Short Papers

Wave Penetration Through Bent Slots

Jean-Fu Kiang and Shau-Hua Chen

***Abstract*—Shielding effectiveness of bent slots carved in a metal plate of finite thickness is analyzed by forming a set of integral equations based on the equivalence principle. Method of moments is used to solve the integral equations for the transmission cross sections. The effects of slot geometry, filling permittivity, and filling conductivity are studied. It is found that the penetrating field is mainly determined by the slot length, filling permittivity, and filling conductivity. Resonances are also observed when the slot length is integer multiples of half wavelengths.**

***Index Terms*—Bent slot, integral equation, method of moments, wave penetration.**

I. Introduction

Scattering and transmission properties of apertures can be studied in different ways. In [1], holes with simple shapes in a plate of zero thickness are analyzed by using equivalent electric and magnetic dipoles. Wave penetration through holes in thick plates has been studied by using static approaches where equivalent electric polarizability and magnetic susceptibility are derived [2], [3], or by using dynamic approaches where equivalent magnetic surface currents are assumed on the aperture [4]–[6].

Slots are generally cut in the equipment case for ventilation. Interferences between the internal circuitries and the external equipments may occur through the slots. Detailed field distributions in and around the slots need to be considered to obtain accurate results. For plate of zero thickness, FDTD [7], method of moments [8], and Gaussian beam expansion [9] have been used to solve for the equivalent magnetic surface current across the slots. For slots in thick plates, FDTD method [10], method of moments [5], [11], finite-element method [12], and mode-matching technique [4] have been used to study their scattering and transmission properties. Finite-element method has also been used to study the scattering problem of a cavity-backed aperture [13].

In [14], field penetration through a corrugated slot is studied by using equivalent magnetic surface currents at junctions between subsections. In [15], the slot in a thick plate is modeled as an equivalent dipole. In [16], penetration of wave through an aperture loaded with various kinds of conductive material is studied. In [5], the shielding effectiveness of single and double plates with narrow slots against an incident TM plane wave has been studied. It is found that the shielding effectiveness can be improved by laterally shifting the slot in one plate relative to that in the other plate.

In [17], the scattering properties of a bent slot is studied by using the equivalence principle and finite element method. Long slots are expected to reduce the penetration power, and reflection from junctions of concatenated segments may further reduce the penetration. In this paper, we will analyze a bent slot carved into a plate of finite thickness, the contour of the slot is bent four times to increase its length.

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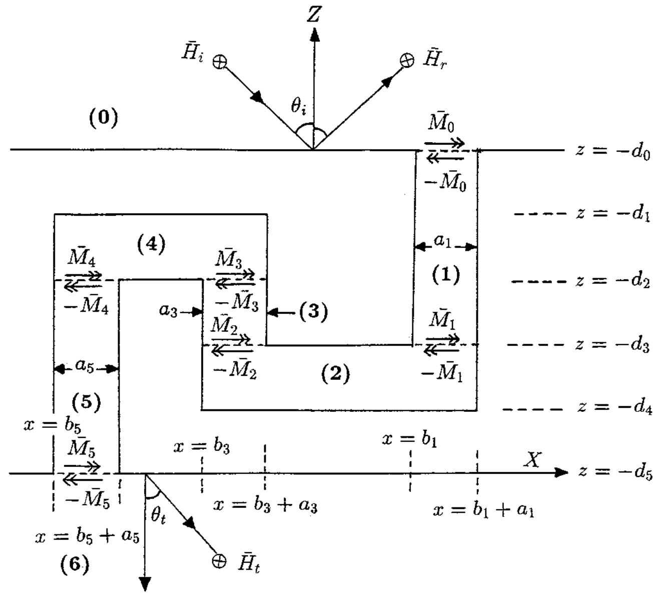

Fig. 1. Configuration of a bent slot exposed to an incident TM plane wave.

In the next section, a set of integral equations will be derived for a TM plane wave incident upon a bent slot. The formulation for the TE incident plane wave is briefly described. Results of transmission cross sections will then be presented, followed by the conclusions.

