

Penetration electric field characteristics of dual plates with narrow slots for the incident plane wave

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Abstract: This study examined the properties of the electric field penetration of a dual metallic wall with narrow slots when the plane wave is incident. Integral equations for aperture electric fields on slots were derived and solved by applying Galerkin's method of moments (MoM). The numerical results showed that a high level of electric field penetration, which is known as transmission resonance, can be obtained for a small plate spacing and two slots with the resonant length when both slots have a slight offset in the slot width direction. The maximum transmission resonance occurred at a transverse slot offset of 0.07λ for a given plate spacing. In addition, the penetration electric field fluctuates with the spacing of the plate, and the fluctuation period is approximately 0.5λ . The experimental measurements are also presented to validate the theory.

Keywords: dual plate, electric field penetration, narrow slot, incident plane wave

Classification: Electromagnetic theory

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1 Introduction

The mechanism for the penetration of electric fields into electrical and electronic enclosures through slots has attracted considerable interest. The coupling of electromagnetic fields between the isolated regions through the apertures is widely encountered, and the transmission of an electromagnetic field through a slot aperture in a conducting plate is a canonical problem that has attracted the attention of many researchers [1, 2, 3, 4, 5, 6, 7]. These studies have generally considered 2D problems. Recently, studies have focused on the reduction of electromagnetic penetration through narrow slots in a conducting screen [8, 9, 10] and a study of the electric shielding effectiveness was considered for a dual plate with narrow slots as the 3D problem [11]. In [11], for certain plate spacings, the narrow slot becomes resonant, and gives an electric shielding effectiveness of less than 0 dB. High transmission resonance occurs near the slot. Therefore, it is essential to analyze in detail the behavior of electric field penetration near the slot for power transmission applications, near-field imaging for microscopy, and electromagnetic compatibility (EMC) problems.

This paper focuses on the problem of a penetration electric field between two half-space regions separated by two narrow slots and parallel conducting planes as a 3D problem. The method of moments (MoM) using the Galerkin's procedure was used to determine the electric field penetration through the narrow slots. The procedure is the same as that used elsewhere [11].

The numerical results showed that a high level of electric field penetration, which is known as the transmission resonance, can be obtained for a small plate spacing and the resonant length of two slots when both slots have a slight offset in the y -direction (direction of the slot width). Leviatan [4] reported maximum transmission resonances become at transverse shift that approach multiples of 0.5λ . The present study focused on 3D problems, the maximum transmission resonance occurs at a transverse slot offset of 0.07λ for a given plate spacing. Note that this phenomenon was newly observed in the present study. At the present time, the mechanism for this phenomenon is unclear.

To check the validity of the numerical calculations, the calculated electric field penetration of the dual metallic wall with narrow slots were compared with the experimental results.

2 Formulation of the problem

Fig. 1 shows the geometry and coordinate system of a dual conducting wall with narrow slots and an infinite conducting plane. Conducting ground plane #1 was located in the xy -plane with the origin at the center of the slot aperture, and another ground plane #2 was placed in the xy -plane apart from $z = d$. The narrow slot #1 of length a_1 and width b_1 is in the infinite conducting ground plane #1 at $z = 0$ and is placed near another slot #2 of length a_2 and width b_2 in the infinite conducting ground plane #2, which is placed by offsets x_0 and y_0 from the x - and y -axes. Here, z_p is the field point along the z -axis in region III, which is located from the ground plane #2. The conducting ground planes are a perfect electric conductor with zero thickness.

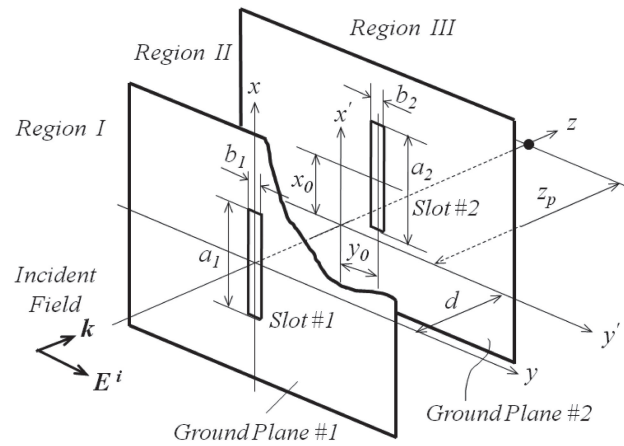


Fig. 1. Geometry of the narrow slots in a dual metallic wall excited by an incident plane wave.

