ABSTRACT This study investigated the enhancement characteristics of the shielding effectiveness (SE) of a double-layer shielding structure with narrow slots when a plane wave is incident on the slot. Integral equations for aperture magnetic currents in narrow slots were derived and solved by applying Galerkin’s method of moments. The numerical results demonstrate that SE depends on the layer wall spacing for a given frequency. The SE fluctuates with the spacing of the layers, and the fluctuation period is approximately $0.5\lambda$ at the resonant frequency. These periodic SE patterns gradually increase in magnitude with increasing layer wall spacing. To enhance the SE against electromagnetic interference at the resonant frequency, two parallel wires were used to minimize the transmission (maximize SE) through the narrow slots. The analysis results show that the SE can be enhanced by connecting the parallel wires to the slots at the resonant frequency. Experimental results are presented to validate the theory.

INDEX TERMS Double-layer shielding structure, minimum transmission, narrow slot, shielding effectiveness, two parallel wires.

I. INTRODUCTION

The mechanism of penetration of electromagnetic fields and aperture coupling between two half-space regions has been studied by many researchers [1], [2], [3], [4], [5], [6]. The coupling of electromagnetic fields between regions through slot apertures is widely encountered in electromagnetic interference and electromagnetic compatibility (EMI/EMC) and electromagnetic engineering problems [7], [8], [9]. In many practical situations, aperture-coupled problems of this nature arise in the penetration of an electromagnetic field into shielded buildings and electronic equipment, and windows must be created in the walls for signal lines and heat dispersion. In areas with electromagnetic pulses, the protection of electronic equipment and buildings is also of considerable interest for achieving high shielding effectiveness (SE).

Recently, some studies have reported the reduction of electromagnetic penetration through narrow slots in a single-layer shielding structure by connecting parallel wires to the slot [10], [11]. This structure involves wires connected to the slot acts as an aperture-cutoff filter (ACF), as explained in a previous article [11]. This article deals with the method for enhancing the SE for the slot-related shielding structure such as ACF by attaching the outer open stub circuitry without the perturbing of the original slot shape and area. If the slot is divided into two equal slots of equal length using the shorting wire, the SE increases by about 22 dB [10]. Electromagnetic coupling between two half-space regions separated by two slot-perforated parallel double-layer structures has been reported [12], [13], [14]. Two-stage enclosures have also been studied for applications requiring EMI shielding to protect the equipment from penetrating electromagnetic fields.
fields [15], [16]. In addition, some studies have focused on the resonance transmission (or extraordinary transmission) of dual-plate slots [17].

Double-layer walls provide excellent shielding performance compared with single-layer walls. To improve the SE of double-layer shielding structures, the enhancement of SE for EMI/EMC applications using the two parallel wires was considered, as proposed previously for a single-layer shielding structure. The analysis results demonstrate that SE enhancement can be achieved using parallel wires connected to the resonant slots. This enhanced SE (or minimum transmission) phenomenon is the ACF [11].

For double-layer walls with narrow resonant slots, a high SE occurs effectively with two parallel wires connected to both slots for a given wall spacing at the resonant frequency. To verify the validity of the theoretical analysis, also it was compared with experimental results.

II. FORMULATION OF THE DOUBLE-LAYER SHIELDING STRUCTURES

Fig. 1 shows the geometry of double-layer conducting walls with narrow half-wavelength slots excited by an incident plane wave. The double-layer conducting walls are divided into three regions: a half-space containing the incident plane wave (region I, \( z < 0 \)), interior region of two conducting walls (region II, \( 0 < z < d \)), and half-space containing the penetrating field (region III, \( z > 0 \)). These three regions are assumed to be free spaces. The slots are resonant at the operating frequency, and the maximum fields penetrate region III through the slots from region I.

