Reduction Characteristics of Electromagnetic Penetration through Narrow Slots in Conducting Screen by Loading Parallel Wire Arrays

Ki-Chai Kim[1] · Sung Min Lim[2]

Abstract

This paper presents a method of reducing penetration of penetrated electromagnetic fields through a narrow slot with parallel wire arrays in a planar conducting screen of infinite extent. An integral equation for the aperture electric field on the narrow slot is derived and solved by applying Galerkin's method of moments. When a plane wave is excited to the narrow slot, the aperture electric field is easily controlled by the parallel wire arrays connected on the slot and therefore the magnitude of the penetrated electric field is effectively reduced by loading the parallel wire arrays. The numerical results show that the magnitude of the penetrated electromagnetic field can be effectively reduced by installing the parallel wire arrays on the slot. The results of the calculated penetration electric fields are in good agreement with that of the measured results.

Key words : Narrow Slot, Reduction of Electromagnetic Penetration, *N*-Wire Parallel Arrays.

I . Introduction

Electromagnetic shields have traditionally been used to reduce electromagnetic interference(EMI) in sensitive electrical equipment and systems. In many cases, the effectiveness of an electromagnetic shield is determined by apertures or slots that exist in the shielded enclosures. Electromagnetic coupling through apertures is important when considering shielding of electronic equipment and systems. The problem of electromagnetic field penetrations through an aperture in a planar conducting plane of infinite extent has been considered by a number of authors[1]~[5]. To minimize the penetration of electromagnetic fields through an aperture, the aperture is sometimes covered or loaded with conductive material[6]. In recent work by the author[7]~[9], a method of reducing penetration of the electromagnetic fields on the single and double parallel wires loading were calculated by solving the integral equation numerically using the method of moments.

In this paper, reduction characteristics of the electromagnetic penetration through a narrow slot with *N*-wire parallel arrays (*N*: number of arrays) when a plane wave is excited into the slot on an infinitely large conducting screen are considered. The reduction technique described uses the *N*-wire parallel arrays installed on 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. When the plane wave is excited into the narrow slot, the results show that the magnitude of the penetrated electromagnetic field is effectively reduced by installing the *N*-wire parallel arrays on the slot. To check the validity of the theoretical analysis, the magnitude of the penetrated electric field was measured and compared.

II . Principles of Reduction

Fig. 1 illustrates the aperture electric field and the penetrated electric field distributions through the narrow slot to explain the principles of the reduction of the penetrated electric field by loading parallel wires. Fig. 1(a) and (b) show an unloaded slot and a parallel wire

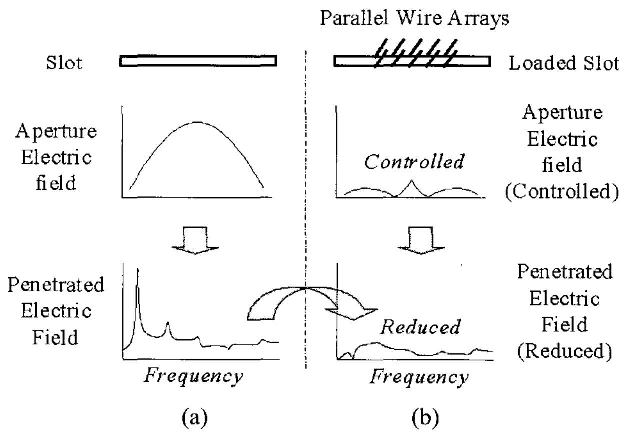

Fig. 1. Principle of reduction of electromagnetic fields penetrated through a slot using parallel wire arrays.

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loaded slot, respectively. The unloaded slot causes the aperture electric field distribution to have single sine waves with a constant phase when the slot is excited by the plane wave as shown in Fig. 1(a). In contrast, since the magnitude of the aperture electric field, as shown in Fig. 1(b), is controlled by the loaded parallel wires on the slot, the magnitude of the penetrated electromagnetic field can be effectively reduced by loading and adjusting the length of the parallel wires.

