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On the Possibility of Electrostatic Transformation by Anisotropic Dielectric Environment

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ABSTRACT: *A study of the peculiarities of the electric field distribution in an anisotropic dielectric environment was investigated and the dependence of its longitudinal and transverse components on geometric factors was established. The distribution of the electric field was considered in the case of a rectangular plate. The electrical polarization of the plate volume and the appearance of both longitudinal and transverse components of the electric induction vector was observed at the time of application of some potential difference to its upper and lower end faces. The possibility of electrostatic transformation of constant and variable values of the electric field is demonstrated. Original devices for electrostatic transformation are offered. The transformation coefficient of such devices is determined, on the one hand, by the value of the conversion factor, on the other – by the coefficient of its form. An analysis was performed, which showed that to create competitive devices with better technical characteristics that would replace the existing ones, it is possible in the case of using artificial anisotropic dielectric materials. The introduction of the described method of electrostatic transformation and devices designed on its basis will expand the possibilities of practical application, which in turn will lead to the emergence of new devices and equipment for electricity, infra, low frequency (LF), high frequency (HF), ultra-high frequency (UHF) techniques, electronics and instrumentation.*

KEYWORDS: *dielectric constant, anisotropy, tensor, transformer.*

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I. INTRODUCTION

The American scientist Joseph Henry, known for his groundbreaking research in the field of electromagnetism, in 1830 discovered the phenomenon of electromagnetic induction during experiments. However, the Englishman Michael Faraday was the first to publish the discovery of the phenomenon of electromagnetic induction in 1831.

The discovery of electromagnetic induction and transformation (Heinrich Rumkorf, 1852) led to the emergence of a number of new scientific and technical directions that determined the energy information state of modern civilization, which allowed Russian electrical engineer Pavel Yablochkov in 1876 to propose and create the first device called a transformer [1]. The work of a modern transformer is based on the principle proposed by Joseph Henry.

Nikola Tesla, an American of Serbian descent, is best known for his inventions in the fields of electricity, magnetism and electrical engineering. He invented original design solutions for transformers. One such transformer is named after him, the Tesla Transformer (1891). Nowadays, there are a large number of different design solutions for transformer construction, based on the use of the phenomenon of electromagnetic induction. However, this cannot be said about the phenomenon of electrostatic induction, which has been known since the time of the ancient Greek Thales of Miletus (600 BC) and was later developed in the works of the French Charles Dufay (1733) and Charles Coulomb (1785) [1].

Materials and methods. The authors set the task of developing a fundamentally new method of transformation, which would expand its use in the field of energy, electronics, LF, HF, UHF techniques and other fields of science. In particular, considerable attention was paid to the phenomenon of electrostatic induction.

The aim of this study was to identify the features of the electric field distribution in anisotropic dielectric environment and the possibility of converting its value.

II. EQUATION OF ELECTRIC FIELD TRANSFORMATION E

Consider an anisotropic dielectric environment, the main crystallographic axes *X*, *Y*, *Z* of which coincide with the axes *X′*, *Y′*, *Z′* of the selected laboratory coordinate system. The tensor of its dielectric constant $\hat{\varepsilon}$ is presented in the following case as follows [2]:

$$\hat{\varepsilon} = \varepsilon_0 \cdot \begin{vmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{vmatrix}. \quad (1)$$

Creating from such a material a rectangular plate of size $a \times b \times c$ $(a >> b \geq c)$, the crystallograpic axes *X* and *Z* of which are located in the plane of the side face $a \times b$, and one of these axes is placed at an angle α to the edge *a* (Fig.1), the tensor $\hat{\varepsilon}$ will take the form

$$\hat{\varepsilon} = \varepsilon_0 \cdot \begin{vmatrix} \varepsilon_{xx}cos^2\alpha + \varepsilon_{yy}sin^2\alpha & (\varepsilon_{xx} - \varepsilon_{yy})sin\alpha \cdot cos\alpha & 0 \\ (\varepsilon_{xx} - \varepsilon_{yy})sin\alpha \cdot cos\alpha & \varepsilon_{xx}sin^2\alpha + \varepsilon_{yy}cos^2\alpha & 0 \\ 0 & 0 & \varepsilon_{zz} \end{vmatrix}. \quad (2)$$