Conducting wall #1 is located in the \( xy \)-plane with the origin at the center of the slot aperture, and conducting wall #2 is located in the \( xy \)-plane, apart from \( z = d \). Narrow slot #1 of length \( a_1 \) and width \( b_1 \) is in infinite conducting plane #2 and is located near slot #2 of length \( a_2 \) and width \( b_2 \) in infinite conducting plane #2. Both slots are aligned along the same \( z \)-axis because the maximum penetration field occurs in this case. This corresponds to the worst-case scenario. Here, \( z_p \) is the field point in region III. The conducting planes are perfect electric conductors with zero thickness.

Fig. 2 shows loading types of two parallel wires in the slots to enhance the SE of the double-layer shielding structures. Fig. 2(a) is for the unloading case. Figs. 2(b) and (c) correspond, respectively, to the slot #1 loading case and the loading case for both slot #1 and slot #2.

If the plane wave is incident on the narrow slot in metallic wall #1, then the simultaneous integral equations for the unknown magnetic currents \( M_1 \) and \( M_2 \) on the slot apertures can be expressed as

\[
\hat{\mathbf{z}} \times \iint_{S_{a1}} \left( \bar{R}_{11m}^{H} + \bar{R}_{11m}^{H} \right) \cdot \bar{M}_{1}^{'d} dS_{a1}' \\
\hat{\mathbf{z}} \times \iint_{S_{a2}} \bar{R}_{12m}^{H} \cdot \bar{M}_{2}^{'d} dS_{a2}'
\]

where \( \bar{R}_{11m}^{H} = z \frac{\mathbf{E}_{d1}}{\eta_0} \) and \( \bar{R}_{12m}^{H} = z \frac{\mathbf{E}_{d2}}{\eta_0} \). Here, \( \mathbf{E}_{d1} \) and \( \mathbf{E}_{d2} \) represent the aperture electric fields at the slot apertures, \( \mathbf{H}_{SC} = -z \frac{2 E_{0y}}{\eta_0} \) is the short-circuited magnetic field when the slot is covered by a conducting plate, \( E_{0y} \) is the amplitude of the incident electric field, and \( \eta_0 \) is the wave impedance of free space. The kernels are dyadic Green’s functions, expressed as

\[
\bar{K}^{I, II, III}_{ijh}(\bar{r}, \bar{r}') = \frac{1}{j \omega \mu_0} \left( \bar{k}_{0}^2 + \nabla \nabla \right) \cdot G^{I, II, III}_{ijh}(\bar{r}, \bar{r}')
\]
where \( \overline{K}_{ijh}^{I} \), \( \overline{K}_{ijh}^{II} \), and \( \overline{K}_{ijh}^{III} \) are the dyadic Green’s functions of the half space, yielding a magnetic field caused by a magnetic current, and \( i, j = 1 \) or \( 2 \). Here, \( k_0 = \omega \sqrt{\epsilon_0 \mu_0} \) is the wave number in regions I, II, and III, and \( \omega \) is the angular frequency. Superscripts I, II, and III denote the corresponding regions. In addition, \( \vec{T} \) is a unit dyadic, and \( \vec{e} \) is a unit vector in the \( z \)-direction. The position vectors \( \vec{r} \) and \( \vec{r}' \) correspond to the observation and source points, respectively. The time dependence \( \exp(i \omega t) \) is assumed and is omitted throughout this article.

The load currents \( I_1 \) and \( I_2 \) flow across the slot at the connection position \( c_1 \) and \( c_2 \) of the two parallel wires can be expressed as

\[
I_1 = \frac{V_{L1}}{jX_{L1}} = \frac{1}{jX_{L1}} \left( \int_{-b_{1/2}}^{b_{1/2}} E_a(c_1, y) \, dy \right) \quad (3a)
\]

\[
I_2 = \frac{V_{L2}}{jX_{L2}} = \frac{1}{jX_{L2}} \left( \int_{-b_{2/2}}^{b_{2/2}} E_a(c_2, y) \, dy \right) \quad (3b)
\]

where \( V_{L1} \) and \( V_{L2} \) are the voltages at the wire-loading point. Here, \( X_{L1} \) and \( X_{L2} \) are the reactances of the two parallel wires and are expressed as \( X_{L1} = -Z_0 \cot(\beta h_1) \) and \( X_{L2} = -Z_0 \cot(\beta h_2) \), respectively, where \( Z_0 = 120\pi \left( \xi + \sqrt{\xi^2 - 1} \right) \) and \( \xi = s/r \), \( s = b_1/2 + r \) and \( r \) denote the half-spacing and radius of the wires, respectively. In addition, \( \beta \) is the propagation constant of the wires.

