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Uniform Asymptotic Physical Optics Solutions for a Set of Diffraction Problems

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1. Introduction

Scattering occurs when an object, inserted in the path of a propagating electromagnetic (EM) wave, modifies the field distribution in the surrounding space. The ability to describe and solve scattering problems is the key to very important applications such as planning radio links, designing antennas and identifying radar targets. In such frameworks one could resort purely numerical methods, f.i., Finite Element Method (FEM) or Method of Moments (MoM), to generate a solution to the considered problem. Unfortunately such techniques have an inherent drawback: they are based on a discrete representation of the system, typically using cell sizes on the order of one-tenth the wavelength of the incident field. Because the number of degrees of freedom increases with frequency, the computation becomes computer-intensive (if not unmanageable) at high frequencies, where asymptotic methods work more efficient. One of these methods has received considerable attention during the last decades because of its peculiarities: the Geometrical Theory of Diffraction (GTD) originated by J.B. Keller (Keller, 1962). What is the essence of this theory? It incorporates the diffraction phenomenon into the ray-oriented framework of the Geometrical Optics (GO), which is based on the assumption that waves can be represented by rays denoting the direction of travel of the EM energy, and that wave fields are characterised mathematically by amplitude, phase propagation factor and polarisation. Diffraction, like reflection and refraction GO mechanisms, is a local phenomenon at high frequencies and is determined by a generalisation of the Fermat principle. It depends on the surface geometry of the obstacle and on the incident field in proximity to the diffraction points creating discontinuities in the GO field at incidence and reflection shadow boundaries.

When using GTD to solve a scattering problem, the first step is to resolve it to smaller and simpler components, each representing a canonical geometry, so that the total solution is a superposition of the contributions from each canonical problem. Accordingly, GTD allows one to solve a large number of real scattering problems by using the solutions of a relatively small number of model problems. In addition, it is simple to apply, it provides physical insight into the radiation and scattering mechanisms from the various parts of the structure, it gives accurate results that compare quite well with experiments and other methods, and it can be combined with numerically rigorous techniques to obtain hybrid methods. The GTD fails, however, in the boundary layers near caustics and GO shadow boundaries. Its uniform

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version originated by R.C. Kouyoumjian and P.H. Pathak (Kouyoumjian & Pathak, 1974), i.e., the Uniform Theory of Diffraction (UTD), overcomes such limitations and gives useful uniform asymptotic solutions for the calculation of the diffracted field. Because of its characteristics, UTD is usually preferred by researchers and practising engineers for treating real structures with edges, and its formulation for perfectly conducting canonical geometries represents the starting point for heuristic solutions based on (Burnside & Burgener, 1983) and (Luebbers, 1984).

This Chapter is devoted to the Uniform Asymptotic Physical Optics (UAPO) solutions for a set of diffraction problems involving edges in penetrable or opaque planar thin layers (compared to wavelength) illuminated by incident plane waves. Under the assumption that the excited surface waves can be neglected, the analytical difficulties are here attenuated by modelling the truncated layer as a canonical half-plane and by taking into account its geometric, electric and magnetic characteristics into the GO response.

The starting point for obtaining a UAPO solution is that of considering the classical radiation integral with a PO approximation of the electric and magnetic surface currents. By PO current one usually means that representation of the surface current in terms of the incident field, and this dependence is here obtained by assuming the surface currents in the integrand as equivalent sources originated by the discontinuities of the tangential GO field components across the layer. As a matter of fact, by taking into account that the field approaching the layer from the upper side is given by the sum of the incident and reflected fields, whereas the transmitted field furnishes the field approaching the layer from the lower side, the here involved PO surface currents depend on the incident field, the reflection and transmission coefficients. Obviously, this last dependence must be considered only if the transmitted field exists. A useful approximation and a uniform asymptotic evaluation of the resulting radiation integral allow one to obtain the diffracted field, which results to be expressed in terms of the GO response of the structure and the standard transition function of UTD. Accordingly, the UAPO solutions have the same effectiveness and ease of handling of those derived in the UTD framework and, in addition, they have the inherent advantage of providing the diffracted field from the knowledge of the GO field. In other words, it is sufficient to make explicit the reflection and transmission coefficients related to the considered structure for obtaining the UAPO diffraction coefficients. Note that also the heuristic solutions have this advantage, but they do not possess a rigorous analytical justification and therefore should be used with considerable attention.

It must be stressed that the UAPO solutions allow one to compensate the discontinuities in the GO field at the incidence and reflection shadow boundaries, and that their accuracy has been proved by comparisons with purely numerical techniques.

The Chapter is organised as follows. Section 2 is devoted to explain the methodology for obtaining the UAPO expression of the field diffracted by the edge of a penetrable or opaque half-plane when illuminated by an incident plane wave. The solution is given in terms of the UTD transition function and requires the knowledge of the reflection and transmission coefficients, whose expressions are explicitly reported in Section 3 with reference to some test-bed cases. To show the effectiveness of the corresponding UAPO solutions, Section 3 also includes numerical results and comparisons with COMSOL MULTIPHYSICS® simulations. Diffraction by junctions of layers is considered in Section 4. Concluding remarks and future activities are collected in Section 5.

2. UAPO diffracted field by half-planes

The diffraction phenomenon related to a linearly polarised plane wave impinging on a penetrable half-plane surrounded by free-space is considered in the frequency domain. As shown in Fig. 1, the z -axis of a reference coordinate system is directed along the edge and the x -axis is on the illuminated face. The angles (β', ϕ') fix the incidence direction: the first is a measure of the skewness with respect to the edge ($\beta' = 90^\circ$ corresponds to the normal incidence) and the latter gives the aperture of the edge-fixed plane of incidence with respect to the illuminated face ($\phi' = 0$ corresponds to the grazing incidence). The case $0 < \phi' < \pi$ is considered from this point on. The observation direction is specified by (β, ϕ) .

Fig. 1. Diffraction by the half-plane edge.

