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INTERFERENTIAL ENERGETIC INTERACTION OF DIPOLE ELECTROMAGNETIC EMITTERS

This research covers interferential electromagnetic energy flux onto an elementary dipole emitter located in arbitrary external electromagnetic field. Based on the results obtained, the research was performed to investigate interferential interaction of two arbitrarily oriented dipoles transmitting on the same frequency and located within a given distance from each other in a homogeneous dielectric medium (vacuum). Presented below are some physical aspects of EM signal transmission and reception using interferential energy flux.

Interference of Electromagnetic (EM) wave fields[1]) from the viewpoint of energetic can be regarded as interferential energetic interaction of these wave emitters. The above interaction is conditioned by the fact that energy of one emitter within EM field of another emitter changes, and it emits or absorbs additional energy. Available within the space surrounding the sources located at some distance from each other is total EM field having a complex energy flux structure created by local interferential fluxes. This forms integral energy fluxes additionally coming to the emitters or additionally emitted by them into space.

Features of interferential energetic interaction of specific emitters can be identified by analyzing interference of EM waves they emit, which are determined by the geometry and the type of EM emitters and constitutive parameters of the medium, where the waves propagate. Such interaction was investigated in the research works [1-3] for a passive (not emitting independently) elementary (point) electric dipole located within plane EM wave field. It is determined that energy from plane EM wave field to the emitter comes in the form of flux that occurs due to interference of two waves - plane and spherical dipole ones. It is shown that effective cross-section area of dipole antenna energy absorption is substantially greater than its geometric cross-section area and corresponds to a value close to the square of the wavelength of the received EM radiation. Therefore, the dipole antenna receives energy of the EM signals from the transmitter antenna due to the interferential interaction manifesting itself as interferential energy flux structure between the emitters.

This flux structure is described and investigated in research works [4-7] for the effect of tunneling EM interference, i.e. interference of fields of EM counter-running waves in the tunnel area, where the wave vectors are purely imaginary for a medium with total internal reflection and complex for a medium with absorption. It is experimentally found [4,5] that using interferential energy flux structure in absorbing media it is possible to transmit EM signals whose level is significantly less than the minimum limit level of signals transmitted conventionally with a single wave. It is also shown [5, 7] that tunneling EM interference in media with absorption is accompanied by a kind of energy dissipation, which significantly affects interaction of a medium with EM field.

Undoubtedly, throughout the energy emission and absorption by EM emitters, the energy aspects of interference play a significant role, which is not properly appreciated. In particular, interferential energetic interaction of transmitting and receiving radio communication emitters has not been essentially investigated yet. There is no any analysis of this interaction in important for both theory and practical use of case of two active (independently emitting) dipole antennas.

[1]) ***The principle of superposition of EM fields, as follows from the Maxwell's equations, does not mean that total field has only properties of the source fields. A new EM field may have additional physical properties, which is verified, in particular, by phenomenon of interference.***

Interferential EM energy flux onto elementary dipole emitter

Consider the elementary dipole emitter harmonically oscillating with angular frequency ω. It is placed in an arbitrary external EM field with complex components of intensities at the dipole location point $\vec{E} = E_0 e^{i(\omega t-\beta)}\hat{\vec{E}}$, and $\vec{H} = H_0 e^{-i(\omega t-\beta)}\hat{\vec{H}}$, harmonically oscillating with frequency equal to the dipole oscillation frequency. Complex dipole moments are written as $\vec{p} = p_0 e^{-i(\omega t-\alpha)}\hat{\vec{p}}$ (electric dipole) and $\vec{m} = m_0 e^{-i(\omega t-\alpha)}\hat{\vec{m}}$ (magnetic dipole). Here $\hat{\vec{p}}, \hat{\vec{m}}, \hat{\vec{E}}, \hat{\vec{H}}$ are the actual unit director vectors, and the angles α and β specify, respectively, initial oscillation phases of the dipole emitter and EM field at the dipole location point.

Assume that the electric dipole is placed at the origin of the Cartesian coordinate system (0,0,0) so that the vector of its dipole moment is oriented along the axis *oz*. Then $\hat{\vec{p}} = \vec{e}_3$ ($\vec{e}_3$ - орт оси *oz*). The equations for the complex intensities of electric and magnetic fields produced by the specified dipole in a spherical coordinate system look as follows [8]

$$\vec{E}^p = \frac{p_0}{2\pi\varepsilon_0}\cos\theta\left(\frac{1}{r^3} - \frac{ik}{r^2}\right)e^{-i(\omega t-kr)}\vec{e}_r + \frac{p_0}{4\pi\varepsilon_0}\sin\theta\left(\frac{1}{r^3} - \frac{ik}{r^2} - \frac{k^2}{r}\right)e^{-i(\omega t-kr)}\vec{e}_\theta;$$

$$\vec{H}^p = -\frac{p_0}{4\pi}i\omega\sin\theta\left(\frac{1}{r^2} - \frac{ik}{r}\right)e^{-i(\omega t-kr)}\vec{e}_\varphi, \tag{1}$$

where $\vec{e}_r, \vec{e}_\theta, \vec{e}_\varphi$ - are unit vectors of the coordinate system; ε_0 - is electric constant, $k = \omega/c$ - is wave number, c - is speed of wave propagation; index mark "p" indicates field of electric dipole.

