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EFFECTS OF EXTERNAL BODIES MADE OF DIFFERENT MATERIALS ON PLAN-PARALLEL SYSTEM FIELD HOMOGENEITY

ZLATA Ž. CVETKOVIĆ[1], ŽAKLINA J. MANČIĆ[1], MILKA M. POTREBIĆ[2], SAŠA S. ILIĆ[1]

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A system of four charged plan-parallel electrodes is used to generate a homogeneous electrostatic field. The influence of a cylindrical external body on the generated uniform electrostatic field is analyzed. The body made of different types of material is observed. The expressions for the field inside and outside of the cylinder made of perfectly conducting, isotropic dielectric and bi-isotropic material of Tellegen type are derived by applying the method of images. Numerical results of uniform field deformation, caused by the presence of external cylinder, are presented.

1. INTRODUCTION

The problem of generating fields, both magnetic and electric, is present for decades. In recent years, the need for generating a stable homogeneous electrostatic field has increased due to its application in modern medical devices [1]. Analogously with Helmholtz coils, which produce a uniform magnetic field [2−6], it is possible to produce a uniform electrostatic field using two-charged coaxial equal-diameter coils [7]. The homogeneity of the field and the size of the space covered by homogeneous field can be increased by using a system, which consists of two charged spherical bowls [8]. In addition, the homogeneous electrostatic field can be generated using two-wire and four-wire transmission line simulators [9, 10].

The authors have already proposed a variety of complex system models for generating uniform electrostatic field, realized using coils [11−13], biconical electrode simulators [12−15], and plan-parallel electrode simulators [12, 16, 17]. In the paper [12], complex plan-parallel systems are modelled and the primary N-th order cell, whose electrodes are positioned on an imaginary cylindrical surface, was defined. The analysis of the efficiency and stability of the proposed systems in the case of small deviations of some geometric parameters of the system (comparing to the calculated values) is presented in [16]. Once a homogeneous electrostatic field is generated, it is of interest to determine to what extent an external body, placed into this electrostatic field, affects the achieved homogeneity. A body can be made of different types of materials. In [17], the influence of a conducting external body on a homogeneous electrostatic field, obtained using plan-parallel electrodes, is observed. Next, a detailed analysis of the field distribution inside and outside of two infinitely long parallel dielectric cylinders, made of different dielectric materials in a homogeneous electrostatic field, was performed in [18]. Furthermore, calculation of field and potential distribution in the vicinity of bi-isotropic cylindrical and spherical bodies placed in a homogeneous electrostatic field was presented in [19].

The aim of this paper is to examine the influence of an external body on the achieved homogeneity of the field obtained by using the plan-parallel electrodes. The external body is modelled using cylinder whose axis coincides with the axial axis of the system. We have observed bodies made of conducting, isotropic dielectric and bi-isotropic material of Tellegen type, whose specificity is that they can be at the same time polarized and magnetized if they are placed into external electric or magnetic fields [18, 24]. Due to simplicity, it is desirable to apply image theorem whenever it is possible [20−22]. In this paper, image theorem is applied in order to determine the electric potential of the external cylinder placed in the generated homogeneous field.

Bi-isotropic materials considered in [23] represent a special class of bi-anisotropic materials as tensors that appear in constituent relationships are reduced to scalars [24]. Bi-isotropic materials are being widely applied in optics for years [24], whereas its potential usage in shielding or absorption materials, chiro-microstrip antennas, chiro-waveguides and twisted polarizers is researched [25]. For such materials, modified image theorem is applied [19, 23, 26−28].

The paper isorganized as it follows. Firstly, the procedure of homogeneous electrostatic field generation is provided in Section 2. The primary cell is described while the cells of the higher order, which provide better homogeneity of the field, are mentioned. Section 3 gives an overview of the image theorem for charges per unit length outside of the perfectly conducting, isotropic and bi-isotropic dielectric cylinder. Next, Section 4 presents numerical results for conducting, isotropic dielectric and bi-isotropic cylinder inserted into the generated homogeneous electrostatic field. Finally, detailed analysis of the presented results and appropriate conclusions are provided in Sections 4 and 5, respectively.

