J.09.> Studying electromagnetic scattering by dielectric cylinders: An engineering electromagnetics' exercise at the Technological Educational Institute of Crete

ARTICLE *in* ADVANCES IN ENGINEERING EDUCATION · NOVEMBER 2004

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Studying Electromagnetic Scattering by Dielectric Cylinders: An Engineering Electromagnetics' Exercise at the Technological Educational Institute of Crete

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Abstract: - Scattering of arbitrarily polarized electromagnetic plane waves by a dielectric cylinder buried in an unbounded dielectric space and enclosing an array of parallel doubly layered (pipeline-type) dielectric circular cylinders is studied, in case of oblique incidence. The objective of this work is to present an exercise suitable for an advanced course on engineering electromagnetics. Using the boundary-value approach combined with the generalized separation variables method, we formulate the problem via a linear algebraic system with unknowns the field expansion constants. Solving this system, with single-term matrix elements, results in analytical expressions for both the scattered field and the scattering cross section of the structure. Numerical results are given for several configurations along with comparisons with previously published data.

Keywords: - Electromagnetic scattering, engineering electromagnetics education, plane-wave scattering, oblique incidence, cylinder array, dielectric cylinders, scattering cross section, separation of variables method.

1 Introduction

1.1 Electromagnetics education

Electromagnetic waves play [1] an increasingly important role in wireless communications, cellular telephony, wireless local- and personal- area networks, remote sensing, radar technology, multi-sensor integrated systems' detection and identification, microwave hardware design, bio-electromagnetics, electromagnetic compatibility, as well as in many other applications at complex natural or man-made environments. Thus electromagnetics, being the foundation of many different branches of engineering sciences and technologies, deserves a special place in modern electronic and computer engineering education.

The Technological Educational Institute of Crete Greece (TEI-C), as any other university, has three major objectives, i.e., the education of students, the generation and assignment of competent young engineers to industries, and the evolvement of basic and applied research. Combining these roles, our Microwave Communications & Electromagnetic Applications (MCEMA) Lab has comprehensive modern facilities for teaching and research activities in theoretical and computational electromagnetics, antenna analysis and design, microwave theory and applications, advanced communication and radar systems, and electromagnetic compatibility issues.

Here we concentrate upon electromagnetics engineering education [2] at TEI-C's Electronic Engineering Dept, whose undergraduate curriculum includes an advanced elective course in applied electromagnetics, called: *Propagation, Radiation & Scattering of Electromagnetic Waves*. This course is fully supported by the MCEMA Lab, with many exercises and computer simulations, while most of the lectures are sustained by text books [11]-[12].

Electromagnetic scattering by cylindrical structures is an important problem with many applications in mobile communications, defense industry, geophysical exploration, and electro-magnetic compatibility, such as simulation of complex bodies, control of the scattering cross-sections of several objects, communication inside tunnels, and remote sensing of pipelines.

The above discussion makes imperative, from educational point of view, an exercise for engineers on the study of electromagnetic scattering.

1.2 Scattering by a dielectric cylinder array

Plane-wave scattering by two or more parallel, concentric or eccentric, conducting or dielectric, circular cylinders, at normal [3]-[8] or oblique [9] incidence, has been treated by many researchers, using a variety of methods (separation of variables, moment methods, integral equations, perturbational techniques). The most extensive study can be found in [10], where scattering of obliquely incident waves from a bianisotropic cylinder enclosing other bianisotropic cylinders and placed in an unbounded bianisotropic space has been resolved.

In this paper we use an extension of the analytical method applied in [10], in order to address the problem, shown in Fig. 1(a), of a dielectric circular cylinder (region 1) embedded in the unbounded dielectric space (region 0) and loaded by an array of L-1 parallel doubly layered dielectric (in general lossy) circular cylinders (regions $2,3,...,2L-1$).

Each region ($i;\ i=0,1,...,2L-1$) is identified through the corresponding dielectric constant ε_i, magnetic permeability μ_i, and electric conductivity σ_i. The radius of any cylindrical region (ℓ; $\ell=1,2,...,2L-1$) is denoted by α_ℓ. All cylinders are parallel, with off-axis distance denoted by D_{pq} ($p,q=1,2,...,L$). For the analysis we employ L cylindrical coordinate systems (one for each cylinder): $O_1(\rho_1,\varphi_1,z)$ for regions (0) and (1), and $O_p(\rho_p,\varphi_p,z)$ for the cladding and core regions ($2(p-1)$) and ($2(p-1)+1$) of the p-cylinder.