The principles of the reduction technique are the following. The aperture electric field distribution on the narrow slot can be controlled (see middle of Fig. 1(b)) by properly changing the position and length of the parallel wires or parallel wire arrays connected on the slot. In other words, if we extensively utilize the controlled amplitudes of the aperture electric field distribution on the slot aperture, we can control the electromagnetic penetration through the narrow slot. The fact mentioned above, as will be shown later in section 4, was proved by both numerical and experimental results.

Ⅲ. Theoretical Analysis

Fig. 2 shows the coordinate system of the infinitely large conducting screen with a narrow slot loaded with N-wire parallel arrays. The conducting screen is located in the xy-plane with the origin at the center of the narrow slot. The screen is a perfect electric conductor (PEC) of zero thickness. The slot aperture is parallel to the x-axis. The parallel wire arrays with length l are connected along the x-axis by a distance nd and $-nd$ (n=1, 2, ⋯, $N-1$), and are parallel to the z-axis. The parameter d is the distance between the parallel wire arrays.

The problem can be divided into two regions as illustrated in Fig. 2. 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. 2. The incident electromagnetic fields penetrate into Region Ⅱ (z>0) through the narrow slot. The two regions are assumed to be free-space and the time dependence exp($j\omega t$) is assumed and omitted throughout this paper.

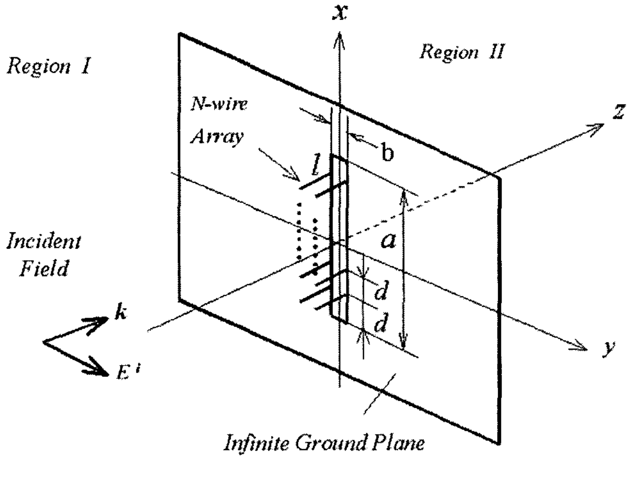


Fig. 2. Aperture in planar conducting screen of infinite extent loaded with N-wire parallel arrays.

The magnetic current sheet with the width b on the narrow slot can be replaced by the magnetic current cylinder with the equivalent radius $b/4$ when b is much smaller than the wavelength. 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

$$\hat{z}\times\Big[\boldsymbol{H}^i+\boldsymbol{H}^r+\hat{y}\sum_{n=1}^{N}\{I_n(nd)\delta(x-nd)+I_n(-nd)\delta(x+nd)\} + \frac{1}{j\omega\mu_0}\iint_{s'_a}\overline{\boldsymbol{K}}_m^{\,I}(\boldsymbol{r},\boldsymbol{r}')\cdot\{\hat{z}\times\boldsymbol{E}_a(\boldsymbol{r}')\}dS'_a\Big] = \hat{z}\times\frac{1}{j\omega\mu_0}\iint_{s'_a}\overline{\boldsymbol{K}}_m^{\,II}(\boldsymbol{r},\boldsymbol{r}')\cdot[-\hat{z}\times\boldsymbol{E}_a(\boldsymbol{r}')]dS'_a \quad (1)$$

where incident magnetic field $\boldsymbol{H}^i$, reflected magnetic field $\boldsymbol{H}^r$, and kernels can be expressed as follows.