Local interferential energy flux whose complex Poynting vector is $\vec{S}^p_{\text{int}} = \frac{1}{2}[\vec{E}^p, \vec{H}^*] + [\frac{1}{2}[\vec{E}, \vec{H}^{p*}]$ (where the index mark "*" indicates complex conjugation) occurs at each point in space, along with energy fluxes of EM fields emitted by a dipole and an external EM field. Integrating the radial component of this vector on the surface of σ_r sphere of arbitrary radius r centered at the origin of coordinates, after averaging over the period of oscillation, we get the dipole emitted integral interference flux of EM energy $Э^p_{\text{int}} = \text{Re}\left(\int_{\sigma_r} S^p_{r\ \text{int}}\, d\sigma\right)$. After simple algebraic manipulations we arrive at the

$$Э^p_{\text{int}} = \frac{1}{2}\text{Re}\left\{\int_{\sigma_r}\left([\vec{n}, \vec{E}^p]\vec{H}^*\right)d\sigma\right\} + \frac{1}{2}\text{Re}\left\{\int_{\sigma_r}\left([\vec{H}^{p*}, \vec{n}]\vec{E}\right)d\sigma\right\}, \tag{2}$$

where $\vec{n} = \vec{e}_r$ - is outward normal to a surface σ_r, and $d\sigma = r^2\sin\theta\, d\theta d\varphi$. Now substituting formula (1) in equation (2), we get

$$Э^p_{\text{int}} = \text{Re}\left\{\frac{1}{8\pi\varepsilon_0}\left(\frac{1}{r^3} - \frac{ik}{r^2} - \frac{k^2}{r}\right)p_0 e^{-i(\omega t-kr)}\left[\int_{\sigma_r}\sin\theta\left(\vec{e}_\varphi, \vec{H}^*\right)d\sigma\right]\right\} +$$

$$+\text{Re}\left\{\frac{i\omega}{8\pi}\left(\frac{1}{r^2} + \frac{ik}{r}\right)p_0^* e^{i(\omega t-kr)}\left[\int_{\sigma_r}\sin\theta\left(\vec{e}_\theta, \vec{E}\right)d\sigma\right]\right\}. \tag{3}$$

Consider the first integral in formula (3): $J_1 = \int_{\sigma_r}\sin\theta\left(\vec{e}_\varphi, \vec{H}^*\right)d\sigma$.

Given that $(\vec{e}_\varphi, \vec{H}^*) = -\sin\varphi\ H_x^* + \cos\varphi\ H_y^*$, having expanded the functions H_x^* and H_y^* in a Taylor series in x, y, z in a neighborhood of (0,0,0) point for small r, we get

$$J_1 \cong r^3 \frac{4\pi}{3}\left\{-\frac{\partial H_x^*}{\partial y}(0) + \frac{\partial H_y^*}{\partial x}(0)\right\}, \tag{4}$$

(Argument (0) means that the corresponding derivatives are taken at the (0,0,0) point). Formula (4) can be transformed by using Maxwell's equations $rot\ \vec{H} = \varepsilon_0 \frac{\partial \vec{E}}{\partial t} = -i\omega\varepsilon_0 \vec{E}$. Then

$$J_1 \cong -\frac{4\pi}{3} r^3 i\omega\varepsilon_0 E_z^*(0). \tag{5}$$

The same is for the second integral from the equation (3), given that $(\vec{e}_\theta, \vec{E}) = \cos\theta\cos\varphi\ E_x + \cos\theta\cos\varphi\ E_y -$

$-\sin\theta\ \ E_z$. Assuming that $E_x \cong E_x(0)$, $E_y \cong E_y(0)$, $E_z \cong E_z(0)$, we get

$$J_2 = \int_{\sigma_r} \sin\theta\left(\vec{e}_\theta, \vec{E}\right)\ d\sigma \cong -\frac{8\pi}{3} r^2 E_z(0) \quad .$$
(6)

Having substituted equations (5) and (6) into the formula (3) considering $E_z(0) = E_{oz} \times e^{-i(\omega t - \beta)}$ and passing to the limit with $r \to 0$, we can write

$$Э_{\text{int}}^p = -\frac{1}{2}\omega\ p_0 E_{oz}\sin\left(\alpha - \beta\right), \tag{7}$$

where E_{oz} - is the amplitude of the actual z component of electric field intensity of external EM wave at the dipole location point; p_0 - is the actual amplitude of dipole oscillations.

In case of arbitrary directed $\hat{\vec{p}}$ the generalized formula for the averaged by oscillation period integral interferential flux of EM energy emitted by a dipole in unit time, with available arbitrary external EM field looks as follows

$$Э_{\text{int}}^p = -\frac{1}{2}\omega\ \ \text{Im}\left\{\left(\vec{p}, \vec{E}^*\right)\right\}. \tag{8}$$

Similar reasoning can be made for the elementary magnetic dipole emitter located at the origin (0,0,0) and producing EM filed with complex intensities [8]

$$\vec{E}^m = \frac{m_0}{4\pi} i\omega\mu_0 \sin\theta\ \left(\frac{1}{r^2} - \frac{ik}{r}\right)\ e^{-i(\omega t - kr)}\vec{e}_\varphi\ ;$$

$$\vec{H}^m = \frac{m_0}{2\pi}\cos\theta\ \left(\frac{1}{r^3} - \frac{ik}{r^2}\right)\ e^{-i(\omega t - kr)}\vec{e}_r + \frac{m_0}{4\pi}\sin\theta\ \left(\frac{1}{r^3} - \frac{ik}{r^2} - \frac{k^2}{r}\right)e^{-i(\omega t - kr)}\vec{e}_\theta, \tag{9}$$

where the index mark "m" stands for magnetic dipole field; μ_0 - is a magnetic constant.