2. EXTERNAL BODY IN THE HOMOGENEOUS ELECTROSTATIC FIELD

2.1 MODELLING OF PLAN-PARALLEL PRIMARY CELL FOR HOMOGENEOUS ELECTROSTATIC FIELD GENERATION

For generating homogeneous electrostatic field with plan-parallel electrodes a so-called primary cell is used [17]. It consists of two pairs of plan-parallel, straight linear

[1] Faculty of Electronic Engineering, University of Niš, Aleksandra Medvedeva 14, 18106 Niš, Serbia,
E-mail: zlata.cvetkovic@elfak.ni.ac.rs, zaklina.mancic@elfak.ni.ac.rs, sasa.ilic@elfak.ni.ac.rs
[2] School of Electrical Engineering, University of Belgrade, Bulevar kralja Aleksandra 73, 11120 Belgrade, Serbia,
E-mail: milka_potrebic@etf.rs

conductors with a circular cross-section of radius r_0, where $r_0 << d, h$ and it is shown in Fig. 1.

A pair of electrodes with equal electric potential values is placed at a distance $2d$ and separated by a distance $2h$ from electrodes with opposite electric potential values. For the coordinate system as in Fig. 1 [12, 17], symmetry plane is $y = 0$, i.e. $\theta = \pi/2$ for the zero potential. The charges per unit length of the positive and negative electrodes are q' and $-q'$, respectively.

The lengths of the electrodes are significantly longer compared to dimensions of the area in which the uniform electrostatic field is obtained. Therefore, the length of the electrodes can be considered infinite.

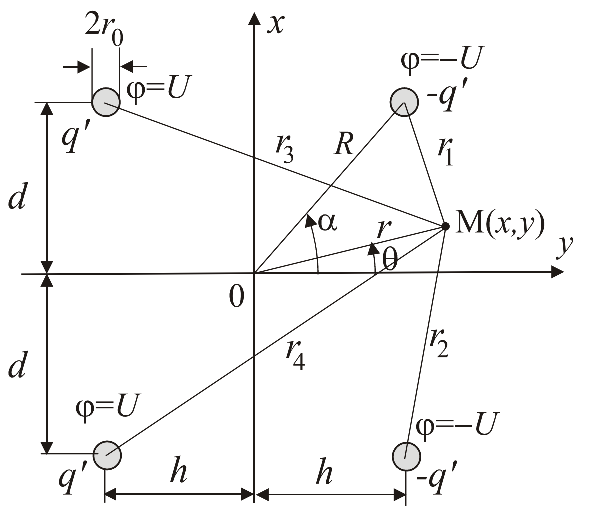

Fig.1 — Cross section of the plan-parallel primary cell.

Electric potential at the point $\mathrm{M}(x, y)$, for the system in the presence of air, is [12,17]:

$$\varphi = \frac{q'}{2\pi\varepsilon_0} \ln\left(\frac{r_1 r_2}{r_3 r_4}\right), \tag{1}$$

where:

$$r_1 = \sqrt{(d-x)^2 + (y-h)^2} = \sqrt{r^2 + R^2 - 2rR\cos(\alpha - \theta)},$$

$$r_2 = \sqrt{(d+x)^2 + (y-h)^2} = \sqrt{r^2 + R^2 - 2rR\cos(\alpha + \theta)},$$

$$r_3 = \sqrt{(d-x)^2 + (y+h)^2} = \sqrt{r^2 + R^2 - 2rR\cos(\pi - \alpha - \theta)},$$

$$r_4 = \sqrt{(d+x)^2 + (y+h)^2} = \sqrt{r^2 + R^2 - 2rR\cos(\pi - \alpha + \theta)},$$

where $R^2 = d^2 + h^2$, $\mathrm{tg}(\alpha) = \dfrac{d}{h}$, x and y are Cartesian coordinates, while r and θ are cylindrical coordinates. The distribution of the electric potential along the axis of the system, ($\theta = 0$, $r = y$), is:

$$\varphi(\theta = 0,\ r = y) = \frac{q'}{2\pi\varepsilon_0} \ln\left(\frac{1 + \zeta^2 - 2\zeta\cos(\alpha)}{1 + \zeta^2 + 2\zeta\cos(\alpha)}\right), \tag{2}$$

where $\zeta = y/R$ is a parameter, for which in the central area of the system is valid $\zeta^2 < 1$. In these conditions can be used the development in the Fourier series

$$\ln\left(1 + \zeta^2 - 2\zeta\cos\alpha\right) = -2\sum_{n=1}^{\infty} \frac{\cos(n\alpha)}{n}\zeta^n, \tag{3}$$

so the expression for the potential along the y direction can be presented in the form of series:

$$\varphi(0, y) = \sum_{n=0}^{\infty} \varphi_{2n+1} y^{2n+1}, \tag{4}$$

where

$$\varphi_{2n+1} = -\frac{2q'}{\pi\varepsilon} \frac{\cos(2n+1)\alpha}{(2n+1)R^{2n+1}}. \tag{5}$$