As shown in Fig. 1, the dual conducting wall structure is divided into three regions: a half-space containing the incident plane wave (Region I ($z < 0$)), an interior region of two conducting ground planes (Region II ($0 < z < d$)), and a half-space containing the penetrating field (Region III ($z > 0$)). These three regions are assumed to be free-space.

If the plane wave is incident the narrow slot in the metallic ground plane #1, then the simultaneous integral equations for the unknown magnetic currents \bar{M}_1^\pm and \bar{M}_2^\pm on slot apertures can be expressed as:

$$(\bar{H}^i + \bar{H}^r) + \bar{H}_t^I(\bar{M}_1^-) = \bar{H}_t^{II}(\bar{M}_1^+) + \bar{H}_t^I(\bar{M}_2^-) \quad (1a)$$

$$\bar{H}_t^{II}(\bar{M}_1^+) + \bar{H}_t^{II}(\bar{M}_2^-) = \bar{H}_t^{III}(\bar{M}_2^+) \quad (1b)$$

where \bar{H}^i and \bar{H}^r are the incident and reflected magnetic fields given by the following:

$$\bar{H}^i = -\hat{x} \frac{1}{Z_0} E_{0y}^i e^{-jkz} \quad (2)$$

$$\bar{H}^r = -\hat{x} \frac{1}{Z_0} E_{0y}^i e^{jkz} \quad (3)$$

where E_{0y}^i is the amplitude of the incident electric field, and Z_0 is the wave impedance in free space, $\bar{M}_1^\pm = \mp \hat{z} \times \bar{E}_{a1}(\vec{r}')$ and $\bar{M}_2^\pm = \mp \hat{z} \times \bar{E}_{a2}(\vec{r}')$, and \bar{E}_{a1} and

\bar{E}_{a2} represent the aperture electric fields at the slot apertures. In addition, \hat{x} and \hat{z} are the unit vectors in the x - and z -directions, $k = \omega\sqrt{\epsilon_0\mu_0}$, and ω represents the angular frequency.

For a solution of simultaneous integral equations for the unknown, aperture electric fields are expanded as follows:

$$\bar{E}_{a1}(x) = \hat{y} \sum_{n=1}^N V_{1n} F_n(x) \quad (4a)$$

$$\bar{E}_{a2}(x) = \hat{y} \sum_{m=1}^M V_{2m} F_m(x) \quad (4b)$$

where V_{1n} and V_{2m} are the coefficients to be determined, and F_n and F_m are piecewise sinusoidal expansion functions. Equations (1) and (2) are transformed into the matrix forms by substituting the assumed aperture electric fields into the integral equations (1) and (2) and employing Galerkin's MoM.

When a plane wave is excited toward a narrow slot aperture in the metallic ground plane #1, the electric field penetration in regions III is obtained in the following form:

$$\bar{E} = - \iint_{S_{a2}} \nabla \times \bar{G}_{m22}^{III}(\bar{r}, \bar{r}') \cdot \{-\hat{z} \times \bar{E}_{a2}(\bar{r}')\} dS'_{a2} \quad (5)$$

where \bar{G}_{m22}^{III} is the dyadic Green function of region III, and once the aperture electric fields are known, the field penetration can be determined.

3 Numerical results and discussion

The fields in region II were not considered in this paper because the field characteristics for region III focuses mainly on power transmission applications and EMC problems. The slot used in the numerical calculation is narrow compared to the wavelength. In the following numerical calculations, the width of the narrow slots is $b_1 = b_2 = 1$ mm.

Fig. 2 presents the electric field penetration characteristics at $x_0 = y_0 = 0$ and $z_P = 5$ cm ($= 0.167\lambda$ at 1 GHz) in region III as a function of the plate spacing d for various values of slot lengths, a_2 , when the plane wave is incident to the narrow slot. As shown in Fig. 2, for plate spacings below 0.1λ and 0.015λ , high electric field penetration was obtained at the slot #2 length of $a_2 = 0.5\lambda$ and $a_2 = 0.6\lambda$ for $a_1 = 0.5\lambda$ (slot length of the slot #1), respectively. This is because the narrow slot becomes resonant (i.e., exceptionally large transmission of energy can occur) for the plate spacings below 0.1λ and 0.015λ for $a_2 = 0.5\lambda$ and $a_2 = 0.6\lambda$, respectively. This phenomenon is not surprising because it has already been observed in similar situations [4, 5]. In the field of near-field imaging for microscopy, this phenomenon known as “transmission resonance” [12, 13]. The electric field penetration is highest if the length is 0.5λ for both slots, and the other cases are less than the case of 0.5λ . The electric field penetration fluctuates with the plate spacing, and the fluctuation period is approximately 0.5λ . These periodic electric field penetration patterns decrease gradually in magnitude with increasing spacing between ground planes #1 and #2.