II. Formulation

Consider a TM plane wave incident upon a bent slot as shown in Fig. 1, the magnetic field in each region can be expressed as

$$
\begin{aligned}
H_{0y} &= H_{iy} + H_{ry} + \int_{-\infty}^{\infty} dk_x e^{ik_x x + ik_{0z} z_0} \tilde{h}_0(k_x) \\
H_{1y} &= \sum_{n=0}^{\infty} \cos\alpha_{1n}(x-b_1) \\
&\quad \cdot \left[h_n^{(1a)} \cos\gamma_{1n} z_1 + h_n^{(1b)} \cos\gamma_{1n}(z_1 - h_1) \right] \\
H_{2y} &= \sum_{n=0}^{\infty} \cos\alpha_{2n}(x-b_3) \left[h_n^{(2)} \cos\gamma_{2n} z_2 \right] \\
H_{3y} &= \sum_{n=0}^{\infty} \cos\alpha_{3n}(x-b_3) \\
&\quad \cdot \left[h_n^{(3a)} \cos\gamma_{3n} z_3 + h_n^{(3b)} \cos\gamma_{3n}(z_3 - h_3) \right] \\
H_{4y} &= \sum_{n=0}^{\infty} \cos\alpha_{4n}(x-b_5) \left[h_n^{(4)} \cos\gamma_{4n}(z_4 - h_4) \right] \\
H_{5y} &= \sum_{n=0}^{\infty} \cos\alpha_{5n}(x-b_5) \\
&\quad \cdot \left[h_n^{(5a)} \cos\gamma_{5n} z_5 + h_n^{(5b)} \cos\gamma_{5n}(z_5 - h_5) \right] \\
H_{6y} &= \int_{-\infty}^{\infty} dk_x e^{ik_x x - ik_{6z} z_6} \tilde{h}_6(k_x)
\end{aligned} \tag{1}
$$

where

$$\begin{aligned} z_0 &= z + d_0 \\ z_1 &= z_3 = z + d_3 \\ z_2 &= z + d_4 \\ z_4 &= z + d_2 \\ z_5 &= z_6 = z + d_5 \\ \alpha_{\ell n} &= n\pi/a_\ell, 1 \le \ell \le 5 \end{aligned}$$

and a_2 and a_4 are the width of regions (2) and (4), respectively, defined as

$$a_2 = b_1 + a_1 - b_3 \quad a_4 = b_3 + a_3 - b_5$$

and

$$\begin{aligned} k_x^2 + k_{\ell z}^2 &= k_\ell^2, \qquad \ell = 0, 6 \\ \alpha_{\ell n}^2 + \gamma_{\ell n} &= k_\ell^2, \qquad 1 \le \ell \le 5 \end{aligned}$$

and h_ℓ is the height of region (ℓ) with

$$\begin{aligned} h_1 &= d_3 - d_0 \\ h_2 &= d_4 - d_3 \\ h_3 &= d_3 - d_2 \\ h_4 &= d_2 - d_1 \\ h_5 &= d_5 - d_2 \end{aligned}$$

and H_{iy} is the incident magnetic field, and H_{ry} is the reflected magnetic field when the slot is absent. The explicit forms of $\overline{H}_i$ and $\overline{H}_r$ are $\overline{H}_i = \hat{y} H_o e^{ik_0(x\sin\theta_i - z_0\cos\theta_i)}$ and $\overline{H}_r = \hat{y} H_o e^{ik_0(x\sin\theta_i + z_0\cos\theta_i)}$, respectively.

By applying the Ampère's law, the electric fields in each region are derived. By applying the equivalence principle at the interfaces between any two adjacent regions, equivalent magnetic surface currents are defined in terms of the electric fields. By using the orthogonality properties of the wave modes in each region, the field coefficients are expressed in terms of the magnetic surface currents. Substituting these relations into (1), the magnetic fields are expressed in terms of the magnetic surface currents as

$$H_{0y} = H_{iy} + H_{ry} + \int_{-\infty}^{\infty} dk_x e^{ik_x x + ik_{0z} z_0} \left(\frac{\omega\epsilon_0}{k_{0z}}\right) \tilde{M}_{0y}(k_x)$$

$$H_{1y} = \sum_{n=0}^{\infty} \cos\alpha_{1n}(x - b_1) \left(\frac{i\omega\epsilon_1}{\gamma_{1n}}\right) \cdot \left[-M_{0n} \frac{\cos\gamma_{1n} z_1}{\sin\gamma_{1n} h_1} + M_{1n} \frac{\cos\gamma_{1n}(z_1 - h_1)}{\sin\gamma_{1n} h_1}\right]$$