We consider an arbitrarily polarized plane wave, propagating in the external region (0) and obliquely incident on the structure, as the primary excitation. Applying the generalized separation of variables method yields infinite series solutions for the scattered field in region (i), consisting of Bessel and Hankel functions with unknown expansion coefficients. Then implementing the corresponding boundary conditions and using the translational addition theorems for Bessel and Hankel functions, results in an infinite linear algebraic system for the field expansion constants. Solving this system after truncation yields to analytical expressions for the scattered fields and the scattering cross-section of the structure of Fig. 1(a).

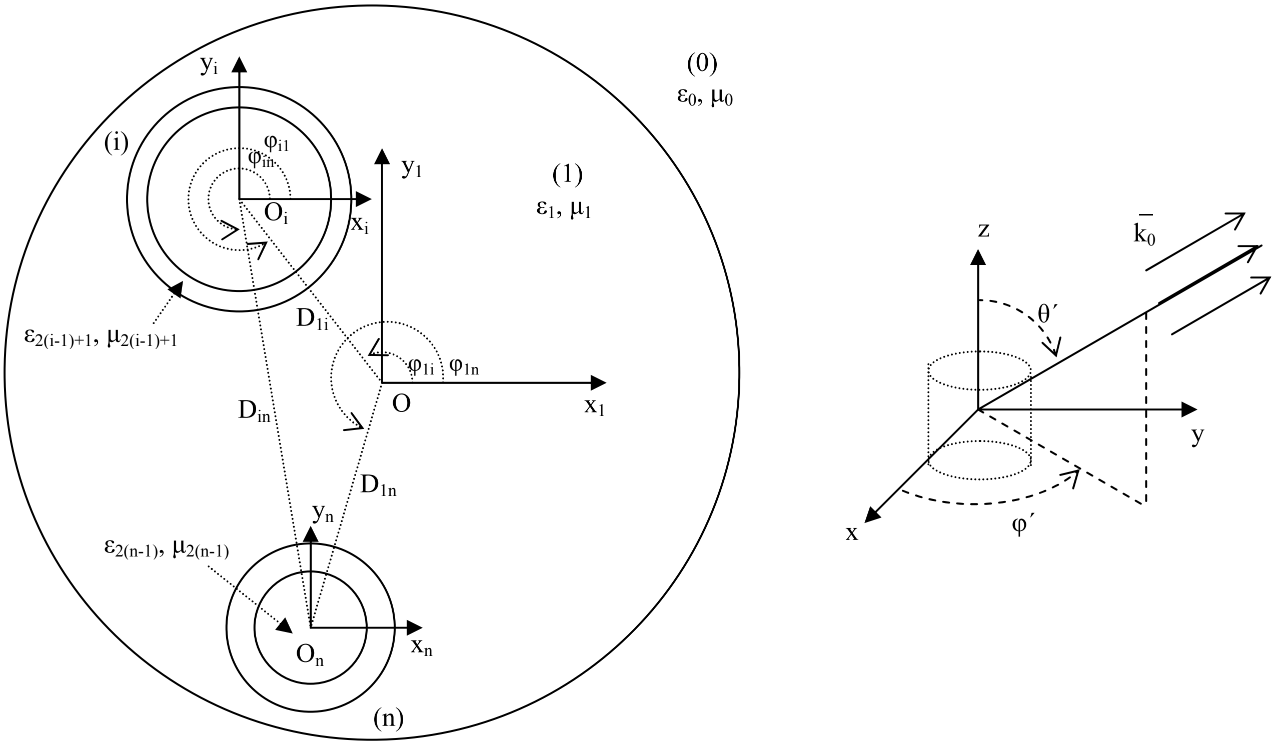

Figure 1. (a) The most general case of a cylinder array: a dielectric cylinder (1) embedded in (0) and enclosing multiple pipeline-type cylinders (2), (3), …, (L). **(b)** The plane wave incident upon the cylindrical structure.