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

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

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

where $\hat{x}$, $\hat{y}$ 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. $\delta(\cdot)$ is the Dirac delta-function, $k=\omega\sqrt{\varepsilon_0\mu_0}$, and ω represents the angular frequency. The superscripts I and II denote region I and region II, respectively. 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, $\overline{G}_m^{\,I}$ and $\overline{G}_m^{\,II}$ are the dyadic Green functions of the half-space.

In (1), I_n is the current at the connecting position of the N-wire parallel arrays and is given by

$$I_n(\pm nd)=\frac{V_L(\pm nd)}{Z_L} \quad (5)$$

where $V_L(\pm nd)$ is the voltage of the loading point. Z_L ($=jX_n$) is the impedance of the N-wire parallel arrays with a length l. The value of impedance can be expressed as [10]

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

where β is the propagation constant of the two parallel wires along the z direction. $h=b/2+r$ and r denote half-spacing and radius of the two parallel wires, respectively.

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

$$\boldsymbol{E}_a(x)=\hat{y}\sum_{m=1}^{M} V_m F_m(x) \tag{7}$$

where V_m are coefficients to be determined and F_m are the piecewise sinusoidal expansion functions as follows.

$$F_m=\begin{cases} \dfrac{\sin k(x-x_{m-1})}{\sin k\triangle x_m}, & x_{m-1}\le x\le x_m \\ \dfrac{\sin k(x_{m+1}-x)}{\sin k\triangle x_m}, & x_m\le x\le x_{m+1} \end{cases} \tag{8}$$

where $\triangle x_m = x_m - x_{m-1} = x_{m+1} - x_m$.

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

$$\sum_{m=1}^{M} V_m Y_{m'm} = I_{m'} + \sum_{n=1}^{N} (I_{ym'}^{n+} + I_{ym'}^{n-}) \tag{9}$$

where

$$Y_{m'm} = \frac{-2}{j\omega\mu_0}\iint F_{m'}(x)\left(k^2 \frac{\partial^2}{\partial x^2}\right)\frac{e^{-jkR}}{2\pi R}F_m(x')dx'dx \tag{10}$$

$$I_{ym'}^{n\pm} = \frac{V_L(\pm nd)}{jX_n}\int F_{m'}(x)\,\partial(x\mp nd)dx \tag{11}$$

$$I_{m'} = -(H_x^i + H_x^r)\int F_{m'}(x)dx \tag{12}$$

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

Once the aperture electric field distribution on the slot is given, the penetrated electric field in region II can be determined. When a plane wave is incident on the narrow slot, the penetrated electric field in region II is obtained in the following form.

$$E_y = -\frac{1}{2\pi}\sum_{m=1}^{M} V_m \frac{1}{\sin k\triangle x_m}[S_L + S_U] \tag{13}$$

where

$$S_L = \int_{x_{m-1}}^{x_m} \frac{\partial}{\partial z}\left(\frac{e^{-jkR}}{R}\right)\sin k(x' - x_{m-1})dx' \tag{14}$$

$$S_U = \int_{x_m}^{x_{m+1}} \frac{\partial}{\partial z}\left(\frac{e^{-jkR}}{R}\right)\sin k(x_{m+1} - x')dx'. \tag{15}$$

Ⅳ. 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. The length of the slot, 15 cm, is slightly under the resonance length of 1 GHz.

