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*Keywords:* *dielectric, conductor, kinetic inductance of charges, dispersion of dielectric constant, plasmo-like medium.*

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# Electrodynamics of the Dielectrics

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## I. Introduction

In the scientific literature is in sufficient detail opened the role of the kinetic inductance of charges in the conductors and the plasmo-like media [1-4], but it is not opened the role of this parameter in the electrodynamics of dielectrics. However, this parameter in this case plays not less important role, than in the electrodynamics of the conductors [5-8]. This most important question fell out from the field of the sight of scientists and this article completes this deficiency.

## II. Electrodynamics Of The Dielectrics

Let us examine the simplest case, when oscillating processes in atoms or molecules of dielectric obey the law of mechanical oscillator [5, 6]:

$$\left(\frac{\beta}{m}-\omega^2\right)\mathbf{r}_m=\frac{e}{m}\mathbf{E} \qquad (1)$$

Where $\mathbf{r}_m$ - deviation of charges from the position of equilibrium, $\beta$ - coefficient of elasticity, which characterizes the elastic electrical binding forces of charges in the atoms and the molecules. Introducing the resonance frequency of the bound charges

$$\omega_0=\beta/m\,,$$

we obtain from (1)

$$\mathbf{r}_m=-\frac{e\,\mathbf{E}}{m(\omega^2-\omega_o^2)}. \qquad (2)$$

Is evident that in relationship (2) as the parameter is present the natural vibration frequency, into which enters the mass of charge. This speaks, that the inertia properties of the being varied charges will influence oscillating processes in the atoms and the molecules.

Since the general current density on medium consists of the bias current and conduction current

$$\mathrm{rot}\,\mathbf{H}=\mathbf{j}_\Sigma=\varepsilon_0\frac{\partial\mathbf{E}}{\partial t}+ne\mathbf{v}.$$

That, finding the speed of charge carriers in the dielectric as the derivative of their displacement through the coordinate

$$\mathbf{v}=\frac{\partial\mathbf{r}_m}{\partial t}=-\frac{e}{m(\omega^2-\omega_o^2)}\frac{\partial\mathbf{E}}{\partial t}.$$

From relationship (2) we find

$$\mathrm{rot}\,\mathbf{H}=\mathbf{j}_\Sigma=\varepsilon_0\frac{\partial\mathbf{E}}{\partial t}-\frac{1}{L_{kd}(\omega^2-\omega_0^{\ 2})}\frac{\partial\mathbf{E}}{\partial t}. \qquad (3)$$

Let us note that the value

$$L_{kd}=m/\left(ne^2\right)$$

presents the kinetic inductance of the charges, entering the constitution of atom or molecules of dielectrics, when to consider charges free. Therefore (3) let us rewrite in the form:

$$\mathrm{rot}\,\mathbf{H}=\mathbf{j}_\Sigma=\varepsilon_0\left(1-\frac{1}{\varepsilon_0 L_{kd}(\omega^2-\omega_0^{\ 2})}\right)\frac{\partial\mathbf{E}}{\partial t}. \qquad (4)$$

Since the value

$$1/\left(\varepsilon_0 L_{kd}\right)=\omega_{pd}^{\ \ 2}$$

presents the plasma frequency of charges in atoms and molecules of dielectric, if we consider these charges free, then relationship (9.4) takes the form:

$$\mathrm{rot}\,\mathbf{H}=\mathbf{j}_\Sigma=\varepsilon_0\left(1-\frac{\omega^2{}_{pd}}{(\omega^2-\omega_0^{\ 2})}\right)\frac{\partial\mathbf{E}}{\partial t}. \qquad (5)$$

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It is possible to name the value

$$\varepsilon^*(\omega) = \varepsilon_0 \left(1 - \frac{\omega^2{}_{pd}}{(\omega^2 - \omega_0{}^2)}\right) \qquad (6)$$

by the effective dielectric constant of dielectric and it depends on frequency. But this mathematical parameter is not the physical dielectric constant of dielectric, but has composite nature. It includes three those not depending on the frequency of the value: electrical constant, natural frequency of atoms or molecules and plasma frequency for the charge carriers, entering their composition, if we consider charges free[7].

