Electromagnetic Scattering by Nonplanar Junctions of Resistive Sheets

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***Abstract*—Approximate uniform asymptotic expressions are provided to determine the field scattered by a penetrable wedge illuminated at normal incidence. The wedge is formed by two resistive sheets or two thin dielectric slabs definable as resistive sheets having identical geometric and electromagnetic characteristics. The solution is limited to wedge angles and source positions where internal reflections cannot occur. It is obtained by using a geometrical optics (GO) approximation for the field internal to the slabs and by performing a uniform asymptotic evaluation of the physical optics (PO) radiation integral in the hypothesis that a resistive sheet condition is valid. Samples of numerical results so obtained are presented and compared with other methods to demonstrate the effectiveness of the proposed technique.**

***Index Terms*—Electromagnetic scattering, resistive sheets.**

I. INTRODUCTION

THE high-frequency description of scattering by edges in penetrable surfaces is of interest in a large class of applications. In this context, resistive sheet conditions may provide a useful model for several practical configurations. Rigorous integral solutions have been presented in literature for the canonical problem concerning planar junctions between dielectric sheets. These solutions have been derived by applying either the Wiener–Hopf's technique or the Maliuzhinets' method [1]. In the case of an unpenetrable impedance wedge, Maliuzhinets' technique [2] allows one to determine appropriate integral representations. A heuristic method for developing an approximate diffraction coefficient concerning a thin dielectric half-plane has been derived in [3] and extended by Marhefka [4] to junctions between dielectric sheets forming resistive wedges. When considering a junction of two dielectric slabs joined at an arbitrary angle, Maliuzhinets technique produces a functional equation that has not yet been solved analytically [5]. Only recently, resorting to the Maliuzhinets' technique and by imposing the resistive boundary conditions, four coupled functional equations have been derived. Then, by following a mixed analytical-numerical procedure, the two unknown spectral functions have been obtained [6].

An approximate high-frequency solution in the framework of the uniform theory of diffraction (UTD) [7] for the scattering of a TM$_z$ plane wave orthogonally incident on a penetrable wedge, surrounded by free-space, is presented in this paper. The wedge

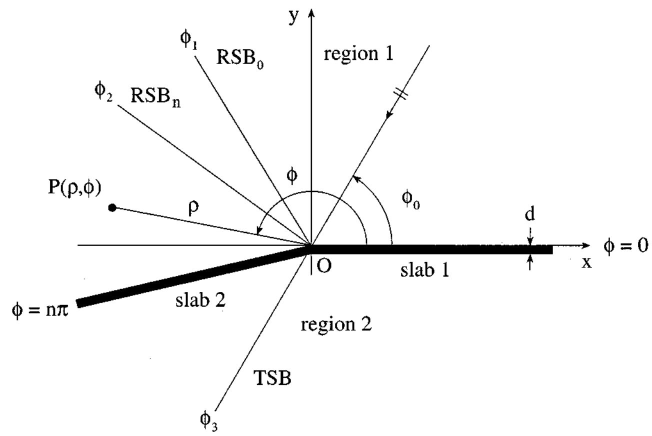

Fig. 1. Geometry of the problem and shadow boundaries.

is composed by two identical dielectric slabs joined at an arbitrary angle. The solution is based on the hypothesis that the resistive sheet condition is valid and uses a physical optics (PO) approximation for the surface current densities. The proposed approach has been previously introduced to determine an approximate uniform solution for the diffraction coefficients relevant to an anisotropic half-plane [8]. Moreover, to obtain a better confidence about the analytical results, a rigorous integral method leading to a single boundary integral equation is also employed [9].

The formulation of the problem is reported in Section II and a PO approximation of the radiation integral is given in Section III. Expressions for the diffracted field in the context of uniform asymptotic PO (UAPO) solutions are given in Section IV. In Section V the aforementioned integral technique is introduced as reference solution to validate the analytical UAPO solution. Finally, some numerical results are shown in Section VI and compared with those available in the literature in order to test the accuracy of the proposed technique. Conclusions are collected in Section VII.