2 Methodology

2.1 Incident field

Assume a plane wave propagating, in the direction: $k\ \sin\theta'\ (\cos\phi'\ \hat{x}+\sin\phi'\ \hat{y})+\ k\ \cos\theta'\ \hat{z}$ inside the infinite region (0), which is taken to be vacuum. In (1), θ' and φ' are the incidence angles shown in Fig. 1(b).

This plane wave obliquely incident on the configuration of Fig. 1(a), is the primary excitation of the structure. The arbitrarily polarized field

$[\overline{E}^{inc}(\overline{\rho}), \overline{H}^{inc}(\overline{\rho})]\, e^{-j\beta z}$ excited at $\overline{\rho} \in (0)$ will be termed the incident field, while E_0, H_0 are the magnitudes of the incident electric, magnetic fields.

2.2 Scattered field

The field $[\overline{E}^{sc}(\overline{\rho}), \overline{H}^{sc}(\overline{\rho})]e^{-j\beta z}$ excited at $\overline{\rho} \in (i)$; $i = 0, 1, \ldots, 2L-1$, because of the presence of the L dielectric cylinders of Fig. 1(a), will be termed the scattered field. In the cylindrical coordinate system (O_q), the z-components of the scattered field are:

$$\begin{bmatrix} E_z^{sc}(\overline{\rho}) \\ H_z^{sc}(\overline{\rho}) \end{bmatrix} = \sum_{n=-\infty}^{\infty} \Bigg\{ (1-\delta_{i,0}) J_n(k_{ci}\rho_q) e^{jn\phi_q} \begin{bmatrix} a_n^i \\ b_n^i \end{bmatrix} + \\ + \delta_{i,2(q-1)} H_n^{(2)}(k_{ci}\rho_q) e^{jn\phi_q} \begin{bmatrix} c_n^{i+1} \\ d_n^{i+1} \end{bmatrix} + \\ + \delta_{i,1} \sum_{s=2}^{L} H_n^{(2)}(k_{c1}\rho_s) e^{jn\phi_s} \begin{bmatrix} c_n^{2(s-1)} \\ d_n^{2(s-1)} \end{bmatrix} + \\ + \delta_{i,0} H_n^{(2)}(k_{c0}\rho_1) e^{jn\phi_1} \begin{bmatrix} c_n^1 \\ d_n^1 \end{bmatrix} \Bigg\}, \qquad (1)$$

where i designates the region of space, q designates the corresponding cylinder, (ρ_q, φ_q) denote the polar coordinates of $\overline{\rho}$ in the coordinate system (O_q), a_n^i, c_n^i and b_n^i, d_n^i are, respectively, the electric and magnetic field expansion coefficients, $\delta_{i,\ell}$ $(=1$, only if $i=\ell)$ is the Kronecker delta, $J_n(.)$ stands for the Bessel function of order n, $H_n^{(2)}(.)$ is the Hankel function of the second kind and order n, $k_{ci} = \sqrt{k_i^2 - \beta^2}$, $\beta = k_0 \cos\theta'$ is the propagation constant, and $k_i = \sqrt{\varepsilon_i \mu_i \omega^2 - j\omega\mu_i\sigma_i}$.

2.3 Boundary conditions

Since the total field $[\overline{E}^{tot}(\overline{\rho}), \overline{H}^{tot}(\overline{\rho})]e^{-j\beta z}$ at $\overline{\rho} \in (i)$ can be expressed as:

$$\begin{bmatrix} E_z^{tot}(\overline{\rho}) \\ H_z^{tot}(\overline{\rho}) \end{bmatrix} = \begin{bmatrix} E_z^{sc}(\overline{\rho}) \\ H_z^{sc}(\overline{\rho}) \end{bmatrix} + \delta_{i,0} \begin{bmatrix} E_z^{inc}(\overline{\rho}) \\ H_z^{inc}(\overline{\rho}) \end{bmatrix}, \qquad (2)$$