As well-known, the total electric field at a given observation point P can be determined by the adding the incident field $\underline{E}^i$ and the scattered field $\underline{E}^s$. This last can be represented by the classical radiation integral in the PO approximation:

$$\underline{E}^s = -jk_0 \iint_S \left[(\underline{I} - \hat{R}\hat{R})\zeta_0 \underline{J}_s^{PO} + \underline{J}_{ms}^{PO} \times \hat{R} \right] G(\underline{r}, \underline{r}') dS \quad (1)$$

where ζ_0 and k_0 are the impedance and the propagation constant of the free-space, $\underline{r} = x\hat{x} + y\hat{y} + z\hat{z} = \underline{\rho} + z\hat{z}$ and $\underline{r}' = x'\hat{x} + z'\hat{z} = \underline{\rho}' + z'\hat{z}$ denote the observation and source points, $\hat{R}$ is the unit vector from the radiating element at $\underline{r}'$ to P , and $\underline{I}$ is the 3×3 identity matrix. The electric and magnetic PO surface currents $\underline{J}_s^{PO}$ and $\underline{J}_{ms}^{PO}$ induced on S are given in terms of the incident field and can be so expressed:

$$\zeta_0 \underline{J}_s^{PO} = \zeta_0 \underline{J}_s^* e^{jk_0(x' \sin \beta' \cos \phi' - z' \cos \beta')} \quad (2)$$

$$\underline{J}_{ms}^{PO} = \underline{J}_{ms}^* e^{jk_0(x' \sin \beta' \cos \phi' - z' \cos \beta')} \quad (3)$$

Moreover,

$$G(\underline{r}, \underline{r}') = \frac{e^{-jk_0|\underline{r}-\underline{r}'|}}{4\pi|\underline{r}-\underline{r}'|} = \frac{e^{-jk_0\sqrt{(x-x')^2+y^2+(z-z')^2}}}{4\pi\sqrt{(x-x')^2+y^2+(z-z')^2}} = \frac{e^{-jk_0\sqrt{|\underline{\rho}-\underline{\rho}'|^2+(z-z')^2}}}{4\pi\sqrt{|\underline{\rho}-\underline{\rho}'|^2+(z-z')^2}} \quad (4)$$

is the three-dimensional Green function.

To evaluate the edge diffraction confined to the Keller cone for which $\beta = \beta'$, it is possible to approximate $\hat{R}$ by the unit vector $\hat{s}$ in the diffraction direction, i.e., $\hat{R} = \hat{s} = \sin\beta'\cos\phi\hat{x} + \sin\beta'\sin\phi\hat{y} + \cos\beta'\hat{z}$. Accordingly, it results:

$$\begin{aligned} \underline{E}^s &= -\frac{jk_0}{4\pi} \left[(\underline{I} - \hat{s}\hat{s})\zeta_0 \underline{J}_s^* + \underline{J}_{ms}^* \times \hat{s} \right] \int_0^\infty \int_{-\infty}^\infty e^{jk_0(x'\sin\beta'\cos\phi - z'\cos\beta')} \frac{e^{-jk_0\sqrt{|\underline{\rho}-\underline{\rho}'|^2+(z-z')^2}}}{\sqrt{|\underline{\rho}-\underline{\rho}'|^2+(z-z')^2}} dz' dx' \\ &= \left[(\underline{I} - \hat{s}\hat{s})\zeta_0 \underline{J}_s^* + \underline{J}_{ms}^* \times \hat{s} \right] I_s \end{aligned} \quad (5)$$

2.1 Electric and magnetic PO surface currents

The expressions of the PO surface currents in terms of the incident electric field are here obtained by assuming such currents as equivalent sources originated by the discontinuities of the tangential GO field components across the layer, i.e.,

$$\underline{J}_s^{PO} = \hat{y} \times \left(\underline{H}^+ - \underline{H}^- \right) \Big|_S = \hat{y} \times \left(\underline{H}^i + \underline{H}^r - \underline{H}^t \right) \Big|_S = \hat{y} \times \left(\underline{H}_0^i + \underline{H}_0^r - \underline{H}_0^t \right) e^{jk_0(x'\sin\beta'\cos\phi - z'\cos\beta')} \quad (6)$$

$$\underline{J}_{ms}^{PO} = \left(\underline{E}^+ - \underline{E}^- \right) \Big|_S \times \hat{y} = \left(\underline{E}^i + \underline{E}^r - \underline{E}^t \right) \Big|_S \times \hat{y} = \left[\left(\underline{E}_0^i + \underline{E}_0^r - \underline{E}_0^t \right) \times \hat{y} \right] e^{jk_0(x'\sin\beta'\cos\phi - z'\cos\beta')} \quad (7)$$

where the superscripts *i*, *r* and *t* denote the incident, reflected and transmitted fields, respectively. As well-known, it is convenient to work in the standard plane of incidence and to consider the GO field components parallel ($\parallel$) and perpendicular ($\perp$) to it. If the ray-fixed coordinate systems sketched in Fig. 2 are used, the EM field can be so expressed:

$$\underline{E}_0^{i,r,t} = E_{\parallel}^{i,r,t} \hat{e}_{\parallel}^{i,r,t} + E_{\perp}^{i,r,t} \hat{e}_{\perp} \quad (8)$$

$$\underline{H}_0^{i,r,t} = \frac{1}{\zeta_0} \left[E_{\parallel}^{i,r,t} \hat{e}_{\perp} - E_{\perp}^{i,r,t} \hat{e}_{\parallel}^{i,r,t} \right] \quad (9)$$

with $\hat{e}_{\parallel}^t = \hat{e}_{\parallel}^i$. Accordingly, if $\hat{t} = \hat{n} \times \hat{e}_{\perp} = \hat{y} \times \hat{e}_{\perp}$ and θ^i is the standard incidence angle, it results:

$$\zeta_0 \underline{J}_s^* = \left(E_{\perp}^i - E_{\perp}^r - E_{\perp}^t \right) \cos\theta^i \hat{e}_{\perp} + \left(E_{\parallel}^i + E_{\parallel}^r - E_{\parallel}^t \right) \hat{t} \quad (10)$$

$$\underline{J}_{ms}^* = \left(E_{\parallel}^i - E_{\parallel}^r - E_{\parallel}^t \right) \cos\theta^i \hat{e}_{\perp} - \left(E_{\perp}^i + E_{\perp}^r - E_{\perp}^t \right) \hat{t} \quad (11)$$

where the reflected and transmitted field components can be given in terms of the incident field components by means of the reflection matrix $\underline{R}$ and the transmission matrix $\underline{T}$:

$$\begin{pmatrix} E_{\parallel}^r \\ E_{\perp}^r \end{pmatrix} = \underline{\underline{R}} \begin{pmatrix} E_{\parallel}^i \\ E_{\perp}^i \end{pmatrix} = \begin{pmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{pmatrix} \begin{pmatrix} E_{\parallel}^i \\ E_{\perp}^i \end{pmatrix} \quad (12)$$

$$\begin{pmatrix} E_{\parallel}^t \\ E_{\perp}^t \end{pmatrix} = \underline{\underline{T}} \begin{pmatrix} E_{\parallel}^i \\ E_{\perp}^i \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} E_{\parallel}^i \\ E_{\perp}^i \end{pmatrix} \quad (13)$$

Fig. 2. Ray-fixed coordinate systems for the GO field.