Then $Э_{\text{int}}^m = -\frac{1}{2}\mu_0\omega\ \ \text{Im}\left\{\left(\vec{m}, \vec{H}^*\right)\right\}.$ (10)

Interferential energetic interaction of dipole electromagnetic emitters

Equations (8) and (10) can be applied to the interferential energetic interaction of two different type elementary dipole emitters oscillating with the same frequency ω. Arbitrary field intensities $\vec{E}, \vec{H}$ in the formulas (8), (10) are substituted by intensities of EM field generated by the second dipole emitter (formulas (1) for the electric dipole or (9) for the magnetic one) at the location of the first emitter. Let us assume that the dipoles are located at a distance R from each other. Let us introduce the following notation: β_1 and β_2 - for the angles between the directions of unit vectors of the dipole moments and the straight line segment connecting the dipoles; γ - for the angle between directions of dipole moments; ψ - for spatial dihedral angle between the planes drawn through the dipole moment vectors and the segment connecting the dipoles.

Then averaged by oscillation period integral interferential flux of EM energy $Э_{1p}^{p}$ arising from the first electric dipole with the second electric dipole radiation, as well as interferential flux of EM energy $Э_{1m}^{m}$ arising from the magnetic dipole with the presence of the field second dipole, shall be determined as follows

$$Э_{1p}^{p} = F_{12}\sqrt{Э_{1p}Э_{2p}}\,; \qquad Э_{1m}^{m} = F_{12}\sqrt{Э_{1m}Э_{2m}}\,, \tag{11}$$

where

$$F_{12} = \frac{3}{2}\left[\left(\frac{1}{kR} - \frac{3}{(kR)^3}\right)\cos\beta_1\cos\beta_2 + \left(\frac{1}{kr} - \frac{1}{(kr)^3}\right)\cos\gamma\right]\sin(\alpha_1 - \alpha_2 + kR) +$$
$$+\frac{3}{2}\left[\frac{3}{(kR)^3}\cos\beta_1\cos\beta_2 + \frac{1}{(kR)^2}\cos\gamma\right]\cos(\alpha_1 - \alpha_2 + kR);$$

α_1, α_2 - are the initial phases of oscillation of the dipole moments. With no external EM field, energy fluxes of self-radiation from the electric or magnetic dipole are, respectively [8]

$$Э_{p} = \frac{\mu_0\sqrt{\varepsilon_0\mu_0}}{12\pi}\omega^4 p_0^2\,; \quad Э_{m} = \frac{\varepsilon_0\mu_0^2\sqrt{\varepsilon_0\mu_0}}{12\pi}\omega^4 m_0^2 \quad . \tag{12}$$

Similarly, averaged by oscillation period interferential flux of EM energy $Э_{1p}^{m}$ resulting from the electric dipole in the presence of the magnetic dipole radiation field, as well as interferential flux of EM energy $Э_{1m}^{p}$ resulting from the magnetic dipole in the presence of the electric dipole field look as follows

$$Э_{1p}^{m} = G_{12}\sqrt{Э_{1p}Э_{2m}}\,; \qquad Э_{1m}^{p} = G_{12}\sqrt{Э_{1m}Э_{2p}}\,, \tag{13}$$

where $\quad G_{12} = \frac{3}{2}\eta\sin\beta_1\sin\beta_2\sin\psi\left[\frac{1}{(kR)^2}\cos(\alpha_1 - \alpha_2 + kR) + \frac{1}{kR}\sin(\alpha_1 - \alpha_2 + kR)\right].$

In the formula for G_{12} the multiplier $\eta = 1$, if the vectors $\hat{\vec{p}}, \hat{\vec{R}}, \hat{\vec{m}}_2$, or $\hat{\vec{m}}_1\hat{\vec{R}}, \hat{\vec{p}}_2$ form the right-hand of vector system, and $\eta = -1$ if the left-hand of vector system. (Note that the formula (11) and (13) does describe not total energy fluxes, but only relevant interferential ones).

Values F_{12} and G_{12} included in the formulas (11) and (13) have a simple physical meaning. They should be considered as coefficients of interferential power connectivity between emitters, similar to coefficients of mutual capacitance and mutual induction in electrical circuits. The coefficients F_{12} and G_{12} specifying efficiency of interferential energetic interaction of the two dipole EM emitters are completely similar to the coefficient of interferential propagation $T = Э_{int} / \sqrt{Э_{10}Э_{20}}$, introduced to describe the phenomenon of tunneling EM interference [4]. Fig. 1 shows the calculated plots of F_{12} and G_{12} vs. the parameter kR for several values of the difference $\alpha_1 - \alpha_2$ with the following angles of mutual orientation of the emitters in space: $\beta_1 = \beta_2 = \gamma = \psi = 0$ for $F_{12}(kR)$ and $\beta_1 = \beta_2 = \gamma = \psi = 90^\circ$ for $G_{12}(kR)$.