The integral equations for aperture magnetic currents in narrow slots are solved by applying Galerkin’s method of moments (MoM). To solve the simultaneous integral equations, the aperture electric fields in the slots, \( E_{a1} \) and \( E_{a2} \), were expressed as

\[
E_{a1} = \sum_{n=1}^{N} v_{1n} F_n(x) \quad \text{and} \quad E_{a2} = \sum_{m=1}^{M} v_{2m} F_m(x).
\]

Where \( v_{1n} \) and \( v_{2m} \) are the coefficients to be determined, and \( F_n(x) \) and \( F_m(x) \) are piecewise sinusoidal expansion functions. The load currents \( I_1 \) and \( I_2 \), i.e. Eq. (3), can then be expressed as follows:

\[
I_1 = -\frac{b_1}{jX_{L1}} \sum_{n=1}^{N} v_{1n} F_n(c_1) \quad (4a)
\]

\[
I_2 = -\frac{b_2}{jX_{L2}} \sum_{m=1}^{M} v_{2m} F_m(c_2) \quad (4b)
\]

In the EMC field, the SE characteristics of region III are considered the most interesting subject. In electromagnetic shielding problems, reduces or ideally prevents the coupling of unwanted electromagnetic energy, and it also reduces the transmission of undesirable emissions through the slot. The SE is typically defined and used for electromagnetic shielding problems. The electric SE at the field point in region III is defined as

\[
SE = 20 \log_{10} \left( \frac{\bar{E}_{II}(\vec{r})}{\bar{E}_0(\vec{r})} \right) \, \text{dB}, \quad (5)
\]

where \( \bar{E}_{II}(\vec{r}) \) and \( \bar{E}_0(\vec{r}) \) are the electric fields at the field point from the plane wave in the presence and absence of conducting ground planes #1 and #2, respectively. In Eq. (5), when a plane wave excites narrow slot #1, the penetrating electric field in region III through narrow slot #2 is obtained in the following form.

\[
\bar{E}_{II} = \frac{1}{j\omega \mu_0} \int_{S'_{a2}} \overline{K}_{m22}^{III} (\vec{r}, \vec{r}') \cdot \left( -\hat{z} \times \bar{E}_{a2} (\vec{r}') \right) \, dS'_{a2} \quad (6)
\]

In this article, it is demonstrated how to obtain enhanced SE through two narrow slots separated by conducting wall spacing using two parallel wires loaded to both slots. Even in the resonant slot, the SE is enhanced by the two parallel wires, resulting in the possibility of reduction in the penetrating electromagnetic field. The lengths of the two parallel wires satisfying the maximum SE at the resonant frequency are calculated using Eq. (5).

### III. NUMERICAL RESULTS AND DISCUSSION

The SE characteristics of an electromagnetic field penetrating through rectangular slots in double-layer walls were investigated. The slot widths used in the calculation were narrow compared with the wavelength, and the slot lengths were half the resonant wavelength. The dimensions of the slots were \( a_1 = a_2 = 3 \) and \( 15 \) cm (resonant at 4.65 and 0.96 GHz, respectively), \( b_1 = b_2 = 1 \) mm, and \( d = 1 \) cm. The frequencies of 4.65 and 0.96 GHz were used to consider the SE in region III of the double-layer walls with narrow half-wavelength slots. The SE in region II was not considered in this study because the EMC problem deals with the penetrating field in region III from the incident electric field of region I.