we apply the continuity conditions for the E_z, H_z, E_φ and H_φ components of the total field over all circular cylindrical boundaries $(\rho_p = \alpha_1, \alpha_{2(p-1)}, \alpha_{2(p-1)+1}$; $p = 1, \ldots, L)$ of the structure, and obtain the following infinite, linear, algebraic system for the unknown expansion constants, in compact form:

$$\Bigg[\delta_{q,2(p-1)} \begin{bmatrix} J_M(k_{cq}\alpha_q)\overline{\overline{I}} & -H_M^{(2)}(k_{c1}\alpha_q)\overline{\overline{I}} \\ {}^M\overline{\overline{G}}_q^J(\alpha_q) & -{}^M\overline{\overline{G}}_1^H(\alpha_q) \end{bmatrix} + \left(\delta_{q,1} + \delta_{q,2(p-1)+1}\right) \begin{bmatrix} J_M(k_{cq}\alpha_q)\overline{\overline{I}} & -H_M^{(2)}(k_{c(q-1)}\alpha_q)\overline{\overline{I}} \\ {}^M\overline{\overline{G}}_q^J(\alpha_q) & -{}^M\overline{\overline{G}}_{(q-1)}^H(\alpha_q) \end{bmatrix} \Bigg] \begin{bmatrix} \begin{pmatrix} a_M^q \\ b_M^q \end{pmatrix} \\ \begin{pmatrix} c_M^q \\ d_M^q \end{pmatrix} \end{bmatrix} + \\ + \delta_{q,2(p-1)} \begin{bmatrix} H_M^{(2)}(k_{cq}\alpha_q)\overline{\overline{I}} \\ {}^M\overline{\overline{G}}_q^H(\alpha_q) \end{bmatrix} \begin{pmatrix} c_M^{q+1} \\ d_M^{q+1} \end{pmatrix} - \delta_{q,2(p-1)+1} \begin{bmatrix} J_M(k_{c(q-1)}\alpha_q)\overline{\overline{I}} \\ {}^M\overline{\overline{G}}_{(q-1)}^J(\alpha_q) \end{bmatrix} \begin{pmatrix} a_M^{q-1} \\ b_M^{q-1} \end{pmatrix} - \\ - \delta_{q,2(p-1)} \sum_{n=-\infty}^{\infty} \Bigg[J_{n-M}(k_{c1}D_{1p}) e^{j(n-M)\varphi_{1p}} \begin{bmatrix} J_M(k_{c1}\alpha_q)\overline{\overline{I}} \\ {}^M\overline{\overline{G}}_1^J(\alpha_q) \end{bmatrix} \begin{pmatrix} a_n^1 \\ b_n^1 \end{pmatrix} + \\ + \sum_{s=2}^{L}{}' H_{n-M}^{(2)}(k_{c1}D_{sp}) e^{j(n-M)\varphi_{sp}} \begin{bmatrix} J_M(k_{c1}\alpha_q)\overline{\overline{I}} \\ {}^M\overline{\overline{G}}_1^J(\alpha_q) \end{bmatrix} \begin{pmatrix} c_n^{2(s-1)} \\ d_n^{2(s-1)} \end{pmatrix} \Bigg] + \\ + \delta_{q,1} \sum_{n=-\infty}^{\infty} \sum_{s=2}^{L} J_{n-M}(k_{c1}D_{s1}) e^{j(n-M)\varphi_{s1}} \begin{bmatrix} H_M^{(2)}(k_{c1}\alpha_1)\overline{\overline{I}} \\ {}^M\overline{\overline{G}}_1^H(\alpha_1) \end{bmatrix} \begin{pmatrix} c_n^{2(s-1)} \\ d_n^{2(s-1)} \end{pmatrix} = \delta_{q,1}\, j^M e^{-jM\varphi'} \begin{bmatrix} J_M(k_{c0}\alpha_1)\overline{\overline{I}} \\ {}^M\overline{\overline{G}}_0^J(\alpha_1) \end{bmatrix} \begin{bmatrix} E_0 \\ H_0 \end{bmatrix}. \qquad (3)$$

The shorthand symbols ${}^n\overline{\overline{G}}_i^\Lambda(\rho)$ stand for:

$$\begin{bmatrix} \dfrac{\beta n}{k_{ci}^2 \rho} \Lambda(k_{ci}\rho) & \dfrac{j\omega\mu_i}{k_{ci}} \Lambda'(k_{ci}\rho) \\ -\dfrac{j\omega\varepsilon_i + \sigma_i}{k_{ci}} \Lambda'(k_{ci}\rho) & \dfrac{\beta n}{k_{ci}^2 \rho} \Lambda(k_{ci}\rho) \end{bmatrix},$$

where $\Lambda \equiv J_n(.)$, $H_n^{(2)}(.)$ and $\Lambda' \equiv J_n'(.)$, $H_n'^{(2)}(.)$ are the derivatives of the Bessel and Hankel functions with respect to their arguments.