$$H_{2y} = \sum_{n=0}^{\infty} \cos\alpha_{2n}(x - b_3) \left(\frac{i\omega\epsilon_2}{\gamma_{2n}}\right) \cdot \left[-(\tilde{M}_{1n} + \tilde{M}_{2n}) \frac{\cos\gamma_{2n} z_2}{\sin\gamma_{2n} h_2}\right]$$

$$H_{3y} = \sum_{n=0}^{\infty} \cos\alpha_{3n}(x - b_3) \left(\frac{i\omega\epsilon_3}{\gamma_{3n}}\right) \cdot \left[-M_{3n} \frac{\cos\gamma_{3n} z_3}{\sin\gamma_{3n} h_3} + M_{2n} \frac{\cos\gamma_{3n}(z_3 - h_3)}{\sin\gamma_{3n} h_3}\right]$$

$$H_{4y} = \sum_{n=0}^{\infty} \cos\alpha_{4n}(x - b_5) \left(\frac{i\omega\epsilon_4}{\gamma_{4n}}\right) \cdot \left[(\tilde{M}_{3n} + \tilde{M}_{4n}) \frac{\cos\gamma_{4n}(z_4 - h_4)}{\sin\gamma_{4n} h_4}\right]$$

$$H_{5y} = \sum_{n=0}^{\infty} \cos\alpha_{5n}(x - b_5) \left(\frac{i\omega\epsilon_5}{\gamma_{5n}}\right) \cdot \left[-M_{4n} \frac{\cos\gamma_{5n} z_5}{\sin\gamma_{5n} h_5} + M_{5n} \frac{\cos\gamma_{5n}(z_5 - h_5)}{\sin\gamma_{5n} h_5}\right]$$

$$H_{6y} = -\int_{-\infty}^{\infty} dk_x e^{ik_x x - ik_{6z} z_6} \left(\frac{\omega\epsilon_6}{k_{6z}}\right) \tilde{M}_{5y}(k_x). \tag{2}$$

Next, impose the following boundary conditions that the tangential magnetic fields are continuous across the interfaces between any two adjacent regions

$$\begin{aligned} H_{0y}(z_0 = 0) &= H_{1y}(z_1 = h_1) \quad \text{on} \quad S_0 \\ H_{1y}(z_1 = 0) &= H_{2y}(z_2 = h_2) \quad \text{on} \quad S_1 \\ H_{2y}(z_2 = h_2) &= H_{3y}(z_3 = 0) \quad \text{on} \quad S_2 \\ H_{3y}(z_3 = h_3) &= H_{4y}(z_4 = 0) \quad \text{on} \quad S_3 \\ H_{4y}(z_4 = 0) &= H_{5y}(z_5 = h_5) \quad \text{on} \quad S_4 \\ H_{5y}(z_5 = 0) &= H_{6y}(z_6 = 0) \quad \text{on} \quad S_5 \end{aligned}$$

where S_i is the interface at the junction between regions (i) and $(i+1)$. Thus, we obtain six coupled integral equations.

To solve these integral equations by using method of moments, first choose six sets of basis functions to expand the magnetic surface currents. Substitute these basis expansions into the coupled integral equations, then choose the same sets of basis functions as weighting functions. Take the inner product of these weighting functions with the six integral equations to obtain a matrix equation.

For a TE plane wave incident upon the same bent structure shown in Fig. 1, first express the y-component of the electric fields as a series in each slot segment, and as an integral in the open regions (0) and (6). By applying the equivalence principle across all the interfaces, the field coefficients are expressed in terms of the equivalent magnetic surface currents lying at the interfaces between adjacent slot segments and the two air-slot interfaces. Six coupled integral equations are obtained by imposing the continuity condition of tangential magnetic fields across all the interfaces. Finally, method of moments is applied to solve these coupled integral equations for the magnetic surface currents from which the transmitted fields can be derived.

III. Results and Discussions

First, we present the results with an incident TM plane wave. To check the accuracy of this approach, first consider a plane wave incident upon a straight slot. Fig. 2 shows the transmission cross section of a straight slot. The results obtained by using this approach match reasonably well with those in [5]. It takes only a few seconds to obtain one curve by using a Pentium 100 personal computer.