II. FORMULATION OF THE PROBLEM

The geometry of the considered scattering structure is depicted in Fig. 1. The z-axis of the cylindrical coordinate system is directed along the edge of the wedge formed by the junction of two thin dielectric slabs with the same electromagnetic characteristics (ε_r is their complex relative permittivity). Since the scattering problem does not depend on the z coordinate, we will suppose that the resulting two-dimensional problem is in the plane $z = 0$ from this point on. The first slab is located at $\phi = 0$ and the latter is at $\phi = n\pi = (1 + \Delta)\pi$, where Δ represents

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the deviation from the planar case. This structure divides the surrounding space (assumed to be free-space) in two regions: the exterior region (region 1, $0 < \phi < n\pi$) and the interior region (region 2, $n\pi < \phi < 2\pi$). A time harmonic plane wave impinges normally on the edge of the wedge from a direction ϕ_0, belonging to the exterior region. In this work the analysis is limited to a TM$_z$ ($H_z^i = 0$) polarized plane wave and an $e^{j\omega t}$ time dependence is assumed and suppressed in the following. The corresponding incident electric field is given by

$$\underline{E}^i = E_z^i \hat{z} = u^i(\rho,\phi)\hat{z} = e^{jk\rho\cos(\phi-\phi_0)}\hat{z} \tag{1}$$

k being the free-space wavenumber.

The total field $u(\rho,\phi) = E_z(\rho,\phi)$ must satisfy the Helmholtz equation together with appropriate resistive sheet conditions [1] at the dielectric slabs

$$\begin{cases} u(\rho,\phi=0^+) = u(\rho,\phi=2\pi^-) \\ \dfrac{1}{\rho}\left[\left.\dfrac{\partial u(\rho,\phi)}{\partial\phi}\right|_{\phi=0^+} - \left.\dfrac{\partial u(\rho,\phi)}{\partial\phi}\right|_{\phi=2\pi^-}\right] \\ \quad -jk\dfrac{\zeta}{R_s}u(\rho,\phi=0) = 0 \end{cases} \tag{2}$$

$$\begin{cases} u(\rho,\phi=n\pi^+) = u(\rho,\phi=n\pi^-) \\ \dfrac{1}{\rho}\left[\left.\dfrac{\partial u(\rho,\phi)}{\partial\phi}\right|_{\phi=n\pi^-} - \left.\dfrac{\partial u(\rho,\phi)}{\partial\phi}\right|_{\phi=n\pi^+}\right] \\ \quad +jk\dfrac{\zeta}{R_s}u(\rho,\phi=n\pi) = 0 \end{cases}. \tag{3}$$

In (2) and (3), ζ is the free-space impedance and

$$R_s = \frac{-j\zeta}{kd(\varepsilon_r - 1)} \tag{4}$$

is the so-called resistivity of the dielectric sheet, which is a complex scalar quantity independent of the position and depending on the geometric and electric characteristics of the sheet ("d" is the thickness of the slabs). In presence of losses, ε_r can include the effects of conductivity assuming complex values.

III. Physical Optics Approximation of the Radiation Integral

The polarization currents induced by the incident plane wave in the dielectric slabs can be interpreted as sources of the scattered field $u^s(\rho,\phi)$, which can be expressed as

$$u^s(\rho,\phi) = u(\rho,\phi) - u^i(\rho,\phi) = I_0(\rho,\phi) + I_{n\pi}(\rho,\phi) \tag{5}$$

where $I_{0,n\pi}$ are the standard radiation integrals relevant to the two slabs. By applying the volumetric equivalence theorem in the resistive sheet hypothesis, the resulting surface polarization currents $j_{s_{0,n\pi}}$ can be simply written as a function of the tangential components of the total electric field evaluated at the generic point (ρ',ϕ') on the sheets

$$\begin{aligned} j_{s_{0,n\pi}}&(\rho',\phi'=0,n\pi) \\ &= j\omega d\varepsilon_0(\varepsilon_r - 1)u(\rho',\phi'=0,n\pi). \end{aligned} \tag{6}$$

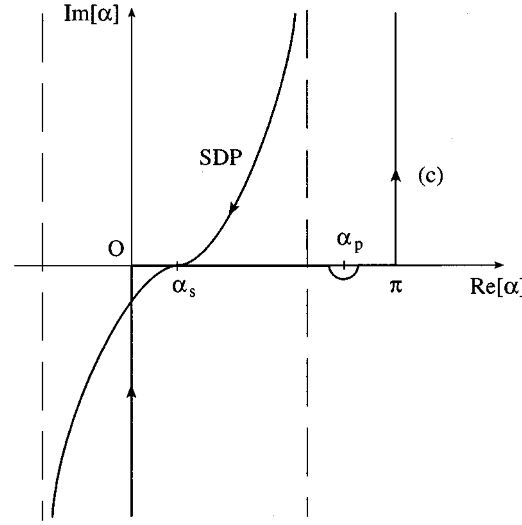

Fig. 2. Closed integration path (c) + SDP in the complex α-plane.