Let us examine two limiting cases:

*a) If $\omega << \omega_0$, then from (5) we obtain*

$$\mathrm{rot}\,\mathbf{H} = \mathbf{j}_\Sigma = \varepsilon_0 \left(1 + \frac{\omega_{pd}{}^2}{\omega_0{}^2}\right)\frac{\partial \mathbf{E}}{\partial t}. \qquad (7)$$

In this case the coefficient, confronting the derivative, does not depend on frequency, and it presents the static dielectric constant of dielectric. As we see, it depends on the natural frequency of oscillation of atoms or molecules and on plasma frequency. This result is intelligible. Frequency in this case proves to be such low that the charges manage to follow the field and their inertia properties do not influence electrodynamic processes. In this case the bracketed expression in the right side of relationship (7) presents the static dielectric constant of dielectric. As we see, it depends on the natural frequency of oscillation of atoms or molecules and on plasma frequency. Hence immediately we have a prescription for creating the dielectrics with the high dielectric constant. In order to reach this, should be in the assigned volume of space packed a maximum quantity of molecules with maximally soft connections between the charges inside molecule itself.

*b) The case is exponential $\omega >> \omega_0$. In this case*

$$\mathrm{rot}\,\mathbf{H} = \mathbf{j}_\Sigma = \varepsilon_0 \left(1 - \frac{\omega_{pd}{}^2}{\omega^2}\right)\frac{\partial \mathbf{E}}{\partial t}$$

dielectric became conductor (plasma) since. The obtained relationship exactly coincides with the equation, which describes plasma.

One cannot fail to note the circumstance that in this case again nowhere was used this concept as polarization vector, but examination is carried out by the way of finding the real currents in the dielectrics on the basis of the equation of motion of charges in these media. In this case in this mathematical model as the initial electrical characteristics of medium are used the values, which do not depend on frequency.

From relationship (5) is evident that in the case of fulfilling the equality $\omega = \omega_0$, the amplitude of fluctuations is equal to infinity. This indicates the presence of resonance at this point. The infinite amplitude of fluctuations occurs because of the fact that they were not considered losses in the resonance system; in this case its quality was equal to infinity. In a certain approximation it is possible to consider that lower than the point indicated we deal concerning the dielectric, whose dielectric constant is equal to its static value. Higher than this point we deal already actually concerning the metal, whose density of current carriers is equal to the density of atoms or molecules in the dielectric.

Now it is possible to examine the question of why dielectric prism decomposes polychromatic light into monochromatic components or why rainbow is formed. For this the phase speed of electromagnetic waves on Wednesday must depend on frequency (frequency wave dispersion). Let us add to (5) the first Maxwell equation [8]:

$$\mathrm{rot}\,\mathbf{E} = -\mu_0 \frac{\partial \mathbf{H}}{\partial t}; \quad \mathrm{rot}\,\mathbf{H} = \varepsilon_0 \left(1 - \frac{\omega^2{}_{pd}}{(\omega^2 - \omega_0{}^2)}\right)\frac{\partial \mathbf{E}}{\partial t},$$

from where we immediately find the wave equation:

$$\nabla^2 \mathbf{E} = \mu_0 \varepsilon_0 \left(1 - \frac{\omega_{pd}{}^2}{\omega^2 - \omega_0{}^2}\right)\frac{\partial^2 \mathbf{E}}{\partial t^2}.$$

If one considers that

$$\mu_0 \varepsilon_0 = 1/c^2,$$

Where $c$ - the speed of light then is easy to see the presence in dielectrics of frequency dispersion. But the dependence of phase speed on the frequency is connected not with the dependence on it of physical dielectric constant. In the formation of this dispersion it will participate immediately three, which do not depend on the frequency, physical quantities: the self-resonant frequency of atoms themselves or molecules, the plasma frequency of charges, if we consider it their free, and the dielectric constant of vacuum.

Now let us show the weak places of the traditional approach, based on the use of a concept of polarization vector.