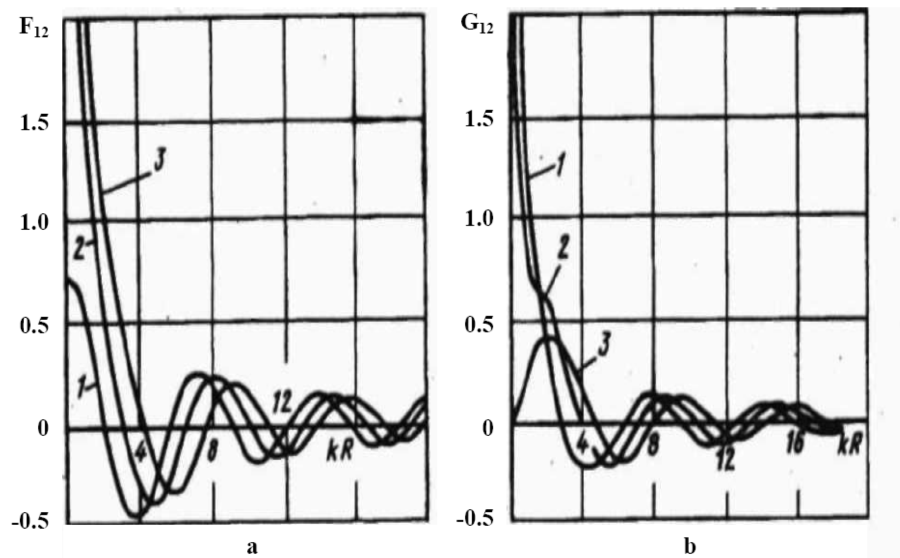

Fig. 1. Calculated plots of interferential power connectivity F_{12} factors for the single-type (a) and G_{12} for different-type (b) dipoles vs. parameter kR: 1- $\alpha_1 - \alpha_2 = 0$; 2 - 45°; 3 -90°

Interferential energy flux for two dipole systems in a quasi-static and wave approximation

Formulas (11) and (13) shows that the factors F_{12} and G_{12} depend on the nondimensional parameter kR, i.e. on the distance between the dipoles and the frequency of their radiation. Let us investigate the limiting cases: $kR << 1$ (the emitters are located in areas near each other) and $kR >> 1$ (emitters are located in the wave zones of each other).

Option $kR << 1$. In formulas (11), (13) the most essential are the members proportional to $1/(kR)^3$ for F_{12} and $1/(kR)^2$ for G_{12}, therefore

$$F_{12} \cong -\frac{3}{2(kR)^3}(3\cos\beta_1\cos\beta_2 + \cos\gamma)\sin(\alpha_1 - \alpha_2);$$

$$G_{12} = \frac{3\eta}{2(kR)^2}\sin\beta_1\sin\beta_2\sin\psi\cos(\alpha_1 - \alpha_2)\ . \tag{14}$$

Since in this case emitting elementary dipoles are at relatively small distance from each other compared with the wavelength, then the focus on the total flux of EM energy radiated to infinity through a closed surface surrounding both emitters. For example, for two electric dipoles the mentioned interferential energy flux $kR \to 0$ looks like this

$$Э_{1p}^{p} + Э_{2p}^{p} = \frac{\mu_0\sqrt{\varepsilon_0\mu_0}}{6\pi}\omega^4 p_{10}p_{20}\cos\gamma\cos(\alpha_1 - \alpha_2). \tag{15}$$

This result has a simple interpretation. Assuming that $\vec{p} = \vec{p}_1 + \vec{p}_2$ we get $p^2 = (\vec{p}, \vec{p}^*) = p_{10}^2 + p_{20}^2 +$

$+2p_{10}p_{20}\cos\gamma\cos(\alpha_1-\alpha_2)$. Having substituted $(\vec{p},\vec{p}^*)$ into the formula (12) and retained only the interferential item, we get the formula (15).

In the case of two magnetic dipoles the similar interferential energy flux is

$$Э_{1m}^{m}+Э_{2m}^{m}=\frac{\varepsilon_0\mu_0^2\sqrt{\varepsilon_0\mu_0}}{6\pi}\omega^4 m_{10}m_{20}\cos\gamma\cos(\alpha_1-\alpha_2). \tag{16}$$

It also represents the interferential item in the formula (12) for emission of magnetic dipole with moment $\vec{m}=\vec{m}_1+\vec{m}_2$.

Integral interferential energy flux to infinity with interaction of pairs of different type dipoles could be calculated from the formulas (13):

$$Э_{1p}^{m}+Э_{2m}^{p}=\eta\frac{\varepsilon_0\mu_0^2\sqrt{\varepsilon_0\mu_0}}{12\pi}\omega^5 R p_{10}m_{20}\sin\beta_1\sin\beta_2\sin\psi\sin(\alpha_1-\alpha_2). \tag{17}$$

It is seen that at $R=0$ the specified flux is zero and does not depend on relative orientation of the emitters and their radiation parameters.

