cross section from a slit on a thick plate: $\theta_i = 0$, $h_1 = 0.25\lambda_0$, $\epsilon_1 = \epsilon_o$, o: [9], exact, *: [9], approximate.

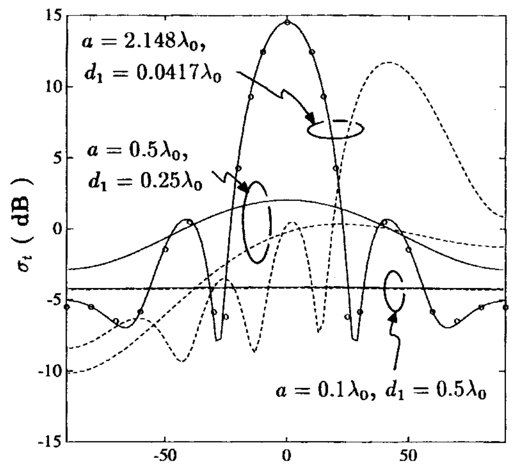

Fig. 3. Transmission cross section through a slit on a thick plate. $\epsilon_1 = \epsilon_o$, ——: $\theta_i = 0$, - - - : $\theta_i = 45°$, o: results from [7].

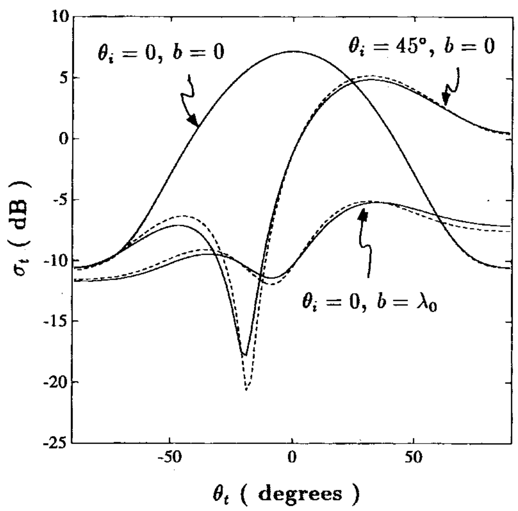

Fig. 4. Transmission cross section through slits on stacked thick plates. $a = \lambda_0$, $h_1 = 0.001\lambda_0$, $h_2 = 0.25\lambda_0$, $h_3 = 0.001\lambda_0$, $\epsilon_1 = \epsilon_2 = \epsilon_3 = \epsilon_o$, ——: finite thickness approach, - - - : zero-thickness approach.

obtained by using this approach in all incident angles. As the slit width is decreased from $a = 2.2\lambda_0$ down to $a = 0.1\lambda_0$, the backscattering cross section becomes more omnidirectional, and the magnitude around $\theta_i = 0$ is monotonically reduced.

The transmitted field strength can be described by a transmission cross section defined as

$$\sigma_t(\theta_t, \theta_i) = 10 \log_{10} \left(2\pi\rho \frac{|H_{2y}(\bar{\rho})|^2}{|E_o/\eta_o|^2}\right) \text{dB}. \tag{10}$$

Fig. 3 shows the transmission cross section of a plane wave upon a slit on single plate. The transmitted pattern is sensitive to the incident angle for wide and thin slits, but almost omnidirectional for thick and narrow slits. The results from [7] match reasonably well with ours.

Next, we analyze the transmission properties of slits on stacked thin plates. As shown in Fig. 4, the results of the finite-thickness approach match reasonably well with those of the zero-thickness approach. It is also observed that by laterally shifting the slits with respect to each other, the transmission through a slit with width around one wavelength is significantly reduced. Since the transmission pattern through a narrow slit is close to omnidirectional, the shielding effectiveness by laterally shifting the slit position may not render good shielding results.

In Fig. 5, the transmission cross sections of $0.1\lambda_0$-wide slits in various configurations are presented. By inserting a dielectric $\epsilon_1 = 5\epsilon_o$ in the slit on a single plate, the transmission cross section is reduced by approximately 8 dB. If slight loss is added in the inserted dielectric, the transmission cross section