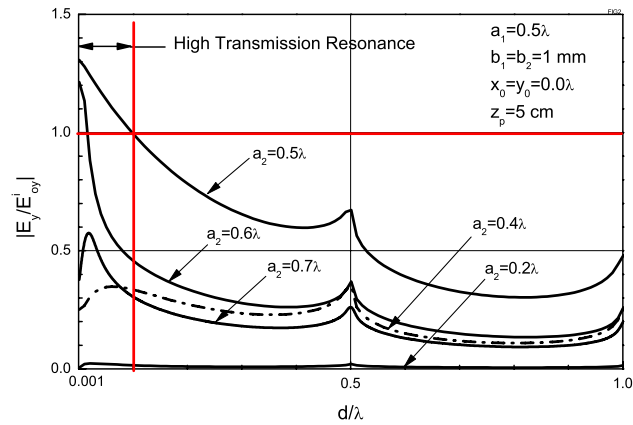


Fig. 2. Electric field penetration vs. plate spacing as a parameter of various slot lengths.

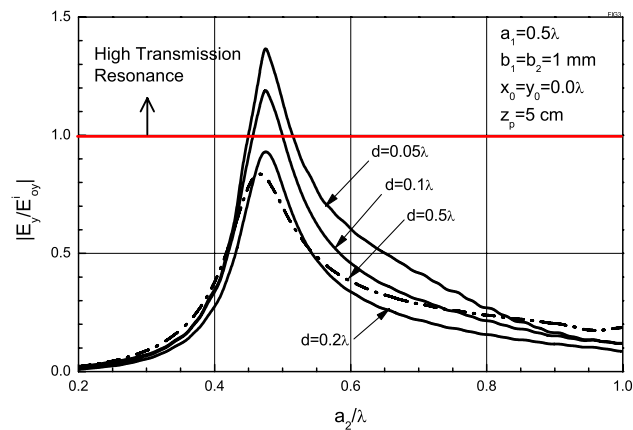


Fig. 3. Electric field penetration vs. slot length as a parameter of various plate spacings.

Fig. 3 shows the electric field penetration characteristics at $x_0 = y_0 = 0$ and $z_P = 5 \text{ cm}$ ($= 0.167\lambda$ at 1 GHz) in region III as a function of the slot #2 length a_2 for various plate spacings d when the plane wave is incident to the narrow slot. As shown in Fig. 3, for slot lengths between $a_2 = 0.45\lambda$ (0.46λ) and $a_2 = 0.51\lambda$ (0.5λ), the large transmission of energy can occur at the plate spacing $d = 0.05\lambda$ (0.1λ) for $a_1 = 0.5\lambda$. This is because the narrow slot becomes resonant for slot #2 lengths between 0.45λ and 0.51λ at small plate spacings below $d = 0.1\lambda$. The highest transmission resonance occurs at $a_2 = 0.475\lambda$ for $a_1 = 0.5\lambda$ when both slots have the same axis (i.e., $x_0 = y_0 = 0$). A high level of electric field penetration known as transmission resonance can be obtained at small plate spacings and the resonant length of two slots for a given frequency.

Fig. 4 presents the electric field penetration for the plate spacing as a parameter of various values of slot offsets. Fig. 4(a) compares the electric field penetration with a plate spacing for various x -direction slot offsets x_0 (direction of the slot length), and Fig. 4(b) compares them for various y -direction slot offsets, y_0 (direction of the slot width). As shown in Fig. 4(a), high transmission resonance occurs when both slots have the same axis (i.e., $x_0 = y_0 = 0$) at plate spacings below $d = 0.1\lambda$, the electric field penetration is highest, and the other cases are