By using the above results, the scattered field can be given in the following matrix formulation:

$$\underline{\underline{E}}^s = \begin{pmatrix} E_{\beta}^s \\ E_{\phi}^s \end{pmatrix} = \underline{\underline{M}}_0 \begin{pmatrix} E_{\parallel}^i \\ E_{\perp}^i \end{pmatrix} I_s = \underline{\underline{M}}_0 \underline{\underline{M}}_1 \begin{pmatrix} E_{\beta'}^i \\ E_{\phi'}^i \end{pmatrix} I_s = \underline{\underline{M}} \begin{pmatrix} E_{\beta'}^i \\ E_{\phi'}^i \end{pmatrix} I_s \quad (14)$$

with

$$\underline{\underline{M}}_1 = \begin{pmatrix} \hat{e}_{\parallel}^i \cdot \hat{\beta}' & \hat{e}_{\parallel}^i \cdot \hat{\phi}' \\ \hat{e}_{\perp}^i \cdot \hat{\beta}' & \hat{e}_{\perp}^i \cdot \hat{\phi}' \end{pmatrix} = \frac{1}{\sqrt{1 - \sin^2 \beta' \sin^2 \phi'}} \begin{pmatrix} \cos \beta' \sin \phi' & \cos \phi' \\ -\cos \phi' & \cos \beta' \sin \phi' \end{pmatrix} \quad (15)$$

2.2 Matrix elements

The matrix $\underline{\underline{M}}_0$ in (14) allows one to relate the scattered field components along $\hat{\beta}$ and $\hat{\phi}$ to the incident field components along $\hat{e}_{\parallel}^i$ and $\hat{e}_{\perp}^i$. It accounts for the expressions of the PO surface currents and can be so formulated:

$$\underline{\underline{M}}_0 = \underline{\underline{M}}_7 \left[\underline{\underline{M}}_2 \underline{\underline{M}}_4 \underline{\underline{M}}_5 + \underline{\underline{M}}_3 \underline{\underline{M}}_4 \underline{\underline{M}}_6 \right] \quad (16)$$

where

$$\underline{\underline{M}}_7 = \begin{pmatrix} \hat{\beta} \cdot \hat{x} & \hat{\beta} \cdot \hat{y} & \hat{\beta} \cdot \hat{z} \\ \hat{\phi} \cdot \hat{x} & \hat{\phi} \cdot \hat{y} & \hat{\phi} \cdot \hat{z} \end{pmatrix} = \begin{pmatrix} \cos \beta' \cos \phi & \cos \beta' \sin \phi & -\sin \beta' \\ -\sin \phi & \cos \phi & 0 \end{pmatrix} \quad (17)$$

$$\underline{\underline{M}}_2 = \begin{pmatrix} 1 - \sin^2 \beta' \cos^2 \phi & -\sin \beta' \cos \beta' \cos \phi \\ -\sin^2 \beta' \sin \phi \cos \phi & -\sin \beta' \cos \beta' \sin \phi \\ -\sin \beta' \cos \beta' \cos \phi & \sin^2 \beta' \end{pmatrix} \quad (18)$$

$$\underline{\underline{M}}_3 = \begin{pmatrix} 0 & -\sin \beta' \sin \phi \\ -\cos \beta' & \sin \beta' \cos \phi \\ \sin \beta' \sin \phi & 0 \end{pmatrix} \quad (19)$$

$$\underline{\underline{M}}_4 = \begin{pmatrix} \hat{x} \cdot \hat{e}_\perp & \hat{x} \cdot \hat{t} \\ \hat{z} \cdot \hat{e}_\perp & \hat{z} \cdot \hat{t} \end{pmatrix} = \frac{1}{\sqrt{1 - \sin^2 \beta' \sin^2 \phi'}} \begin{pmatrix} -\cos \beta' & -\sin \beta' \cos \phi' \\ -\sin \beta' \cos \phi' & \cos \beta' \end{pmatrix} \quad (20)$$

$$\underline{\underline{M}}_5 = \begin{pmatrix} -(R_{21} + T_{21}) \cos \theta^i & (1 - R_{22} - T_{22}) \cos \theta^i \\ 1 + R_{11} - T_{11} & R_{12} - T_{12} \end{pmatrix} \quad (21)$$

$$\underline{\underline{M}}_6 = \begin{pmatrix} (1 - R_{11} - T_{11}) \cos \theta^i & -(R_{12} + T_{12}) \cos \theta^i \\ -(R_{21} + T_{21}) & -(1 + R_{22} - T_{22}) \end{pmatrix} \quad (22)$$

2.3 Uniform asymptotic evaluation and diffracted field

It is now necessary to perform the evaluation of the following integral:

$$I_s = -\frac{jk_0}{4\pi} \int_0^\infty e^{jk_0 x' \sin \beta' \cos \phi'} \int_{-\infty}^\infty e^{-jk_0 z' \cos \beta'} \frac{e^{-jk_0 \sqrt{|\underline{\rho} - \underline{\rho}'|^2 + (z - z')^2}}}{\sqrt{|\underline{\rho} - \underline{\rho}'|^2 + (z - z')^2}} dz' dx' \quad (23)$$

By making the substitution $z' - z = |\underline{\rho} - \underline{\rho}'| \sinh \zeta$ and using one of the integral representations of the zeroth order Hankel function of the second kind $H_0^{(2)}$, it results (see Appendix D in (Senior & Volakis, 1995) as reference):

$$\int_{-\infty}^\infty e^{-jk_0 z' \cos \beta'} \frac{e^{-jk_0 \sqrt{|\underline{\rho} - \underline{\rho}'|^2 + (z - z')^2}}}{\sqrt{|\underline{\rho} - \underline{\rho}'|^2 + (z - z')^2}} dz' = -j\pi e^{-jk_0 z \cos \beta'} H_0^{(2)}(k_0 |\underline{\rho} - \underline{\rho}'| \sin \beta') \quad (24)$$

Another useful integral representation of the involved Hankel function can be now considered (Clemmow, 1996):

$$H_0^{(2)}(k_0 |\underline{\rho} - \underline{\rho}'| \sin \beta') = \frac{1}{\pi} \int_C e^{-jk_0 |\underline{\rho} - \underline{\rho}'| \sin \beta' \cos(\theta \mp \alpha)} d\alpha \quad (25)$$

where C is the integration path in the complex α -plane as in Fig. 3. The angle θ is between the illuminated face and the vector $\underline{\rho} - \underline{\rho}'$, and the sign $- (+)$ applies if $y > 0$ ($y < 0$).

Fig. 3. Integration path C.

If $\rho = |\underline{\rho}|$, according to the geometry shown in Fig. 4, $|\underline{\rho} - \underline{\rho}'| \sin \theta = \rho \sin \phi$ and $|\underline{\rho} - \underline{\rho}'| \cos \theta = \rho \cos \phi - x'$, so obtaining

$$H_0^{(2)}\left(k_0 |\underline{\rho} - \underline{\rho}'| \sin \beta'\right) = \frac{1}{\pi} \int_C e^{-jk_0 \rho \sin \beta' \cos(\alpha \mp \phi)} e^{jk_0 x' \sin \beta' \cos \alpha} d\alpha \tag{26}$$

and then

$$\begin{aligned} I_s &= -\frac{k_0}{4\pi} e^{-jk_0 z \cos \beta'} \int_0^\infty \int_C e^{-jk_0 \rho \sin \beta' \cos(\alpha \mp \phi)} e^{jk_0 x' \sin \beta' (\cos \alpha + \cos \phi')} d\alpha dx' = \\ &= -\frac{k_0}{4\pi} e^{-jk_0 z \cos \beta'} \int_C e^{-jk_0 \rho \sin \beta' \cos(\alpha \mp \phi)} \int_0^\infty e^{jk_0 x' \sin \beta' (\cos \alpha + \cos \phi')} dx' d\alpha \end{aligned} \tag{27}$$

Fig. 4. Geometry in the plane perpendicular to the edge.