We now consider interferential EM energy flux between the emitters. According to the formulas (14), F_{12} and G_{12} are such that interferential energy flux can significantly exceed energy radiation fluxes of individual dipoles. At first glance, such an outcome seems absurd. However, please note that with $kR<<1$ the given interferential energy fluxes are associated exclusively with quasi-static (electrical) interaction of dipoles featured by the factors of mutual capacitance C_{12} and mutual induction M_{12}. Energy fluxes emitted by the dipoles are negligible compared with their interaction energy flux (e.g. in an inductive transformer).

Let us consider dipole interaction energy in accordance with general formulas of electrostatics and magnetostatics:

$$U_{12}^{p}=-\left(\vec{p}_1,\vec{E}_2\right);\qquad U_{12}^{m}=-\left(\vec{m}_1,\vec{B}_2\right),$$

where $\vec{E}_2$ and $\vec{B}_2$ are the actual vectors of electric intensity and magnetic induction produced by the second dipole at the first dipole location.

For the same types of electric or magnetic dipoles, taking into account the formulas (1) and (9) when $\omega=0$, we get

$$U_{1p}^{p}=\frac{p_1p_2}{4\pi\varepsilon_0R^3}\left(3\cos\beta_1\cos\beta_2+\cos\gamma\right);\qquad U_{1m}^{m}=\frac{\mu_0m_1m_2}{4\pi R^3}\left(3\cos\beta_1\cos\beta_2+\cos\gamma\right).$$

These static formulas can be also used in case when $\vec{p}$ and $\vec{m}$ depend on time (in particular, when $\vec{p}=p_0\cos(\omega t-\alpha)\hat{\vec{p}}$ and $\vec{m}=m_0\cos(\omega t-\alpha)\hat{\vec{m}}$), if EM radiation of dipoles can be ignored. Then, in the quasi-static approximation ($\omega\to 0$) integral interferential fluxes are calculated as $Э_{1p}^{p}=\langle dU_{1p}^{p}/dt\rangle$ and $Э_{1m}^{m}=\langle dU_{1m}^{m}/dt\rangle$ (angular brackets denote averaging over oscillation period). It is easy to see that the resulting formulas coincide with the formulas (11) when $kR<<1$.

The case of different type dipoles in the quasi-static theory was not regarded as in static condition (when $\omega=0$) there is no energy of their interaction. However, in the quasi-static approximation ($kR<<1$, $\omega\to 0$) the energy of interaction of different types of dipoles can be calculated. Indeed, the electric dipole with time-varying moment $\vec{p}(t)$ can be compared with the vector element of the current $i\,dl=d\vec{p}/dt$, which generates magnetic field according to Biot-Savart law

$$\vec{B} = \mu_0 \left[\frac{d\vec{p}}{dt}, \vec{r} \right] / 4\pi \ r^3 \ ,$$

where $\vec{r}$ is radius vector with the origin at the dipole location and the end at the point where we consider the vector $\vec{B}$. The interaction energy of the magnetic dipole placed in this field looks as follows

$$U^p_{1m} = \frac{\mu_0 m_1}{4\pi R^2} \frac{dp_2}{dt} \sin\beta_1 \sin\beta_2 \sin\psi \ .$$

Then $Э^p_{1p} = \langle dU^p_{1p} / dt \rangle$. In case of harmonic dipole moments $m_1 = m_{10} \ \cos(\omega t - \alpha_1)$, $p_2 = p_{20} \ \cos(\omega t - \alpha_2)$ of the emitters, varying with the same frequency, we get an formula coinciding with the formula (13) when $kR << 1$.

Note that the electrical theory of quasi-static EM phenomena is, of course, approximate. It is the asymptotic limit of studied in this research strict electrodynamics theory of interferential energy interaction of the two dipole emitters at $\omega \to 0$ or $R \to 0$. With increasing kR, corrections appear in two forms: for the dipole own radiation and for adjustment of interferential flux vs. parameter kR relation form.

Option $kR >> 1$. In the formulas (11) and (13) for F_{12} and G_{12} the most important are the members proportional to $1/kR$, so

$$F_{12} \cong \frac{3}{2kR}(\cos\beta_1 \cos\beta_2 + \cos\gamma)\sin(\alpha_1 - \alpha_2 + kR);$$

$$G_{12} \cong \frac{3\eta}{2kR}\sin\beta_1 \sin\beta_2 \sin\psi \sin(\alpha_1 - \alpha_2 + kR). \qquad (18)$$

In this case, the EM field generated by the second dipole in the vicinity of the first dipole location passes into the plane wave field. Thus, at $kR >> 1$ the task on the two dipoles interaction becomes a task on the dipole located in the plane EM wave field.