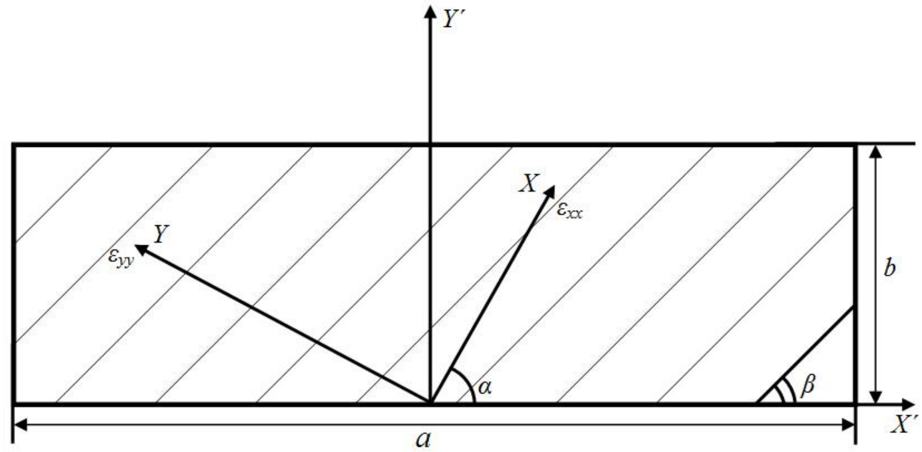

Fig. 1. Anisotropic dielectric plate

and $\hat{\varepsilon}$ is characterized by the presence of both longitudinal ($\varepsilon_{\parallel}$) and transverse ($\varepsilon_{\perp}$) components:

$$\varepsilon_{\parallel} = \varepsilon_0(\varepsilon_{xx}cos^2\alpha + \varepsilon_{yy}sin^2\alpha), \quad (3)$$

$$\varepsilon_{\perp} = \varepsilon_0(\varepsilon_{xx} - \varepsilon_{yy})sin\alpha \cdot cos\alpha. \quad (4)$$

The boundary conditions imposed on the lower and upper faces of the plate will be written as follows, respectively

$$U|_{x=0,\ y=0,z=0} = U|_{x=a,\ y=0,z=0} = U|_{x=0,\ y=0,z=c} = U|_{x=a,\ y=0,z=c} = U_1, \quad (5)$$

$$U|_{x=0,\ y=b,z=0} = U|_{x=a,\ y=b,z=0} = U|_{x=0,\ y=b,z=c} = U|_{x=a,\ y=b,z=c} = U_2. \quad (6)$$

The gradient of the electric potential along the *Y* axis will be expressed by the formula grad *grad U* = - $(U_2$-$U_1)/b$ and is linear.

Studies have shown [3] that when the length of the plate is much larger than its height (a >> b), the boundary conditions at the end faces of the plate are not taken into account, ie the curvature of the electric field in the volume of the plate near the end faces is not taken into account.

The electrical contacts applied to the central parts of the end faces have the following coordinates: left end face – *x*=0; *y*=0,5·b; *z*=0,5·*c*; right – *x*=*a*; *y*=0,5·*b*; *z*=0,5·*c*.

