Degeneration of Shielding Effectiveness of Planar Shields Due to Oblique Incident Plane Waves

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Abstract: This paper addresses shielding effectiveness of multilayer planar shields against oblique incident plane waves in arbitrary polarized and incident direction using TL modelling. New results are presented to confirm the degeneration of the shielding effectiveness due to an oblique incident plane wave. It is also shown that the direction of polarization would be changed when the plane wave penetrates the shield. Previous conclusions for normal incidence can be verified by inserting the normal incidence condition into the new results for oblique incidence.

Keywords: EM leakage, shielding, and transmission line modelling.

1 INTRODUCTION

Electromagnetic shielding is one of the key techniques for protection against illumination from both external fields and electromagnetic leakage from electronic products. Variety of shielding techniques are needed and play crucial roles in either EMC/EMS compliance testing or system design. Previous studies and practices on shielding solved many practical problems, but there are still more that present special challenges to engineers concerned with EMI/EMC.

As for the planar shielding case, there are few publications [1,2] which address the validity of transmission line (TL) modelling for shielding effectiveness for normal plane wave incidence. However, previous studies [1,3] ignored that shielding effectiveness may vary widely with the direction of both polarization and angle of incidence of the incident wave. There are currently few published works which address the equivalence of transmission line modelling and shielding effectiveness for oblique incident plane wave, i.e., a plane wave that might be in arbitrary polarization and incidence angle with the shield plane.

A shielding effectiveness is usually evaluated or calculated with respect to a normal incident field instead of arbitrary orientation. This could lead to significant errors if a practical shielding design is based on such assumptions. In many practical problems, the direction of incident plane wave may be arbitrary instead of normal to the shield surface. In such case, the direction of polarized electric and magnetic fields may be neither normal nor vertical to the plane of the incident and refracted wave. Thus, the results for a normal incident wave are not valid. It seems quite common that practical shielding effectiveness may differ substantially from theoretical models if these models are not justified. As for a planar shield, TL modelling is an effective approach to calculate shielding effectiveness of planar shields against normal incident plane wave. However, an extensive study needs to be carried out on the validity of the TL modelling for plane wave in arbitrary polarized and incident direction. In other words, it is necessary to have a model to account for the degeneration in shielding effectiveness due to oblique incident fields.

In this paper, results are presented to confirm the degeneration of the shielding effectiveness due to an oblique incident plane wave. First, the shielding effectiveness for a multilayer planar shield for a normal incident plane wave is derived by transmission line model. Unlike previous results [1], the factor \( \exp\left[ j \omega \left( \sum_{k=1}^{n} l_k \right) \right] \) appears in the new formulation, indicating the shielding effect would be reduced in conductive media like water and the earth. Furthermore, to validate the TL modelling, the plane wave in arbitrary direction of incidence and polarization is divided into three groups of components, two of which are orthogonal series corresponding to normal incident waves. It is proved that the direction of polarization could be changed when the plane wave penetrating through the shield. The difference between oblique and normal incidence in shielding effect depends on the direction of both incidence and polarization.

In the oblique incidence case, the transmission coefficient would be more complex. In general, the equi-amplitude plane is not parallel to the equi-phase plane in the refracting region. Thus, the uniform plane wave would be changed to a nonuniform plane wave. But in conductive shields, it is proved that the wave transmission and the amplitude loss are in the same direction and normal to the shield surface. Thus, the conclusions for normal incidence are still valid in the conductive region and the shielding effectiveness for multilayer shields to arbitrary incident plane wave could be easily calculated. According to this concept, the shielding effectiveness for a multilayer plane screen against incident plane waves in arbitrary direction is finally arrived, and the conclusions for normal incidence could be easily derived by the new results.