Fig. 3 shows the SE for narrow slots with \( a_1 = a_2 = 3 \) cm and 15 cm at \( z_p = 5 \) cm in region III without the two parallel wires (unloading case), as shown in Fig. 2(a). As shown in Fig. 3, when \( a_1 = a_2 = 3 \) cm, the worst SE (11.75 dB) occurs at a resonant frequency of 4.65 GHz for the wall spacing \( d = 1 \) cm (\( d = 1.55a_2 \)). When \( a_1 = a_2 = 15 \) cm, the worst SE (−3.66 dB) occurs at a resonant frequency of 0.96 GHz for the wall spacing \( d = 1 \) cm (\( d = 0.032a_2 \)). The worst SE corresponds to the maximum transmission through the slots. This phenomenon is known as “transmission resonance” (maximum transmission) through the slots. In EMC problems, this phenomenon is the worst case for equipment protection. This paper demonstrates how to minimize the maximum transmission of double-layer shielding structures with narrow resonant slots.

Fig. 4 shows the SE characteristics in region III as a function of the conducting wall spacing at 4.65 GHz when the plane wave is incident on narrow slots with \( a_1 = a_2 = 3 \) cm. The SE fluctuates with the wall spacing, and the fluctuation period is approximately 0.5\( a_2 \). In addition, the SE gradually decreases below 0.5\( a_2 \) for all \( z_p \). These periodic SE patterns gradually increase in magnitude with increasing wall spacing (between conducting walls #1 and #2). This is caused by the propagation power in the region of the two parallel conducting walls (region II) from slot aperture #1.
Hence, the penetrating electromagnetic field from slot aperture #2 is very small, as expected. Thus, the wall spacing affects the SE because the electromagnetic power propagates in region II. This study focused on enhancing the SE around the resonant frequencies (i.e., 4.65 and 0.96 GHz) of double-layer shielding structures. The minimum transmission (maximum SE or high-level SE) from the resonant slot with \( a_1 = a_2 = 3 \) and 15 cm and using two parallel wires was considered. The SE in region II was not considered in this study because the SE characteristics of region III are primarily focused in EMC problems.

A method of connecting two parallel wires to the slots was used to enhance the SE for slot lengths of 3 and 15 cm at resonance frequencies of 4.65 and 0.96 GHz, respectively. The two parallel wires connected to the slots act as an ACF, and this method has successfully enhanced the SE in a single-layer slot [11].

The two parallel wires act as a reactance element. Two cases were addressed in this study, as shown in Fig. 2:

1. **Slot #1 loading case**: structure with \( h_1 \) connected to slot #1 — see Fig. 2(b)
2. **Slots #1 and #2 loading case**: structure with \( h_1 \) connected to slot #1 and \( h_2 \) connected to slot #2 — see Fig. 2(c)

In the SE calculation, the field point is selected as \( z_p = 5 \) cm. Fig. 5 shows the SE versus the length of the reactance for slot lengths of 3 and 15 cm at resonant frequencies of 4.65 and
0.96 GHz, respectively, for the slot #1 loading case. For the reactance length of $h_1 = 1.226$ cm, the SE is enhanced to 56.91 dB from 11.75 dB and is approximately 45.16 dB larger than that of the unloaded slot at a resonant frequency of 4.65 GHz. For a reactance length of $h_1 = 6.875$ cm, the SE is enhanced to 41.84 dB from $-3.66$ dB and is approximately 45.50 dB larger than that of the unloaded slot at a resonant frequency of 0.96 GHz. Thus, the SE can be effectively enhanced using two parallel wires connected to slot #1. In addition, adjusting the wall spacing can further increase the SE, as shown in Fig. 4.