To study the shielding effectiveness of the bent slot, a transmission cross section is defined as

$$\sigma_t(\theta_t, \theta_i) = 10\log_{10}\left[2\pi\rho\frac{|H_{6y}(\overline{\rho})|^2}{|H_o|^2}\right] \text{ dB} \tag{3}$$

where θ_i and θ_t are the incidence and the transmission angle, respectively. If not mentioned otherwise, both θ_i and θ_t are set to zero in all the results to be presented.

Fig. 3 shows the transmission cross section of a bent slot $0.003\lambda_o$ wide. Two geometrical parameters are defined: the vertical offset $b = d_3 - d_2$ and the horizontal offset $c = b_1 - (b_3 + a_3) = b_3 - (b_5 + a_5)$. For this case, the plate thickness is $0.03\lambda_o$, the horizontal offset c is set to $0.003\lambda_o$ and $0.006\lambda_o$, respectively. The transmission cross section of a straight slot having the same length as the bent slot is also calculated. The transmission cross section through a straight slot $0.03\lambda_o$

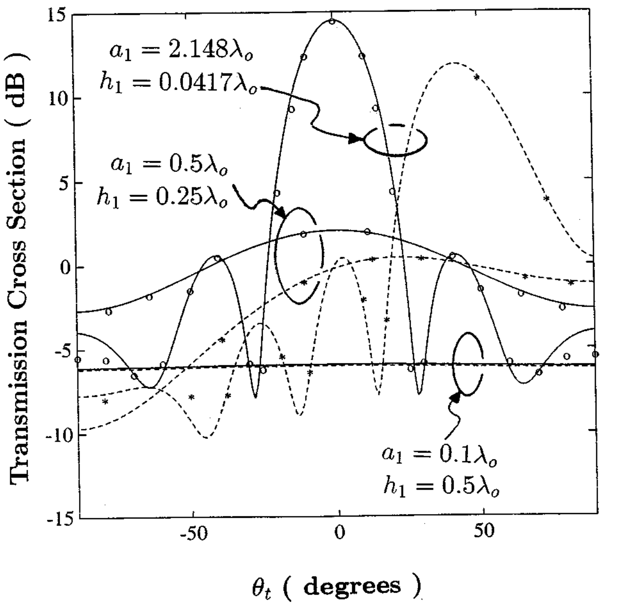

Fig. 2. Transmission cross section of a straight slot in a thick plate, —: $\theta_i = 0°$, - - -: $\theta_i = 45°$, o : results in [5] ($\theta_i = 0°$), * : results in [5] ($\theta_i = 45°$).

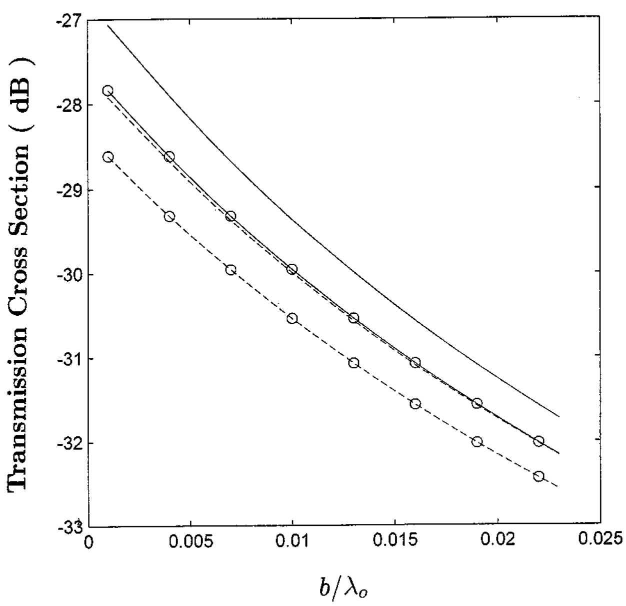

Fig. 3. Transmission cross section of a bent slot in a plate $0.03\lambda_o$ thick, slot width is $0.003\lambda_o$, $\theta_i = 0$, $\epsilon_i = \epsilon_o$ with $0 \leq i \leq 6$, —: bent slot with $c = 0.003\lambda_o$, —o—: straight slot with the same length as the bent slot ($c = 0.003\lambda_o$), - - -: bent slot with $c = 0.006\lambda_o$, - -o- -: straight slot with the same length as the bent slot ($c = 0.006\lambda_o$).