The application to the upper and lower faces of the $a \times c$ plate of some potential difference ΔU leads to electric polarization of its volume and the appearance of both longitudinal $\vec{D}_{\parallel}$ and transverse $\vec{D}_{\perp}$ components of the vector of electric induction $\vec{D}$ [4].

$$\vec{D}_{\parallel} = \frac{\Delta U}{b}(\varepsilon_{xx}cos^2\alpha + \varepsilon_{yy}sin^2\alpha), \quad (7)$$

$$\vec{D}_{\perp} = \frac{\Delta U}{b}(\varepsilon_{xx} - \varepsilon_{yy})sin\alpha \cdot cos\alpha. \quad (8)$$

Optimization of the values of (7) and (8) by the angle α $\left(\frac{\partial \vec{D}}{\partial \alpha} = 0,\ \frac{\partial^2 \vec{D}}{\partial \alpha^2} < 0\right)$ showed that their maximum is observed at $\alpha_{opt.}$=45°.

In this case

$$\vec{D}_{\parallel} = \frac{\Delta U}{2b}(\varepsilon_{xx} + \varepsilon_{yy}), \quad (9)$$

$$\vec{D}_{\perp} = \frac{\Delta U}{2b}\left(\varepsilon_{xx} - \varepsilon_{yy}\right) \tag{10}$$

and the potential difference $U_{\perp}$ transformed between the centers of the left and right opposite end faces $b \times c$ of the plate is represented by the following expression:

$$U_{\perp} = \frac{U}{2b} \cdot \varepsilon_0 \left(\varepsilon_{xx} - \varepsilon_{yy}\right) a. \tag{11}$$

The transformation coefficient n of such a device is determined, on the one hand, by the value of the conversion coefficient m, which is equal to the ratio of the difference between the dielectric constant ε_{xx} and ε_{yy} of the plate material to their sum, on the other – its coefficient a/b [5].

$$n = \frac{U_{\perp}}{U_{\parallel}} = \frac{k-1}{k+1} \cdot \frac{a}{b} = m \cdot f, \tag{12}$$

where $k = \varepsilon_{xx}/\varepsilon_{yy}$;

m is the conversion factor of anisotropic dielectric transformer material;

f is the coefficient of shape of the plate;

It should be noted that the effect under consideration allows transforming both constant and alternating electric fields.

Figure 2 shows the dependence of the conversion factor m on the value of the anisotropy k of the plate material, from which it follows that with increasing k the value of m increases monotonically, reaching saturation at $k = 50$ *(m = 89.1%).*

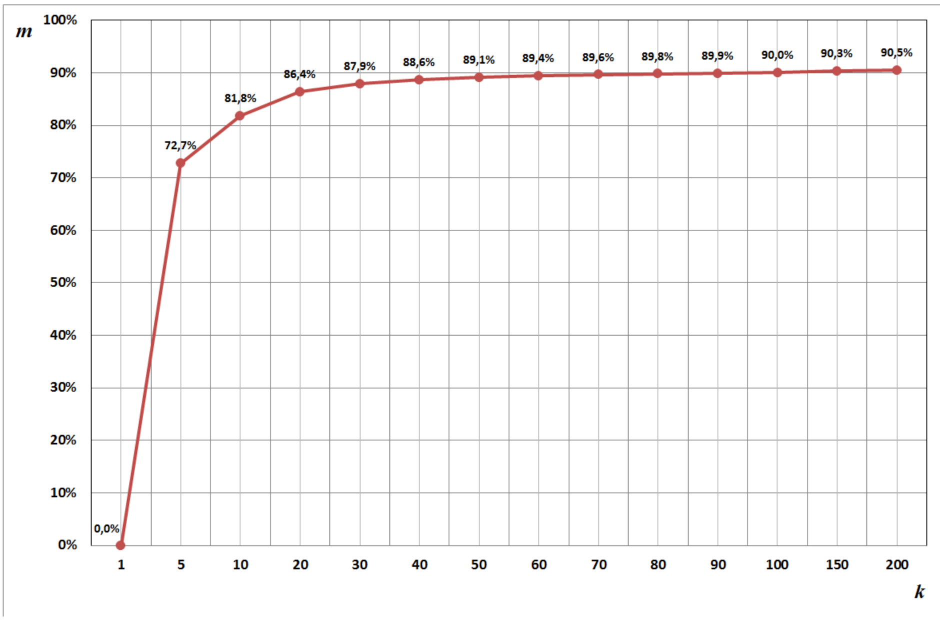

Fig. 2. Graph of the dependence of the conversion factor *m* on the value of the anisotropy of the material *k*