For the loading case with slots #1 and #2, Fig. 6(a) shows the SE versus the length $h_2$ for slot lengths of 3 cm at a fixed length of $h_1 = 1.226$ cm. When $h_2 = 1.658$ cm is selected at $h_1 = 1.226$ cm, the SE is enhanced to 77.82 dB from 11.75 dB and is approximately 66.07 dB larger than that of the unloaded slot at a resonant frequency of 4.65 GHz. Fig. 6(b) shows the SE versus length $h_2$ for slot lengths of 15 cm at a fixed length of $h_1 = 6.875$ cm. When $h_2 = 11.438$ cm is selected at $h_1 = 6.875$ cm, the SE is enhanced to 56.62 dB from $-3.66$ dB and is approximately 60.28 dB larger than that of the unloaded slot at a resonant frequency of 0.96 GHz. These results show that the SE of the slots #1 and #2 loading case becomes larger by approximately 20.91 dB for 4.65 GHz and 14.78 dB for 0.96 GHz than that of the slot #1 loading case. Thus, the SE can be more effectively enhanced using two parallel wires connected to slots #1 and #2.

The penetrating electric fields for various values of the positions of the two parallel wires were discussed in an earlier article [11]. When the two parallel wires are connected to the center of the slot aperture, the magnitude of the penetrated electric field is more effectively reduced. Thus, to enhance the SE of double-layer shielding structures, two parallel wires are also connected to the slots at the center positions along the long edge sides. Fig. 7 shows, as an example, the SE for the loading positions of the two parallel wires as a parameter of various lengths of two parallel wires at 4.65 GHz. For the slot #1 loading case, as shown in Fig. 7(a), the SE is effectively enhanced when the two parallel wires of $h_1$ are connected to the center ($c_1 = 0$ cm) of the slot #1. For the case of both slots #1 and #2 loading, the SE is also effectively enhanced by the two parallel wires of $h_2$ connected to the center ($c_2 = 0$ cm) of the slot #2, as shown in Fig. 7(b). In addition, when the two parallel wires are connected to the end ($c_1 = c_2 = 1.5$ cm) of the slots, the SE is the same as the unloading case because the two parallel wires do not affect the aperture electric field of the slot.

Fig. 8 shows the SE versus a radius of the two parallel wires at 4.65 GHz. For $h_1 = h_2 = 2.0$ cm, if the radius increases...
from 1 mm (0.0155λ) to 2 mm (0.031λ), the SE increases by ∼1.9 dB.

Fig. 9(a), (b), and (c) show the amplitude and phase distribution of the aperture electric field in the slots #1 and #2 for the following three cases at resonant frequency of 4.65 GHz. Fig. 9(a) corresponds to the unloading case. Fig. 9(b) corresponds to the slot #1 loading case and Fig. 9(c) corresponds to the case of both slots #1 and #2 loading. For the unloading case, as shown in Fig. 9(a), the peak amplitudes are 0.067 V/m on the slot #1 and 0.041 V/m on the slot #2. Therefore, the aperture electric field in the slot #2 is reduced by ∼38.81% by the presence of the plate #2. For reference, the phases $\phi_1$ and $\phi_2$ of the aperture electric fields in the slots #1 and #2 for the unloading case are almost constant along the x-axis.

When the two parallel wires of $h_1 = 1.226$ cm is connected to the slot #1, i.e., for the slot #1 loading case, the aperture electric field distribution is symmetrical with respect to the center of the slot by the two parallel wires connected to the center of the slot #1, and the aperture field is divided into three parts ($1.5 < x < 0.5$ and $-0.5 < x < 0.5$), as shown in Fig. 9(b). Interestingly, at the center of the slot #1, the peak amplitude remains approximately the same as the unloading case ($\sim 0.067$ V/m), but the peak amplitudes are 0.0018 V/m at the two side secondly maximum similar to the side lobe in the antenna radiation pattern, as shown in Fig. 9(b). In this case, the peak amplitude ($\sim 0.067$ V/m) of the slot #1 is reduced to 2.23 $\times$ 10$^{-4}$ V/m in the slot #2 and the peak amplitude in the slot #2 is reduced by $\sim 96.67\%$ from the amplitude in the slot #1 by use of the loading wires of $h_1 = 1.226$ cm connected to the slot #1. The phase $\Phi_2$ in the slot #2 is gradually changed, but the phase $\Phi_1$ in the slot #1 is seen to be reversed at the position around $x = \pm 0.5$ cm where the aperture electric field distribution is divided into three parts.

