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Energy fluxes during the interference of electromagnetic waves

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Contents

Abstract. Expressions are given for the interference energy flux (IEF) of the active and reactive components of co- and counterpropagating waves with an arbitrary structure of their electromagnetic field. The formation conditions of the IEF and its role in energy transfer processes are analyzed in the examples of homogeneous plane waves in an absorbing medium, directed planar-waveguide modes, and a system of radiating dipoles. The possibility of using the IEF for controlling the radiation, transfer, and dissipation of electromagnetic energy is discussed. The IEF of the waves of two coherent sources is shown to contain two interrelated components, which control different energy processes.

1. Introduction

From an energy viewpoint, interference consists in the fact that the resulting intensity of two coherent waves in the region of their overlap differs from the sum of the intensities of the initial waves. The average energy flux density vector of two monochromatic coherent waves can be represented as

$$\mathbf{S} = \mathbf{S}_1 + \mathbf{S}_2 + \mathbf{S}_{\text{int}}\,, \quad \mathbf{S}_j = \tau\,\mathrm{Re}\,(\mathbf{e}_j \times \mathbf{h}_j^*)\,,$$
$$\mathbf{S}_{\text{int}} = \tau\,\mathrm{Re}\left[(\mathbf{e}_1 \times \mathbf{h}_2^*) + (\mathbf{e}_2 \times \mathbf{h}_1^*)\right]\,, \tag{1}$$

where $\mathbf{S}_j$ is the energy flux of each wave ($j = 1, 2$), $\mathbf{S}_{\text{int}}$ is the interference flux (IF), $\tau = c/8\pi$, c is the speed of light in the vacuum, and $\mathbf{e}_j$ and $\mathbf{h}_j$ are the complex electric and magnetic field strengths, respectively. The IF formation is a fundamental feature that unifies various manifestations of interference. For example, two different phenomena — electromagnetic-energy tunneling through a thin substance layer when a wave is incident at an angle higher than the critical angle of total internal reflection and the nonradiative energy transfer between atoms in a medium — are based on the formation of the IF reactive components of an electromagnetic field. The behavior of the IF can differ strongly from the behavior of single-wave fluxes; in particular, the IF can exist even when energy cannot be transferred by a single wave (e.g., during electromagnetic-wave tunneling [1 – 3]).

The special role of the IF in energy transfer processes was first noted in [4 – 6], where the energy balance was studied for light incident on the boundary of two semiinfinite media when at least one of them is semiabsorbing. Experiments on the interference of counterpropagating waves (ICWs) in the optical and microwave regions in thin metallic films are described in [7 – 9]: it was found that an undamped IF of the reactive components of wave fields appears when ICWs are present in absorbing media and that the IF intensity oscillates in the direction of damping of the initial waves. Such behavior of an IF occurs not only in absorbing but also in amplifying media [10]; in the general case, this behavior occurs in dispersion media with a complex refractive index [10 – 14]. A further analysis showed that for directed inhomogeneous waves in various waveguide structures, an oscillating IF can be generated by not only the reactive components but also the active components of wave fields for both counter- and copropagating waves [15, 16].

The situation where the amplitude and phase of one of the waves can be changed irrespective of the corresponding characteristics of the second wave and the parameters of the medium in which interference occurs is of particular interest. When changing the phase difference of the initial waves at the point of observation, one can control both the magnitude and direction of interference and the total energy fluxes. The idea of using the IF for controlling the electromagnetic radiation energy transfer and dissipation was developed in [7 – 14, 17 – 20], where ICWs were studied for the incidence of two coherent waves on opposite sides of a parallel-sided layer (film) or a planar layered structure.

One of the most important and interesting manifestations of the interference of electromagnetic waves consists in

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interference phenomena in the near-field radiation zone of the radiators of these wave. The specific features of such phenomena and the appearance of useful effects were considered for a passive electric dipole in the field of an incident plane wave [21, 22] and for a system of two or several elementary dipole radiators [23–25].

In this work, we use these manifestations of interference in various physical situations as examples and consider the problems related to the physical nature and conditions of IF and its role in the transfer and dissipation of electromagnetic-wave energy using the same approach.

2. Interference fluxes of the active and reactive components of wave fields

In contrast to the active components of the electric and magnetic field vectors of a single electromagnetic wave (which have no phase shift between themselves), the reactive components (separated by the phase shift $\pi/2$) do not contribute to the wave intensity. However, when two or more coherent waves are superimposed in space, the reactive components of their fields can cause an IF in directions where energy transfer is absent for a single wave. Below, we present general expressions for the energy fluxes that occur during the interference of the active and reactive components of the fields of two coherent waves.