In (3) $M = 0, \pm 1, \pm 2, \ldots, \pm N_r, \ldots, \pm\infty$ (truncated to N_r for evaluation), $p = 1, \ldots, L$; $s = 2, \ldots, L$; $q = 1, 2, \ldots, 2(L-1)+1$, $\overline{\overline{I}}$ is the 2×2 identity matrix,

D_{sp} denotes the off-axis distance between (O_s) and (O_p) coordinate systems, φ_{sp} denotes the position angle of the (O_p) coordinate system with respect to (O_s), and α_q denotes the radius of the cladding or the core region of the p-cylinder.

The matrix elements and constant terms of the resulting algebraic $20(2N_r+1)\times 20(2N_r+1)$ system (3) are given in closed form by simple analytical expressions (mostly single-term Bessel or Hankel functions). Solving this system leads to an extremely accurate, very fast and highly efficient (requiring small truncation sizes N_r) evaluation of the field expansion coefficients in (1).

2.4 Far field and total radar cross section

Letting $\bar{\rho}(\rho_1,\varphi_1)\in(0)$ and $\rho_1\to\infty$ in (1), we find for the z- components of the far-scattered field:

$$\begin{bmatrix} E_z^{sc}(\bar{\rho}) \\ H_z^{sc}(\bar{\rho}) \end{bmatrix} = e^{-j\left[k_{c0}\rho_1-\frac{\pi}{4}\right]}\sqrt{\frac{2}{\pi k_{c0}\rho_1}}\sum_{n=-\infty}^{\infty} e^{jn\left[\phi_1+\frac{\pi}{2}\right]}\begin{bmatrix} c_n^1 \\ d_n^1 \end{bmatrix} \quad (4)$$

and finally the total scattering radar cross section (RCS) σ_t of the structure [13] is given by:

$$\sigma_t = \frac{4\left(k_0(\sin\theta')^2\right)^{-1}}{E_0^2+Z_0^2H_0^2}\sum_{n=-\infty}^{\infty}\left(\left|c_n^1\right|^2+\left|Z_0\,d_n^1\right|^2\right). \quad (5)$$

3 Numerical Results

In Figs. 2-6 the scattered far-fields and the total radar cross section are given for arrays of dielectric pipeline-type cylinders (special cases of the structure of Fig. 1(a)) and for both polarizations.

Figs. 2-3 refer to a couple of dielectric cylinders ($L=3$), while Figs. 4-5 refer to a couple of lossy dielectric pipeline-type cylinders ($L=3$), and Fig. 6 refers to a quadruplet of dielectric cylinders ($L=5$). In all cases we assume that regions (1) and (0), is vacuum.

Fig. 2 shows, in polar coordinates, the scattered far-field pattern $|E_z^{sc}(\varphi_1)|$ of the inset structure, for $\varphi'=90^o$ and for several values of θ' in the case of E-polarized obliquely incident plane wave excitation. The curve $\theta'=90^o$ (case of normal incidence) is indistinguishable from [3, Fig.5].

In Fig. 3 we present the scattered far-field pattern $|H_z^{sc}(\varphi_1)|$ of the inset structure, for $\varphi'=0^o$ and for several values of θ' in the case of H-polarized obliquely incident plane wave excitation. In the special case of normal incidence (dashed curve), our results coincide with [8, Fig.3].