The electrostatic field is determined using $\mathbf{E}(x, y) = -\operatorname{grad}\varphi(x, y)$ [29]. Electrostatic field has only transverse components.

In order to achieve homogeneous electrostatic field along the axial axis of the system, the potential function (4) in that domain has to be linearly dependent on y. Since the series (4) are decreasing, system dimensions can be chosen so that, a certain number of high-order coefficients can be annulled, and the approximately linear dependence of the potential is achieved. In the general case, the dimensions of the primary cell of N^{th} order are obtained from the condition that the coefficient with y^{2N+1} is equal to zero. This gives an equation:

$$\varphi_{2N+1} = 0, \tag{6}$$

i.e.

$$\cos[(2N+1)\alpha] = 0, \tag{7}$$

which has N positive solutions:

$$\alpha_k = \frac{k\pi}{2(2N+1)}, \quad \text{for } k = 1, 2, ..., N, \tag{8}$$

so there exist N different primary cells whose dimensions are:

$$h_k/R = \cos(\alpha_k) \text{ and } d_k/R = \sin(\alpha_k). \tag{9}$$

This cell is of N^{th} order and it has k different primary cells with the same distribution of potential, where is $k = 1, 2, ..., N$. It is assumed that all conductors of the primary cell of the same order lie on the same cylindrical surface of the radius R.

In order to remove the affect of other series terms from y^3 to y^{2N-1}, it can be found the following system of equations

$$\phi_{2n+1} = 0, \text{ for } n = 1, 2, ..., N-1.$$

The solutions of this system give charges per unit length q'_n.

3. METHOD OF IMAGES FOR CYLINDRICAL SURFACE

In this paper the primary cell of the first order, $N = 1$, whose dimensions are $h = 0.8660254R$ and $d = 0.5R$ will be exploited for generating the homogeneous electrostatic field. We observed the influence of an external cylindrical shaped body. Since the system has an axial symmetry, it is appropriate to solve the problem using the cylindrical coordinate system. Thus, it is possible to apply the method of images, in mathematical terms, and to determine in an easy way how and to what extent the cilindrical body material, "spoils" the homogeneity of the field.

3.1 METHOD OF IMAGES FOR PERFECTLY CONDUCTING MATERIALS

In order to calculate the influence of a perfectly conducting external body on the plan-parallel electrode field, we have used the method of images. Images are positioned along the cylindrical surface of the radius $D = a^2 / R$ [17].

These images are obtained from mapping of electrodes' line-charge density into the cylindrical mirror. They are used to determine electric scalar potential outside the external body.

The primary electrode cell and mapped charges are taken into account to find overall electric scalar potential outside the external body at any field point for $a < r < R$.

In the aforementioned equation for calculating radius D, parameter a is the radius of the conducting body, while R represents the radius of the imaginary cylinder. Circle of radius R determines the place points where plan-parallel electrodes are located for a generating homogeneous electrostatic field.

3.2 METHOD OF IMAGES FOR ISOTROPIC DIELECTRIC MATERIALS

If the external body is made of lossless dielectric material, which is described using the absolute permittivity $\varepsilon = \varepsilon_r \varepsilon_0$, placed in air (for air the relative permittivity is $\varepsilon_r = 1$ whereas the vacuum permittivity is $\varepsilon_0 = 8.8541878\ \mathrm{F/m}$), using the image theorem in the cylindrical mirror it is obtained the electric scalar potential outside the external body [30].

Outside external body the equivalent system consists of original charges per unit length q' and images $\mathrm{A}q'$ and $\mathrm{B}q'$ (Fig. 2.), where constants A and B depend on the permittivity of the cylindrical body and the environment in which it is located (in air) [21]:

$$\mathrm{A} = -\mathrm{B} = \frac{\varepsilon_0 - \varepsilon}{\varepsilon_0 + \varepsilon}, \tag{10}$$

In electrostatic state, it can be considered that $\varepsilon \to \infty$ (for the conducting body), so we get $\mathrm{A} = -\mathrm{B} = -1$.