We consider two monochromatic electromagnetic waves with a frequency ω that interfere with each other. The field of each wave always contains one or several pairs of interrelated components of the magnetic and electric fields, which are perpendicular to each other. We choose one such pair of components of the first wave (h_1, e_1) and a similar pair of collinear components of the second wave (h_2, e_2). These fields can be written as

$$\begin{aligned} h_j &= a_j \exp\left[\mathrm{i}(\omega t + \chi_j)\right], \\ e_j &= Z_j a_j \exp\left[\mathrm{i}(\omega t + \chi_j + \zeta)\right], \end{aligned} \tag{2}$$

where χ_j are coordinate-dependent phase terms ($j = 1, 2$) and ζ is the phase shift between the components of the electric and magnetic fields. The amplitude coefficients a_j are certain functions of coordinates, and the impedances Z_j represent the ratios of the electric- and magnetic-field amplitudes.

According to (1), the chosen components of the wave field generate a Poynting vector component in the direction that is normal to both the electric and magnetic fields,

$$S = \tau \operatorname{Re}\left[(e_1 + e_2)(h_1 + h_2)^*\right]. \tag{3}$$

With Eqn (2), we can rewrite Eqn (3) as

$$\begin{aligned} S = \tau\Big\{ &\left[Z_1 a_1^2 + Z_2 a_2^2 + (Z_1 + Z_2)\, a_1 a_2 \cos\Delta\chi\right] \cos\zeta \\ &+ (Z_1 - Z_2)\, a_1 a_2 \sin\Delta\chi \sin\zeta \Big\}, \end{aligned} \tag{4}$$

where $\Delta\chi = \chi_2 - \chi_1$. Apart from the terms related to each wave, Eqn (4) contains interference terms that are proportional to the amplitude product $a_1 a_2$. In the particular case of active components ($\zeta = 0$), Eqn (4) takes the form

$$S_{\mathrm{a}} = \tau\left[Z_1 a_1^2 + Z_2 a_2^2 + (Z_1 + Z_2)\, a_1 a_2 \cos\Delta\chi\right]. \tag{5}$$

The condition of the presence of an IF in this expression is that the sum of the impedances is nonzero, $Z_1 \neq -Z_2$. If the components are reactive ($\zeta = \pm\pi/2$), the average energy flux is a purely interference flux,

$$S_{\mathrm{r}} = \pm\tau\,(Z_1 - Z_2)\, a_1 a_2 \sin\Delta\chi, \tag{6}$$

and is nonzero if $Z_1 \neq Z_2$. Equations (5) and (6) exhaust all possible cases of phase relations between the fields of an electromagnetic wave because at an arbitrary phase shift ζ, the electric field in Eqn (2) can be decomposed into active and reactive components (with respect to the magnetic field).

Thus, energy IFs can be generated by both active and reactive components of wave fields. The equations given above are convenient for energy fluxes during the interference of co- and counterpropagating waves with an arbitrary structure of the wave field to be analyzed by decomposing this field into active and reactive components.

3. Interference fluxes of co- and counterpropagating waves

Let two plane homogeneous and linearly polarized waves propagate in an infinite dispersion-free medium with the following complex material parameters: the magnetic permeability $\mu = \mu' - \mathrm{i}\mu''$ and the permittivity $\varepsilon = \varepsilon' - \mathrm{i}\varepsilon''$. Waves in this medium are characterized by a complex wavenumber $k = k_0(\varepsilon\mu)^{1/2} = k' - \mathrm{i}k''$ (where $k_0 = \omega/c$); a real propagation constant k' and a real damping coefficient k'' are defined by the relations

$$\begin{aligned} k' &= \frac{k_0}{\sqrt{2}}\left(|\varepsilon||\mu| + \varepsilon'\mu' - \varepsilon''\mu''\right)^{1/2}, \\ k'' &= \frac{k_0}{\sqrt{2}}\left(|\varepsilon||\mu| - \varepsilon'\mu' + \varepsilon''\mu''\right)^{1/2}. \end{aligned} \tag{7}$$