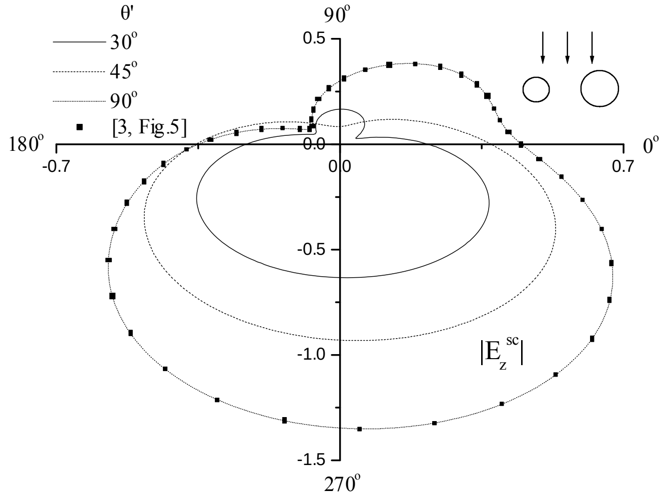

Figure 2. Far field pattern of the structure of Fig. 1(a) in case: L=3, $D_{23}=0.4\lambda_0$, $E_0=1$, $H_0=0$, $\varepsilon_3=\varepsilon_5=2\varepsilon_1=2\varepsilon_2=2\varepsilon_4=2\varepsilon_0$, $\alpha_5=2\alpha_3=0.2\lambda_0$, $\mu_i=\mu_0$, $\sigma_i=0$ ($i=1,2,3,4,5$).

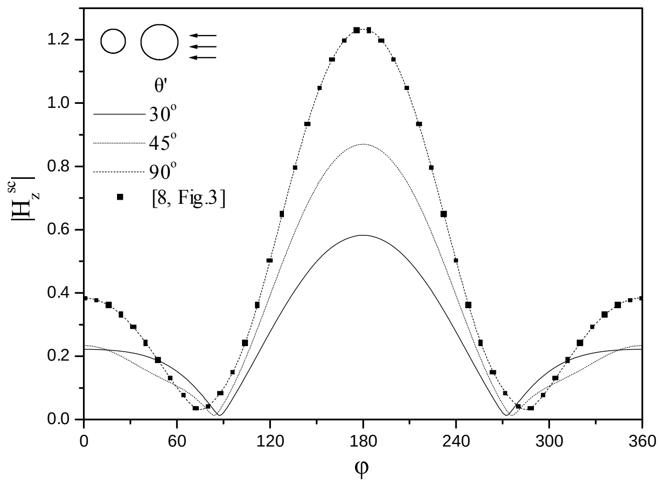

Figure 3. Far field pattern of the structure of Fig. 1(a) in case: L=3, $D_{23}=0.4\lambda_0$, $E_0=0$, $H_0=1$, $\varepsilon_3=\varepsilon_5=2\varepsilon_1=2\varepsilon_2=2\varepsilon_4=2\varepsilon_0$, $\alpha_5=2\alpha_3=0.2\lambda_0$, $\mu_i=\mu_0$, $\sigma_i=0$ ($i=1,2,3,4,5$).

For $\theta'=70^o$, $\varphi'=45^o$ and for several values of the conductivities σ_2,σ_4 of the cladding regions, Fig. 4 shows the scattered far-field pattern $|E_z^{sc}(\varphi_1)|$ of the inset structure. Note that farther increase of the cladding regions' conductivities σ_2 and σ_4, does not affect the solid curve field pattern corresponding to $\sigma_2=\sigma_4=50\,S/m$, while several lobes are observed, among which the main one is at $\varphi_1\approx 228^o$.