Studies have also shown that the two-dimensionality of electric induction $\vec{D}$ determines the placement of equipotential planes of the transverse component of the electric field in the volume of the plate at an angle β to the Y' axis:

$$\beta = arctg\left(\frac{\varepsilon_{xx} - \varepsilon_{yy}}{\varepsilon_{xx} + \varepsilon_{yy}}\right). \tag{13}$$

The Coulomb force [1], which arises in the volume of the anisotropic plate in the case under consideration, also contains both longitudinal $F_{\parallel}$ and transverse $F_{\perp}$ components. The longitudinal component $F_{\parallel}$ is directed along b, and the transverse $F_{\perp}$ is directed along the length a, and is represented by the following expressions:

$$F_{\parallel} = U_{\parallel}^2 \cdot C_{\parallel}^2 = 0{,}125 \cdot U^2 \left[\left(\varepsilon_{xx} + \varepsilon_{yy}\right) \cdot \frac{ac}{b^2}\right]^2, \tag{14}$$

$$F_{\perp} = U_{\perp}^2 \cdot C_{\perp}^2 = U^2 \left(\varepsilon_{xx} - \varepsilon_{yy}\right)^4 \cdot c^2. \tag{15}$$

The conversion factor σ is represented by the following expression

$$\sigma = \frac{F_{\perp}}{F_{\parallel}} = \left[\frac{\varepsilon_{xx} - \varepsilon_{yy}}{\varepsilon_{xx} + \varepsilon_{yy}}\right]^4 \cdot \frac{b^2}{a^2} \tag{16}$$

and is determined by both the anisotropy of the dielectric constant of the plate material and the coefficient of its shape.

III. DESIGN FEATURES OF ANISOTROPIC DIELECTRIC TRANSFORMER (ADT)

In the general case, the choice of design of ADT [5] is determined by the conditions of its operation [6]. One of the possible variants of this device [4] is shown in Fig. 3. Its base is a rectangular plate l of length *a*, height *b*, width *c* of anisotropic dielectric material, the crystallographic axes of which are placed in the plane of the side face $a\times b$ with the axis with value ε_{xx} placed at an angle $\alpha_{opt.}$=45° to length *a*.