By applying the Sommerfeld-Maliuzhinets inversion formula (Maliuzhinets, 1958), it results:

$$\int_0^{\infty} e^{jk_0 x' \sin \beta' (\cos \alpha + \cos \phi')} dx' = \frac{-1}{jk_0 \sin \beta' (\cos \alpha + \cos \phi')} \quad (28)$$

so that

$$I_s = \frac{e^{-jk_0 z \cos \beta'}}{2 \sin \beta'} \frac{1}{2\pi j} \int_C \frac{e^{-jk_0 \rho \sin \beta' \cos(\alpha \mp \phi)}}{\cos \alpha + \cos \phi'} d\alpha \quad (29)$$

where the sign $- (+)$ applies in the range $0 < \phi < \pi$ ($\pi < \phi < 2\pi$). Such an integral can be evaluated by using the Steepest Descent Method (see Appendix C in (Senior & Volakis, 1995) as reference). To this end, the integration path C is closed with the Steepest Descent Path (SDP) passing through the pertinent saddle point α_s as shown in Fig. 5. According to the Cauchy residue theorem, the contribution related to the integration along C (distorted for the presence of singularities in the integrand) is equivalent to the sum of the integral along the SDP and the residue contributions $\text{Res}_i(\alpha_p)$ associated with all those poles that are inside the closed path $C+SDP$, i.e.,

$$I_s(\Omega) = \frac{1}{2\pi j} \int_C g(\alpha) e^{\Omega f(\alpha)} d\alpha = \sum_i \text{Res}_i(\alpha_p) - \frac{1}{2\pi j} \int_{SDP} g(\alpha) e^{\Omega f(\alpha)} d\alpha = \sum_i \text{Res}_i(\alpha_p) + I(\Omega) \quad (30)$$

in which

$$I(\Omega) = -\frac{1}{2\pi j} \int_{SDP} g(\alpha) e^{\Omega f(\alpha)} d\alpha = -\frac{e^{\Omega f(\alpha_s)}}{2\pi j} \int_{SDP} g(\alpha) e^{\Omega [f(\alpha) - f(\alpha_s)]} d\alpha \quad (31)$$

$$\Omega = k_0 \rho \quad (32)$$

$$g(\alpha) = \frac{e^{-jk_0 z \cos \beta'}}{2 \sin \beta'} \frac{1}{\cos \alpha + \cos \phi'} = \frac{A}{\cos \alpha + \cos \phi'} \quad (33)$$

$$f(\alpha) = -j \sin \beta' \cos(\alpha \mp \phi) \quad (34)$$

Note that Ω is typically large, $\alpha_p = \pi - \phi'$ and $\alpha_s = \phi$ ($\alpha_s = 2\pi - \phi$) if $0 < \phi < \pi$ ($\pi < \phi < 2\pi$). Moreover, by putting $\alpha = \alpha' + j\alpha''$ and imposing that $\text{Im}[f(\alpha)] = \text{Im}[f(\alpha_s)]$ and $\text{Re}[f(\alpha)] \leq \text{Re}[f(\alpha_s)]$, the considered SDP is described by:

$$\alpha' = \alpha_s + \text{sgn}(\alpha'') \cos^{-1} \left(\frac{1}{\cosh \alpha''} \right) = \alpha_s + \text{gd}(\alpha'') \quad (35)$$

where $\text{gd}(\alpha'')$ is the Gudermann function. By using now the change of variable $f(\alpha) - f(\alpha_s) = -\tau^2 < 0$, (31) can be written as

$$I(\Omega) = \pm \int_{-\infty}^{\infty} G(\tau) e^{-\Omega \tau^2} d\tau \quad (36)$$

wherein

$$G(\tau) = \frac{1}{2\pi j} g(\alpha(\tau)) e^{\Omega f(\alpha_s)} \frac{d\alpha}{d\tau} \quad (37)$$

Fig. 5. Integration path.

When α_p is approaching α_s , the function $G(\tau)$ cannot be expanded in a Taylor series. To overcome this drawback it is convenient to regularise the integrand in (36). This procedure (to be referred to as the Multiplicative Method) was described in (Kouyoumjian & Pathak, 1974) as the modified Pauli-Clemmow method (Clemmow, 1950). It requires to introduce the regularised function

$$G_p(\tau) = (\tau - \tau_p) G(\tau) \quad (38)$$

with

$$\tau_p^2 = f(\alpha_s) - f(\alpha_p) = -j \sin \beta' [1 + \cos(\phi \pm \phi')] = -j 2 \sin \beta' \cos^2 \left(\frac{\phi \pm \phi'}{2} \right) = -j \delta \quad (39)$$

and δ is a measure of the distance between α_p and α_s . Accordingly,

$$I(\Omega) = \pm \int_{-\infty}^{\infty} G_p(\tau) \frac{e^{-\Omega \tau^2}}{\tau - \tau_p} d\tau \quad (40)$$

Since $G_p(\tau)$ is analytic near $\tau = 0$, it can be expanded in a Taylor series. By retaining only the first term (i.e., the $\Omega^{-1/2}$ - order term) since $\Omega \gg 1$, it results:

$$I(\Omega) \approx \pm \left[\sqrt{\frac{\pi}{\Omega}} \frac{G_p(0)}{(-\tau_p)} F_t(j\Omega \tau_p^2) \right] \quad (41)$$

in which

$$\frac{G_p(0)}{(-\tau_p)} = G(0) = \frac{1}{2\pi j} g(\alpha_s) e^{\Omega f(\alpha_s)} \frac{d\alpha}{d\tau} \bigg|_{\tau=0} = \frac{1}{2\pi j} \frac{A e^{-j\Omega \sin \beta'}}{\cos \phi + \cos \phi'} \left[\pm \sqrt{\frac{2}{\sin \beta'}} e^{j\pi/4} \right] \quad (42)$$

and

$$F_t(\eta) = 2j\sqrt{\eta} e^{j\eta} \int_{\sqrt{\eta}}^{\infty} e^{-j\xi^2} d\xi \quad (43)$$

is the UTD transition function (Kouyoumjian & Pathak, 1974). By substituting (32), (39) and (42) in (41), the explicit form of the asymptotic evaluation of $I(\Omega)$ is:

$$\begin{aligned} I(\Omega) &\approx \frac{e^{-j\pi/4}}{2\sqrt{2\pi k_0 \rho} \sin \beta'} \frac{e^{-jk_0(\rho \sin \beta' + z \cos \beta')}}{\sin \beta' (\cos \phi + \cos \phi')} F_t \left(2k_0 \rho \sin \beta' \cos^2 \left(\frac{\phi \pm \phi'}{2} \right) \right) = \\ &= \frac{e^{-j\pi/4}}{2\sqrt{2\pi k_0}} \frac{e^{-jk_0 s}}{\sqrt{s}} \frac{1}{\sin^2 \beta' (\cos \phi + \cos \phi')} F_t \left(2k_0 s \sin^2 \beta' \cos^2 \left(\frac{\phi \pm \phi'}{2} \right) \right) \end{aligned} \quad (44)$$

where the identities $\rho = s \sin \beta'$ and $z = s \cos \beta'$ are used on the diffraction cone. The above analytic result contributes to the UAPO diffracted field to be added to the GO field and is referred to as a uniform asymptotic solution because $I(\Omega)$ is well-behaved when $\alpha_p \rightarrow \alpha_s$. In the GTD framework, the matrix formulation (14) can be rewritten as

$$\underline{\underline{E}}^d = \begin{pmatrix} E_\beta^d \\ E_\phi^d \end{pmatrix} = \underline{\underline{M}} \begin{pmatrix} E_{\beta'}^i \\ E_{\phi'}^i \end{pmatrix} I(\Omega) = \underline{\underline{D}} \begin{pmatrix} E_{\beta'}^i \\ E_{\phi'}^i \end{pmatrix} \frac{e^{-jk_0 s}}{\sqrt{s}} \quad (45)$$

so that the UAPO solution for the 2×2 diffraction matrix $\underline{\underline{D}}$ is given by:

$$\underline{\underline{D}} = \frac{1}{2\sqrt{2\pi k_0}} \frac{e^{-j\pi/4}}{\sin^2 \beta' (\cos \phi + \cos \phi')} F_t \left(2k_0 s \sin^2 \beta' \cos^2 \left(\frac{\phi \pm \phi'}{2} \right) \right) \underline{\underline{M}} \quad (46)$$

Accordingly, the UAPO solutions have the same ease of handling of those derived in the UTD framework and, in addition, they have the inherent advantage of providing the diffracted field from the knowledge of the GO response of the structure. In other words, it is sufficient to make explicit the reflection and transmission coefficients related to the considered structure for obtaining the UAPO diffraction coefficients.

As demonstrated in (Ferrara et al., 2007a), by taking advantage on the fact that the UAPO solutions are UTD-like as regards the frequency if the elements of reflection and transmission matrices are independent on the frequency, it is possible to determine the time domain UAPO diffraction coefficients by applying the approach proposed in (Veruttipong, 1990).

3. Test-bed cases

The effectiveness of the UAPO solution when applied to some test-bed cases is analysed in this Section. As previously stated, the corresponding diffraction coefficients are determined by making explicit the reflection and transmission coefficients to be used in (21) and (22). The numerical results obtained by using the radio frequency module of COMSOL MULTIPHYSICS®, which is a powerful interactive environment for modelling and solving problems based on partial differential equations via FEM, are considered as reference in the case of normal incidence ($\beta' = 90^\circ$).

3.1 Lossy dielectric layer

A lossy dielectric layer having thickness d , relative complex permittivity ϵ_r and relative permeability $\mu_r = 1$ is now considered. The structure is penetrable and, according to (Ferrara et al., 2007b), the elements of $\underline{\underline{R}}$ and $\underline{\underline{T}}$ can be so expressed:

$$R_{11} = R_{\parallel} = \frac{\bar{R}_{\parallel} [1 - (P_{da} P_{att})^2 P_a]}{1 - \bar{R}_{\parallel}^2 (P_{da} P_{att})^2 P_a} \quad R_{22} = R_{\perp} = \frac{\bar{R}_{\perp} [1 - (P_{da} P_{att})^2 P_a]}{1 - \bar{R}_{\perp}^2 (P_{da} P_{att})^2 P_a} \quad (47)$$

$$R_{12} = R_{21} = 0 \quad (48)$$

$$T_{11} = T_{\parallel} = \frac{(1 - \bar{R}_{\parallel}^2) P_{da} P_{att} P_t}{1 - \bar{R}_{\parallel}^2 (P_{da} P_{att})^2 P_a} \quad T_{22} = T_{\perp} = \frac{(1 - \bar{R}_{\perp}^2) P_{da} P_{att} P_t}{1 - \bar{R}_{\perp}^2 (P_{da} P_{att})^2 P_a} \quad (49)$$

$$T_{12} = T_{21} = 0 \quad (50)$$

in which

$$\bar{R}_{\parallel} = \frac{\epsilon_r \cos \theta^i - \sqrt{\epsilon_r - \sin^2 \theta^i}}{\epsilon_r \cos \theta^i + \sqrt{\epsilon_r - \sin^2 \theta^i}} \quad (51)$$

$$\bar{R}_{\perp} = \frac{\cos \theta^i - \sqrt{\epsilon_r - \sin^2 \theta^i}}{\cos \theta^i + \sqrt{\epsilon_r - \sin^2 \theta^i}} \quad (52)$$

$$P_{da} = e^{-j\beta_{eq} d / \cos \theta^t} \quad (53)$$

$$P_{att} = e^{-\alpha_{eq} d} \quad (54)$$

$$P_a = e^{j2k_0 d \sin \theta^i \tan \theta^t} \quad (55)$$

$$P_t = e^{jk_0 d \cos(\theta^i - \theta^t) / \cos \theta^t} \quad (56)$$

where β_{eq} and α_{eq} are the equivalent phase and attenuation factors relevant to the propagation through the layer (Balanis, 1989), and θ^t is the real angle between the propagation direction and that of attenuation in the layer.

A sample of interesting results is here reported. The first set of figures from Fig. 6 to Fig. 9 refers to a layer characterised by $\epsilon_r = 4 - j0.23$ and $d = 0.15 \lambda_0$ (λ_0 is the free-space wavelength) when a plane wave having $E_{\beta'}^i = 1$, $E_{\phi'}^i = 0$ impinges on the structure from $\beta' = 45^\circ$, $\phi' = 60^\circ$. The magnitudes of the electric field β -components of the GO field and the UAPO diffracted field on a circular path with $\rho = 7 \lambda_0$ are considered in Fig. 6. As expected, the GO pattern presents two discontinuities in correspondence of the incidence and reflection shadow boundaries at $\phi = 240^\circ$ and $\phi = 120^\circ$, respectively. The UAPO field contribution is not negligible in the neighbourhood of such boundaries and guarantees the continuity of the total field across them as shown in Fig. 7. Analogous considerations can be made by considering the electric field ϕ -components as reported in Figs. 8 and 9.

The next four figures relevant to a lossy dielectric layer are useful to assess the accuracy of the UAPO-based approach by means of comparisons with the results obtained by running COMSOL MULTIPHYSICS® in the case of normal incidence. The layer has the same characteristics considered in the first set of figures and the field is observed on the same circular path. An excellent agreement is attained in all the cases, thus confirming the effectiveness of the here described approach.