The impedance is also a complex quantity, $Z = (\mu/\varepsilon)^{1/2} = Z' + \mathrm{i}Z''$, where

$$\begin{aligned} Z' &= \frac{1}{|\varepsilon|\sqrt{2}}\left(|\varepsilon||\mu| + \varepsilon'\mu' + \varepsilon''\mu''\right)^{1/2}, \\ Z'' &= \frac{1}{|\varepsilon|\sqrt{2}}\left(|\varepsilon||\mu| - \varepsilon'\mu' - \varepsilon''\mu''\right)^{1/2}. \end{aligned} \tag{8}$$

Equations (2) describe the field components h_{jy} and e_{jx} of waves propagating along the z axis. In the $z = 0$ plane, the waves are assumed to have amplitudes A_j and initial phases φ_j. We write the impedance in the form $Z = |Z| \exp(\mathrm{i}\zeta)$ and see that the electric fields e_{jx} can be decomposed into an active component, which is proportional to $Z' = |Z| \cos\zeta$, and a reactive component, which is proportional to $Z'' = |Z| \sin\zeta$.

We first assume that both waves are unidirectional and propagate in the positive direction of the z axis. Then, in Eqn (2), we set $a_j = A_j \exp(-k''z)$, $Z_1 = Z_2 = |Z|$, and $\chi_j = -k'z + \varphi_j$. For the total energy flux along the z axis, we obtain

$$S_z = \tau Z' \exp(-2k''z)(A_1^2 + A_2^2 + 2A_1A_2\cos\delta), \tag{9}$$

where $\delta = \varphi_2 - \varphi_1$. In this case, the total energy flux is seen to be induced by only the active components and to include an IF that decays along the z axis identical to the flux of the single wave.

We now consider the case of ICWs. In Eqn (2), we set $a_j = \pm A_j \exp(\mp k'' z)$, $Z_1 = -Z_2 = |Z|$, and $\chi_j = \mp k' z + \varphi_j$ (the upper signs in $\pm$ and $\mp$ pertain to the direct wave, and the lower signs, to the counterpropagating wave) and represent the total flux in the form

$$S_z = \tau\{Z'[A_1^2 \exp(-2k''z) - A_2^2 \exp(2k''z)] - 2Z'' A_1 A_2 \sin(2k'z + \delta)\} . \tag{10}$$

Apart from the 'active' energy fluxes of the single waves, this expression involves an undamped IF of the reactive components, which oscillates along the z axis with the spatial period $\pi/k' = \lambda/2$ (where λ is the wavelength).

To reveal the role of the IF in electromagnetic energy transfer processes, we analyze its relation to other energy wave characteristics. For counterpropagating waves, we write the expression

$$\begin{aligned} w &= \frac{\varepsilon'}{16\pi} |e_1 + e_2|^2 + \frac{\mu'}{16\pi} |h_1 + h_2|^2 \\ &= \frac{1}{16\pi} \{(\varepsilon'|Z|^2 + \mu')[A_1^2 \exp(-2k''z) + A_2^2 \exp(2k''z)] \\ &\quad + 2(\varepsilon'|Z|^2 - \mu') A_1 A_2 \cos(2k'z + \delta)\} \end{aligned} \tag{11}$$

for the average electromagnetic-energy density w of two waves, and the expression

$$\begin{aligned} P = -\frac{dS_z}{dz} &= \frac{\omega}{8\pi} \{(\varepsilon''|Z|^2 + \mu'') \\ &\times [A_1^2 \exp(-2k''z) + A_2^2 \exp(2k''z)] \\ &+ 2(\varepsilon''|Z|^2 - \mu'') A_1 A_2 \cos(2k'z + \delta)\} \end{aligned} \tag{12}$$

for the heat release P (which is the time-averaged power density of heat loss). Comparing Eqns (11) and (12), we can see that both expressions contain interference terms that vary along the z axis in accordance with the same law. The interference terms of the energy density of the electric and magnetic fields oscillate in antiphase: the maxima of the electric energy coincide with the minima of the magnetic energy and vice versa. Therefore, the contributions of two types of losses (electric and magnetic) enter the interference component of heat release with opposite signs. As a result, the interference maxima and minima of heat release are superimposed on the maxima and minima of either the electric or the magnetic energy density, depending on the predominant type of losses. When the condition $\varepsilon''|Z|^2 = \mu''$ is satisfied, the interference component of heat release is absent.

Based on Eqns (10)–(12), we can reveal the role of the 'reactive' IF in the motion of counterpropagating waves in a lossy medium. This flux transfers energy to regions of its high consumption (i.e., to the maxima of heat release) and takes energy away from regions with its low consumption (i.e., from the minima of heat release). Thus, the IF plays a 'redistributing' role via the control of energy distribution within a spatial 'cell' half-wavelength long; therefore, the IF is related to spatial heat-release oscillations.