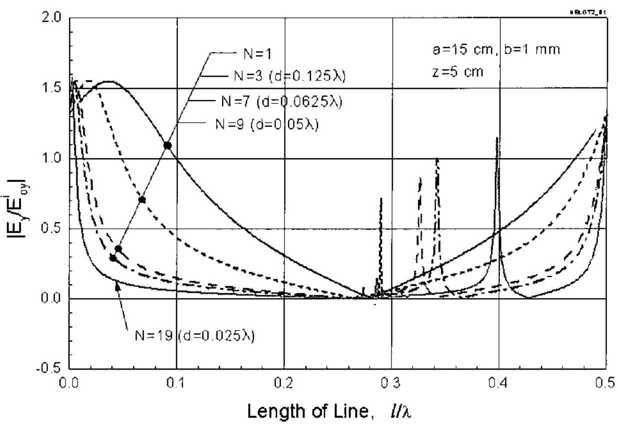
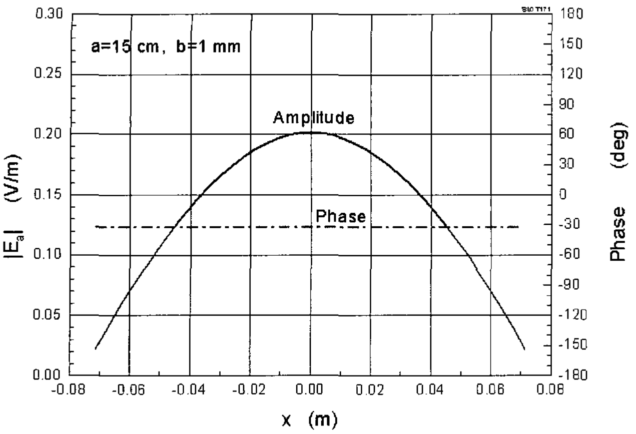


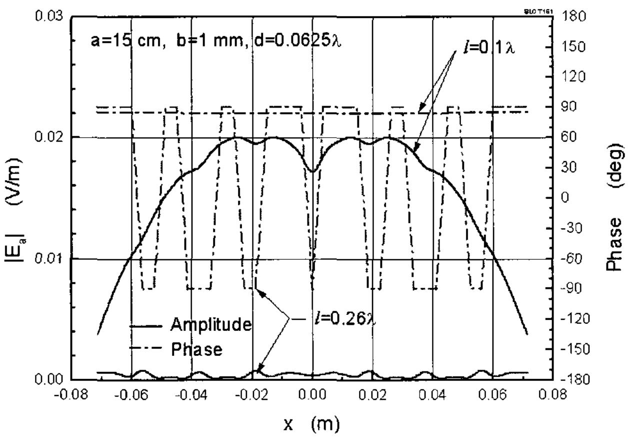
Fig. 3. Penetrated electric fields versus length of the N-wire parallel arrays at 1 GHz.

Fig. 3 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 number of N-wire parallel arrays are shown with dashed and solid lines. As shown in Fig. 3, the magnitude of the penetrated electric field is reduced to zero by selecting the N-wire parallel arrays length of around 0.26 λ. Several peaks appear with length above 0.26 λ and the length of the parallel arrays above 0.26 λ becomes very large in the real installation on the narrow slot. Therefore lengths above 0.26 λ is too long to be applied to a real enclosure. The magnitude of the penetrated electric field is effectively reduced by the loaded short parallel wires as N increases. For example, in the case of the 7-wire parallel arrays (in case of N=7, the interval of arrays is d=0.0625 λ), the magnitude of the penetrated electric field is more reduced by the short parallel wires than single parallel wires[9]. For the single parallel wires, as reported in [9], the magnitude of the penetrated electric field is reduced to zero by selecting the single parallel wires length of around 0.27 λ ~0.3 λ.

Fig. 4(a) and (b) show the aperture electric field distribution on the slot. Fig. 4(a) shows the aperture electric field distribution when no parallel wires are present on the slot. Fig. 4(b) represents the aperture electric field distribution when the 7-wire parallel arrays length of 0.260 λ (=7.80 cm at 1 GHz) and 0.1 λ (=3.0 cm at 1 GHz) are connected at d=0.0625 λ on the narrow slot. The solid lines show the amplitude of the aperture electric fields and dash dot lines represent the phase of the aperture electric fields. In these cases the amplitude of the aperture electric field are effectively controlled by the 7-wire parallel arrays connected on the slot. The amplitude of the aperture electric field is easily reduced