$$\begin{aligned}
-\frac{2E_o}{\eta_o}\int_0^a dx e^{ik_0 x \sin\theta_i} f_{0q}(x) &= \sum_{p=1}^{N_0} u_{0p} 2\pi \int_{-\infty}^{\infty} dk_x f_{0q}(-k_x)\left(\frac{\omega\epsilon_0}{k_{0z}} + \frac{i\omega\epsilon_1}{k_{1z}} \cot k_{1z}h_1\right) f_{0p}(k_x) \\
&\quad - \sum_{p=1}^{N_1} u_{1p} 2\pi \int_{-\infty}^{\infty} dk_x f_{0q}(-k_x) \frac{i\omega\epsilon_1}{k_{1z}} \csc k_{1z}h_1 f_{1p}(k_x), \qquad 1 \le q \le N_0 \\
\sum_{p=1}^{N_0} u_{0p} \int_{-\infty}^{\infty} dk_x f_{1q}(-k_x) \frac{i\omega\epsilon_1}{k_{1z}} \csc k_{1z}h_1 f_{0p}(k_x) &- \sum_{p=1}^{N_1} u_{1p} \int_{-\infty}^{\infty} dk_x f_{1q}(-k_x)\left(\frac{i\omega\epsilon_1}{k_{1z}} \cot k_{1z}h_1 + \frac{\omega\epsilon_2}{k_{2z}}\right) f_{1p}(k_x) \\
&= 0, \qquad 1 \le q \le N_1
\end{aligned} \tag{8}$$

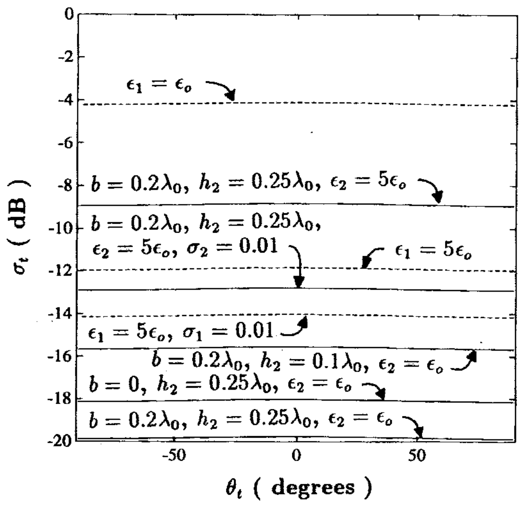

Fig. 5. Transmission cross section through slits on single and stacked thick plates. $\theta_i = 0$, $a = 0.1\lambda_0$, for single plate: $h_1 = 0.5\lambda_0$, for stacked plates: $h_1 = h_3 = 0.25\lambda_0$, $\epsilon_1 = \epsilon_3 = \epsilon_o$, ——: stacked plates, - - - : single plate.

is further reduced by 2 dB. If the plate is split into two thinner ones with equal thickness, and separated by $0.25\lambda_0$, the transmission cross section can be significantly reduced by 14 dB. If the two slits are laterally shifted by $0.2\lambda_0$, the cross section is reduced further by 2 dB. If the two plates are moved closer to $0.1\lambda_0$, the transmission cross section is increased by about 4 dB, mainly due to multiple reflection by both plates. If a dielectric with $\epsilon_2 = 5\epsilon_o$ is inserted between the two plates, the transmission cross section is increased, which is contrary to the single plate case. For the latter case, the inserted dielectric scatters more power back to region (0); for the former case, the inserted dielectric focuses more power into region (4). The cross section can be reduced by adding slight loss in the dielectric.

In summary, by splitting a thick plate into two thinner ones and separating them in free space, the transmission cross section can be significantly reduced (by 16 dB in Fig. 5). This mechanism can be utilized to design shielding cabinet for electronic equipments. For example, the ventilation slits on an equipment chassis can be designed by stacking two plates with the slit on one plate laterally shifted with respect to the slit on the other plate. The finite-element method or other commercial field simulators may be useful if the effects of surrounding parts or structures on the field near the slit need to be considered.

IV. Conclusions

A Galerkin's method has been developed to analyze the scattering and transmission properties of slits on single and stacked thick plates. The limiting cases of zero-thickness plates are also formulated. The effects of slit width and depth have been analyzed. It is also observed that using two thin plates with proper separation is better than a thick plate to shield incident waves.

Acknowledgment

The author would like to thank the reviewers for their useful comments in revising this paper.

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Jean-Fu Kiang (S'87–M'87) was born in Taipei, Taiwan, R.O.C., on February 2, 1957. He received the B.S.E.E. and M.S.E.E. degrees from National Taiwan University, Taipei, Taiwan, R.O.C., in 1979 and 1981, respectively, and the Ph.D. degree from the Massachusetts Institute of Technology (MIT), Cambridge, in 1989.

He professional experience includes having been with IBM Watson Research Center, Bellcore, and Siemens. He is currently with the Department of Electrical Engineering, National Chung-Hsing University, Taichung, Taiwan, R.O.C.