Accordingly, it results in

$$\begin{aligned} I_{0,n\pi}(\rho,\phi) = \frac{k\zeta}{R_s}\int_0^{+\infty} & G(\rho,\phi;\rho',\phi'=0,n\pi) \\ & \times u(\rho',\phi'=0,n\pi)\,d\rho' \end{aligned} \tag{7}$$

where $G(\rho,\phi;\rho',\phi')$ is the free-space Green's function. When dealing with the sheet at $\phi = 0$, the following integral representation [10] on the path (c) depicted in Fig. 2 can be assumed for the Green's function in (7)

$$\begin{aligned} G(\rho,\phi,&\rho',\phi'=0) \\ &= -\frac{1}{4\pi}\int_{(c)} e^{jk\rho'\cos\alpha}e^{-jk\rho\cos(\alpha+q_0\phi)}\,d\alpha \end{aligned} \tag{8}$$

where

$$q_0 = \begin{cases} -1, & \text{for } \{0 < \phi < \pi\} \\ 1, & \text{for } \{\pi < \phi < 2\pi\}. \end{cases} \tag{9}$$

An analogous expression holds for the Green's function relevant to the sheet at $\phi = n\pi$.

The unknown total field appearing in the radiation integrals can be estimated by applying a geometrical optics (GO) approximation, which, in the hypothesis that both faces are directly illuminated, gives

$$\begin{aligned} u(\rho',\phi'=0) &= T(R_s,\phi_0)e^{jk\rho'\cos\phi_0} \\ &= [1+\Gamma(R_s,\phi_0)]e^{jk\rho'\cos\phi_0} \end{aligned} \tag{10}$$

$$\begin{aligned} u(\rho',\phi'=n\pi) &= T(R_s,n\pi-\phi_0)e^{jk\rho'\cos(n\pi-\phi_0)} \\ &= [1+\Gamma(R_s,n\pi-\phi_0)]e^{jk\rho'\cos(n\pi-\phi_0)}. \end{aligned} \tag{11}$$

This corresponds to a PO approximation of the currents in the radiation integrals. In the above relations, the functions

$$\Gamma(R_s,\xi) = -\frac{\zeta}{\zeta + 2R_s\sin\xi} \tag{12}$$

$$T(R_s,\xi)=1+\Gamma(R_s,\ \xi)=\frac{2R_s\sin\xi}{\zeta+2R_s\sin\xi} \qquad (13)$$

are the reflection and transmission coefficients, respectively, at the interface of the dielectric half-planes.

By substituting the relations (8) and (10) in (7), we obtain

$$I_0(\rho,\phi)=-\frac{k\zeta}{4\pi R_s}T(R_s,\phi_0)\int_{(c)}e^{-jk\rho\cos(\alpha+q_0\phi)} \times\int_0^{+\infty}e^{jk\rho'(\cos\alpha+\cos\phi_0)}\,d\rho'\,d\alpha. \qquad (14)$$

By taking into account that [11]

$$e^{jk\rho\cos\xi}=\frac{1}{2\pi j}\int_\gamma\frac{j}{1-e^{j\eta}}e^{jk\rho\cos(\xi-\eta)}\,d\eta \qquad (15)$$

where γ is the Sommerfeld's integration contour, and by applying the Sommerfeld-Maliuzhinets' inversion formula [12], (14) can be rewritten as follows:

$$I_0(\rho,\phi)=\frac{1}{2\pi j}\frac{\zeta\sin\phi_0}{\zeta+2R_s\sin\phi_0} \times\int_{(c)}\frac{1}{\cos\alpha+\cos\phi_0}e^{-jk\rho\cos(\alpha+q_0\phi)}d\alpha. \qquad (16)$$