2 MODELS FOR PLANAR SHIELDS AGAINST NORMAL INCIDENT WAVE

2.1 Field method for single layer shield

Fig.1 shows a single layer planar shield against normal incident plane wave and its equivalent transmission line circuit. Suppose \( E_x \) is the strength of the incident electric field. From electromagnetic theory, the electric and magnetic fields satisfy the following relations

\[
F_x(x) = F_0 e^{-j\omega x} + F_0' e^{j\omega x} \quad (1a)
\]
\[
E_x(x) = A e^{-j\omega x} + B e^{j\omega x} \quad (1b)
\]
\[
H_x(x) = C e^{-j\omega x} \quad (1c)
\]

Fig.1 (a) Single plane shield, (b) its equivalent TL circuit

\[
H_0(x) = \frac{1}{\eta_0} \left( E_0 e^{-j\omega x} - E_0' e^{j\omega x} \right) \quad (2a)
\]
\[
H_1(x) = \frac{1}{\eta_1} \left( A e^{-j\omega x} - B e^{j\omega x} \right) \quad (2b)
\]
\[
H_s(x) = \frac{C}{\eta_2} e^{-j\omega x} \quad (2c)
\]

where \( \eta_i = \sqrt{\frac{j \omega \mu_i}{\sigma_i + j \omega \epsilon_i}} \) and \( \gamma_i = \sqrt{j \omega \mu_i \left( \sigma_i + j \omega \epsilon_i \right)} = \alpha_i + j \beta_i \) are wave impedance and complex propagation constant in media \( i \).
If \( n_0 = n_2 \), the shield is inserted in a homogeneous media. In free space, \( n_0 = \sqrt{\mu_0/\varepsilon_0} \), \( \alpha = 0 \), and \( \beta = \frac{2\pi}{\lambda} \). The constant \( C \) in (2) can be determined using boundary conditions,

\[
C = \frac{4n_0n_2E_o}{(n_0 + n_1)(n_1 + n_2)} \exp(-y_2, \gamma_y) \left( 1 - \frac{(n_1 - \alpha_0)(n_1 + n_2)}{(n_0 + n_1)(n_1 + n_2)} \exp(-2\gamma_y l) \right)
\]

Then, the shielding effectiveness of the single shield against electric and magnetic fields at \( x = l \) can be determined respectively by

\[
SE = -20 \log \left[ \left| \mathbb{T} \right| \right]
\]

\[
S_H = -20 \log \left[ \left| \mathbb{H} \right| \right]
\]

in which

\[
\mathbb{T} = \frac{E(x)}{E_0} \exp(-\gamma_x x)
\]

\[
\mathbb{H} = \frac{H(x)}{H_0} \exp(-\gamma_x x)
\]

where

\[
P_H = \frac{4n_0n_2}{(n_0 + n_1)(n_1 + n_2)}
\]

\[
P_E = \frac{4n_0n_2}{(n_0 + n_1)(n_1 + n_2)}
\]

\[
q_1 = \frac{(n_1 - \alpha_0)(n_1 - n_2)}{(n_0 + n_1)(n_1 + n_2)}
\]

Unlike [1], the factor \( \exp(\gamma_x l) \) appears in (4) which may reduce the shielding effectiveness if the medium on both sides of the shield is conductive. However, if media 0 and 2 are identical, i.e., \( n_1 = n_0 \), the shield effects for electric and magnetic fields are the same. In fact, the results in reference [1] reflect transmission attenuation instead of shield effectiveness, because the factor \( \exp(\gamma_x l) \) was not taken into account.

It would be much more difficult to use the field method to analyze the multilayer shield against plane wave. However, it is convenient if such analysis is based on a transmission line model.

### 2.2 Transmission line model for multilayer shield

The equivalent circuit to represent a single layer planar shield is shown in Fig.1(b). According to TL modelling, the voltage and current at \( x = l \) satisfy

\[
V(l) = \frac{Z_c}{Z_c \cosh(\gamma y) + Z_c \sinh(\gamma y)} V(0)
\]

\[
I(l) = \frac{Z_c}{Z_c \cosh(\gamma y) + Z_c \sinh(\gamma y)} I(0)
\]

where \( V(0) \) and \( I(0) \) are voltage and current at \( x = 0 \). \( \gamma = \sqrt{Z_c} \) denotes the propagation constant, \( Z_c = \frac{V(l)}{I(l)} \) the load impedance at \( x = l \), and \( Z_c \) the characteristic impedance of the circuit. The input impedance of the circuit is the impedance seen at \( x = 0 \) toward the right hand side and is given by

\[
Z_{in} = \frac{Z_c \cosh(\gamma y) + Z_c \sinh(\gamma y)}{Z_c \sinh(\gamma y) + Z_c \cosh(\gamma y)}
\]

