Reduction Characteristics of Electromagnetic Penetration through Narrow Slots in Conducting Screen

Eun Jung Park · Ki-Chai Kim

Abstract

This paper presents the reduction characteristics of penetrated electromagnetic fields through a narrow slot in a planar conducting screen of infinite extent. When a plane wave is excited to the narrow slot, the aperture electric field is controlled by the parallel wire or parallel plate connected on the slot. The magnitude of penetrated electromagnetic fields through a narrow slot is controlled by electric field distributions on the slot. An integral equation for the aperture electric field on narrow slots is derived and solved by applying Galerkin's method of moments. The results show that the magnitude of the penetrated electromagnetic field can be effectively reduced by installing the parallel wire or parallel plate on the slot.

Key words : Reduction of Electromagnetic Fields, Narrow Slot, Parallel Wire, Parallel Plate.

Ⅰ. Introduction

The electromagnetic field penetration through an aperture in a planar conducting plane of infinite extent are studied by many researchers[1]~[7]. Electromagnetic coupling through slot apertures is important when considering shielding of electronic equipments and systems. It was reported that the research was a reduction technique of the electromagnetic penetration through a narrow slot in conducting screen by the parallel wires[8],[9].

In this paper, reduction characteristics of the electromagnetic penetration through a narrow slot with a reactance element(constructed by parallel plates or parallel wires) when a plane wave is excited into the slot on an infinitely large conducting screen are considered. The reduction technique described is using the installing reactance elements on the narrow slot. When the plane wave is excited into the narrow slot, the aperture electric field is controlled by the parallel wires or parallel plates connected on the slot. This controlled aperture electric field gives a reduction of the electromagnetic penetration through the narrow slot.

The integral equation for the electric field on the slot aperture is derived and solved by applying Galerkin's method of moments. The results show that the magnitude of the penetrated electromagnetic field is effectively reduced by installing the parallel plates or wires on the slot. To verify the theoretical analysis, the calculated electric field penetrations are compared with experiments.

Ⅱ. Theoretical Analysis

Fig. 1 shows the coordinate system of a narrow slot loaded with parallel wires or parallel plates in the infinitely large conducting screen. The conducting screen is located in the xy-plane with the origin at the center of the slot. The slot is parallel to the x-axis. The parallel wires with length l are connected along the x-axis by a distance c, and are parallel to the z-axis. As shown in Fig. 1(b), the parallel plates with length l and width w are connected along the x-axis by a distance c, and are parallel to the z-axis.

The problem can be divided into two regions as illustrated in Fig. 1. Region Ⅰ($z<0$) is defined as the half-space containing the incident plane wave and bounded by the conducting screen as shown in Fig. 1. The incident electromagnetic fields is penetrated into Region Ⅱ($z>0$). The two regions are assumed to be free-space.

The magnetic current sheet with the width b can be replaced by the magnetic current cylinder with the equivalent radius $b/4$ when b is much smaller than the wavelength[8]. If the plane wave is incident into the narrow slot, the integral equation for the unknown aperture electric field $\boldsymbol{E}_a$ in the narrow slot can be written as

$$\hat{z}\times\left\{(\boldsymbol{H}^i+\boldsymbol{H}^r)+\hat{y}I_y\delta(x-c)+\frac{1}{j\omega\mu_0}\iint_{s'_a}\overline{\boldsymbol{K}}_m{}^{I}\cdot[\hat{z}\times\boldsymbol{E}_a]dS'_a\right\} = \hat{z}\times\frac{1}{j\omega\mu_0}\iint_{s'_a}\overline{\boldsymbol{K}}_m{}^{II}\cdot[-\hat{z}\times\boldsymbol{E}_a]dS'_a \quad (1)$$

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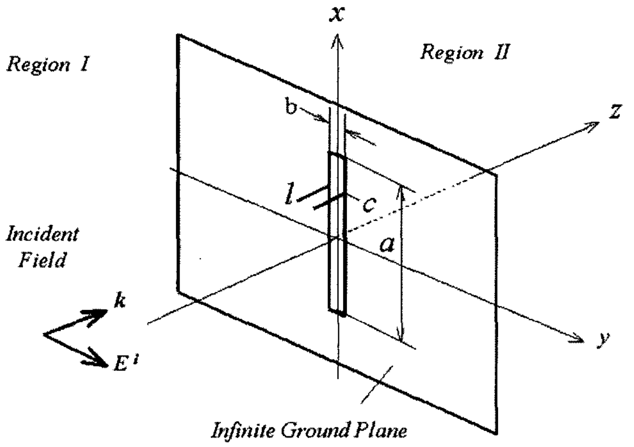
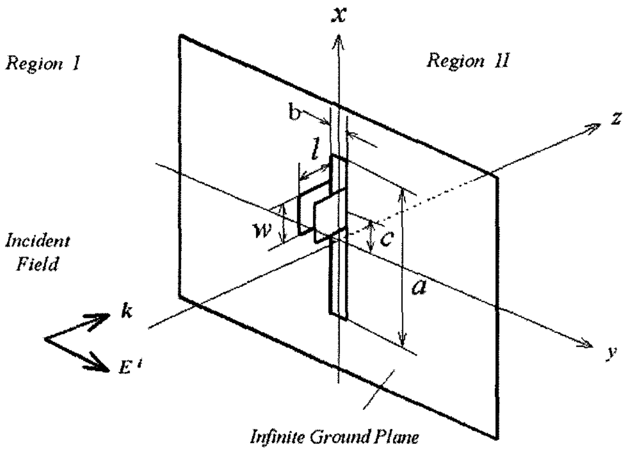