The same procedure, applied to the $I_{n\pi}$ integral gives

$$I_{n\pi}(\rho,\phi)=\frac{1}{2\pi j}\frac{\zeta\sin(n\pi-\phi_0)}{\zeta+2R_s\sin(n\pi-\phi_0)} \times\int_{(c)}\frac{e^{-jk\rho\cos(\alpha+q_n(\phi-n\pi))}}{\cos\alpha+\cos(\phi_0-n\pi)}\,d\alpha \qquad (17)$$

where

$$q_n=\begin{cases}-1 & \text{for } \{0<\phi<(n-1)\pi\}\cup\{n\pi<\phi<2\pi\}\\ 1 & \text{for } \{(n-1)\pi<\phi<n\pi\}\end{cases}. \qquad (18)$$

It is important to note that since the procedure is based on the Sommerfeld–Maliuzhinets' inversion formula [12], it can be applied in all those cases in which the unperturbed field can be expressed in terms of the Sommerfeld's spectral representations along the path γ. This is for instance the case of the planar junction between two resistive sheets with different electric properties.

IV. Uniform Asymptotic Physical Optics Solution

By applying Cauchy's theorem, the original contribution due to the integration along the contour (c) in (16) and (17), distorted for the presence of singularities in the integrand, is equivalent to the summation of the integral along the steepest descent path (SDP) passing through the pertinent saddle-point α_s and the residue contributions associated with all those poles α_p that are inside the closed path $(c)+\mathrm{SDP}$ (see Fig. 2).

According to the UTD formulation, the total field is expressed as sum of the GO field (u^{go}) and the field (u^d) diffracted by the resistive wedge. For each half-plane, a standard uniform asymptotic solution [13], [14] of the integral along SDP provides the corresponding contribution to this last field in terms of the UTD transition function [7] (UAPO edge diffraction solution), while the sum of u^i and the residues (their presence depends on the observation direction) determines the GO field contribution.

In the following, we will make explicit reference to a penetrable wedge with a generic aperture, choosing the incident plane wave so that both faces bounding region 1 are directly illuminated ($(n-1)\pi<\phi_0<\pi$). In this case, by introducing the function $f(x)=e^{jk\rho\cos x}$, the GO field is expressed by (19), shown at the bottom of the page, where, as depicted in Fig. 1, the angles $\phi_1=\pi-\phi_0$ and $\phi_2=(2n-1)\pi-\phi_0$ correspond to the shadow boundaries for the field reflected from the sheet at $\phi=0$ (RSB_0) and the sheet at $\phi=n\pi$ (RSB_n), respectively. The angle $\phi_3=\pi+\phi_0$ corresponds to the shadow boundary for the transmitted fields (TSB).

The field u^d is given by the superposition of the fields diffracted by each of the resistive half-sheets, namely $u^d(\rho,\phi)=u_0^d(\rho,\phi)+u_n^d(\rho,\phi)$. As previously stated, they are evaluated by performing the integral along the pertinent SDP paths so obtaining the UAPO solution (20) and (21), shown at the bottom of the next page, where $F(x)$ is the standard UTD transition function [7] and $a(x)=2\cos^2(x/2)$.

Since the field diffracted by the resistive wedge is given as the superposition of that diffracted by two noninteracting sheets, the result obtained for each of them can be compared with the heuristic solution of Burnside and Burgener [3] (see Section VI).

It is useful to note that the developed solution can be straightforwardly extended to the case of an arbitrary resistive wedge with $\Delta\le 0.5$ (this guarantees the absence of internal reflections) when only one face is directly illuminated by the incident wave. The explicit expressions of the total field valid in such cases are not reported here to save space. However, they have been used in the section devoted to the numerical simulations.

V. Reference Numerical Technique

To verify the accuracy of the proposed analytical solution, we resort to a rigorous numerical technique based on a boundary element method (BEM). The configuration chosen for the test is constituted by a junction between two truncated dielectric sheets

$$u^{\mathrm{go}}=\begin{cases}f(\phi-\phi_0)+\Gamma(R_s,\phi_0)f(\phi+\phi_0), & \text{for } 0<\phi<\phi_1\\ f(\phi-\phi_0), & \text{for } \phi_1<\phi<\phi_2\\ f(\phi-\phi_0)+\Gamma(R_s,n\pi-\phi_0)f(\phi+\phi_0-2n\pi), & \text{for } \phi_2<\phi<n\pi\\ T(R_s,n\pi-\phi_0)f(\phi-\phi_0), & \text{for } n\pi<\phi<\phi_3\\ T(R_s,\phi_0)f(\phi-\phi_0), & \text{for } \phi_3<\phi<2\pi\end{cases} \qquad (19)$$