Corresponding to (5a) and (5b), the electric field, magnetic field, and input impedance at \( x = l \) with respect to a infinite planar shield of thickness \( l \) can be expressed by [1]

\[
E(l) = \frac{Z(l)}{Z_c \cosh(\gamma y) + Z_c \sinh(\gamma y)} E(0)
\]

\[
H(l) = \frac{Z(l)}{Z_c \cosh(\gamma y) + Z_c \sinh(\gamma y)} H(0)
\]

\[
Z_{in} = \frac{Z(l)}{Z_c \cosh(\gamma y) + Z_c \sinh(\gamma y)}
\]

where \( n_0 \) and \( \gamma \) represent characteristic impedance and propagation constant of the shield; \( Z(l) = \eta_1 \) is the load impedance at \( x = l \); and \( E(0) \) and \( H(0) \) represents the electric and magnetic fields at \( x = 0 \). They are not the same as the incident wave.

At \( x = 0 \), the following relationship can be arrived by using field boundary conditions or transmission line equations

\[
\frac{E(0)}{E_0} = \frac{Z_{in} - Z_2}{\eta_0 + Z_2}, \quad \frac{H(0)}{H_0} = \frac{Z_{in}}{\eta_0 + Z_2}
\]

According to the definition of shielding effectiveness in (3), the ratio of transmitted electric and magnetic fields to incident fields at \( x = l \) can be given by

\[
T_E = \frac{E(l)}{E(0)} = \frac{E(l)}{E(0)} = \frac{Z_{in}}{\eta_0 + Z_2}
\]

\[
T_H = \frac{H(l)}{H(0)} = \frac{H(l)}{H(0)} = \frac{Z_{in}}{\eta_0 + Z_2}
\]

where

\[
P_E = \frac{4n_0n_2}{(n_0 + n_1)(n_1 + n_2)}
\]

\[
P_H = \frac{4n_0n_2}{(n_0 + n_1)(n_1 + n_2)}
\]

\[
q_1 = \frac{(n_1 - \alpha_0)(n_1 - n_2)}{(n_0 + n_1)(n_1 + n_2)}
\]

Noticing \( Z(l) = \eta_1 \), it is obvious that the results in (12) using TL modelling are identical to those in (4) using field method. It is apparent as well that if the media at both sides of the shield are identical, i.e., \( Z_2 = \eta_2 \), the shield effects for electric and magnetic fields are identical. Furthermore, the factor \( \exp(\gamma_x l) \) appears again in the shielding effectiveness, showing that the shielding effectiveness would be reduced if the medium on both sides of the shield is conductive.

It is convenient to model the shielding performance of a multilayer planar shield against normal incident plane waves using TL modelling. For multilayer shielding against plane waves, the
transmission line method is still valid and much simpler than the field method. Fig.2 shows a multilayer planar shield against normal incident plane waves and its equivalent transmission line circuit. Similar to the above analysis, the input impedance of the multilayer shield seen at the left hand boundary of the $i$th layer toward its right hand side is determined by

$$Z_{in}(l_i) = \eta_1 \frac{Z(l_i) \cosh(y_i l_i) + \eta_i \sinh(y_i l_i)}{Z(l_i) \sinh(y_i l_i) + \eta_i \cosh(y_i l_i)} \quad i = 1, 2, \ldots, n$$

where $l_i$, $\eta_i$, and $Z(l_i)$ respectively represent the thickness, wave impedance, and load impedance, of the $i$th layer. Also, $Z_{in}(l_1) = Z(l_{i-1})$ and $Z_{in}(l_n) = \eta_{n+1}$.

![Fig.2 (a) multilayer plane shield, (b) its equivalent TL circuit](image)

For a two layer shield ($n = 2$), the shield ratio against electric and magnetic fields could be similarly determined by

$$T_e = \frac{E(l_1 + l_2)}{E_0} = \frac{E(l_1)}{E_0} \frac{E(l_1 + l_2)}{E(l_1)}$$

$$T_H = \frac{H(l_1 + l_2)}{H_0} = \frac{H(l_1)}{H_0} \frac{H(l_1 + l_2)}{H(l_1)}$$

From transmission line principles, $E(l_1 + l_2)$ and $H(l_1 + l_2)$ satisfy

$$E(l_1 + l_2) = \frac{Z(l_2)}{Z(l_1) \cosh(y_1 l_1 + y_2 \sinh(y_1 l_1))} E(l_1)$$

$$H(l_1 + l_2) = \frac{\eta_1}{\eta_1 \cosh(y_1 l_1 + Z(l_2) \sinh(y_1 l_1))} H(l_1)$$