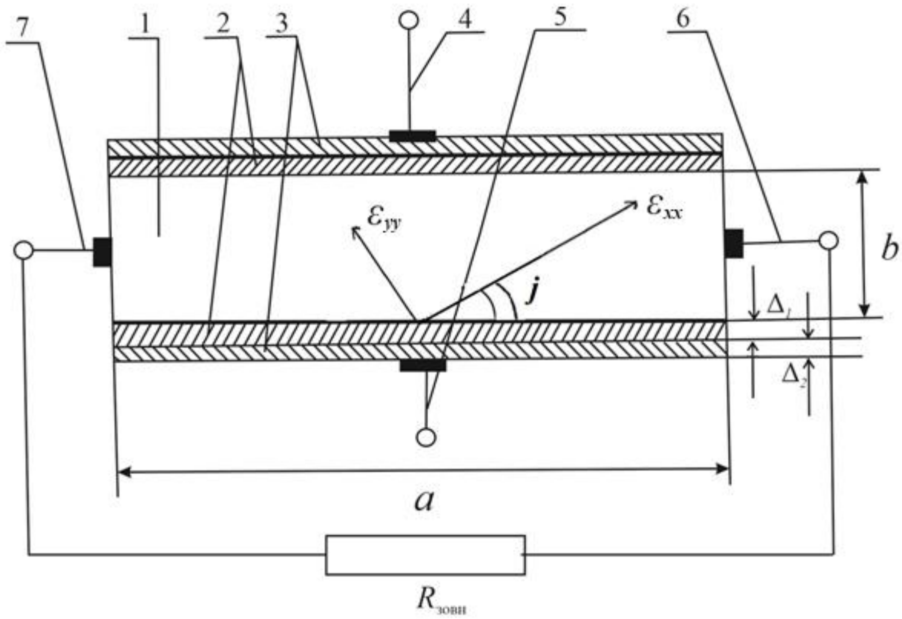

Fig. 3. Design of anisotropic dielectric transformer

The upper and lower faces $a\times c$ of this plate contain dielectric layers 2, thickness Δ_1 with dielectric constant ε_c. Their outer sides contain electrically conductive layers 3 with a thickness Δ_2 with input electrical inputs 4, 5. The output electrical terminals 6, 7 are placed on opposite end faces ($b\times$c) of the plate 1.

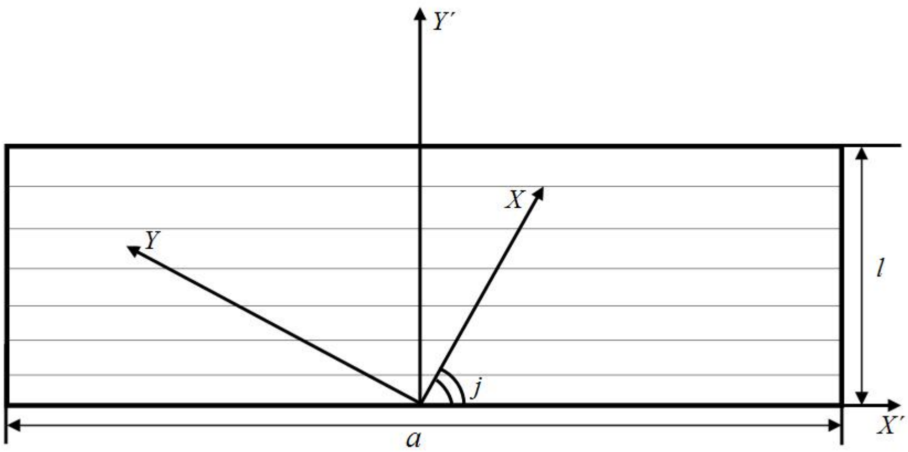

Fig. 4. Distribution of equipotential surfaces of the transverse component of the electric field in the volume of the plate

Analysis of the electric field distribution of the plate 1 when placing the crystallographic axis at an angle $\alpha_{opt.}$=45° showed (Fig. 1) that the presence of conductive layers 3 on the upper and lower faces $a\times c$ leads to some distortion of the equipotential surfaces of the electric field in its volume and, accordingly, to reduce the value of the transformation coefficient *n*. If the axis is placed at an angle $j=\alpha_{opt.}-\beta$ (Fig. 4) then the equipotential surfaces of the electric field are parallel to the upper and lower faces $a\times c$, and the value of the transformation coefficient n_1 ADT in this case is determined by the expression

$$n_1 = \frac{(k-1)\cdot sin j\cdot cos j}{k\cdot cos^2 j+sin^2 j}\cdot\frac{a}{b}. \qquad (17)$$

This design solution virtually eliminates the influence of conductive layers on the volumetric distribution of the equipotential electrical surfaces of the transformer under consideration.

The circuit of electrical substitution of such a device relative to the electrical inputs 4 and 5 is a three series-connected capacitors C_1, C_2, C_3 (capacitors C_1, C_3 are formed by a conductive layer 3 and surfaces $a\times c$ on both sides of the plate; C_2 – upper and lower surfaces $a\times c$). With

$$C_1 = C_3 = \varepsilon_c \cdot \frac{ac}{\Delta_1}, \quad (18)$$

$$C_2 = 0{,}5\left(\varepsilon_{xx} + \varepsilon_{yy}\right) \cdot \frac{bc}{a}. \quad (19)$$

Since, $\varepsilon_c >> (\varepsilon_{xx} + \varepsilon_{yy})$, and $b >> \Delta_1$, then $C_1 = C_3 >> C_2$, which means that almost all the potential difference ΔU connected to the power lines 4, 5 is applied directly to the upper and lower faces $a\times c$.