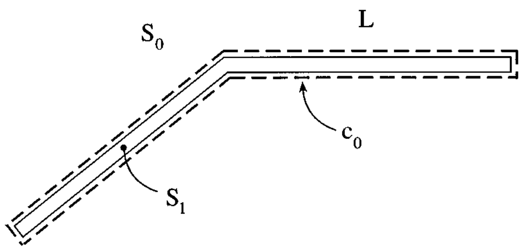

Fig. 3. Geometry for the BEM approach.

as depicted in Fig. 3. The truncation of the two sheets is a necessary condition to apply a numerical analysis technique. The scattering problem can be formulated in terms of a single integral equation, instead of resorting to the conventional set of two coupled integral equations [9]. This reduces by half the number of unknowns required in the BEM implementation but complicates at the same time the equation kernel.

The cross section is bounded by a contour c_0. By following the same procedure described in [9], a single integral equation for this scattering problem is obtained

$$\frac{1}{2}G_0\{\eta_0\} - N_1[G_0(\eta_0)] + G_1[N_0'(\eta_0)] + \frac{1}{2}G_1(\eta_0) = -\frac{u^i}{2} - N_1(u^i) - G_1\left\{\frac{du^i}{dn_0}\right\} \quad (22)$$

where η_0 is the unknown function defined on c_0. This function represents the jump discontinuity of the normal derivative of a function which coincides with the scattered field u^s in S_0. The same function is continuous in S_0 and satisfies everywhere an Helmholtz equation involving $k_0 = k$. In (22) the functionals are given by

$$G_m\{\Phi\}(\mathbf{r}) = \frac{j}{4}\int_{c_0} H_0^{(2)}(k_m R)\Phi(s')\,ds' \quad m = 0, 1 \quad (23)$$

$$N_0'\{\Phi\}(\mathbf{r}) = -\frac{jk_0}{4}\int_{c_0} \frac{\hat{\mathbf{n}}_0 \cdot \mathbf{R}}{R} H_1^{(2)}(k_0 R)\Phi(s')\,ds' \quad (24)$$

$$N_1\{\Phi\}(\mathbf{r}) = -\frac{jk_1}{4}\int_{c_0} \frac{\hat{\mathbf{n}}_0' \cdot \mathbf{R}}{R} H_1^{(2)}(k_1 R)\Phi(s')\,ds' \quad (25)$$

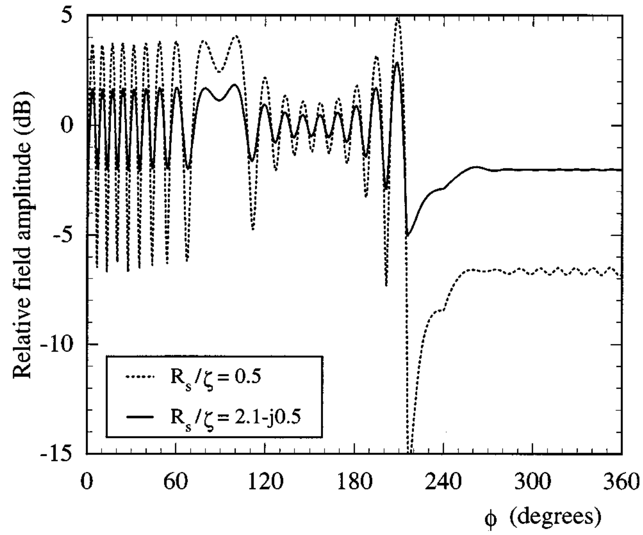

Fig. 4. Total field due to a plane wave incident at $\phi_0 = \pi/3$ on resistive wedges with $\Delta = 0.2$ and evaluated at $\rho = 5\lambda$.

where $H_n^{(2)}(\cdot)$ is the Hankel function of second kind of order n, $\mathbf{R} = \mathbf{r} - \mathbf{r}'$, $R = |\mathbf{R}|$, $\mathbf{r}$, and $\mathbf{r}'(s')$ localize the field point and the source point, respectively, s' being a curvilinear abscissa along the contour c_0. Moreover, $\hat{\mathbf{n}}_0'$ and $\hat{\mathbf{n}}_0$ are the normals to c_0 at $\mathbf{r}'$ and $\mathbf{r}$, respectively. The solution of the integral equation in (22) is reduced to the solution of a linear system by resorting to a standard BEM approach.