(a) Loaded by parallel wires



(b) Loaded by parallel plates

Fig. 1. Aperture with a reactance element in planar conducting screen of infinite extent.

where

$$H^i = -\hat{x}\frac{1}{Z_0}E^i_{0y}e^{-jkz} \tag{2}$$

$$H^r = -\hat{x}\frac{1}{Z_0}E^i_{0y}e^{jkz} \tag{3}$$

$$\overline{K}_m^{\,I,II}(\boldsymbol{r},\boldsymbol{r}') = (\overline{I}k^2 + \nabla\nabla)\cdot\overline{G}_m^{\,I,II}(\boldsymbol{r},\boldsymbol{r}') \tag{4}$$

$\boldsymbol{H}^i$ and $\boldsymbol{H}^r$ are the incident and reflected magnetic fields. E^i_{0y} is the amplitude of the incident electric field and Z_0 is the wave impedance in free space. $\overline{I}$ is unit dyadic, $\delta(\cdot)$ is the Dirac delta-function, $k=\omega\sqrt{\varepsilon_0\mu_0}$, and ω represents the angular frequency. The time dependence $exp(j\omega t)$ is assumed and omitted throughout this paper. The superscripts I and II denote region I and region II, respectively. $\hat{x}$, $\hat{y}$, and $\hat{z}$ are unit vectors in the x, y, and z direction, respectively. Position vectors $\boldsymbol{r}$ and $\boldsymbol{r}'$ are for the observation and source points, respectively. dS'_a denotes an element of area on the slot aperture, $\overline{G}_m^{\,I}$ and $\overline{G}_m^{\,II}$ are the dyadic Green functions of the half-space. I_y is the current at the connecting position of the two parallel wires and is given by

$$I_y = \frac{V_L}{Z_L} \tag{5}$$

where V_L is the voltage of loading point. And Z_L is the impedance of the reactance element constructed by two parallel wires with a length l, the value of impedance can be expressed as

$$Z_L = -j120\ln\left(\frac{h}{r}+\sqrt{\left(\frac{h}{r}\right)^2-1}\right)\cot(\beta l) \tag{6}$$

where β is the propagation constant of the two parallel wires. $h=b/2+r$ and r denote half-spacing and radius of the two parallel wires, respectively. The impedance of the reactance element constructed by parallel plates with a length l and width w, the value of impedance can be expressed as

$$Z_L = \eta\frac{l}{w} \tag{7}$$

where η is the characteristic impedance of free space.

To solve the integral equation for the unknown, the aperture electric field $\boldsymbol{E}_a$ is expanded as

$$\boldsymbol{E}_a(x) = \hat{y}\sum_{n=1}^{N} V_n F_n(x) \tag{8}$$

where V_n are coefficients to be determined, and F_n are the piecewise sinusoidal expansion functions as follows.

$$F_n = \begin{cases} \dfrac{\sin k(x-x_{n-1})}{\sin k\triangle x_n}, & x_{n-1}\le x\le x_n \\ \dfrac{\sin k(x_{n+1}-x)}{\sin k\triangle x_n}, & x_n\le x\le x_{n+1} \end{cases} \tag{9}$$

where $\triangle x_n = x_n - x_{n-1} = x_{n+1} - x_n$.

Substituting the assumed basis function into the integral equation (1) and employing Galerkin's method of moments, we obtain a set of linear equations for the unknown expansion coefficients

$$\sum_{n=1}^{N} V_n = (Y_{n'n} - Y^L_{n'n}) = I_{n'} \tag{10}$$

where

$$Y_{n'n} = \frac{-2}{j\omega\mu_0}\iint F_{n'}(x)\left(k^2+\frac{\partial^2}{\partial x^2}\right)\frac{e^{-jkR}}{2\pi R}F_n(x')dx'dx \tag{11}$$

$$Y^L_{n'n} = \frac{-b}{Z_L}F_c(c)\int F_{n'}(x)\delta(x-c)dx \tag{12}$$

$$I_{n'} = -(H^i_x + H^r_x)\int F_{n'}(x)dx \tag{13}$$

and R is the distance between the source and the field points.