3.3 METHOD OF IMAGES FOR BI-ISOTROPIC MATERIALS

Recently bi-isotropic materials are widely applied, thus we are going to consider the case of bi-isotropic material external body. Sihvola introduced a generalized non-reciprocal chiral material described with expressions [23]:

$$\mathbf{D} = \varepsilon \mathbf{E} + (\xi - j\chi)\sqrt{\varepsilon_0 \mu_0}\,\mathbf{H}, \tag{11}$$

and

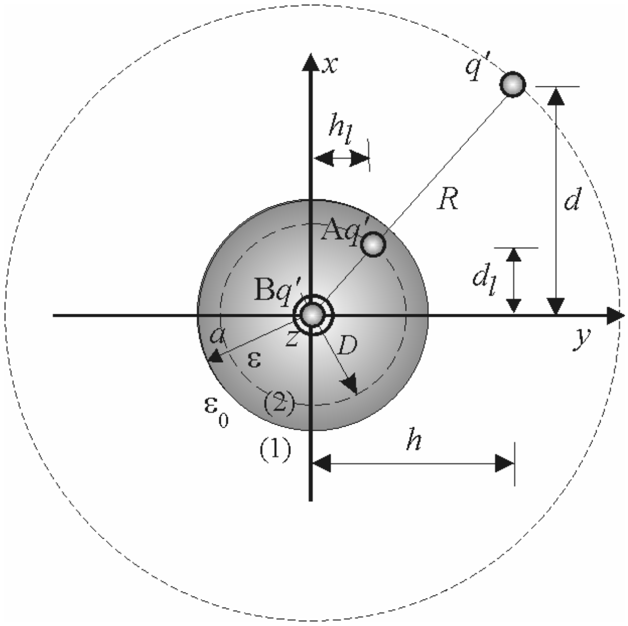

Fig. 2 — Charges per unit length and its images in the dielectric cylindrical mirror.

$$\mathbf{B} = \mu \mathbf{H} + (\xi + j\chi)\sqrt{\varepsilon_0 \mu_0}\,\mathbf{E}, \tag{12}$$

where ξ is the Tellegen parameter, which represents a measure of the non-reciprocity of the generalized bi-isotropic material whereas χ is the degree of chirality. If the condition $\chi = 0$ is fulfilled, it is assumed that it is a non-reciprocal achiralic material of the Tellegen type [31, 32]. On the other hand, if the condition $\xi = 0$ is fulfilled, the material is considered Pasteur medium.

Constituent relations between vectors **E**, **D**, **B** and **H** for bi-isotropic Tellegen medium are defined as:

$$\mathbf{D} = \varepsilon \mathbf{E} + \xi \mathbf{H} \text{ and } \mathbf{B} = \mu \mathbf{H} + \xi \mathbf{E}, \tag{13}$$

where $\varepsilon = \varepsilon_r \varepsilon_0$ and $\mu = \mu_r \mu_0$ (μ_r is the relative magnetic permeability and $\mu_0 = 4\pi \cdot 10^{-7}\ \mathrm{H/m}$ is the vacuum magnetic permeability). Taking into account the condition $\varepsilon\mu \neq \xi^2$, according to Tellegen [19], such a material consists of elements that have permanent electric and magnetic dipoles, oriented parallel or antiparallel with others, so that the electrostatic and magnetic fields in this material simultaneously regulates both electric and magnetic dipoles. Therefore, these materials could be at the same time polarized and magnetized if they are placed into external electric or magnetic fields [19, 23, 26–28]. Starting from the Maxwell's equations and the constitutive relationships presented in (13), in the case of these materials $\mathrm{div}(\mathbf{E}) = \rho / \varepsilon\left(1 - \xi^2 / (\varepsilon\mu)\right)$, where ρ is the volume charge density of free electrical charges in the observed environment. By setting $\mathbf{E} = -\mathrm{grad}(\varphi)$ [29], where φ is the electric scalar potential, the Poisson's equation for the electric scalar potential is achieved [19, 32]:

$$\Delta\varphi = -\rho / \varepsilon_e, \tag{14}$$

where is $\varepsilon_e = \varepsilon\left(1-\xi^2/(\varepsilon\mu)\right)$. From equation (13), we have found that $\mathrm{div}(\mathbf{H}) = -\dfrac{\xi}{\mu}\mathrm{div}(\mathbf{E})$ and then replace $\mathbf{H} = -\mathrm{grad}(\varphi_m)$,[29] where φ_m is magnetic scalar potential. In the bi-isotropic environment, Poisson's equation for the magnetic scalar potential of free charges is obtained as follows:

$$\Delta\varphi_m = \frac{\xi}{\varepsilon_e\mu}\rho \,. \tag{15}$$

After solving Poisson's equations for the electric and magnetic scalar potentials, electrostatic and magnetic field can be calculated as:

$$\mathbf{E} = -\mathrm{grad}(\varphi), \tag{16}$$

and

$$\mathbf{H} = -\mathrm{grad}(\varphi_m). \tag{17}$$

In the case of Tellegen type bi-isotropic material external body (Fig. 3), the unknown constants are [19, 27, 28]:

$$\mathrm{A} = -\mathrm{B} = \frac{(\varepsilon_2-\varepsilon_1)(\mu_2+\mu_1)+\xi^2}{(\varepsilon_2+\varepsilon_1)(\mu_2+\mu_1)-\xi^2}, \tag{18}$$

where in the observed case is $\varepsilon_1 = \varepsilon_0$ and $\mu_1 = \mu_0$, as the outside environment is air.

4. NUMERICAL RESULTS

In this paper, a first order plan-parallel primary cell is used for the homogeneous electrostatic field generation. We show numerical results for normalized electric field of the observed system in the presence of external cylindrical body for various values of its normalized radius *a* / *R*.

4.1 PERFECT CONDUCTING BODY INTO A HOMOGENEOUS FIELD

Firstly, the plan-parallel system for homogeneous electrostatic field generation with a perfect conducting external body is observed. The influence of external body's radius on realized field homogeneity is presented in Fig. 3, where *E*(0,0) is the intensity of electrostatic field in the center of the coordinate system without external body, and *E*(0,y) is the intensity of electrostatic field along the *y* axis of the system. From Fig. 3, it can be observed that by increasing the ratio *a* / *R*, the homogenity of the generated electrostatic field decreases. Also, Fig. 3 presents the case without an external body ($a/R = 0$). It should be noted that the field inside a conductor is zero.

4.2 ISOTROPIC DIELECTRIC EXTERNAL BODY PLACED INTO A HOMOGENEOUS ELECTROSTATIC FIELD

The procedure for determining the field inside isotropic dielectric cylinder, placed in a homogeneous field is described in [30], and it is demonstrated, by using the cylindrical coordinate system (r,θ). The function of electric scalar potential inside the cylinder with the radius *a* and the dielectric permitivitty ε, which is placed in the air

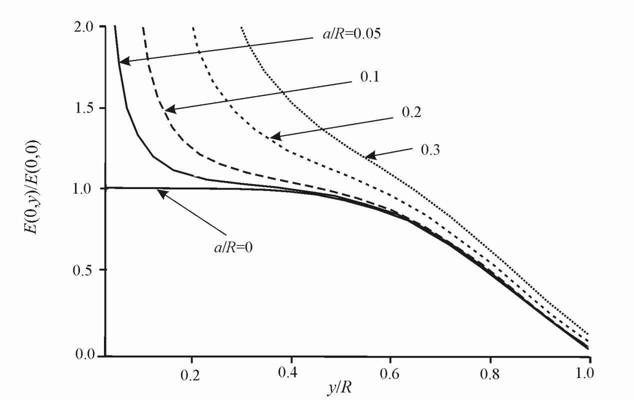

Fig. 3 — The influence of perfect conducting external cylinder's radius on realized field homogeneity.

(dielectric permitivitty ε_0), in homogenous field of intensity *E*, is described as it follows:

$$\varphi = -\frac{2\varepsilon_0}{\varepsilon+\varepsilon_0} rE\cos(\theta),\ r \le a \,. \tag{19}$$

As $y = r\cos(\theta)$ in the coordinate system in Fig. 1, the field inside the cylinder is homogenous and it has *y*-component only

$$E_y = \frac{2\varepsilon_0}{\varepsilon+\varepsilon_0}E \,. \tag{20}$$

Thus, the field inside the isotropic dielectric cylinder is homogeneous and less than the field outside the cylinder.