VI. Numerical Results

In this section, samples of numerical results are presented and compared with other methods in order to validate the proposed solution for the scattering by a penetrable resistive wedge illuminated by a TM_z plane wave. All the reported figures refer to the amplitude of the total field (normalized to the incident one), evaluated at a distance $\rho = 5\lambda$ from the edge.

Representative patterns relevant to two different values of the normalized resistivity R_s/ζ (with and without losses) of the wedge are shown in Fig. 4 for a deviation $\Delta = 0.2$ from the planar junction configuration and a plane wave impinging at $\phi_0 = \pi/3$. As can be seen, the total field is continuous across the

$$u_0^d(\rho,\phi) = -\frac{e^{-j\pi/4}e^{-jk\rho}}{2\sqrt{2\pi k\rho}} \frac{2\sin\phi_0}{\cos\phi + \cos\phi_0} \cdot \begin{cases} \Gamma(R_s,\phi_0)F(k\rho a(\phi+\phi_0)), & \text{for } 0 < \phi < \pi \\ -[1 - T(R_s,\phi_0)]F(k\rho a(\phi-\phi_0)), & \text{for } \pi < \phi < 2\pi \end{cases} \quad (20)$$

$$u_n^d(\rho,\phi) = -\frac{e^{-j\pi/4}e^{-jk\rho}}{2\sqrt{2\pi k\rho}} \frac{2\sin(n\pi-\phi_0)}{\cos(n\pi-\phi) + \cos(n\pi-\phi_0)} \cdot \begin{cases} \Gamma(R_s,n\pi-\phi_0)F(k\rho a(\phi+\phi_0-2n\pi)), & \text{for } (n-1)\pi < \phi < n\pi \\ -[1 - T(R_s,n\pi-\phi_0)]F(k\rho a(\phi-\phi_0)), & \text{for } \{0 < \phi < (n-1)\pi\} \cup \{n\pi < \phi < 2\pi\} \end{cases} \quad (21)$$

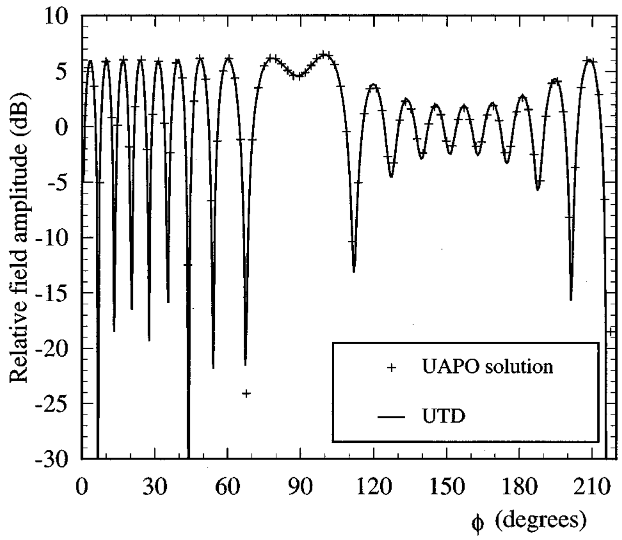

Fig. 5. Total field due to a plane wave incident at $\phi_0 = \pi/3$ on a perfectly conducting wedge with $\Delta = 0.2$ and evaluated at $\rho = 5\lambda$.

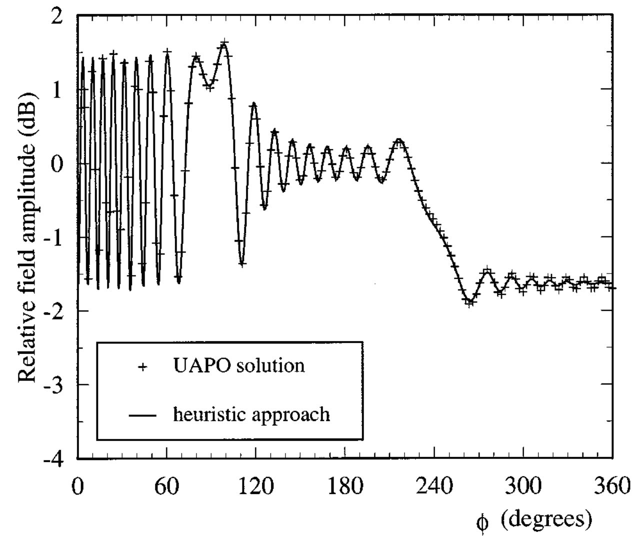

Fig. 7. Total field due to a plane wave incident at $\phi_0 = \pi/3$ on a thin dielectric slab $(R_s/\zeta = 2.5 - j0.9)$ and evaluated at $\rho = 5\lambda$.