Fig. 6. Amplitude of E_β if $E_{\beta'}^i = 1$, $E_{\phi'}^i = 0$ and $\beta' = 45^\circ$, $\phi' = 60^\circ$. Circular path with $\rho = 7 \lambda_0$. Layer characterised by $\epsilon_r = 4 - j0.23$, $\mu_r = 1$ and $d = 0.15 \lambda_0$.

Fig. 7. Amplitude of E_β if $E_{\beta'}^i = 1$, $E_{\phi'}^i = 0$ and $\beta' = 45^\circ$, $\phi' = 60^\circ$. Circular path with $\rho = 7 \lambda_0$. Layer characterised by $\epsilon_r = 4 - j0.23$, $\mu_r = 1$ and $d = 0.15 \lambda_0$.

Fig. 8. Amplitude of E_ϕ if $E_{\beta'}^i = 1$, $E_{\phi'}^i = 0$ and $\beta' = 45^\circ$, $\phi' = 60^\circ$. Circular path with $\rho = 7 \lambda_0$. Layer characterised by $\epsilon_r = 4 - j0.23$, $\mu_r = 1$ and $d = 0.15 \lambda_0$.

Fig. 9. Amplitude of E_ϕ if $E_{\beta'}^i = 1$, $E_{\phi'}^i = 0$ and $\beta' = 45^\circ$, $\phi' = 60^\circ$. Circular path with $\rho = 7 \lambda_0$. Layer characterised by $\epsilon_r = 4 - j0.23$, $\mu_r = 1$ and $d = 0.15 \lambda_0$.

Fig. 10. Amplitude of E_β if $E_{\beta'}^i = 1$, $E_{\phi'}^i = 0$ and $\beta' = 90^\circ$, $\phi' = 30^\circ$. Circular path with $\rho = 7 \lambda_0$. Layer characterised by $\epsilon_r = 4 - j0.23$, $\mu_r = 1$ and $d = 0.15 \lambda_0$.

Fig. 11. Amplitude of E_ϕ if $E_{\beta'}^i = 0$, $E_{\phi'}^i = 1$ and $\beta' = 90^\circ$, $\phi' = 30^\circ$. Circular path with $\rho = 7 \lambda_0$. Layer characterised by $\epsilon_r = 4 - j0.23$, $\mu_r = 1$ and $d = 0.15 \lambda_0$.

Fig. 12. Amplitude of E_β if $E_{\beta'}^i = 1$, $E_{\phi'}^i = 0$ and $\beta' = 90^\circ$, $\phi' = 140^\circ$. Circular path with $\rho = 7 \lambda_0$. Layer characterised by $\epsilon_r = 4 - j0.23$, $\mu_r = 1$ and $d = 0.15 \lambda_0$.

Fig. 13. Amplitude of E_ϕ if $E_{\beta'}^i = 0$, $E_{\phi'}^i = 1$ and $\beta' = 90^\circ$, $\phi' = 140^\circ$. Circular path with $\rho = 7\lambda_0$. Layer characterised by $\epsilon_r = 4 - j0.23$, $\mu_r = 1$ and $d = 0.15\lambda_0$.

3.2 Lossless double-negative metamaterial layer

Double-negative metamaterials are unconventional media having negative permittivity and permeability simultaneously, so that they are characterised by antiparallel phase and group velocities, or negative refractive index. Such media can be artificially fabricated by embedding various classes of small inclusions in host media (volumetric structure) or by connecting inhomogeneities to host surfaces (planar structure), and may be engineered to have new physically realizable response functions that do not occur, or may not be readily available, in nature.

A lossless double-negative metamaterial layer having thickness d , relative permittivity $\epsilon_r = -C$, where C is a positive constant, and relative permeability $\mu_r = -1$ is now considered. The structure is penetrable and, according to (Gennarelli & Riccio, 2009a), the elements of $\underline{\underline{R}}$ and $\underline{\underline{T}}$ are:

$$R_{11} = R_{\parallel} = \frac{\bar{R}_{\parallel}^{12} + \bar{R}_{\parallel}^{23} e^{j2k_2 d \cos \theta_2}}{1 + \bar{R}_{\parallel}^{12} \bar{R}_{\parallel}^{23} e^{j2k_2 d \cos \theta_2}} \quad R_{22} = R_{\perp} = \frac{\bar{R}_{\perp}^{12} + \bar{R}_{\perp}^{23} e^{j2k_2 d \cos \theta_2}}{1 + \bar{R}_{\perp}^{12} \bar{R}_{\perp}^{23} e^{j2k_2 d \cos \theta_2}} \quad (57)$$

$$R_{12} = R_{21} = 0 \quad (58)$$

$$T_{11} = T_{\parallel} = \frac{\bar{T}_{\parallel}^{12} \bar{T}_{\parallel}^{23} e^{jk_2 d \cos \theta_2}}{1 + \bar{R}_{\parallel}^{12} \bar{R}_{\parallel}^{23} e^{j2k_2 d \cos \theta_2}} \quad T_{22} = T_{\perp} = \frac{\bar{T}_{\perp}^{12} \bar{T}_{\perp}^{23} e^{jk_2 d \cos \theta_2}}{1 + \bar{R}_{\perp}^{12} \bar{R}_{\perp}^{23} e^{j2k_2 d \cos \theta_2}} \quad (59)$$

$$T_{12} = T_{21} = 0 \quad (60)$$

in which k_2 is the propagation constant in the double-negative metamaterial, θ_2 is the negative refraction angle, and

$$\bar{R}_{\parallel}^{ij} = \frac{k_j \cos \theta_i - k_i \cos \theta_j}{k_j \cos \theta_i + k_i \cos \theta_j} \quad \bar{R}_{\perp}^{ij} = \frac{k_i \cos \theta_i - k_j \cos \theta_j}{k_i \cos \theta_i + k_j \cos \theta_j} \quad (61)$$

$$\bar{T}_{\parallel}^{ij} = \frac{2k_i \cos \theta_i}{k_j \cos \theta_i + k_i \cos \theta_j} \quad \bar{T}_{\perp}^{ij} = \frac{2k_i \cos \theta_i}{k_i \cos \theta_i + k_j \cos \theta_j} \quad (62)$$

In (61) and (62), $k_1 = k_3 = k_0$, $\theta_1 = \theta_3$ and the superscripts i and j refer to the left and right media involved in the propagation mechanism.

Comparisons with COMSOL MULTIPHYSICS® results are reported in Figs. 14 and 15 with reference to $\phi' = 45^\circ$. As can be seen, the UAPO diffracted field guarantees the continuity of the total field across the two discontinuities of the GO field in correspondence of the incidence and reflection shadow boundaries, and a very good agreement is attained. Accordingly, the accuracy of the UAPO-based approach is well assessed also in the case of a lossless double-negative metamaterial layer.