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$$\mathbf{P} = -\frac{ne^2}{m} \cdot \frac{1}{(\omega^2 - \omega_0^2)} \mathbf{E} .$$

Its dependence on the frequency is connected with the presence of mass in the charges, entering the constitution of atom and molecules of dielectrics. The inertness of charges is not allowed for this vector, following the electric field, to reach that value, which it would have in the permanent fields. Since the electrical induction is determined by the relationship

$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{PE} = \varepsilon_0 \mathbf{E} - \frac{ne^2}{m} \cdot \frac{1}{(\omega^2 - \omega_0^2)} \mathbf{E} , \quad (8)$$

that introduced thus, it depends on frequency.

After introducing this induction into the second Maxwell equation, we will obtain:

$$\mathrm{rot}\, \mathbf{H} = \mathbf{j}_\Sigma = \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \frac{\partial \mathbf{P}}{\partial t} .$$

Or

$$\mathrm{rot}\, \mathbf{H} = \mathbf{j}_\Sigma = \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} - \frac{ne^2}{m} \frac{1}{(\omega^2 - \omega_0^2)} \frac{\partial \mathbf{E}}{\partial t} , \quad (9)$$

where $\mathbf{j}_\Sigma$ - the summed current, which flows through the model. In expression (9) the first member of right side presents bias current in the vacuum, and the second - current, connected with the presence of bound charges in atoms or molecules of dielectric. In this expression again appeared the specific kinetic inductance of the charges, which participate in the oscillating process

$$L_{kd} = m / ne^2 ,$$

the determining inductance of bound charges, and (9) takes the form:

$$\mathrm{rot}\, \mathbf{H} = \mathbf{j}_\Sigma = \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} - \frac{1}{L_{kd}} \frac{1}{(\omega^2 - \omega_0^2)} \frac{\partial \mathbf{E}}{\partial t} .$$

Obtained expression exactly coincides with relationship (3). Consequently, the eventual result of examination by both methods coincides, and there are no claims to the method from a mathematical point of view. But from a physical point of view, and especially in the part of the awarding to the parameter, introduced in accordance with relationship (8) of the designation of electrical induction, are large claims, which we discussed. These are the physical quantity of electrical induction, but the certain composite mathematical parameter. In the essence, physically substantiated is the introduction to electrical induction in the dielectrics only in the static electric fields.

Let us show that the equivalent the schematic of dielectric presents the sequential resonant circuit, whose inductance is the kinetic inductance $L_{kd}$, and capacity is equal to the static dielectric constant of dielectric minus the capacity of the equal dielectric constant of vacuum. In this case outline itself proves to be that shunted by the capacity, equal to the specific dielectric constant of vacuum. For the proof of this let us examine the sequential oscillatory circuit, when the inductance $L$ and the capacity $C$ are connected in series.

The connection between the current $I_C$, which flows through the capacity $C$, and the voltage $U_C$, applied to it, is determined by the relationships:

$$U_C = \frac{1}{C} \int I_C dt ,$$

$$I_C = C \frac{dU_C}{dt} . \quad (10)$$

This connection will be written down for the inductance:

$$I_L = \frac{1}{L} \int U_L dt \, ; \; U_L = L \frac{dI_L}{dt} .$$

If the current, which flows through the series circuit, changes according to the law $I = I_0 \sin \omega t$ then a voltage drop across inductance and capacity they are determined by the relationships

$$U_L = \omega L I_0 \cos \omega t \, ; \; U_C = -\frac{1}{\omega C} I_0 \cos \omega t .$$

And total stress applied to the outline is equal

$$U_\Sigma = \left( \omega L - 1/(\omega C) \right) I_0 \cos \omega t .$$

In this relationship the value, which stands in the brackets, presents the reactance of sequential resonant circuit, which depends on frequency. The stresses, generated on the capacity and the inductance, are located in the reversed phase, and, depending on frequency, outline can have the inductive, the weather capacitive reactance. At the point of resonance the summary reactance of outline is equal to zero.