Inserting (7) and (15) into (14), leads to

$$T_e = P_E \frac{\exp(-y_1 l_1 - y_2 l_2 + y_0 l_1)}{[1 - q_1 \exp(-2y_1 l_1)][1 - q_1 \exp(-2y_2 l_2)]}$$

$$T_H = P_H \frac{\exp(-y_1 l_1 - y_2 l_2 + y_0 l_1)}{[1 - q_1 \exp(-2y_1 l_1)][1 - q_1 \exp(-2y_2 l_2)]}$$

where

$$P_H = \frac{2^3 \eta_0 \eta_1 \eta_2}{(\eta_0 + \eta_1)(\eta_1 + \eta_2)(\eta_1 + Z_L)}$$

$$P_E = \frac{2^3 \eta_0 \eta_1 Z_L}{(\eta_0 + \eta_1)(\eta_1 + \eta_2)(\eta_1 + Z_L)}$$

$$q_i = \frac{\eta_i - \eta_{i-1}}{(\eta_i + \eta_{i-1})(\eta_i + Z_L)} \quad i = 1, 2$$

Therefore, when the media at both sides of the shield are identical, i.e., $Z_L = \eta_1 = \eta_0$, the shield effectiveness for electric and magnetic fields are the same.

For multilayer shields ($n$ layers), the electric field and magnetic field in each layer satisfy

$$E(x_i) = \frac{Z(l_i)}{Z(l_i) \cosh(y_i l_i) + \eta_i \sinh(y_i l_i)} E(x_{i-1})$$

$$H(x_i) = \frac{\eta_i}{\eta_i \cosh(y_i l_i) + Z(l_i) \sinh(y_i l_i)} H(x_{i-1})$$

where $x_i = \sum_{j=1}^{i} l_j, \quad i = 1, 2, \ldots, n$.

Similar to previous discussion, the shield ratio can be similarly obtained using (10) and (17)

$$T_e = P_E \prod_{i=1}^{n-1} \frac{\exp(-y_1 l_i - y_2 l_i)}{[1 - q_i \exp(-2y_1 l_i)][1 - q_i \exp(-2y_2 l_i)]}$$

where $a$ represents $E$ and $H$, corresponding to electric and magnetic fields respectively, and

$$P_E = \frac{2^{n-1} \eta_1 \eta_2 \ldots \eta_n Z_n}{(\eta_0 + \eta_1)(\eta_1 + \eta_2) \ldots (\eta_n + Z_n)}$$

$$P_H = \frac{2^{n-1} \eta_1 \eta_2 \ldots \eta_n Z_n}{(\eta_0 + \eta_1)(\eta_1 + \eta_2) \ldots (\eta_n + Z_n)}$$

$$q_i = \frac{\eta_i - \eta_{i-1}}{(\eta_i + \eta_{i-1})(\eta_i + Z_L)} \quad i = 1, 2, \ldots, n$$

The shielding effectiveness corresponding to (18) can be then determined by

$$S_e = -20 \log |T_e|$$

When $Z(l_i) = \eta_{i+1} = \eta_0$, the shielding effectiveness against electric and magnetic fields are the same. In other words, if the wave impedance of the media outside the two side of a multilayer shield are the same, the shielding effectiveness against electric and magnetic fields would be the same.

3 SHIELD AGAINST OBLIQUE INCIDENT PLANE WAVE

In many practical applications, especially in problems of suppression and protection against electromagnetic radiation, the direction of incident plane wave may be arbitrary instead of normal to the shield surface. In such cases, the direction of polarized electric and magnetic fields may neither be normal nor vertical to the plane of the incident and refracted wave. This section will discuss this situation in detail and calculate the shielding effectiveness against arbitrary incident plane waves.

As shown in Fig.2, the $z$ axis represents normal direction of the shield, and $\theta_0$ the angle between propagation direction of incident wave and $z$ axis; $xoy$ plane coincides with the first plane of the shield, $xoz$ represents the incident plane, and plane $x'oy'$ is parallel with the plane of electric and magnetic fields; $\phi$ is the angle between the $x'$ axis and electric field.