3.3 Anisotropic impedance layer

A layer characterised by anisotropic impedance boundary conditions on the illuminated face is now considered. Such conditions are represented by an impedance tensor $\underline{\underline{Z}} = Z_{x'} \hat{x}' \hat{x}' + Z_{z'} \hat{z}' \hat{z}'$ having components along the two mutually orthogonal principal axes of anisotropy $\hat{x}'$ and $\hat{z}'$. The structure is opaque so that the transmission matrix does not exist and, according to (Gennarelli et al., 1999), the elements of $\underline{\underline{R}}$ can be so expressed:

Fig. 14. Amplitude of E_β if $E_{\beta'}^i = 1$, $E_{\phi'}^i = 0$ and $\beta' = 90^\circ$, $\phi' = 45^\circ$. Circular path with $\rho = 5 \lambda_0$. Layer characterised by $\epsilon_r = -4$, $\mu_r = -1$ and $d = 0.125 \lambda_0$.

Fig. 15. Amplitude of E_ϕ if $E_{\beta'}^i = 0$, $E_{\phi'}^i = 1$ and $\beta' = 90^\circ$, $\phi' = 45^\circ$. Circular path with $\rho = 5 \lambda_0$. Layer characterised by $\epsilon_r = -4$, $\mu_r = -1$ and $d = 0.125 \lambda_0$.

$$R_{11} = \frac{-A + (1 + AC + B^2) \cos \theta^i - C \cos^2 \theta^i}{A + (1 - AC - B^2) \cos \theta^i - C \cos^2 \theta^i} \tag{63}$$

$$R_{12} = -R_{21} = \frac{2B \cos \theta^i}{A + (1 - AC - B^2) \cos \theta^i - C \cos^2 \theta^i} \tag{64}$$

$$R_{22} = -\frac{A + (1 + AC + B^2) \cos \theta^i + C \cos^2 \theta^i}{A + (1 - AC - B^2) \cos \theta^i - C \cos^2 \theta^i} \tag{65}$$

in which, if χ is the angle between $\hat{x}'$ and $\hat{e}_\perp$,

$$A = \frac{Z_{x'}}{\zeta_0} \sin^2 \chi + \frac{Z_{z'}}{\zeta_0} \cos^2 \chi \tag{66}$$

$$B = \frac{1}{\zeta_0} (Z_{x'} - Z_{z'}) \sin \chi \cos \chi \tag{67}$$

$$C = -\left[\frac{Z_{x'}}{\zeta_0} \cos^2 \chi + \frac{Z_{z'}}{\zeta_0} \sin^2 \chi \right] \tag{68}$$

If an isotropic impedance boundary condition is considered (i.e., the principal axes of anisotropy does not exist and $Z_{x'} = Z_{z'} = Z$), $R_{12} = R_{21} = 0$, whereas R_{11} and R_{22} reduce to the standard reflection coefficients for parallel and perpendicular polarisations. If the illuminated surface is perfectly electrically conducting, the out diagonal elements are again equal to zero, whereas $R_{11} = 1$ and $R_{22} = -1$ since $Z_{x'} = Z_{z'} = 0$.

Fig. 16. Amplitude of E_β if $E_{\beta'}^i = 1$, $E_{\phi'}^i = 0$ and $\beta' = 90^\circ$, $\phi' = 60^\circ$. Circular path with $\rho = 5 \lambda_0$. Layer characterised by $Z/\zeta_0 = j0.5$.

Fig. 17. Amplitude of E_β if $E_{\beta'}^i = 1$, $E_{\phi'}^i = 0$ and $\beta' = 90^\circ$, $\phi' = 60^\circ$. Circular path with $\rho = 5 \lambda_0$. Layer characterised by $Z/\zeta_0 = j0.5$.

The magnitudes of the electric field β -components of the GO field and the UAPO diffracted field on a circular path with $\rho = 5\lambda_0$ are considered in Fig. 16, where also the diffracted field obtained by using the Maliuzhinets solution (Bucci & Franceschetti, 1976) is reported in the case of an isotropic impedance boundary condition. A very good agreement exists between the two diffracted fields. The accuracy of the UAPO-based approach is further confirmed by comparing the total fields shown in Fig. 17, where also the COMSOL MULTIPHYSICS® results are shown.

4. Junctions of layers

The UAPO solution for the field diffracted by the edge of a truncated planar layer as derived in Section 2 can be extended to junctions by taking into account the diffraction contributions of the layers separately. This very useful characteristic is due to the property of linearity of the PO radiation integral. Accordingly, if the junction of two illuminated semi-infinite layers as depicted in Fig. 18 is considered, the total scattered field in (1) can be so rewritten:

$$\begin{aligned} \underline{E}^s &= -jk_0 \iint_{S_1+S_2} \left[(\underline{I} - \hat{R}\hat{R})\zeta_0 \underline{J}_s^{PO} + \underline{J}_{ms}^{PO} \times \hat{R} \right] G(\underline{r}, \underline{r}') dS = \\ &= -jk_0 \iint_{S_1} \left[(\underline{I} - \hat{R}\hat{R})\zeta_0 \underline{J}_{s_1}^{PO} + \underline{J}_{ms_1}^{PO} \times \hat{R} \right] G(\underline{r}, \underline{r}') dS_1 + \\ &\quad -jk_0 \iint_{S_2} \left[(\underline{I} - \hat{R}\hat{R})\zeta_0 \underline{J}_{s_2}^{PO} + \underline{J}_{ms_2}^{PO} \times \hat{R} \right] G(\underline{r}, \underline{r}') dS_2 = \underline{E}_1^s + \underline{E}_2^s \end{aligned} \quad (69)$$

and then $\underline{D} = \underline{D}_1 + \underline{D}_2$, with $\underline{D}_1$ given by (46). The diffraction matrix $\underline{D}_2$ related to the wave phenomenon originated by the edge of the second layer forming the junction can be determined by using again the methodology described in Section 2. If the external angle of the junction is equal to $n\pi$, a $(n-1)\pi$ rotation of the edge-fixed coordinate system must be considered for the second layer. The incidence and observation angles with respect to the illuminated face are now equal to $n\pi - \phi'$ and $n\pi - \phi$, respectively, so that the UAPO solution for $\underline{D}_2$ uses $n\pi - \phi'$ instead of ϕ' and $n\pi - \phi$ instead of ϕ . The results reported in (Gennarelli et al., 2000) with reference to an incidence direction normal to the junction of two resistive layers confirm the validity of the approach and, in particular, the accuracy of the solution is well assessed by resorting to a numerical technique based on the Boundary Element Method (BEM).

Fig. 18. Junction of two planar truncated layers.