Fig. 4 shows the influence of the isotropic dielectric body on the homogeneity of the field, for the various values of the relative permittivity and depending on y/R. It can be concluded that the external body with a low permittivity value disrupts to a lesser extent the homogeneity of the field compared to the external body whose permittivity is high. It can be seen that by increasing the value of permittivity ($\varepsilon_r > 40$) to a certain level, the influence of the isotropic dielectric body becomes similar to the influence of the conducting body (in electrostatics, the conducting body can be considered as isotropic dielectric body with an infinitely large permittivity).

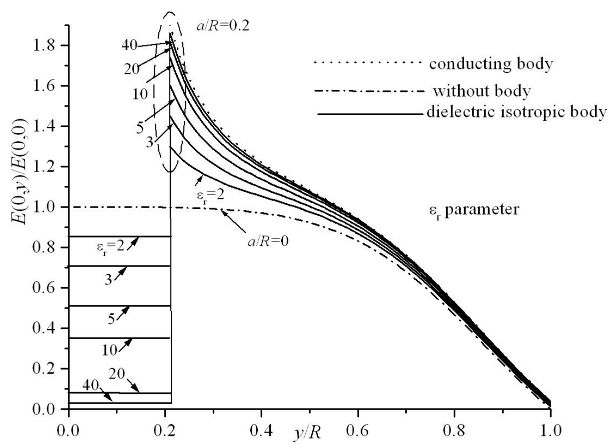

Fig. 4 — Normalized electrostatic field along y - axis of the system with external isotropic dielectric cylindrical body, for different values of ε_r.

The external conducting body significantly disrupts homogeneity of the field for the same set of parameters comparing to the external isotropic dielectric body (radius of the external body and the dimension of the primary cell).

4.3 BI-ISOTROPIC EXTERNAL BODY PLACED INTO A HOMOGENEOUS ELECTROSTATIC FIELD

Normalized values of electrostatic field along the axis in the case of bi-isotropic external body with strong bi-isotropy ($\xi^2/(\varepsilon\mu) = 0.99$) is shown in Fig. 5.

The procedure of field determination inside the bi-isotropic cylinder is provided in [19], where it is shown that the field inside of the cylinder of radius *a,* permitivitty ε, permeability μ and bi-isotropy parameter ξ, which is placed in the air (dielectric permitivitty ε_0) in homogeneous field of intensity *E*, is homogeneous and described as:

$$E_y = \frac{2\varepsilon_0(\mu+\mu_0)}{(\varepsilon+\varepsilon_0)(\mu+\mu_0)-\xi^2}E. \quad (21)$$

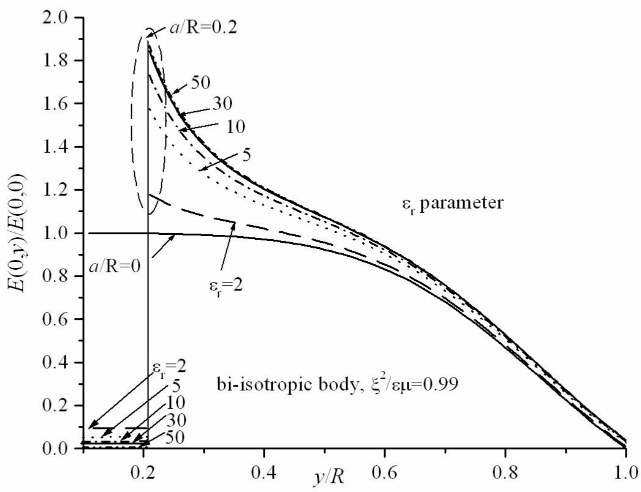

Fig. 5 – Normalized electrostatic field along *y* axis of the system with external bi-isotropic cylindrical body, for different values of ε_r, $\mu_r = 1$.

In Fig. 6, it is shown the normalized field for the conducting, isotropic dielectric and bi-isotropic body with weak ($\xi^2/(\varepsilon\mu) = 0.1$) and strong ($\xi^2/(\varepsilon\mu) = 0.9$) bi-isotropy. It can be noticed that bi-isotropic body with a strong bi-isotropy slightly distrupts the homogeneity of the field, whereas bi-isotropic body with a weak bi-isotropy behaves similarly to an isotropic dielectric of the equal permittivity.