When a plane wave is incident on the narrow slot, the penetrated electric field in region II is obtained in the following form.

$$E_y = -\frac{1}{2\pi}\sum_{n=1}^{N} V_n \frac{1}{\sin k\Delta x_n}[S_L + S_U] \tag{14}$$

where

$$S_L = \int_{x_{n-1}}^{x_n} \frac{\partial}{\partial z}\left(\frac{e^{-jkR}}{R}\right)\sin k(x' - x_{n-1})dx' \tag{15}$$

$$S_U = \int_{x_n}^{x_{n+1}} \frac{\partial}{\partial z}\left(\frac{e^{-jkR}}{R}\right)\sin k(x_{n+1} - x')dx'. \tag{16}$$

III. Numerical Results and Discussion

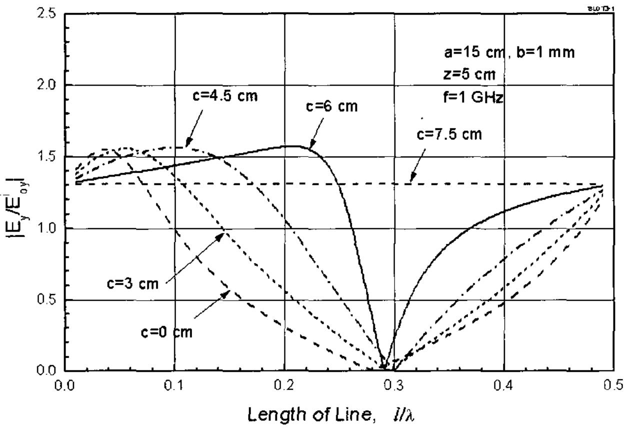
The slot used in the calculation is a narrow slot compared to the wavelength. The dimensions of the slot are a=15 cm and b=1 mm.

Fig. 2(a) shows the magnitudes of the electric field penetration normalized by the incident electric field at z=5 cm in region II when the plane wave with frequency of 1 GHz is incident into the narrow slot. The penetrated electric fields for various values of the two parallel wires position are shown with the various dashed and solid lines. Fig. 2(b) shows the magnitudes of the electric field penetration at z=5 cm when the plane wave with frequency of 1 GHz is incident into the narrow slot with the parallel plates. The penetrated electric fields for various values of the parallel plates width w are shown with the various dashed and solid lines.

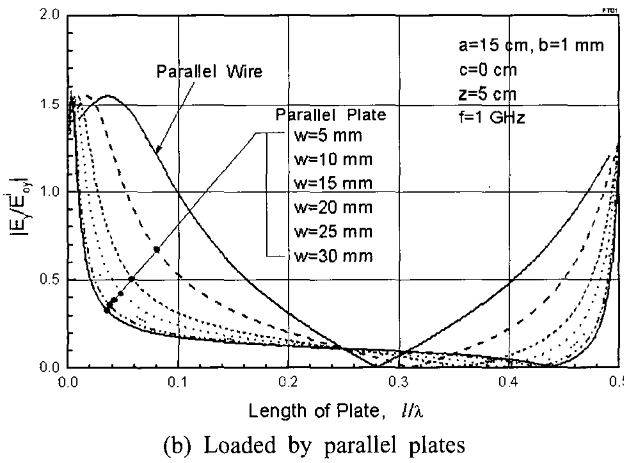
As shown in Fig. 2(a), the amount of reduction is a function of the parallel wires length. The magnitude of the penetrated electric field is reduced to zero by selecting the two parallel wires length of around 0.27 λ ~0.3 λ. If the two parallel wires are connected on the end of the slot aperture(c=7.5 cm), the magnitude of the penetrated electric field is not reduced. In this case the result is same to the case of no parallel wires are present on the slot. As shown in Fig. 2(b), the amount of reduction is a function of the length of the parallel plates. The magnitude of the penetrated electric field is reduced to zero by selecting the parallel plates length of around 0.311 λ ~0.438 λ.

Fig. 3 shows the frequency characteristics of the penetrated electric field at z=5 cm when the parallel plates with length of 3 cm(0.1 λ at 1 GHz) are connected at c=0 cm on the narrow slot. The dash-dot line represents the penetrated electric field when no parallel plates or wires are present on the slot. In this case the maximal penetrated electric fields occur at frequencies of 0.94 GHz and 2.9 GHz. These frequencies correspond to the resonance frequencies of the slot with the length of 15 cm. The magnitude of the electric field penetration through the slot with l=3 cm parallel wires is larger than the case of the parallel plates with l=3 cm. But it is smaller than the case of without plates or wires.