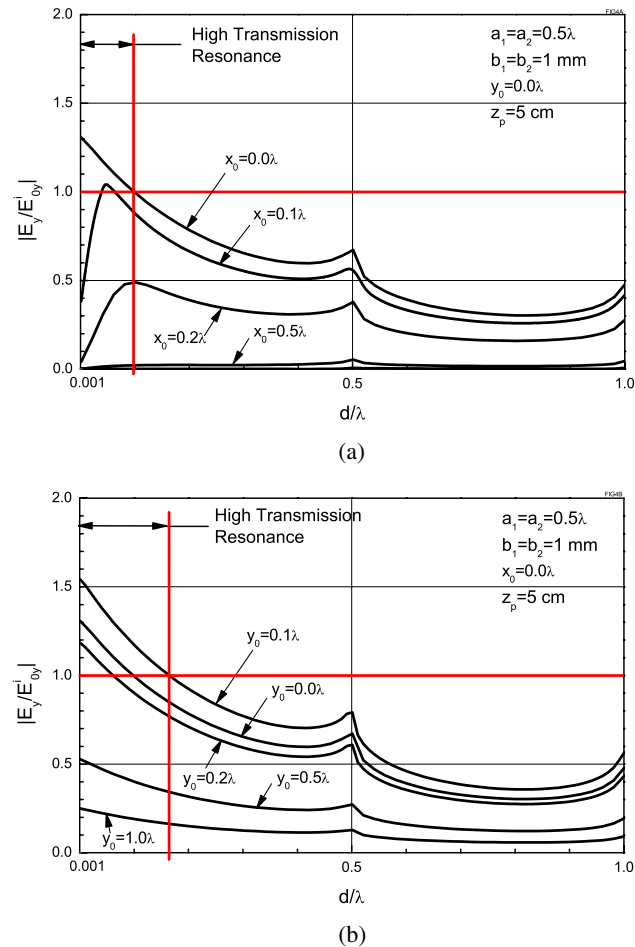


Fig. 4. Electric field penetration as a function of the plate spacing for various slot offsets: (a) as a parameter of x_0 and (b) as a parameter of y_0 .

lower than the case of $x_0 = y_0 = 0$. For $x_0 = 0.1\lambda$, transmission resonance occurs at plate spacings between 0.041λ and 0.061λ . As shown in Fig. 4(b), the high transmission resonance occurs for a small y -direction slot offset, $y_0 = 0.1\lambda$ at a plate spacing of $d = 0.161\lambda$. In the y -direction slot offset, a high level of the electric field penetration can be obtained when both slots have a slightly offset axis (e.g., $x_0 = 0$ and $y_0 = 0.1\lambda$ at $d = 0.161\lambda$).

Fig. 4 shows that the electric field penetration fluctuates with the plate spacing (as mentioned in Fig. 2), and the fluctuation period is approximately 0.5λ . Note that the narrow slot becomes resonant for certain small plate spacings, and exceptionally large transmission of energy can occur. From an EMC point of view, it can be deduced that closely located equipment with slots have very weak electromagnetic interference by strong coupling through the slots. In the field of near-field imaging for microscopy, this phenomenon known as transmission resonance is quite useful.

Fig. 5 shows the electric field penetration for the slot offset as a parameter of various values of the plate spacings. Fig. 5(a) compares the electric field penetration with the x -direction slot offset x_0 (direction of the slot length) for various plate spacings d . Fig. 5(a) shows that in the case of $y_0 = 0$ and $d = 0.05\lambda$, a high level of electric field penetration occurs at the x -direction slot offset below