Apply the formulas (8) and (10) to the interference energy interactions of elementary dipole emitter and the incident plane EM wave. Density of electric and magnetic fields, of a plane wave at the location of the dipole looks as follows [8]

$$\vec{E} = E_0 e^{-i(\omega t - \beta)} \hat{\vec{E}} \ ; \quad \vec{H} = H_0 e^{-i(\omega t - \beta)} \hat{\vec{H}} \ , \qquad (19)$$

where E_0 and H_0 are related by the equation $\sqrt{\varepsilon_0} E_0 = \sqrt{\mu_0} H_0$, β - is the initial phase of the EM wave oscillation field. Substituting the equations (19) into the formula (8) (or (10)), we get averaged over the oscillation period integral interferential fluxes of EM energy:

$$Э^p_{\text{int}} = -\frac{1}{2}\omega \ p_0 E_0 \sin(\alpha - \beta) \ \left(\hat{\vec{p}}, \hat{\vec{E}}\right);$$

$$Э^m_{\text{int}} = -\frac{1}{2}\mu_0 \omega \ m_0 H_0 \sin(\alpha - \beta) \left(\hat{\vec{m}}, \hat{\vec{H}}\right), \qquad (20)$$

where α is the initial phase of dipole oscillations. Denote δ as the angle between $\hat{\vec{p}}$ and $\hat{\vec{E}}$ or $\hat{\vec{m}}$ and $\hat{\vec{H}}$. Then $(\hat{\vec{p}}, \hat{\vec{E}}) = (\hat{\vec{m}}, \hat{\vec{H}}) = \cos\delta$. Note that the formula for $Э^p_{\text{int}}$ was obtained in research [1] for the special case when considering a task of plane EM wave scattering on a passive elementary electric dipole.

Interferential energy interaction of the dipole emitter with plane EM wave field can be described using absorption effective cross-section σ [1], which is determined as the ratio of flux of EM energy absorbed by the emitter $Э_{\text{int}}$, to the average over the oscillation period intensity of EM wave incident on the dipole: $I_0 = \frac{1}{2}\varepsilon_0 E_0^2 c = \frac{1}{2}\mu_0 H_0^2 c$. The equations for absorption effective cross-sections σ_p and σ_m for the electric and magnetic dipoles are respectively:

$$\sigma_p = \frac{Э_{\text{int}}^p}{I_0} = \sqrt{\frac{\mu_0}{\varepsilon_0}}\omega\frac{p_0}{E_0}\cos\delta\sin(\alpha-\beta); \quad \sigma_m = \frac{Э_{\text{int}}^m}{I_0} = \sqrt{\varepsilon_0\mu_0}\,\omega\frac{m_0}{H_0}\cos\delta\sin(\alpha-\beta). \tag{21}$$

It is evident that the area σ depends on dipole moment of the emitter, which is specified for the passive dipole by the amplitude of field of external EM wave incident on the dipole ($p_0 = p_{pas} = \chi E_0$, where χ is a dipole polarization factor), and for the active dipole is also specified by internal source of EM fluctuations of the dipole ($p_0 = p_{pas} + p_{act}$). Since with $kR >> 1$ it is easy to provide $p_{act} >> p_{pas}$, then σ_{act} (of the active dipole emitter) might be much greater than σ_{pas} (of the passive dipole). Within a certain range of $\alpha - \beta$ absorption cross-section of the active dipole is negative, indicating that the dipole emits additional EM energy due to interferential energy interaction of the emitter with external field.

Transmission of electromagnetic signal energy using interferential flux

As it follows from this analysis, EM energy flux coming from the external EM wave onto the dipole emitter used as a receiving antenna, is interferential energy flux of total EM field of two waves: the external wave incident onto the dipole, and the wave emitted by the dipole itself (or re-emitted wave in the case of the passive dipole). Since the receiving EM transmitter converts field energy of incident EM wave into electric current energy coming into the input circuits of the receiver (for the transmitting emitter, on the contrary, electric current energy of EM oscillation source is converted into field energy of emitted EM wave), then to analyze processes EM energy transmission between the dipole emitters it is necessary to consider this conversion.

Formally, the antenna is replaced by some source of induced EMF E_{emf}, generating in a load circuit electric current of EM signal $i = \mathrm{E}_{emf}/(Z_r + Z_n)$, where Z_r and Z_n are, respectively, the antenna and load impedances. Here the total electric capacity of this EMF, averaged over the oscillation period is $W = \langle \mathrm{E}_{emf}\, i\rangle$.

Consider physical nature of generating capacity of "induced EMF" [1]. By definition, $\mathrm{E}_{emf} = \int_l \vec{E}\, d\vec{l} = E_l l$, where $E = E_0\cos(\omega t - \beta)$ is electric intensity of field of EM wave arrived to the emitter; l is effective length of the antenna. The electric current in the antenna $i = \frac{1}{l}\frac{dp}{dt}$, where $p = p_0\cos(\omega t - \alpha)$ is the dipole moment of the antenna. Then power generated by a source of "induced EMF" is

$$W = \left\langle \mathrm{E}_{emf}\, i\right\rangle = -\omega\, p_0 E_0\langle\sin(\omega t-\beta)\cos(\omega t-\beta)\rangle = -\frac{1}{2}\omega\, p_0 E_0\langle\sin(2\omega t-\alpha-\beta)+\sin(\beta-\alpha)\rangle =$$

$$= \frac{1}{2}\omega\, p_0 E_0\sin(\alpha-\beta). \tag{22}$$

Comparing the obtained formula with the formula (7), we can see the equality $W = -Э_{\text{int}}^p$ is executed. A similar calculation is easy to be made for the magnetic dipole antenna.