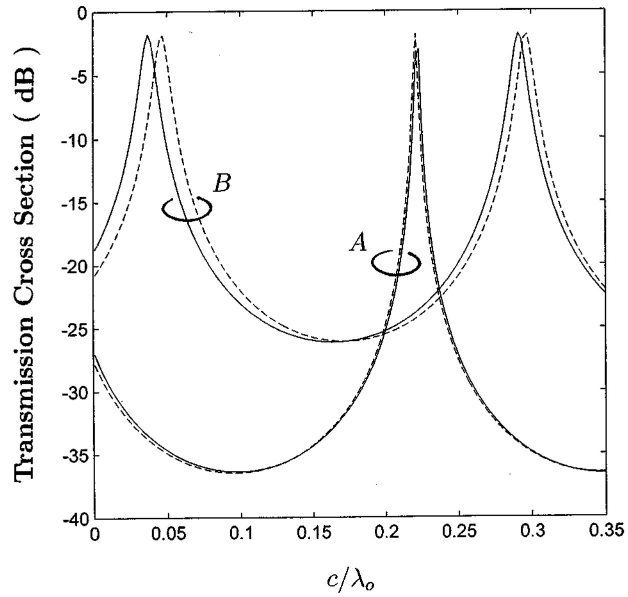

Fig. 4. Transmission cross section of a bent slot in a plate, $\theta_i = 0$, $\epsilon_i = \epsilon_o$ with $0 \leq i \leq 6$, —: bent slot, - - -: straight slot with the same length and width as the bent slot. A: plate thickness is $0.03\lambda_o$, slot width is $0.003\lambda_o$, $b = 0.003\lambda_o$, B: plate thickness is $0.3\lambda_o$, slot width is $0.01\lambda_o$, $b = 0.03\lambda_o$.

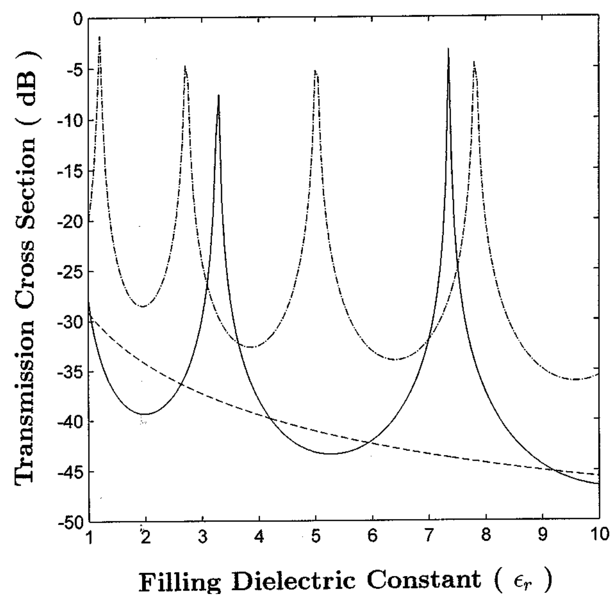

Fig. 5. Effect of filling permittivity on the transmission cross section of a bent slot in a plate, $\theta_i = 0$, $\epsilon_i = \epsilon_r\epsilon_o$ with $1 \leq i \leq 5$, $\epsilon_i = \epsilon_o$ with $i = 0$ and 6, —: plate thickness is $0.03\lambda_o$, slot width is $0.003\lambda_o$, $b = 0.006\lambda_o$, $c = 0.25\lambda_o$, - - -: plate thickness is $0.03\lambda_o$, slot width is $0.003\lambda_o$, $b = 0.006\lambda_o$, $c = 0.006\lambda_o$, -·-·-: plate thickness is $0.3\lambda_o$, slot width is $0.01\lambda_o$, $b = 0.03\lambda_o$, $c = 0.25\lambda_o$.

long is about -24.4 dB. The total length of the bent slot increases when either b or c is increased. The transmission cross section decreases with increasing slot length. For the narrow slots considered, only the dominant TM_0 mode can propagate through them without being cutoff, all the other higher order modes become evanescent.