In order to utilize the results for the normal incident situation discussed above, the incident electric and magnetic fields are divided into three groups of normal components: A, B, and C. The
components in group A and B are parallel to the shield boundary surface, while the components in group C are perpendicular to the boundary surface. Suppose \( y' \) is always in parallel with \( y \) regardless of change in angle \( \theta_0 \) between plane \( x'y'z' \) and \( xoy \). These three groups of components could be written as

\[
H_{y'} = H_{y'} \sin \theta_0 \cos \phi \]

\[
E_{y'} = E_{y'} \sin \phi \cos \theta_0 \]

Fig. 2 Abnormal incident plane wave

Group A:

\[
E_A = E \sin \phi \\
H_A = H \sin \phi \cos \theta_0 \]

(21)

Group B:

\[
E_B = E \cos \phi \cos \theta_0 \\
H_B = H \cos \phi \]

(22)

Group C:

\[
E_C = E \cos \phi \sin \theta_0 \\
H_C = H \sin \phi \sin \theta_0 \]

(23)

where group A and B are orthogonal series and parallel to the shield surface, corresponding to normal incident wave; while group C is vertical to the shield surface.

According to previous discussion on normal incident shielding, components in group A and B could be regarded as two sets of normal incident plane waves. Suppose \( E_{a1}, E_{b1}, H_{a1}, \) and \( H_{b1} \) represent transmitted field components in group A and B. The shielding ratio of the field components for group A and B could be expressed by

\[
T_e = \frac{E_{a2}}{E_a} = \frac{4 \eta_0 \eta_1}{(\eta_1 + \eta_0)} \left[ 1 + \frac{(\eta_2 - \eta_1)^2}{(\eta_1 + \eta_2)} \right] \exp(-2 \gamma / l) \exp(-\gamma / l) \]

(24a)

\[
T_h = \frac{H_{a2}}{H_a} = \frac{4 \eta_0 \eta_1}{(\eta_1 + \eta_0)} \left[ 1 + \frac{(\eta_2 - \eta_1)^2}{(\eta_1 + \eta_2)} \right] \exp(-2 \gamma / l) \exp(-\gamma / l) \]

(24b)

For conductive shields, \( \eta_0 >> \eta_1, \eta_2 >> \eta_1, \) and \( \eta_0 >> \eta_1, \) the above two equations become

\[
T_e \approx \frac{2 \eta_1}{\eta_1 \sinh(y/l)} \\
T_h \approx \frac{2 \eta_1}{\eta_1 \sinh(y/l)} \]

(25a)

The total incident electric and magnetic fields in the tangential direction parallel to the shield surface can be obtained as follows from (21) and (22)

\[
E_i = \sqrt{E_{a1}^2 + E_{b1}^2} = \frac{2 \eta_0 E}{\sinh(y/l)} \sqrt{1 - \sin^2 \phi \sin^2 \theta_0} \]

(26a)

\[
H_i = \sqrt{H_{a1}^2 + H_{b1}^2} = \frac{2 \eta_0 H}{\sinh(y/l)} \sqrt{1 - \sin^2 \phi \cos^2 \theta_0} \]

(26b)

Physical properties of the incident wave are the same as the transmitted wave, and the component of the transmitted wave \( E_{c2} \) and \( H_{c2} \) can be determined by using relation in (29), i.e.,

\[
E_{c2} = \frac{2 \eta_1 \cos \phi \tan \theta_0}{\eta_0 \sinh(y/l)} E \\
H_{c2} = \frac{2 \eta_1 \sin \phi \sin \theta_0 \cos \theta_0}{\eta_0 \sinh(y/l)} H \]

(30a)

(30b)

The total transmitted electric and magnetic fields can be obtained as follows using (27), (30), and (24)

\[
E_z = \sqrt{E_{a2}^2 + E_{b2}^2} = \frac{2 \eta_0 E}{\sinh(y/l)} \sqrt{\sin^2 \phi \cos^2 \theta_0 + \cos^2 \phi \cos^2 \theta_0} \]

(31a)

\[
H_z = \sqrt{H_{a2}^2 + H_{b2}^2} = \frac{2 \eta_0 H}{\sinh(y/l)} \sqrt{\sin^2 \phi \cos^2 \theta_0 + \cos^2 \phi \cos^2 \theta_0} \]

(31b)

It is obvious and expected as well that \( E_z = \eta_0 H_z \). This shows that the transmitted electric and magnetic fields satisfy the same relation as the incident wave.