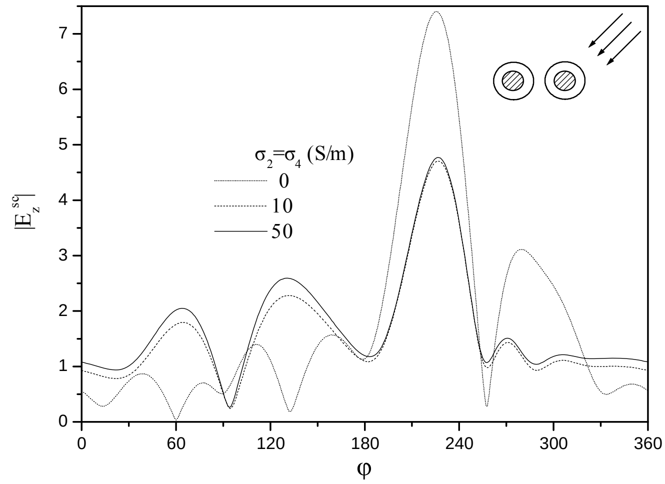

Figure 4. Far field pattern of the structure of Fig. 1(a) in case: L=3, $D_{23} = \lambda_0$, $E_0 = 1$, $H_0 = 0$, $\varepsilon_1 = \varepsilon_0$, $\varepsilon_2 = \varepsilon_4 = 2.32\varepsilon_0$, $\varepsilon_3 = \varepsilon_5 = 4.34\varepsilon_0$, $\alpha_2 = \alpha_4 = 2\alpha_3 = 2\alpha_5 = 0.4\lambda_0$, $\mu_i = \mu_0$ $(i = 1,2,3,4,5)$, $\sigma_1 = \sigma_3 = \sigma_5 = 0$.

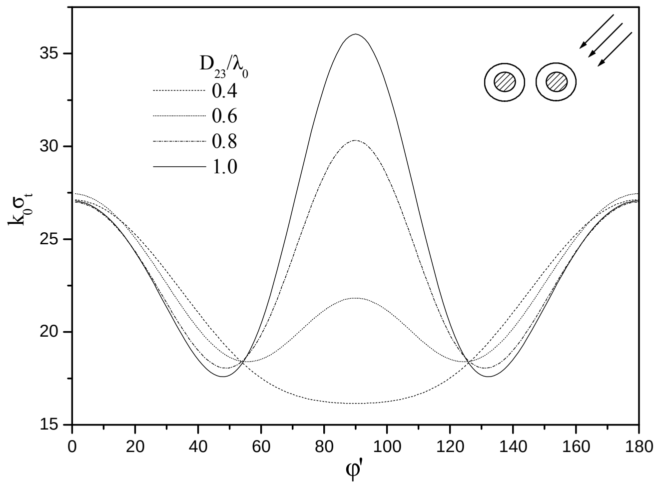

Figure 5. Normalized total radar cross-section vs. φ' for the structure of Fig. 1(a) in case: L=3, $\varepsilon_1 = \varepsilon_0$, $\varepsilon_2 = \varepsilon_4 = 2.32\varepsilon_0$, $\varepsilon_3 = \varepsilon_5 = 4.34\varepsilon_0$, $\alpha_2 = \alpha_4 = 2\alpha_3 = 2\alpha_5 = 0.2\lambda_0$, $\theta' = 45^o$, $E_0 = 1$, $H_0 = 0$, $\sigma_i = 0$, $\mu_i = \mu_0$ $(i = 1,2,3,4,5)$.

Fig. 5 illustrate the normalized total radar cross section ($k_0\sigma_t$) versus φ' for the inset structure, for several values of the off-axis distance D_{23}. The results are symmetrical about the xz plane ($\varphi' = 90^o$), as it is imposed by the geometry of the scatterer. These figures suggest the possibility to control the radar cross section of the structure by changing D_{23}. For example, increasing of D_{23} yields to significantly greater values of σ_t (if $54^o < \varphi' < 126^o$). Moreover, let us note that $k_0\sigma_t$ has, independently of D_{23}, the same value for incidence angles $\varphi' = 54^o, 126^o$.