Fig. 4 shows the effect of varying the horizontal offset c on the transmission cross section. Consider a narrow slot of width $0.003\lambda_o$ in a plate $0.03\lambda_o$ thick and a wide slot of width $0.01\lambda_o$ in a plate $0.3\lambda_o$ thick. In either case, a straight slot of the same width and length as the bent one is used for comparison. For the narrow slot, the results for both the bent and the straight slots are almost the same. This implies that the transmission cross section is mainly determined by the reflections at the two interfaces between slot and air, and the internal junctions do not have significant contributions. The electric-field distribution of the TM_0 mode in a narrow slot mimics that of the electrostatic field between two parallel plates. At the internal junctions, the charges on the two opposite plates redistribute themselves when the straight slot is bent. That can explain why little reflection is incurred. For a wider slot, the electrostatic approximation is less accurate to explain the deviation between the results of the bent slot and the straight one.

Fig. 4 also shows resonance around specific c. For the narrow slots, resonance appears when the slot length is approximately $0.49\lambda_o$ which is calculated along the middle line between the two side walls. For the

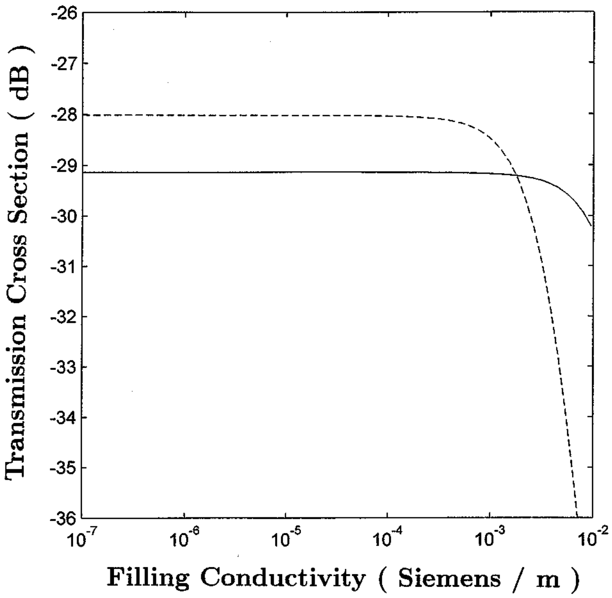

Fig. 6. Effect of filling conductivity on the transmission cross section of a bent slot in a plate $0.03\lambda_o$ thick, slot width is $0.003\lambda_o$, $b = 0.006\lambda_o$, $\theta_i = 0°$, $\epsilon_i = \epsilon_o$ and $\sigma_i = \sigma$ with $1 \leq i \leq 5$, $\epsilon_i = \epsilon_o$ and $\sigma_i = 0$ with $i = 0$ and 6, —: $c = 0.006\lambda_o$, - - -: $c = 0.25\lambda_o$.

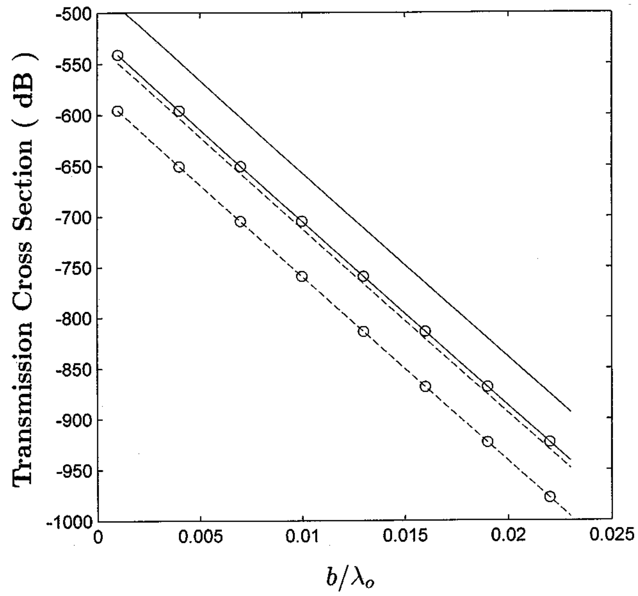

Fig. 7. Transmission cross section of a bent slot in a plate $0.03\lambda_o$ thick, slot width is $0.003\lambda_o$, $\theta_i = 0$, $\epsilon_i = \epsilon_o$ with $0 \leq i \leq 6$, —: bent slot with $c = 0.003\lambda_o$, —o—: straight slot with the same length as the bent slot ($c = 0.003\lambda_o$), - - -: bent slot with $c = 0.006\lambda_o$, - -o- -: straight slot with the same length as the bent slot ($c = 0.006\lambda_o$).