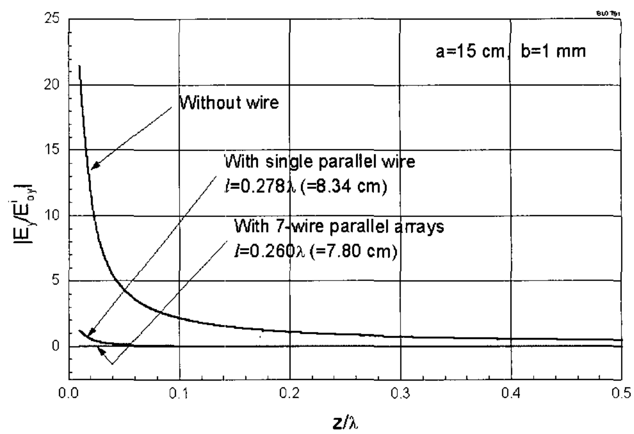


(a) Without parallel wires

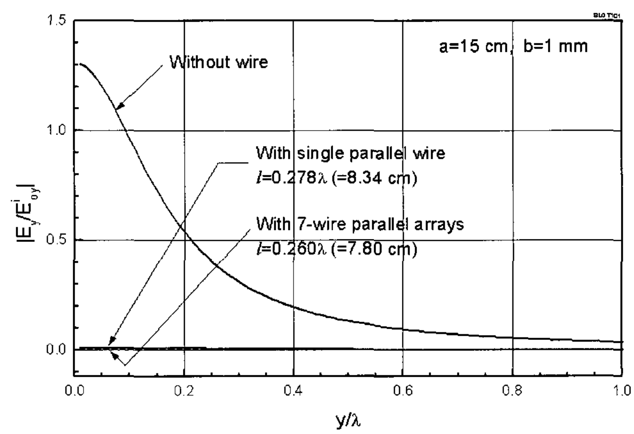


(b) 7-wire parallel arrays

Fig. 4. Aperture electric field distributions on the slot at 1 GHz.



(a) Along the z-axis with (x, y)=(0 cm, 0 cm)



(b) Along the y-axis with (x, z)=(0 cm, 5 cm)

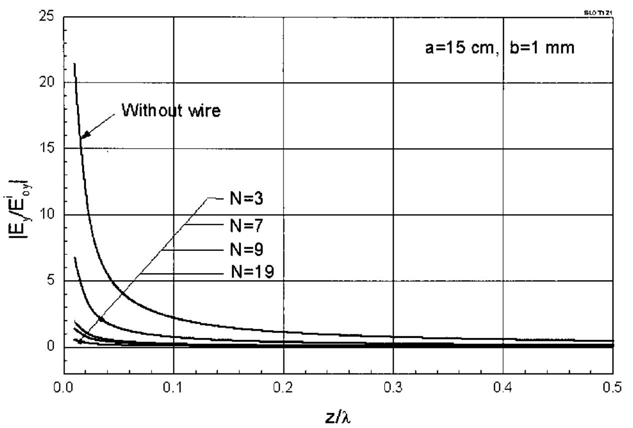
Fig. 5. Penetrated electric fields at 1 GHz versus z- and y- positions.

by approximately 99 % due to the 7-wire parallel arrays loading on the slot. In the case of single parallel wires loading[9], the amplitude of the aperture electric field is reduced by about 93 %.