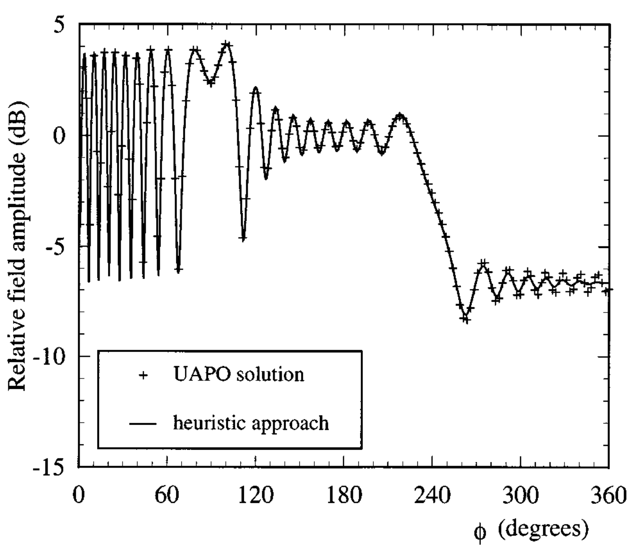

Fig. 6. Total field due to a plane wave incident at $\phi_0 = \pi/3$ on a thin dielectric slab $(R_s/\zeta = 0.5)$ and evaluated at $\rho = 5\lambda$.

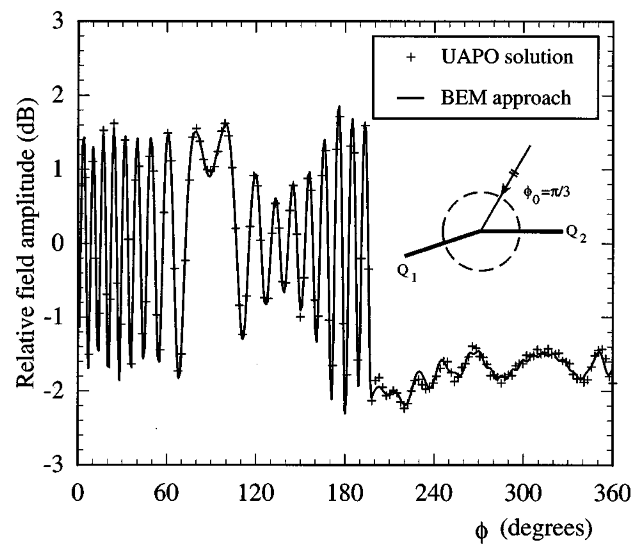

Fig. 8. Total field due to a plane wave incident at $\phi_0 = \pi/3$ on a resistive wedge $(R_s/\zeta = 2.5 - j0.9)$ with $\Delta = 0.1$ and evaluated at $\rho = 5\lambda$.

resistive sheets as well as the incidence and reflection shadow boundaries, thus confirming that the UAPO diffracted field exactly compensates the GO field discontinuities.

Aim of all following figures is to assess the accuracy of the UAPO solution by comparing its results with those obtained by applying other methods. In this context, Fig. 5 provides a first positive check confirming the uniformity of the UAPO solution with respect to the values of resistivity. As matter of fact, the total field predicted by it when considering a perfectly conducting wedge $(R_s \to 0)$ with $\Delta = 0.2$ is practically indistinguishable from that calculated by means of the standard UTD [7].

To get a further confirmation of the effectiveness of the approach, the scattering by a single dielectric slab is considered in Figs. 6 and 7. The comparison concerns the results achieved by applying the proposed approach and those relevant to the heuristic solution [3] in the hypothesis that a resistive sheet condition is valid. As can be seen, a good agreement is obtained in Fig. 6, which refers to the scattering by a lossless dielectric sheet. Even better results are found when considering a lossy dielectric (see Fig. 7).