It is obvious that the connection between the total voltage applied to the outline and the current, which flows through the outline, will be determined by the relationship.



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$$I = -\frac{1}{\omega\left(\omega L - 1/(\omega C)\right)} \frac{\partial U_\Sigma}{\partial t}. \qquad (11)$$

The resonance frequency of outline is determined by the relationship

$$\omega_0 = 1/\sqrt{LC},$$

therefore let us write down

$$I = \frac{C}{\left(1 - \omega^2/\omega_0^2\right)} \frac{\partial U_\Sigma}{\partial t}. \qquad (12)$$

Comparing this expression (12) with relationship (10) it is not difficult to see that the sequential resonant circuit, which consists of the inductance $L$ and capacity $C$, it is possible to present to the capacity of in the form dependent on the frequency:

$$C(\omega) = C/\left(1 - \omega^2/\omega_0^2\right) \qquad (13)$$

The inductance is not lost with this idea, since it enters into the resonance frequency of the outline $\omega_0$. Relationships (12) and (11) are equivalent. Consequently, value $C(\omega)$ is not the physical capacitance value of outline, being the certain composite mathematical parameter.

Relationship (11) can be rewritten and differently:

$$I = -\frac{1}{L\left(\omega^2 - \omega_0^2\right)} \frac{\partial U_\Sigma}{\partial t},$$

and to consider that

$$C(\omega) = -\frac{1}{L\left(\omega^2 - \omega_0^2\right)}. \qquad (14)$$

Is certain, the parameter of, introduced in accordance with relationships (13) and (14) no to capacity refers.

Let us examine relationship (12) for two limiting cases:

*c) When* $\omega << \omega_0$, *we have*

$$I = C\frac{\partial U_\Sigma}{\partial t}.$$

This result is intelligible, since at the low frequencies the reactance of the inductance, connected in series with the capacity, is considerably lower than the capacitive and it is possible not to consider it.

The equivalent the schematic of the dielectric, located between the planes of long line is shown in Figure 1.

*d) When* $\omega >> \omega_0$, *we have*

$$I = -\frac{1}{\omega^2 L} \frac{\partial U_\Sigma}{\partial t}. \qquad (15)$$

Taking into account that for the harmonic signal

$$\frac{\partial U_\Sigma}{\partial t} = -\omega^2 \int U_\Sigma dt,$$

we obtain from (15):