For the case of both slots #1 and #2 loading, as shown in Fig. 9(c), when the two parallel wires of $h_1 = 1.226$ cm and $h_2 = 1.658$ cm are connected to both slots #1 and #2, respectively, the peak amplitude in the slot #1 is almost the same as that of case of the slot #1 loading ($\sim 0.067$ V/m).

In this case, the peak amplitude ($\sim 0.067$ V/m) in the slot #1 is reduced to almost zero ($3.42 \times 10^{-6}$ V/m), which clearly shows that more effective enhancement of the SE can be achieved by use of the two parallel wires of $h_2 = 1.658$ cm connected to the slot #2. Therefore, the peak amplitude in the slot #2 is reduced by $\sim 99.95\%$ from the peak aperture electric field of the slot #1 by the loading wires (open stub) connected to both slots #1 and #2. The phase $\Phi_1$ in the slot #1 is almost identical to the case of the slot #1 loading, but the phase $\Phi_2$ in the slot #2 has a greater variation than that of the case of the
FIGURE 10. Frequency characteristics of SE for double-layer shielding structures with narrow slots excited by an incident plane wave.

As a result, the two parallel wires are used as a method of controlling the aperture electric field distribution on the both slots, and thus the SE can be effectively enhanced in the double-layer shielding structures.

Fig. 10 shows the frequency characteristics of the SE for slot lengths of 3 and 15 cm at fixed lengths of \( h_1 \) and \( h_2 \), which give the maximum SE at resonance frequencies of 4.65 and 0.96 GHz, respectively. To compare the SE for the three case structures, Fig. 10 shows the SE of the unloading case, slot #1 loading case, and slots #1 and #2 loading case. For \( a_1 = a_2 = 3 \) cm and slot #1 loading case, when \( h_1 = 1.226 \) cm is selected and fixed, the maximum SE (56.91 dB) is obtained at a resonance frequency of 4.65 GHz. In addition, for the slots #1 and #2 loading case, when \( h_1 = 1.226 \) cm and \( h_2 = 1.658 \) cm are selected and fixed, the maximum SE (77.91 dB) is obtained at a resonance frequency of 4.65 GHz. For the unloading case, an SE of 11.75 dB is obtained at a resonance frequency of 4.65 GHz.

Also, for \( a_1 = a_2 = 15 \) cm and the slot #1 loading case, when \( h_1 = 6.785 \) cm is selected and fixed, the maximum SE (41.84 dB) is obtained at a resonance frequency of 0.96 GHz. In addition, for the slots #1 and #2 loading case, when \( h_1 = 6.875 \) cm and \( h_2 = 11.438 \) cm are selected and fixed, the maximum SE (56.62 dB) is obtained at a resonance frequency of 0.96 GHz. For the unloading case, an SE of 3.66 dB is obtained at a resonance frequency of 0.96 GHz.

As shown in Fig. 10(a), the SE decreases around the frequencies of 3 and 6.5 GHz when the two parallel wires are connected to the slot to enhance the SE at a resonance frequency of 4.65 GHz. Furthermore, as shown in Fig. 10(b), the SE decreases around frequencies of 0.5, 0.7, and 1.3 GHz when the two parallel wires are connected to the slot to enhance the SE at a resonance frequency of 0.96 GHz. These low SE phenomena are thought to originate from the resonance frequency shifted by the two connected wires; however, a high SE can be obtained at the resonant frequency using parallel wires loaded on the slots.