Thus, for the active receiving dipole emitter, power of "induced EMF" by the condition $p_{act} >> p_{pas}$ is specified by amplitude of electric current in the dipole from an internal source of EM oscillations (a local oscillator). To characterize increasing power of the signal received by the antenna, we introduce the active receiving antenna gain

$$K = \frac{W_{act}}{W_{pas}} = 1 + \frac{p_{act}}{p_{pas}} \sin(\alpha - \beta), \tag{23}$$

similar to signal gain under tunneling EM interference [4].

Thus, the concept of interferential energetic interaction of the dipole emitter with external EM field allows justifying and giving physical content to the term "power of induced EMF". In particular, it provides an opportunity to assess the dipole emitter absorption effective cross-section. It is easy to show that for the passive electric dipole $\sigma_p^{pas} \le 3\lambda^2/4\pi$ (λ - is wavelength) [1], therefore for the active dipole antenna $\sigma_p^{act} = K\sigma_p^{pas}$. Note that while transmitting EM energy using interferential flux along with regular energy flux $Э_0$ emitted by an isolated dipole, there is additional interferential energy flux $Э_{\text{int}}$ emitted or absorbed by the dipole in the presence of incident on the emitter external EM wave. Therefore, the total energy flux $Э = Э_0 + Э_{\text{int}}$. It should be considered that flux $Э_0$ is proportional to ω^4 (formula (12)), and interferential flux $Э_{\text{int}}$ depends linearly on ω (formulas (8) and (10)). Therefore, using interference to transmit of EM energy shall be effective at frequencies $\omega < \omega_0$, when $Э \cong Э_{\text{int}}$. Critical frequency ω_0 can be determined from the proportion $Э_{\text{int}} / Э_0 = 1$. It is equal to $\omega_0 = \left(6\pi \frac{c^3 E_0}{\mu_0 p_0}\right)^{1/3}$ for the electric dipole and $\omega_0 = \left(6\pi \frac{c^3 H_0}{m_0}\right)^{1/3}$ for the magnetic dipole. Here, E_0, H_0 are amplitudes of intensity of external EM wave at the location of the receiving emitter with amplitude of the dipole moment p_0 or m_0.

Using the formulas (11) and (13) it is easy to calculate critical frequency ω_0 when $kR << 1$ for systems of two single-type dipoles: $\omega_0 \cong \frac{c}{R}\left(\frac{p_E}{p_0}\right)^{1/3}$; $\omega_0 \cong \frac{c}{R}\left(\frac{m_H}{m_0}\right)^{1/3}$ and different-type dipoles: $\omega_0 \cong \frac{c}{R}\left(\frac{m_H}{cp_0}\right)^{1/2}$; $\omega_0 \cong \frac{c}{R}\left(\frac{cp_E}{m_0}\right)^{1/2}$ where p_E, m_H - are amplitudes of dipole moments of the emitters generating field of external EM wave. Similarly, from the same formulas we find ω_0 when $kR >> 1$ for the two single-type dipoles: $\omega_0 \cong \frac{c}{R}\left(\frac{p_E}{p_0}\right)$; $\omega_0 \cong \frac{c}{R}\left(\frac{m_E}{m_0}\right)$ and for the two different-type dipoles: $\omega_0 \cong \frac{c}{R}\left(\frac{m_H}{cp_0}\right)$; $\omega_0 \cong \frac{c}{R}\left(\frac{cp_E}{m_0}\right)$. It is seen that critical frequency ω_0, below which transmission of EM energy through interferential flux is effectively implemented, depends both on distance between the emitters and ratio of their dipole moments. For example, the dipoles of equal dipole moments located from each other at distance $R_1 = 10^3$ m, critical frequency is $\omega_{01} \cong 10^5\ s^{-1}$, and $R_2 = 10^6$ m at $\omega_{02} \cong 10^2\ s^{-1}$. In radio communication, where EM energy emitted by the transmitting antenna, is used for transmission of data signals, only a small part of this energy (less than 100-200 dB) comes to the receiving antenna. Then, even for the active receiving antenna the ratio p_E / p_0 (or m_H / m_0) is such that use of interferential energy flux for reception of EM signals is possible up to frequencies of the optical range.

For experimental verification of the formulas (14), (18) and (23) we performed direct measurements of relation of interferential flux of EM energy coming to a single radiating dipole located in another radiating dipole's filed vs. distance R between them. Radiation frequency is the same for both dipoles. At the same time we investigated both electric and magnetic dipole emitters (dipole vibrators about 5 cm long and current coils about 3 cm in diameter made from six-turn wire PEV-1.0) in the frequency bands of 1 to 5 MHz (instance $kR << 1$) and 2 to 4 GHz (instance $kR >> 1$). The distance between the emitters varied within 10 to 80 cm. Restriction from the side of small distances is due to inefficiency of point dipoles model in this area. Recording of interferential energy flux entering the dipole was made in the emitter circuit using a quadratic detector with the beats method ($F \sim 10^3$ Hz).