The transformed potential difference $U_\perp$ occurs between the end faces $b\times c$ of the plate forming the output capacitance $C_4 = U_\perp$, where

$$C_4 = 0{,}5\left(\varepsilon_{xx} - \varepsilon_{yy}\right) \cdot \frac{bc}{a}. \quad (20)$$

If an ADT with a high value of the transformation coefficient n is required, the transforming element 1, which is the basis of the ADT, is characterized by large linear dimensions. This feature leads to some limitation of its practical capabilities.

This shortcoming can be eliminated by the design of the spiral ADT [7, 8], presented in Fig. 5.

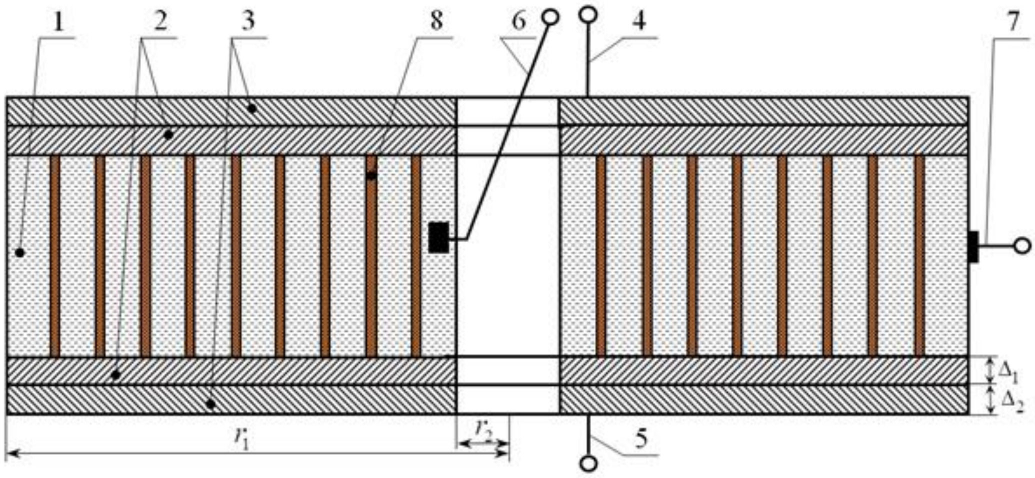

Fig. 5. Design of spiral ADT

This device consists of a transforming element 1 in the form of a plate of length a, height b and width c, based on an anisotropic dielectric material rolled into a spiral and is a disk with a height b of outer r_1 and inner r_2 radii, respectively.

The upper and lower faces of this disk with the area $S = \pi(r_1^2 - r_2^2)$ contain dielectric layers with thickness Δ_1, on the outer sides of which in turn are placed electrically conductive layers 3 with thickness Δ_2. The input electrical inputs 4, 5 are attached to the outer sides of the conductive layers 3, and the output electrical outputs 6, 7 to the inner and outer end faces of the spiral disk. One of the side faces $a\times b$ of the transforming element 1 contains an insulating layer 8 with a thickness Δ_3.

The transformation coefficient n_2, the length of the transforming element a, the number of turns N of the spiral are represented by the following expressions:

$$a = \frac{\pi(r_1^2 - r_2^2)}{c + \Delta_3}, \quad (21)$$

$$N = \frac{\pi(r_1 - r_2)}{c + \Delta_3}, \quad (22)$$

$$n_2 = \frac{k-1}{k+1} \cdot \frac{\pi(r_1^2 - r_2^2)}{b(c + \Delta_3)}. \quad (23)$$

This design of ADT is characterized by small geometric dimensions at high values of the transformation coefficient.