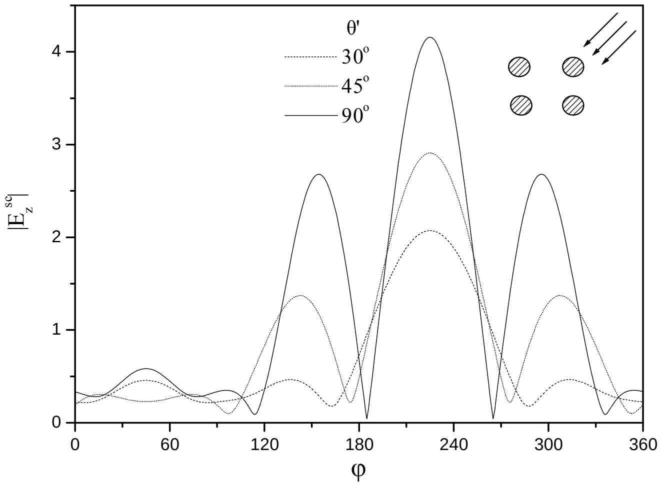

Figure 6. Far field pattern ($\varphi = \varphi_1$) of the structure of Fig. 1(a) in case L=5, $D_{23} = D_{34} = D_{45} = D_{25} = 0.8\lambda_0$, $D_{24} = D_{35} = 0.8\sqrt{2}\,\lambda_0$, $\varepsilon_1 = \varepsilon_2 = \varepsilon_4 = \varepsilon_6 = \varepsilon_8 = \varepsilon_0$, $\alpha_3 = \alpha_5 = \alpha_7 = \alpha_9 = 0.2\lambda_0$, $\varepsilon_3 = \varepsilon_5 = \varepsilon_7 = \varepsilon_9 = 2.32\varepsilon_0$, $\mu_i = \mu_0$, $\sigma_i = 0$ (i=1-9).

Finally, for the dielectric cylinders' quadruplet of the inset structure of Fig. 6, we present the scattered far-field pattern $|E_z^{sc}(\varphi_1)|$ for $\varphi' = 45^o$ and for several values of θ' in case of E-polarization.

N_r	$\lvert E_z^{sc}(\rho_1 \to \infty, \varphi_1 = 45^o)\rvert$
7	56.99990
8	57.30295
9	57.24285
10	57.24623
11	57.23580
12	57.23515
13	57.23517
14	57.23517
15	57.23517

Table 1. Convergence of the algorithm.

The convergence characteristics of the algorithm are illustrated in Table 1, where the values of $|E_z^{sc}(\rho_1 \to \infty, \varphi_1 = 45^o)|$ are shown for several truncation sizes N_r of the linear algebraic system (3). These values correspond to the inset configuration of Fig. 4 when $\theta' = \varphi' = 45^o$, $L = 3$, $E_0 = H_0 = 1$, $D_{23} = 0.7\lambda_0$, $\varepsilon_2 = \varepsilon_4 = 2.32\varepsilon_0$, $\varepsilon_1 = \varepsilon_0$, $\alpha_2 = \alpha_4 = 0.3\lambda_0$, $\varepsilon_3 = \varepsilon_5 = 4.34\varepsilon_0$, $\alpha_3 = \alpha_5 = 0.2\lambda_0$, $\mu_i = \mu_0$, $\sigma_i = 0$ $(i = 1,2,3,4,5)$. Apparently the convergence is very rapid and stable, as $N_r = 12$ suffices to evaluate the far field within six significant decimals.

4 Conclusions

In this work it was presented an exercise on electromagnetic scattering by dielectric cylinders, designed and developed at the MCEMA Lab of TEI-C, aiming to introduce the students to the principles of applied electromagnetics. Furthermore, the students have the opportunity to acquire vast experience on high level programming.

Electromagnetic scattering by an array of lossy dielectric pipeline-type cylinders embedded in an unbounded dielectric space has been investigated in the most general case of obliquely incident arbitrarily polarized plane waves. The solution technique uses the generalized separation variables method and results in a linear algebraic system for the field expansion coefficients, with single-term matrix elements. To validate the developed numerical codes, extended comparisons with available results have been carried out. Plotted results for the far scattered fields and the total radar cross-section reveal how changing several geometrical and physical parameters of the structure may control its scattering properties.

The presented exercise demands the activation, participation, concentration and alertness of every student, cultivating the collaboration skills and fundamental qualifications of the future engineers. Therefore, by introducing novel teaching tools in electromagnetic courses and computerized solutions in microwave problems, students of TEI recovered their interest in microwave engineering courses.

Acknowledgment

This work was supported by the Greek Ministry of National Education and Religious Affairs and the European Union under the ΕΠΕΑΕΚ II projects: “Archimedes – Support of Research Groups in TEI of Crete – Smart antenna study & design using techniques of computational electromagnetics and pilot development & operation of a digital audio broadcasting station at Chania (SMART-DAB)” and “Reformation of the Electronics Dept’s syllabus”.

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