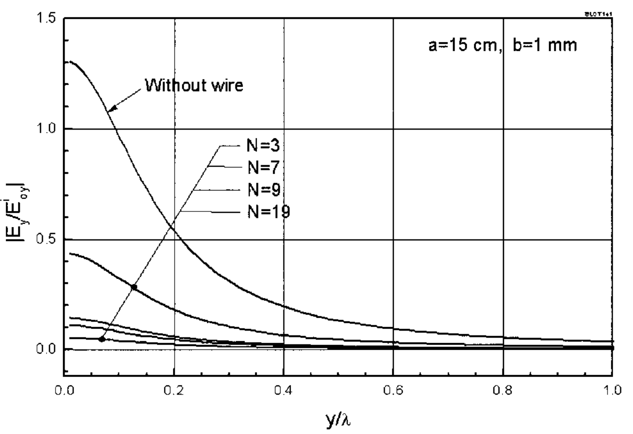
Fig. 5(a) shows the magnitude of the penetrated electric field normalized by the incident electric field along the z-axis at x=y=0 cm in region II when the plane wave with frequency of 1 GHz is incident into the slot. Fig. 5(b) shows the magnitude of the penetrated electric field normalized by the incident electric field along the y-axis at x=0 cm and z=5 cm in region II when the plane wave with frequency of 1 GHz is incident into the slot. As shown in Fig. 5(a) and (b), the magnitude of the penetrated electric field is more effectively reduced (almost zero magnitude) when the 7-wire parallel arrays with length of 0.260 λ (=7.80 cm at 1 GHz) are connected at d=0.0625 λ on the slot. For comparison, Fig. 5(a) and (b) show the magnitude of the penetrated electric field when no parallel wires are present on the slot. As can be seen from Fig. 5, the magnitude of the penetrated electric field is rapidly reduced around the slot. As a result, the magnitude of the penetrated electric field is more effectively reduced for the 7-wire parallel arrays than the single parallel wires loading[9] around the slot.

The N-wire parallel arrays with length of 7.80 cm (0.260 λ at 1 GHz) giving the zero penetration electric field is too long for a real installation. So we can consider using N-wire parallel arrays with a short length. As an example, we consider N-wire parallel arrays with length of 0.1 λ.

Fig. 6(a) and (b) show the magnitude of the penetrated electric field normalized by the incident electric field for the length of 0.1 λ (=3.0 cm at 1 GHz) along the y-axis and z-axis in region II when the plane wave with a frequency of 1 GHz is incident into the slot. The penetrated electric fields for various values of the number of N-wire parallel arrays are shown with solid lines. For comparison, Fig. 6(a) and (b) show the magnitude of the penetrated electric field when no parallel wires are present on the slot. As shown in Fig. 6, the magnitude of the penetrated electric field is effectively redu-



(a) Along the z-axis with (x, y)=(0 cm, 0 cm)



(b) Along the y-axis with (x, z)=(0 cm, 5 cm)

Fig. 6. Penetrated electric fields for l=0.1 λ at 1 GHz versus z- and y- positions.

ced when the number of parallel wires N increases.

Fig. 7 shows the frequency characteristics of the penetrated electric field at z=5 cm in region II when the N-wire parallel arrays are connected at $d=a/(N+1)$ cm on the slot for l=0.1 λ. The penetrated electric fields for various values of the number of N-wire parallel arrays are shown with the various dashed and solid lines. The upper solid line indicated with "Without Wire" represents the penetrated electric field when no parallel 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. As can be seen from Fig. 7, it is found that the penetrated electric field is effectively reduced when the number of parallel wires N increases.

In Figs. 7 and 8, the discontinuity in the frequency characteristics appear for N-wire parallel arrays loading. This discontinuity is due to the different values of M-segment in order to satisfy the equal length segments of 0.0125 λ per slot length at a given frequency on the method of moments.

In order to verify the validity of the numerical calculations, the experimental results are provided. A measurement setup comprised of a 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 as a transmitting antenna and a shielded small loop antenna (has a diameter of 1 cm) was used as a receiving antenna. Measured results at z=5 cm in region II are shown in Fig. 8.