5. Conclusions and future activities

UAPO solutions have been presented for a set of diffraction problems originated by plane waves impinging on edges in penetrable or opaque planar thin layers. The corresponding diffracted field has been obtained by modelling the structure as a canonical half-plane and by performing a uniform asymptotic evaluation of the radiation integral modified by the PO approximation of the involved electric and magnetic surface currents. The resulting expression is given in terms of the UTD transition function and the GO response of the structure accounting for its geometric, electric and magnetic characteristics. Accordingly, the UAPO solution possesses the same ease of handling of other solutions derived in the UTD framework and has the inherent advantage of providing the diffraction coefficients from the knowledge of the reflection and transmission coefficients. It allows one to compensate the discontinuities in the GO field at the incidence and reflection shadow boundaries, and its accuracy has been proved by making comparisons with purely numerical techniques. In addition, the time domain counterpart can be determined by applying the approach proposed in (Veruttipong, 1990), and the UAPO solution for the field diffracted by junctions can be easily obtained by considering the diffraction contributions of the layers separately. To sum up, it is possible to claim that UAPO solutions are very appealing from the engineering standpoint.

Diffraction by opaque wedges has been considered in (Gennarelli et al., 2001; Gennarelli & Riccio, 2009b). By working in this context, the next step in the future research activities may be devoted to find the UAPO solution for the field diffracted by penetrable wedges (f.i., dielectric wedges).

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7. References

- Burnside, W.D. & Burgener, K.W. (1983). High Frequency Scattering by a Thin Lossless Dielectric Slab. *IEEE Transactions on Antennas and Propagation*, Vol. AP-31, No. 1, January 1983, 104-110, ISSN: 0018-926X.
- Balanis, C.A. (1989). *Advanced Engineering Electromagnetics*, John Wiley & Sons, ISBN: 0-471-62194-3, New York.
- Bucci, O.M. & Franceschetti, G. (1976). Electromagnetic Scattering by a Half-Plane with Two Face Impedances, *Radio Science*, Vol. 11, No. 1, January 1976, 49-59, ISSN: 0048-6604.
- Clemmow, P.C. (1950). Some Extensions of the Method of Integration by Steepest Descent. *Quarterly Journal of Mechanics and Applied Mathematics*, Vol. 3, No. 2, 1950, 241-256, ISSN: 0033-5614.
- Clemmow, P.C. (1996). *The Plane Wave Spectrum Representation of Electromagnetic Fields*, Oxford University Press, ISBN: 0-7803-3411-6, Oxford.
- Ferrara, F.; Gennarelli, C.; Pelosi, G. & Riccio, G. (2007a). TD-UAPO Solution for the Field Diffracted by a Junction of Two Highly Conducting Dielectric Slabs. *Electromagnetics*, Vol. 27, No. 1, January 2007, 1-7, ISSN: 0272-6343.

- Ferrara, F.; Gennarelli, C.; Gennarelli, G.; Migliozi, M. & Riccio, G. (2007b). Scattering by Truncated Lossy Layers: a UAPO Based Approach. *Electromagnetics*, Vol. 27, No. 7, September 2007, 443-456, ISSN: 0272-6343.
- Gennarelli, C.; Pelosi, G.; Pochini, C. & Riccio, G. (1999). Uniform Asymptotic PO Diffraction Coefficients for an Anisotropic Impedance Half-Plane. *Journal of Electromagnetic Waves and Applications*, Vol. 13, No. 7, July 1999, 963-980, ISSN: 0920-5071.
- Gennarelli, C.; Pelosi, G.; Riccio, G. & Toso, G., (2000). Electromagnetic Scattering by Nonplanar Junctions of Resistive Sheets. *IEEE Transactions on Antennas and Propagation*, Vol. 48, No. 4, April 2000, 574-580, ISSN: 0018-926X.
- Gennarelli, C.; Pelosi, G. & Riccio, G. (2001). Approximate Diffraction Coefficients of an Anisotropic Impedance Wedge. *Electromagnetics*, Vol. 21, No. 2, February 2001, 165-180, ISSN: 0272-6343.
- Gennarelli, G. & Riccio, G. (2009a). A UAPO-Based Solution for the Scattering by a Lossless Double-Negative Metamaterial Slab. *Progress In Electromagnetics Research M*, Vol. 8, 2009, 207-220, ISSN: 1937-8726.
- Gennarelli, G. & Riccio, G. (2009b). *Progress In Electromagnetics Research B*, Vol. 17, 2009, 101-116, ISSN: 1937-6472.
- Keller, J.B. (1962). Geometrical Theory of Diffraction. *Journal of Optical Society of America*, Vol. 52, No. 2, February 1962, 116-130, ISSN: 0030-3941.
- Kouyoumjian, R.G. & Pathak, P.H. (1974). A Uniform Geometrical Theory of Diffraction for an Edge in a Perfectly Conducting Surface. *Proceedings of the IEEE*, Vol. 62, No. 11, November 1974, 1448-1461, ISSN: 0018-9219.
- Luebbers, R.J. (1984). Finite Conductivity Uniform UTD versus Knife Diffraction Prediction of Propagation Path Loss. *IEEE Transactions on Antennas and Propagation*, Vol. AP-32, No. 1, January 1984, 70-76, ISSN: 0018-926X.
- Maliuzhinets, G.D. (1958). Inversion Formula for the Sommerfeld Integral. *Soviet Physics Doklady*, Vol. 3, 1958, 52-56.
- Senior, T.B.A. & Volakis, J.L. (1995). *Approximate Boundary Conditions In Electromagnetics*. The Institution of Electrical Engineers, ISBN: 0-85296-849-3, Stevenage.
- Veruttipong, T.W. (1990). Time Domain Version of the Uniform GTD. *IEEE Transactions on Antennas and Propagation*, Vol. 38, No. 11, November 1990, 1757-1764, ISSN: 0018-926X.

Wave Propagation in Materials for Modern Applications

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In the recent decades, there has been a growing interest in micro- and nanotechnology. The advances in nanotechnology give rise to new applications and new types of materials with unique electromagnetic and mechanical properties. This book is devoted to the modern methods in electrodynamics and acoustics, which have been developed to describe wave propagation in these modern materials and nanodevices. The book consists of original works of leading scientists in the field of wave propagation who produced new theoretical and experimental methods in the research field and obtained new and important results. The first part of the book consists of chapters with general mathematical methods and approaches to the problem of wave propagation. A special attention is attracted to the advanced numerical methods fruitfully applied in the field of wave propagation. The second part of the book is devoted to the problems of wave propagation in newly developed metamaterials, micro- and nanostructures and porous media. In this part the interested reader will find important and fundamental results on electromagnetic wave propagation in media with negative refraction index and electromagnetic imaging in devices based on the materials. The third part of the book is devoted to the problems of wave propagation in elastic and piezoelectric media. In the fourth part, the works on the problems of wave propagation in plasma are collected. The fifth, sixth and seventh parts are devoted to the problems of wave propagation in media with chemical reactions, in nonlinear and disperse media, respectively. And finally, in the eighth part of the book some experimental methods in wave propagations are considered. It is necessary to emphasize that this book is not a textbook. It is important that the results combined in it are taken “from the desks of researchers”. Therefore, I am sure that in this book the interested and actively working readers (scientists, engineers and students) will find many interesting results and new ideas.

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