Fig. 4 shows the frequency characteristics of the pe-



(a) Loaded by parallel wires



(b) Loaded by parallel plates

Fig. 2. Penetrated electric fields at 1 GHz versus length of the parallel plates and parallel wires.

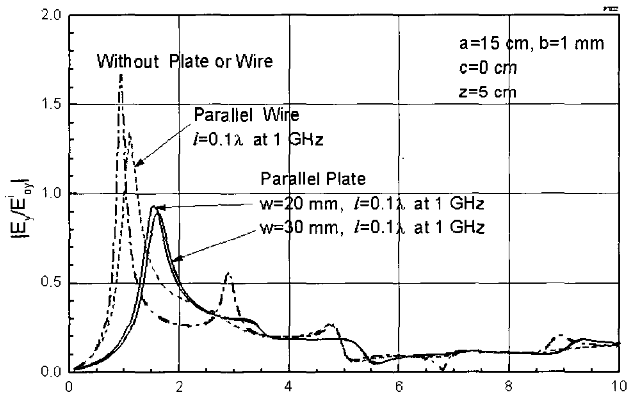


Fig. 3. Frequency characteristics of penetrated electric fields by parallel plates and parallel wires.

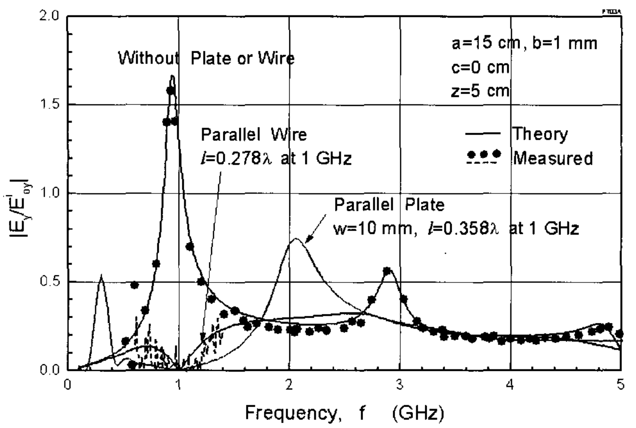


Fig. 4. Frequency characteristics of penetrated electric fields by parallel plates and parallel wires.

netrated electric field at z=5 cm when the parallel plates length of 10.74 cm (0.358 λ at 1 GHz) are connected at c=0 cm and the parallel wires length of 8.34 cm (0.278 λ at 1.GHz) are connected at c=0 cm. As can be seen from the Fig. 4, it is found that the penetrated electric field is effectively reduced by installing the parallel plates than installing the parallel wires on the narrow slot near the resonance frequency of 1 GHz. But it is effectively reduced by installing the parallel wires than installing the parallel plates from a wide frequency band and a practical point of view.

In order to verify the validity of the numerical calculations, the experimental result for parallel wires is provided. From a practical point of view, we experimented in the case of parallel wires loading on the slot. A measurement setup comprised of Wiltron 37225A network analyzer and a large ground plane (2×4 m) attached with a narrow slot (1 mm×15 cm) in an anechoic chamber. A broadband double-ridged horn antenna made by ICU(model No. ICU-MA-04-2, 0.75~6 GHz) was used to a transmitting antenna and a shielded small loop antenna was used to a receiving antenna. Measured results are shown in Fig. 4. In Fig. 4, we described the reference [5]'s and our experimental results. The solid circles present the [5]'s measured results until the 10 GHz. In this paper, we experimented near the resonance frequency of 1 GHz, the most important frequency range, in order to confirm the reduction characteristics of the penetrated electric field near the resonance. It is shown that the calculated electric fields in Region II are in good agreement to experimental results.

Ⅳ. Conclusion

In this paper, reduction characteristics of electromagnetic field penetrations through a narrow slot on an infinite conducting screen by loading parallel wires or parallel plates on a narrow slot are considered and analyzed by the method of moments. As the results, it is found that the penetrated electric field is effectively reduced by installing the parallel wires or installing the parallel plates on the narrow slot. Therefore, connecting the parallel plates or parallel wires on the slot are an effective way to control the level of the electromagnetic field penetration through a narrow slot in a planar conducting screen of infinite extent.

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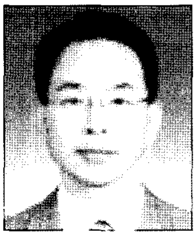

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