The limit value of the transformed power of ADT is represented by the following expression

$$W_{lim} = \frac{abcdF\Delta T}{tg\delta}, \quad (24)$$

where a, b, c are the geometric dimensions of the plate; d, F are specific weight and heat capacity of the plate material, respectively; ΔT is the allowable temperature of overheating of the material of the ADT plate relative to the ambient temperature T_0; $tg\,\delta$ is the tangent of the dielectric losses of the plate material.

Thus, the smaller the value of $tg\,\delta$ and the higher the value of the overheating temperature, the greater the power can transform the considered ADT.

The efficiency η is one of the important parameters of ADT and is defined as the ratio of the active power P_2 of the secondary chain to the total power P_1 of the primary chain

$$\eta = \frac{P_2}{P_1} = \frac{P_2}{P_2 + P_{dis} + P_{ohm} + P_{rep} + P_{res}}, \tag{25}$$

where P_{dis} are the losses due to the scattering of the electric field from ADT to the environment;

P_{ohm} are the losses due to surface and bulk ohmic currents;

P_{rep} are the losses due to repolarization of ADT volume;

P_{res} are the resonant losses of ADT [8, 9].

Studies show that in the nominal mode of ADT, the maximum value of η is observed provided that

$$P_{\parallel} = P_{\perp}, \tag{26}$$

where $P_{\parallel}$ are the losses determined in idle mode;

$P_{\perp}$ are the losses determined in the mode of short circuit.

IV. ANISOTROPIC DIELECTRIC MATERIALS

Nowadays, both natural and artificial anisotropic dielectric materials are known [8, 9]. The first group includes rhinestone (quartz), mica for which $k = \varepsilon_{xx}/\varepsilon_{yy}$=1,1÷1,3. The second group includes artificial materials created by sequential methods of synthesis and directional crystallization, such as *CdSb* [10], Bi_2Te_3 and eutectic needle compositions *CdSb-CoSb* [11], *ZnAs-As* [12], the value of $k = \varepsilon_{xx}/\varepsilon_{yy}$ for which is in the range of 1,5…1,8. The use of such materials allows to obtain the value of the conversion factor $m = (k-1)/(k+1) = (10 \div 25)\%$, which is clearly insufficient given the current conditions.

The analysis showed that a further increase in the value of the coefficient m is possible in the case of using artificial anisotropic dielectric materials, the calculation method of which is given in [13, 14]. The value of m for such materials will be 53÷58% [15].