wide bent slot, resonance occurs when the slot lengths are $0.454\lambda_o$ and $0.962\lambda_o$, respectively. For the wide straight slot, resonance occurs when the slot lengths are $0.474\lambda_o$ and $0.974\lambda_o$, respectively. All the resonances occur when the slot length is approximately integer multiplies of half wavelengths.

Fig. 5 shows the effect of filling permittivity inside the slot on the transmission cross section. For the bent slot which is much shorter than $0.5\lambda_m$ (λ_m is the wavelength in the filling material), the transmission cross section decreases with the filling permittivity mainly due to the reflection at the two air-dielectric interfaces. When the slot length is longer than $0.5\lambda_m$, resonances are observed when the slot length is integer multiplies of $0.5\lambda_m$. For the bent slot with $w = 0.003\lambda_o$ and $c = 0.25\lambda_o$, two peaks occur when the slot lengths are $1\lambda_m$ and $1.5\lambda_m$, respectively. For the bent slot with $w = 0.01\lambda_o$ and $c = 0.25\lambda_o$, four peaks occur when the slot lengths are $1\lambda_m$, $1.5\lambda_m$, $2\lambda_m$, and $2.5\lambda_m$, respectively. Notice that for the wide slot ($w = 0.01\lambda_o$), the minimal transmission cross sections between peaks are larger than those of the narrow slot ($w = 0.003\lambda_o$) because the air-dielectric reflection is smaller for the wide slot than for the narrow one.

Fig. 6 shows the effect of filling conductivity inside the slot. It is found that the filling material with higher conductivity always yields a better shielding effectiveness. When the filling conductivity is lower than 10^{-3} Siemens/m, the transmission cross section is basically determined by the slot length as discussed in Fig. 4. When the conductivity is higher than 10^{-3} Siemens/m, the attenuation inside the slot and the reflection at the air-slot interfaces determine the transmission cross section. With the same filling conductivity, the longer slot incurs smaller transmission cross section than the shorter one, which implies that the attenuation is dominant over the reflection at the air-slot interfaces.

Next, we present the results with an incident TE plane wave. Comparison with literature has been conducted to ensure the accuracy of this approach. Fig. 7 shows the transmission cross section of a bent slot $0.003\lambda_o$ wide. The plate thickness is $0.03\lambda_o$, the horizontal offset, c, is $0.003\lambda_o$ and $0.006\lambda_o$, respectively. When either b or c is increased, the slot length increases. The transmission cross sections of a straight slot with the same length as the bent slot are also shown for comparison. The slot with longer horizontal segments attenuates the transmitted power