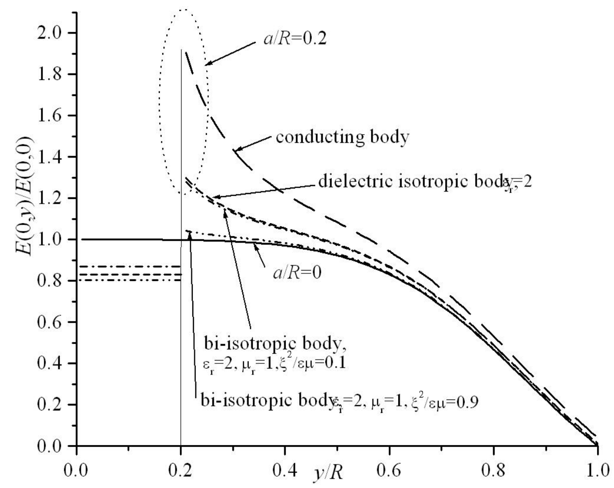

Fig. 6 – Normalized value of electrostatic field along *y* axis of the system with external isotropic dielectric, bi-isotropic and conducting body.

One can notice that the external body with stronger bi-isotropy ($\varepsilon_r = 2,\ \mu_r = 1, \xi^2/\varepsilon\mu = 0.9$) less disrupts the homogeneity of the field than the body with weaker bi-isotropy ($\varepsilon_r = 2,\ \mu_r = 1, \xi^2/\varepsilon\mu = 0.1$) for the same dimensions.

The influence of the external body radius on the field homogeneity is shown in Fig. 7. We analyzed that the external body is made of isotropic and bi-isotropic dielectric materials. As well as can be expected, a larger body disrupts the field homogeneity more than smaller bodies. Also, a strong bi-isotropic body disrupts to a lesser degree the field homogeneity compared to the isotropic dielectric body with the same dimensions and the same permittivity.

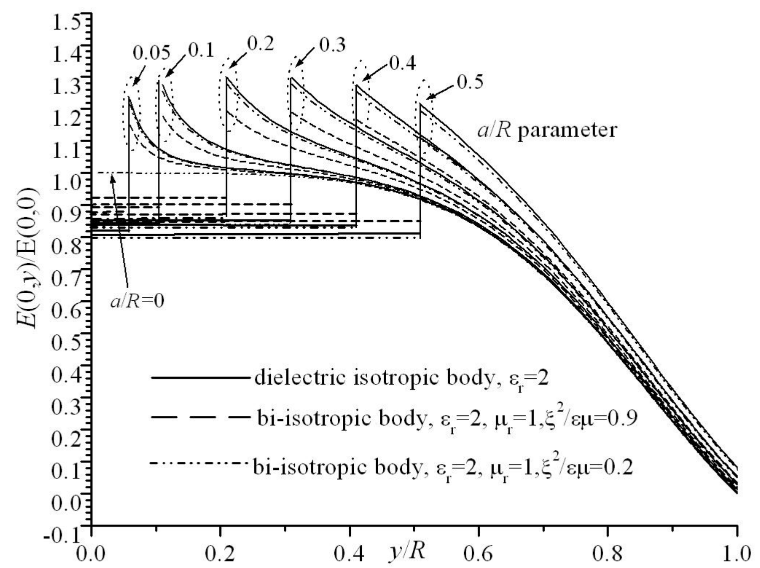

Fig. 7 – The influence of normalized radius of external body, a/R, made of bi-isotropic and isotropic materials, on realized field homogeneity.

5. **CONCLUSIONS**

In this paper, we have presented the external body's influence on electrostatic field homogeneity. The homogenous field was generated by plan-parallel electrodes and the first order primary cell was used. The external body is modelled by using a cylinder whose axis coincides with the system axial axis. The image theorem is used to find the problem solution. The external body was made of conducting, isotropic dielectric and bi-isotropic Tellegen material. The body with larger permittivity ε_r disrupts the field homogeneity more than bodies with lower ε_r. Also, we have shown that a conducting body disrupts the field homogeneity in its vicinity more than an isotropic dielectric body and bodies made of materials with high or low bi-isotropy when all bodies have the same geometrical dimensions. Finally, we have shown that a body with low bi-isotropy has a similar influence on the field homogeneity as isotropic dielectric body with the same ε_r.

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