Using (31), the shielding effectiveness for planar shield against oblique incident plane wave with arbitrary incident angle \( \theta_0 < \frac{\pi}{2} \) can be derived as

\[
S = -20 \log \left( \frac{2 \eta_0}{\eta_0 \sinh(y/l)} \sqrt{\sin^2 \phi \cos^2 \theta_0 + \cos^2 \phi \cos^2 \theta_0} \right) \]

(32)

It is apparent that the shielding effectiveness depends not only on the property of shielding material, but also the directions of both incidence and polarization. This effect due to the oblique incidence may degenerate the expected shielding efficiency and thus should be taken into account in design of a practical shield. (32) can simplified to the following results with different incident
and polarized angles:

a. When \( \theta_0 = 0 \), it is in agreement with the result of normal incidence [1];

b. When \( \varphi = \pi/2 \), the result is identical to that of vertical incidence (corresponding to incident and refracted plane) [4];
c. If \( \varphi = 0 \), the result is identical to that of parallel incidence [4].

The difference of shielding effectiveness between oblique incidence and normal incidence can be evaluated by

\[
\Delta_s = 10 \log \left| \sin \varphi \cos^2 \theta_0 + \frac{\cos^2 \varphi}{\cos \theta_0} \right|
\]

Fig. 4 shows the variation of the shielding effectiveness against the oblique incident plane wave with respect to the normal incident plane wave of the same field strength. The variation of the shielding effectiveness with respect to both the incident angle and polarization angle of the incident wave could be nearly 30 dB for the same incident angle \( \theta_0 \), and up to 60 dB for different \( \theta_0 \). However, if \( \theta_0 \leq 10 \), the variation would be less than 10 dB.

It can also be proved that oblique incidence would lead to change in polarization. Using (21), (22), (24), and (25), the polarization of incident and transmitted electric field is determined respectively by

\[
\tan \varphi = \frac{E_1}{E_\theta \cos \theta_0} \tag{34}
\]
\[
\tan \varphi = \frac{E_2}{E_\theta \cos \theta_0} = \cos \theta_0 \tan \varphi \tag{35}
\]

Thus, the change in the polarization angle is

\[
\Delta \varphi = \arctan(\cos^2 \theta_0 \tan \varphi) - \varphi \tag{36}
\]

The change in (36) is produced purely by the shield itself. There would be an additional change in polarization if the incident wave is a non-linear polarized wave, e.g., elliptically polarized wave.

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**Fig. 4 Variation of SE with respect to normal incidence**

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It should be emphasized that oblique incidence would make the propagation constant in the shield (refracted region) more complex [4]. In such cases, the equi-amplitude surface and equi-phase surface do not coincide. The uniform plane wave would become a nonuniform plane wave in which the equi-amplitude surface would be parallel to the boundary surface of the shield and the equi-phase surface would be in the direction of wave propagation. For the conductive shield, however, the two surfaces would be parallel to shield boundary and the conclusions for normal incidence would be still valid inside the shield.

For multilayer shields, the above method and result can be still applied. Suppose \( T_e \) and \( T_s \) represent shielding ratios for multilayer shields corresponding to group A and B. Then the total shielding effectiveness against oblique incident wave can be given by

\[
\Delta_s = 10 \log \left[ T_e^2 \sin^2 \varphi \cos^2 \theta_0 + T_s^2 \cos^2 \varphi \right] \tag{37}
\]

where \( T_e \) and \( T_s \) are given by (18), and \( \eta_0 \) is replaced by \( \eta_e \) and \( \eta_s \).

**Conclusions**

Equation (37) can be applied to calculate shielding effectiveness for multilayer planar shields against plane waves with arbitrary incidence and polarization direction. It should be noted that the planar shield is assumed to extend infinitely, and thus, diffraction effects are neglected.

It is proven that the shielding effectiveness of a planar shield may vary widely when it is used to screen an oblique incident plane wave. However, as shown in Fig. 4, the decline of the shielding effectiveness may take place only for certain orientations. The maximum decline would be around 10 dB at \( 80^\circ \leq \varphi \leq 90^\circ \) and \( 50^\circ \leq \theta_0 \leq 75^\circ \). In order to avoid such variation from the expected shielding effectiveness, it seems necessary to consider an extra 10 dB margin in practical design of a planar shield.

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**References**