Fig. 11(a) and (b) show how the lengths of the two parallel wires change, providing the maximum SE as the wall spacing changes. For the slot #1 loading case, as shown in Fig. 11(a), the length of the two parallel wires providing the maximum SE as the increase in the wall spacing is almost constant at approximately \( h_1 = 1.226 \) cm. Because the electromagnetic fields penetrating through slot #1 are minimized by the two parallel wires, the length of \( h_1 \) that gives the maximum SE is less affected by the wall spacing. Nevertheless, for the slots #1 and #2 loading case, as shown in Fig. 11(b), the length of \( h_2 \) giving the maximum SE varies from \( h_2 = 1.168 \) cm to 2.284 cm as the wall spacing increases. In addition, the maximum SE increases gradually with an increase in the wall spacing, as expected.
The calculations using Galerkin’s MoM were performed with a ThinkPad Workstation P15 (Intel i7, 2.3 GHz). For the $N = M = 37$, it took 13.23 seconds to obtain the convergent solution for a slot with length $0.5\lambda$ at a single frequency.

The theoretical analysis method was validated by comparing some numerical SE results obtained by this method with the measured results. Fig. 12(a) and (b) show the configuration of the experimental setup and the photograph of the measurement setup, respectively. Two small narrow slots ($15\,\text{cm} \times 1\,\text{mm}$) were constructed on large ground planes ($2 \times 4\,\text{m}$) with a gap of 1 cm in an anechoic chamber. Two parallel wires with a radius of 0.5 mm made of copper were connected at the center of the narrow slot. A broadband double-ridged horn antenna manufactured by KAIST (Model No. ICU-MA-04-2, $0.75 \sim 6\,\text{GHz}$) was used as the transmitting antenna and a shielded small loop antenna with a diameter of 1 cm was used as the receiving antenna. The transmitting antenna was placed 150 cm from the wall to satisfy the far-field condition. The SEs at $z_P = 60\,\text{cm}$ were measured under a normal incidence using an Anritsu MS46322A vector network analyzer. The measured and calculated SEs are shown in Fig. 13. Fig. 13(a), (b), and (c) represent the unloading case, the slot #1 loading case, and the case of both slots #1 and #2 loading, respectively. Also, Fig. 13(d)
shows the measured and calculated SEs versus lengths of the two parallel wires. As shown in Fig. 13, the calculated SEs agree fairly well with the measured data. The deviations in the frequencies below \(~0.5\) GHz are observed and inherent fluctuations remained in the measurements. These deviations and fluctuations were attributed mainly to the influence of finite ground planes and the mutual coupling effects between the antenna and slot, as well as the interactions between the horn antenna and ground plane.

### IV. DOUBLE-LAYER SHIELDING STRUCTURES AND SE PATTERNS BY TWO PARALLEL WIRES

The SE patterns for the double-layer shielding structures can be summarized from the analysis results, as shown in Fig. 14. For the unloading case at the resonant slot length, the minimum SE appeared, as shown in Fig. 14(a). To enhance the SE by loading two parallel wires on the slots, there are two types of loading case: (1) the slot #1 loading case and (2) the slots #1 and #2 loading case. As shown in Fig. 14(b), for the slot #1 loading case, the SE was enhanced by approximately 45 dB from the unloading case by loading two parallel wires on slot #1. In addition, to enhance the SE further from the slot #1 loading case, the two parallel wires should be loaded on slots #1 and #2, as shown in Fig. 14(c). In this case, the SE was enhanced by approximately 66 dB from the unloading case by loading the two parallel wires.

Although the SE can be enhanced at resonant frequencies by connecting the two parallel wires on the slots, low-level SEs appear at low and high frequencies around the resonant frequencies. Methods to enhance the SE in broadband are being studied.

### V. CONCLUSION

The SE characteristics of an incident plane wave that penetrates resonant narrow slots in double-layer shielding structures were investigated. In the analysis, integral equations for aperture magnetic currents were derived and solved by applying Galerkin’s MoM. The numerical results demonstrated that the maximum SE (minimum transmission or high-level SE) can be effectively obtained using parallel wires as loads on the slots. A high SE at the resonant frequency can be realized by connecting the two parallel wires to the slots at the center positions along the long-edge sides. Thus, a useful ACF can be constructed in double-layer conducting walls with narrow slots for minimum transmission (high-level SE) using parallel wires.

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