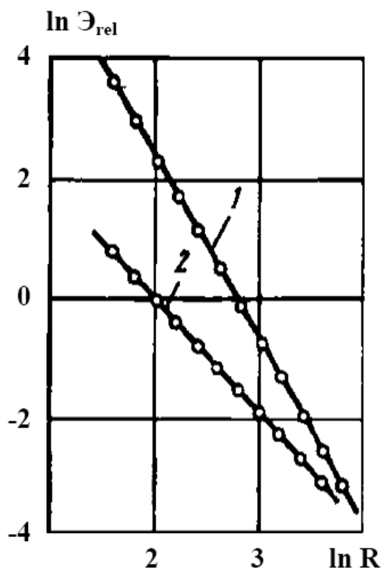

Fig.2 Empirical data of relative interferential flux of EM energy between the active dipole emitters $Э_{int}$ vs. distance R (Option kR << 1): 1 - system of two magnetic emitters; 2 - system of magnetic and electric emitters.

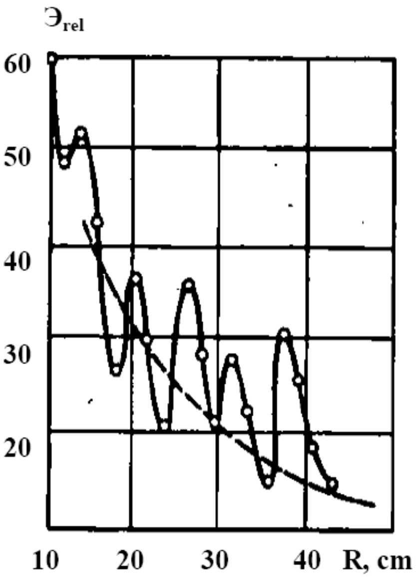

Fig.3 Empirical data of relative interferential flux of dipole emitters $Э_{int}$ vs. distance R (Option kR >> 1).

Fig. 2 shows in logarithmic scale relation of interferential flux between two magnetic dipoles (coils), emitting at 1 MHz vs. distance between the emitters (line 1). It also shows a similar relation for the magnetic dipole within the system of the electric and magnetic dipoles, emitting at 5 MHz (line 2). A slope of straight lines drawn through the test points is - 3.1 and - 1.8 for curves 1 and 2, respectively. Theoretically, these lines should have a slope of - 3.0 and - 2.0. Fig. 3 shows relation of $Э_{rel}(R)$ for $kR >> 1$. Measurements are shown for the system of two dipole vibrators ($l \sim 2$ cm) at 2.5 GHz. The dashed line marks *1/R* relation. In both cases, the experimental data are in satisfactory agreement with the conclusions of the theory both in quasi-static and in wave approximations.

The tests have shown that for the passive dipole receiving emission from the other one, the nature of relation of EM energy flux onto the dipole vs. the distance between the emitters is the same as of relations for the active dipole (see Fig. 2 and 3). EM energy flux coming to the passive dipole is substantially less than it is received by the active emitter, and their ratio corresponds to the formula (23).

Use of interferential flux generated by the active receiving antenna, can dramatically reduce threshold of EM signal reception sensitivity. Therefore, it is possible to implement reception of ultraweak EM signals, whose energy level is substantially lower (in some cases by dozens of decibels) than sensitivity threshold of a real receiver when receiving by a passive antenna. The testing identified interferential reception of EM signals by 4-20 dB below the sensitivity threshold of the radio receiver (0.1-1 MHz), UHF (2-4 GHz) and optical (λ = 632.8 nm) bands. This revealed a possibility of the active antenna to receive EM signals with the level below the receiver sensitivity threshold having strong (by 10-20 dB higher than signal energy) additive noise interference available on the frequency of received signals.

In conclusion, the obtained theoretical results regarding consideration of ideal electrodynamic problems can be also used for analysis of interferential reception of EM signals in real conditions. In this case, the receiving antenna is influenced by EM field of signal $E_s = E_{os}\cos(\omega t - \beta_s)$ with strictly specified initial phase of carrier wave β_s and noise EM field $E_n = E_{on}\cos(\omega t - \beta_n)$ with randomly changing initial phase β_n. To evaluate power generated by induced EMF of the active antenna in such conditions, we shall consider only the dipole moment $p_{act} = p_{0g}\cos(\omega t - \alpha)$, generated on the antenna by a local oscillator (neglecting the dipole moment induced by fields of external EM waves).

Power passing from the active antenna to the receiver input can be calculated using the formula (22). Since the initial phase of the noise field β_n is random, i.e. $\int_0^{2\pi} \sin(\alpha - \beta_n)\ d\beta_n = 0$, then for the time-average total induced EMF considering power noise, eventually we get the equation $W = -\frac{1}{2}\omega\ p_{og}E_{os}\sin(\alpha - \beta_s)$ (noise item disappears). In the vicinity of the active receiving antenna EM fields of signal and local oscillator emission interfere due to coherence and generate an additional EM energy flux onto the antenna. Fields of noise EM waves and local oscillator are incoherent and do not generate the mentioned flux. Of course, this antenna receives the signal and noise in the usual way, i.e. as the passive antenna, but level of the received power will be by K times less (in accordance with the formula (23)). Therefore, the active receiving antenna behaves actively with respect to the signal EM field and passively with respect to the noise EM field. Thus, application of interferential energy flux onto the active receiving antenna can significantly improve the signal/noise ratio at the receiver input, and therefore provide reception of EM signals, whose level at passive reception is lower than the receiver sensitivity threshold.

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