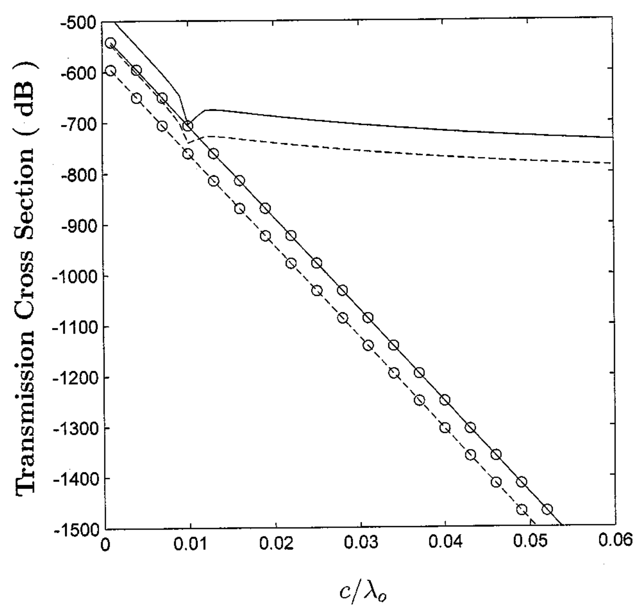

Fig. 8. Transmission cross section of a bent slot in a plate $0.03\lambda_o$ thick, slot width is $0.003\lambda_o$, $\theta_i = 0$, $\epsilon_i = \epsilon_o$ with $0 \leq i \leq 6$, —: bent slot with $b = 0.003\lambda_o$, —o—: straight slot with the same length as the bent slot ($b = 0.003\lambda_o$), - - -: bent slot with $b = 0.006\lambda_o$, - -o- -: straight slot with the same length as the bent slot ($b = 0.006\lambda_o$).

more seriously. The transmission cross section through a bent slot is larger than that through a straight slot of the same length. In either case, the transmission cross section is vanishingly small since all the TE modes are below cutoff. For reference, the transmission cross section through a straight slot in a plate $0.03\lambda_o$ thick is $-$ 359.185 dB.

It is observed that although the straight slot of the same length as the bent slot incurs larger attenuation than the bent slot, the plate of the former is thicker than that of the later. The attenuation through both structures is much larger than that through a straight slot in a plate $0.03\lambda_o$ thick.

Fig. 8 shows the effect of varying the horizontal offset c on the transmission cross section. In general, the transmission cross section decreases with c. The dip near $c = 0.01\lambda_o$ is the result of multiple reflections at junctions of slot segments. As the length of the horizontal segments is increased over $0.01\lambda_o$, the transmitted power does not decrease as for the straight slot. As the transmitted power is coupled from the vertical segments to the horizontal ones, the attenuation constant in the z-direction decreases for longer horizontal segments. That is why the transmission cross section does not decrease further with increasing c.

We also study the effect of varying the dielectric constant and conductivity of the filling inside the slot. It is observed that the transmission cross section is almost a constant. Since all the TE modes are below cutoff, the reflection due to material discontinuity becomes a minor factor than the attenuation due to evanescence.

IV. Conclusions

The shielding effectiveness of a bent slot against an incident plane wave of either TM or TE polarization is analyzed by calculating the transmission cross section. The effects of slot geometry, filling permittivity, and filling conductivity are studied. For an incident TM plane wave, the shielding effectiveness of the slotted plate are mainly determined by the slot length. Resonances are obvious when the slot length is integer multiplies of half-wavelengths. A thin plate with a bent slot provides the same shielding effectiveness as a thick plate with a straight slot. Filling permittivity and filling conductivity can be used to provide further shielding effects.

For an incident TE plane wave, the shielding effectiveness of the slotted plate is mainly due to the evanescence of all the TE modes inside the slot. The transmission cross sections are vanishingly small for practical applications, slot geometry and filling materials provide only secondary effects.

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A New Efficient Method of Analysis for Inhomogeneous Media Shields and Filters

Alessandro Toscano, Lucio Vegni, and Filiberto Bilotti

***Abstract*—In this paper, we discuss the shielding characteristics of an inhomogeneous shield for oblique incidence. The inhomogeneity here considered can be modeled via a continuous spatial variation of the permittivity along the power-flow direction and can be taken into account in the mathematical model involving the transmission line equivalent-circuit representation in terms of a longitudinal-line impedance and a transverse-line admittance varying along the same direction. In order to design a filter or a matching line layout with such a material, new analytical expressions of the reflection coefficient and of the shielding factor for nonuniform dielectric slabs are found. Some numerical examples are also presented for both the TE and TM polarization cases.**

***Index Terms*—Distributed parameter circuits, filters, shielding.**

I. Introduction

Electromagnetic shields are introduced in order to prevent, or, at least, to minimize the unwanted coupling effects of radiated waves on circuits and systems. Shields may be realized in different ways. Usually they are composed of conductor materials with high intrinsic resistive attenuation. However, this kind of shields does not represent the ideal solution for all the possible problems. In fact, for example, it is difficult to obtain through these structures, high values of shielding effectiveness dealing with low frequency radiated magnetic fields, or it is impossible with this kind of shields to perform a frequency-selective shielding. In order to try to optimize the shielding properties of multilayered structures, new electromagnetic materials have been introduced, and in particular, nonhomogeneous dielectric materials offer

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