The following two limit cases of ICWs corresponding to loss-free media ($\mu'' = \varepsilon'' = 0$) are of interest. The first case corresponds to media with $\mu', \varepsilon' > 0$. In these media, according to Eqns (7) and (8), $k'' = 0$ and $Z'' = 0$, the field components in Eqn (2) are purely active, and only single-wave fluxes are retained in Eqn (10). In this case, these fluxes are undamped,

$$S_z = \tau Z'(A_1^2 - A_2^2) . \tag{13}$$

At $A_1 = A_2$, we have the well-known case of a standing wave, which is characterized by the absence of energy transfer in a medium.

The second case is realized in media with a negative value of permeability or permittivity (e.g., $\varepsilon' < 0$, $\mu' > 0$). As follows from Eqns (7) and (8), $k' = 0$ and $Z' = 0$, and the field components are purely reactive. In this case, only the IF is nonzero in Eqn (10); it is then independent of the z coordinate and is determined by the expression

$$S_z = -2\tau Z'' A_1 A_2 \sin\delta . \tag{14}$$

This flux appears upon the superposition of two electromagnetic oscillations that decay exponentially with the damping coefficient $k'' = k_0(|\varepsilon'|\mu')^{1/2}$ in opposite directions and transfers energy even when this is impossible for a single perturbation. The energy transfer direction and the magnitude of the IF are specified by the phase difference δ. Flux (14) is closely related to the interference component of the energy density, which is given by

$$w_{\text{int}} = -\frac{1}{4\pi} \mu' A_1 A_2 \cos\delta , \tag{15}$$

because the change in the IF caused by a possible change in δ is accompanied by the corresponding change in the electromagnetic energy 'stored' in the medium.

The flux transferring energy during the tunneling of an electromagnetic wave has a similar nature [1, 3]. We also note that Eqn (14) is obviously analogous to the relation that is well known for a tunneling superconducting current in the Josephson effect [26].

We now consider the interference of inhomogeneous waves using TM modes propagating in a planar waveguide with ideally conducting boundary media as an example [16]. For simplicity, we suppose that the waveguide represents a planar dielectric layer of thickness d with a permittivity ε and that the waveguide is bounded by ideal conductors (the planes $x = 0$ and $x = d$) from both sides. In this case, the fields of an nth-order waveguide mode propagating along the z axis can be represented as

$$\begin{aligned} h_{yn} &= A \cos q_n x \exp[i(\omega t - k_n z)] , \\ e_{xn} &= \frac{k_n}{k_0\varepsilon} h_{yn} , \quad e_{zn} = \frac{i}{k_0\varepsilon} \frac{\partial h_{yn}}{\partial x} , \end{aligned} \tag{16}$$

where $k_n = (k_0^2 \varepsilon\mu - q_n^2)^{1/2} = k_n' - ik_n''$ is the mode propagation constant and $q_n = \pi n/d$ is the transverse wavenumber.

Without going into the details of the structure of the waveguide mode energy fluxes, we only indicate the differences between this structure and the structure considered in the case of homogeneous waves. The energy flux induced by fields of type (16) has two projections, one longitudinal (S_z) and one transverse (S_x):

$$S_z = \tau \operatorname{Re}(e_x h_y^*) ; \quad S_x = -\tau \operatorname{Re}(e_z h_y^*) . \tag{17}$$

For the interference of co- and counterpropagating modes, the field components in Eqn (17) are the sum of the fields of the interfering waves, as in Eqn (3). For modes of the same order ($n_1 = n_2$), the nature and properties of the longitudinal flux are identical to those of homogeneous waves (only the dependence on the transverse coordinate x appears). For modes of different orders ($n_1 \neq n_2$), the longitudinal IF also includes two terms, the 'active' and 'reactive' ones. Apart from damping, these fluxes have the same oscillating dependence on z: they change in accordance with a cosine law with the period $2\pi/|k_1' - k_2'|$ for copropagating modes and $2\pi/(k_1' + k_2')$ for counterpropagating modes. Oscillations are absent only for $k_1' = k_2' = 0$, i.e., for purely imaginary propagation constants (e.g., for damped modes in the cutoff region). We note that IF oscillations for modes of different indices also occur in the absence of losses. The damping of an IF for copropagating modes is determined by the sum of the imaginary parts of the propagation constants, and that for counterpropagating modes is determined by their difference.