Fig. 8 shows the frequency characteristics of the penetrated electric field at z=5 cm in region II when the 7-wire parallel arrays with length of 7.80 cm (=0.260 λ at 1 GHz) are connected at d=0.0625 λ on the slot. The upper solid line indicated with "Without Wire" represents the penetrated electric field when no parallel wires

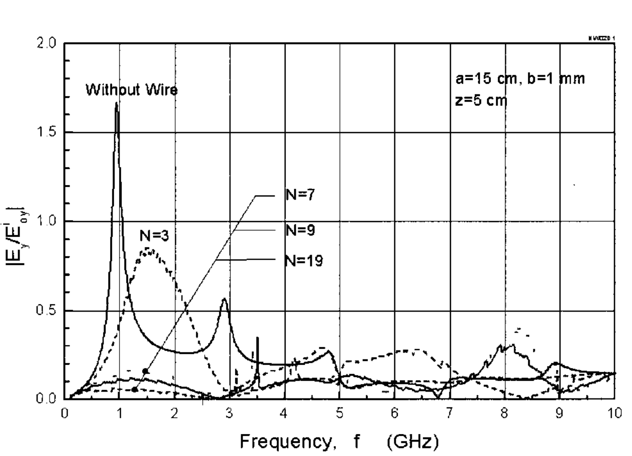


Fig. 7. The frequency characteristics of penetrated electric fields by N-wire parallel arrays for l=0.1 λ.

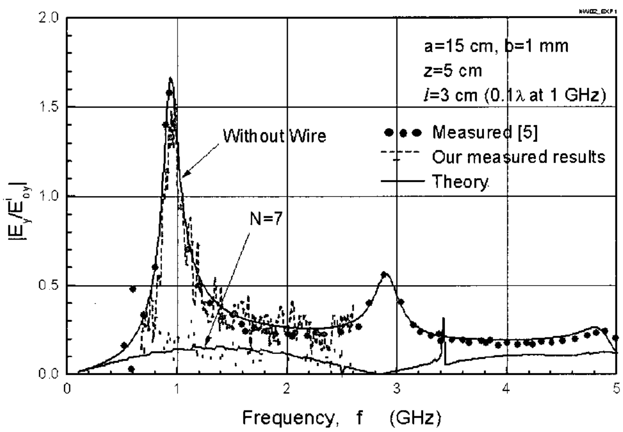


Fig. 8. Measured and calculated frequency characteristics of penetrated electric fields by 7-wire parallel arrays.

are present on the slot. The lower solid line indicated with "N=7" shows the penetrated electric field when the 7-wire parallel arrays are connected on the slot. As can be seen from the Fig. 8, it is found that the penetrated electric field is effectively reduced by installing the 7-wire parallel arrays on the slot. In Fig. 8, we described the reference [5]'s and our experimental results. The solid circles present [5]'s measured results up to 10 GHz. The dashed and dotted lines represent our experimental results near the resonance. 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 with experimental results. The experimental and theoretical results show that the amplitude of the penetrated electric field is effectively reduced by installing the 7-wire parallel arrays on the slot.

V. Conclusion

In this paper, a reduction technique of electromagnetic field penetrations through a narrow slot on an infinite conducting screen is proposed and analyzed by Galerkin's method of moments. As a result, it is found that the magnitude of the penetrated electromagnetic field can be more effectively reduced by adjusting the length of the N-wire parallel arrays on the slot than with the single parallel wires on the slot. Therefore, connecting the short N-wire parallel arrays on the slot is an effective way to control the level of the electromagnetic field penetration through a narrow slot in a planar conducting screen. Theoretical and experimental results indicate that the penetrated electric field is reduced to that of a controlled aperture electric field on the slot. This method could be explored deeper by shortening, the length of the two parallel wires. This approach is worthy of further research.

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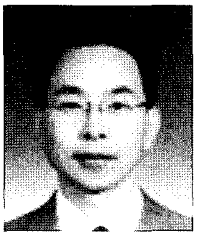

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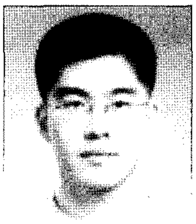

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