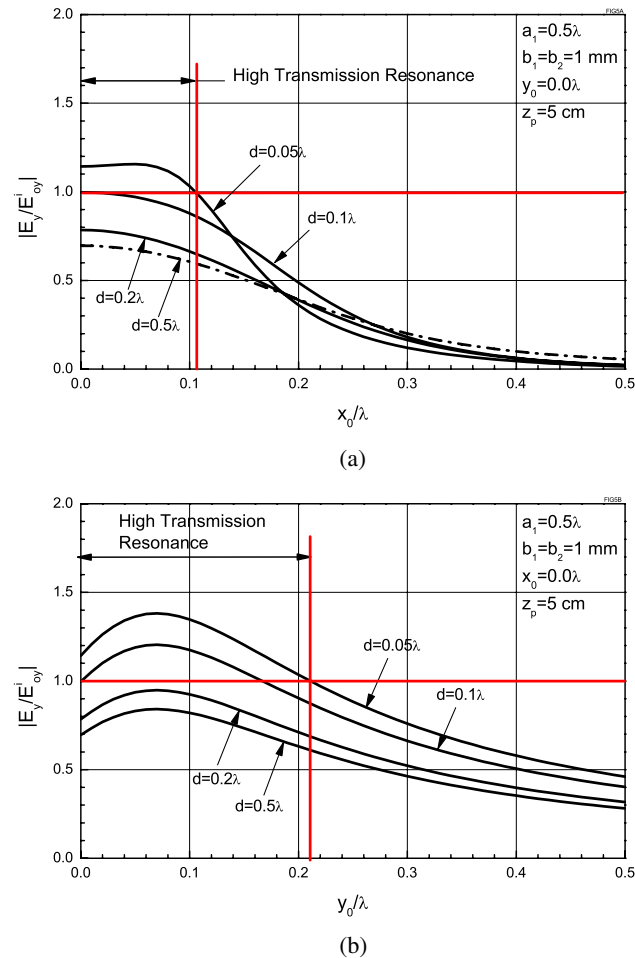


Fig. 5. Electric field penetration as a function of the slot offsets: (a) along the x -direction slot offset and (b) along the y -direction slot offset.

$x_0 = 0.1\lambda$. Fig. 5(b) presents the electric field penetration with the y -direction slot offset, y_0 (direction of the slot width), for various plate spacings d . As shown in Fig. 5(b), high electric field penetration was obtained for a y -direction slot offset below $y_0 = 0.21\lambda$ (0.17λ) at small plate spacings, $d = 0.05\lambda$ (0.1λ). The maximum transmission resonance occurred at the y -direction slot offset (transverse shift) $y_0 = 0.07\lambda$ for a given plate spacing. Leviatan [4] considered this as a 2D problem and reported that the maximum transmission resonances occur at transverse shifts that approaches multiples of 0.5λ . This study focused on 3D problems; the maximum transmission resonances occurred at the transverse slot offset $y_0 = 0.07\lambda$ for a given plate spacing. Note that this phenomenon was newly observed in this study. The mechanism for this phenomenon is currently unclear. A detailed study of this phenomenon will be the subject of future work.

Fig. 6 compares the experimental results with theory. A measurement setup comprised of a Anritsu MS4624B vector network analyzer and large ground planes ($2 \times 4 \text{ m}$) attached with two different narrow slots (i.e., $1 \text{ mm} \times 9 \text{ cm}$ and $1 \text{ mm} \times 15 \text{ cm}$) in an anechoic chamber. A shielded small loop antenna (with a diameter of 1 cm) has been used to a receiving antenna as a probe, and a broadband double-ridged horn antenna made by KAIST (model No. ICU-MA-04-2,

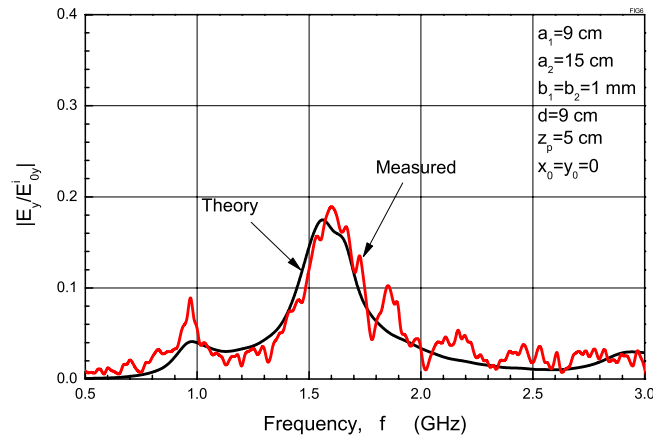


Fig. 6. Measured and theoretical electric field penetrations.

0.75~6 GHz) is used to a transmitting antenna. The calculated electric field penetrations were in good agreement with the measured data. The maximum deviation of the amplitudes was observed at approximately 0.9 GHz. In addition, inherent fluctuations and small peaks above 1.7 GHz remain in the measurements. The cause of the fluctuations and deviation was attributed mainly to the influence of the mutual coupling effects between the probe and slot, and the transmitting horn antenna–ground plane interactions.

4 Conclusion

This paper explained the electric field penetration from an incident plane wave that penetrates narrow slots in infinitely dual conducting ground planes. In the analysis, integral equations for the aperture electric fields were derived and solved by applying Galerkin's MoM. The numerical results revealed a high level of electric field penetration, known as the transmission resonance, for a small plate spacing and two slots with the resonant length when both slots have a slight offset in the slot width direction. The maximum transmission resonance occurs at the transverse slot offset 0.07λ for a given plate spacing. This phenomenon was newly observed and detailed studies of this phenomenon are ongoing.

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