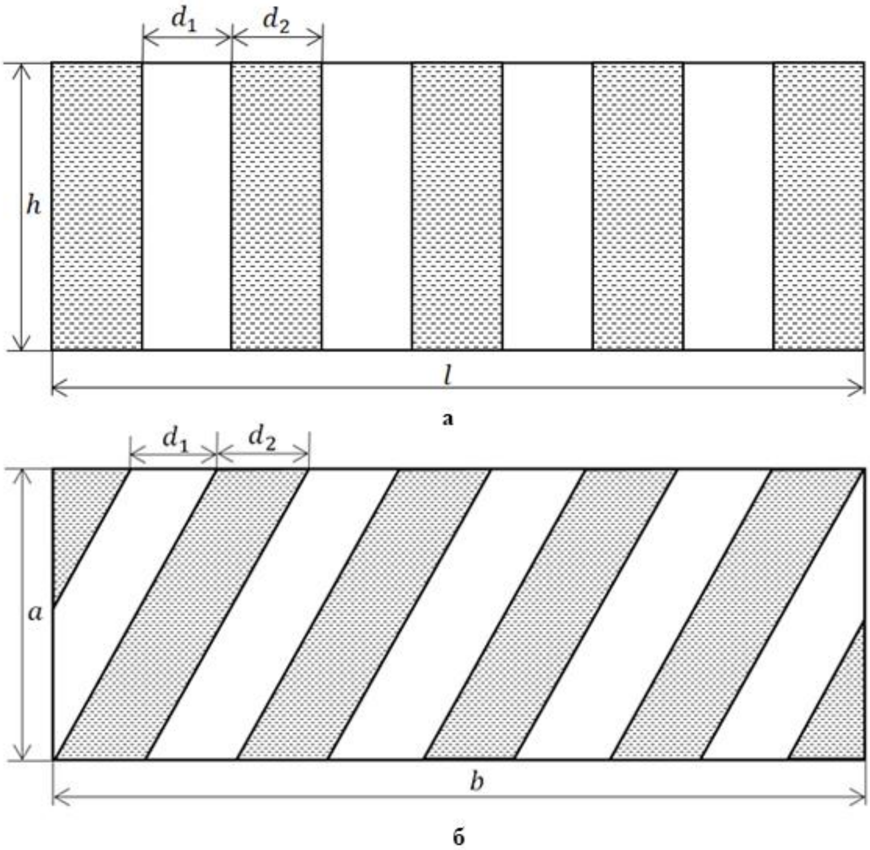

Fig. 6. a) Model of the structure of artificial anisotropic dielectric material; b) Anisotropic transforming element made of artificial anisotropic dielectric material

To create the latest devices with better technical characteristics, which would replace the existing ones, it is necessary to use artificial anisotropic dielectric materials for their manufacture. The basis of such a device, made of the above material, is a rectangular parallelepiped with length l, height h and width s (Fig. 6a), which is made of vertically arranged layers 1 and 2 with thickness d_1 and d_2, respectively, alternating and characterized by dielectric constant ε_1 and ε_2 ($\varepsilon_1 >> \varepsilon_2$).

The values of the values of the longitudinal $\varepsilon_{\parallel}$ and transverse $\varepsilon_{\perp}$ components of the dielectric constant of the environment $\hat{\varepsilon}$ are determined by the following expressions

$$\varepsilon_{\parallel} = \frac{\varepsilon_1 d_1 + \varepsilon_2 d_2}{d_1 + d_2}, \tag{27}$$

$$\varepsilon_{\perp} = \frac{\varepsilon_1 \varepsilon_2 (d_1 + d_2)}{\varepsilon_1 d_1 + \varepsilon_2 d_2} \tag{28}$$

and the values of the thicknesses d_1 and d_2 are related by the following relation:

$$d_1 = d_2 \sqrt{\varepsilon_2 / \varepsilon_1}. \tag{29}$$

Thus, selecting the appropriate materials, as well as thicknesses d_1 and d_2 we obtain an artificial anisotropic dielectric material with a sufficiently high conversion factor $m = 0{,}91 \div 0{,}92$ [15].

The design of the ADT is based on a transforming element based on an optimized artificial anisotropic material, which is presented in Fig. 6b. The transformation coefficient n_3 of such a device is determined by the formula

$$n_3 = \frac{(\varepsilon_1 d_1 + \varepsilon_2 d_2)\cdot(\varepsilon_1 d_2 + \varepsilon_2 d_1) - \varepsilon_1 \varepsilon_2 (d_1 + d_2)^2}{(\varepsilon_1 d_1 + \varepsilon_2 d_2)\cdot(\varepsilon_1 d_2 + \varepsilon_2 d_1) + \varepsilon_1 \varepsilon_2 (d_1 + d_2)^2} \cdot \frac{a}{b} \tag{30}$$

Therefore, the possibility of choosing the appropriate dielectric materials leads to the actual creation of ADT with the necessary functionality.

The use of the considered principle of transformation will allow to expand the possibilities of the relevant fields of science and technology.

V. CONCLUSION

The conducted researches allowed to establish the dependence of the longitudinal and transverse components of the electric field in the anisotropic dielectric environment on geometrical factors. This allowed us to propose a new effective method of electrostatic field transformation. Expressions for the electric field transformation coefficients and its power are obtained, and the directions of their optimization are analyzed. Original designs of rectangular and spiral anisotropic electrostatic transformers, both constant and alternating electric fields, are offered. A method for creating artificially anisotropic alternating layered materials has been developed. The obtained results allow to significantly expand the possibilities of modern electricity.

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