A definitive validation of the UAPO solution is obtained by the comparison with the results produced by using the BEM approach described in Section V. The reported results concern wedges truncated at $L = 10\lambda$ and characterized by $R_s/\zeta = 2.5 - j0.9$. As a consequence, it has been necessary to properly modify the UAPO solution to take into account the diffracted field by the end edges Q_1, Q_2 of the truncated structure. In particular, Figs. 8 and 9 are relevant to the direct illumination of both faces, whereas Fig. 10 refers to the case in which the sheets at $\phi = 0$ and $\phi = 3\pi/2$ are illuminated by the incident and transmitted waves, respectively. As can be seen, the agreement with the BEM results is surprisingly good also for

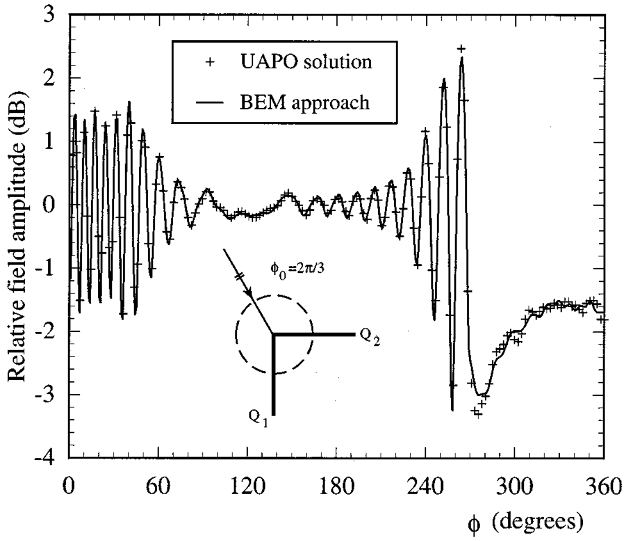

Fig. 9. Total field due to a plane wave incident at $\phi_0 = 2\pi/3$ on a resistive wedge ($R_s/\zeta = 2.5 - j0.9$) with $\Delta = 0.5$ and evaluated at $\rho = 5\lambda$.

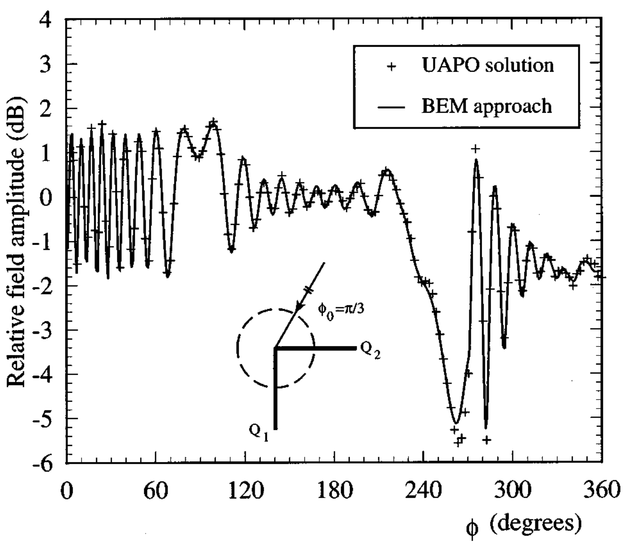

Fig. 10. Total field due to a plane wave incident at $\phi_0 = \pi/3$ on a resistive wedge ($R_s/\zeta = 2.5 - j0.9$) with $\Delta = 0.5$ and evaluated at $\rho = 5\lambda$.

remarkable deviations from the planar junction, giving a further positive check for the validity of the solution.

VII. Conclusion

The scattering problem of a linearly polarized TM_z plane wave incident perpendicularly on a penetrable wedge is tackled and solved. The considered wedge is formed by two dielectric slabs joined at an arbitrary angle and the resistive sheet condition is adopted to take into account the electromagnetic properties of the slabs.

The proposed UAPO solution is obtained by using a GO approximation for the field internal to the slabs and by performing a uniform asymptotic evaluation of the PO radiation integral.

The surprisingly good agreement achieved in all the reported comparisons with other techniques, as well as in many others not shown to save space, confirms the accuracy of the proposed UAPO solution also for remarkable deviations from the planar junction.

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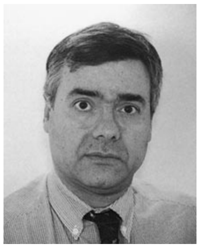

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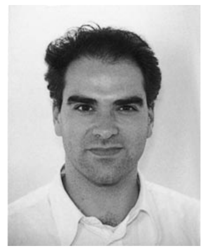

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