$$I_L = \frac{1}{L}\int U_\Sigma dt.$$

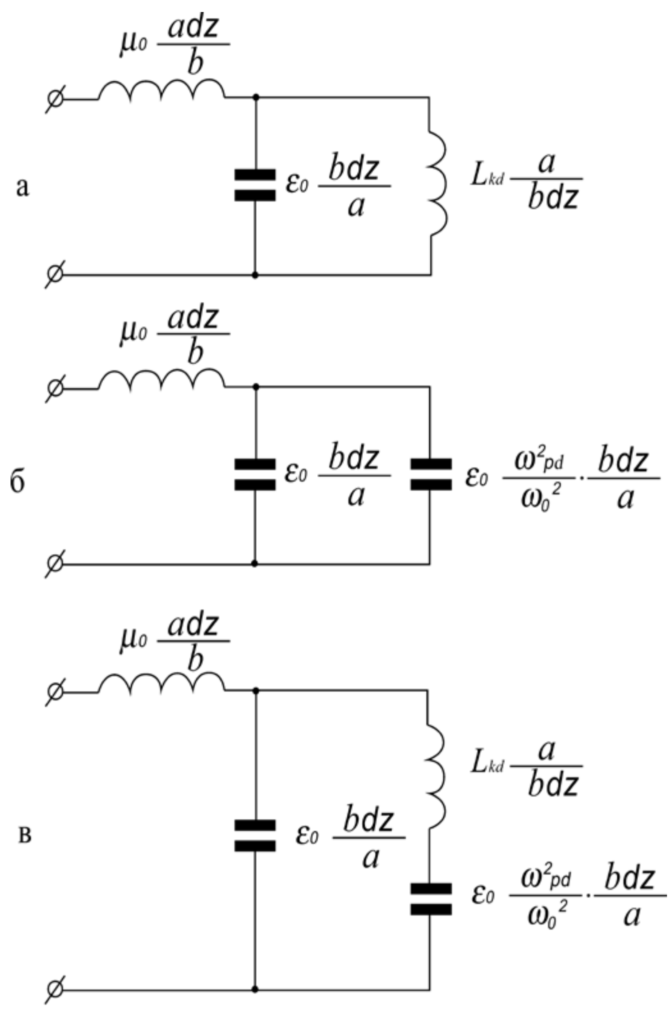


*Figure 1:* a - equivalent the schematic of the section of the line, filled with dielectric, for the by dielectric, for the case $\omega >> \omega_0$;



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б - the equivalent the schematic of the section of line for the case of $\omega << \omega_0$;

в - the equivalent the schematic of the section of line for entire frequency band.

In this case the reactance of capacity is considerably less than in inductance and chain has inductive reactance.

The carried out analysis speaks, that is in practice very difficult to distinguish the behavior of resonant circuits of the inductance or of the capacity. For understanding of true design of circuits it is necessary to remove its amplitude and phase response in the range of frequencies. In the case of resonant circuit this dependence will have the typical resonance nature, when on both sides resonance the nature of reactance is different. However, this does not mean that real circuit elements: capacity or inductance depends on frequency.

In Figure 5аand 5бare shown two limiting cases. $\omega >> \omega_0$, when the properties of dielectric correspond to conductor; $\omega << \omega_0$, when - to dielectric with the static dielectric constant

$$\varepsilon = \varepsilon_0 \left(1 + \omega_{pd}^{\ 2} / \omega_0^{\ 2}\right).$$

Thus, the use of a term "dielectric constant of dielectrics" in the context of its dependence on the frequency is not completely correct. If the discussion deals with the dielectric constant of dielectrics, with which the accumulation of potential energy is connected, then correctly examine only static permeability, which is been the constant, which does not depend on the frequency. Specifically, it enters into all relationships, which characterize the electrodynamic characteristics of dielectrics.

Application of such new approaches most interestingly precisely for the dielectrics. Then each connected pair of charges is a separate unitary unit with its individual characteristics, and its interaction with the electromagnetic field (without taking into account the connections between the pairs) is strictly individual. Certainly, in the dielectrics not all dipoles have different characteristics, but there are different groups with similar characteristics, and each group of bound charges with the identical characteristics will resound at its frequency. Moreover the intensity of absorption and in the excited state and emission, at this frequency will depend on a relative quantity of pairs of this type. Therefore it is possible to introduce the appropriate partial coefficients. Furthermore, these processes will influence the anisotropy of the dielectric properties of molecules themselves, which have the specific electrical orientation in crystal lattice. By these circumstances is determined the variety of resonances and their intensities, which is observed in the dielectric media. With the electric coupling between the separate groups of emitters the lines of absorption or emission can be converted into the strips. Such individual approach to the types of the connected pairs of charges is absent from the available theories.

Let us emphasize the important circumstance, which did not receive thus far proper estimation. In all relationships for any material media (conductors and dielectrics) together with the dielectric and magnetic constant figures the kinetic inductance of the charges, which indicates not less important role of this parameter. This is for the first time noted in a number of the mentioned sources, including in the works [9, 10].

## III. Conclusion

In the scientific literature is in sufficient detail opened the role of the kinetic inductance of charges in the conductors and the plasmo-like media, but it is not opened the role of this parameter in the electrodynamics of dielectrics. This parameter in the electrodynamics of dielectrics plays not less important role, than in the electrodynamics of conductors. In the article the electrodynamics of dielectrics taking into account the kinetic inductance of the charges, which form part of their atoms or molecules is examined. This most important question fell out from the field of the sight of scientists and this article completes this deficiency. Let us emphasize the important circumstance, which did not receive thus far proper estimation. In all relationships for any material media (conductors and dielectrics) together with the dielectric and magnetic constant figures the kinetic inductance of the charges, which indicates not less important role of this parameter.

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