As regards the transverse flux S_x, for a single mode it appears only in the presence of losses. In the absence of losses (for real ε), the components e_z and h_y, which are responsible for its formation, are purely reactive and do not generate the flux. Similarly to the IF of counterpropagating waves in Eqn (10), the transverse flux that appears in the presence of dissipation is related to spatial heat-release oscillations (a heat-release standing wave forms along the x axis even in the case of propagation of a single waveguide mode).

If losses are absent, a transverse flux forms only upon interference of different modes (co- or counterpropagating). Longitudinal and transverse fluxes then appear simultaneously, and their oscillations are interrelated: the maxima and minima of the transverse IF are located in the sections where the longitudinal IF vanishes. As in an absorbing medium, oscillating IFs are involved in the electromagnetic field energy redistribution. An analysis demonstrates that longitudinal-flux oscillations correspond to electromagnetic energy density oscillations depending on z. A change in the energy density along the z axis is related to the energy redistribution across the waveguide structure that is caused by the presence of a transverse IF component.

4. Interference of counterpropagating waves in a parallel-sided layer

In practice, the model of a medium unbounded in the propagation direction can be used to study ICWs only for weak damping. Therefore, most theoretical works concerning ICWs and virtually all related experimental works deal with this phenomenon in the case of normal or oblique incidence of two waves from the vacuum or any transparent medium on a rather thin layer of the material under study. ICW effects inside the layer manifest themselves only indirectly, because the intensities of the waves traveling from the layer to the surrounding transparent medium are measured experimentally. This scheme was realized in [27–29] with the Mach–Zehnder interferometer, and it was used to develop techniques for the determination of the optical constants of thin films. The authors of [7–20] studied ICWs in planar layered structures and showed that the presence of an IF in the total energy flux causes the appearance of a number of specific practically important interference effects.

Let two plane homogeneous coherent waves with the same linear s or p polarization, the amplitudes A_j, and the initial phases φ_j be incident from the vacuum on the opposite

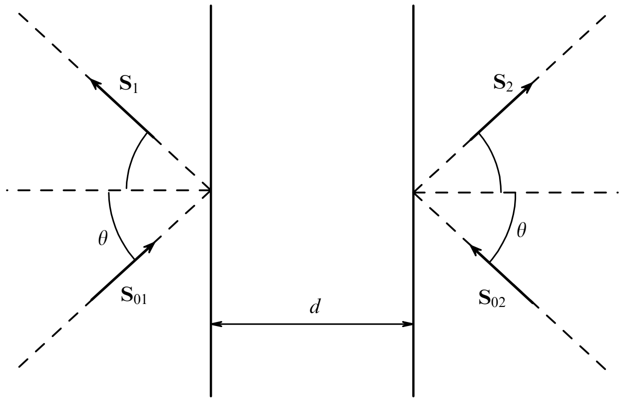

Figure 1. Schematic diagram for energy fluxes during the interference of counterpropagating waves in a parallel-sided layer.

surfaces of a planar layered structure of thickness d (in the simplest case, a single parallel-sided layer) at the same angle θ (Fig. 1). The incident-wave energy fluxes are $S_{0j} = \tau A_j^2$. The layer surfaces emit energy fluxes S_j formed by two counterpropagating waves, the wave reflected by the layer and the wave passing through the layer,

$$S_1 = S_{11} + S_{12} + S_{1\,\mathrm{int}} = \tau\left[RA_1^2 + TA_2^2 + IA_1A_2\cos(\delta - \Delta)\right], \tag{18}$$

$$S_2 = S_{21} + S_{22} + S_{2\,\mathrm{int}} = \tau\left[TA_1^2 + RA_2^2 + IA_1A_2\cos(\delta + \Delta)\right].$$

Here, R and T are the energy reflection and transmission coefficients, which depend on the incidence angle and the structure parameters [30], for waves of the corresponding polarization; $\Delta = \xi_R - \xi_T$ is the phase difference acquired by the waves upon reflection (ξ_R) and transmission (ξ_T) through the layer; and $\delta = \varphi_2 - \varphi_1 + k_0 d$ is the phase difference of the incident waves at the layer surfaces.

The interference transmission factor $I = 2(RT)^{1/2}$ determines the 'amplitude' values of the IF $S_{j\,\mathrm{int}}$ entering fluxes (18). I is maximal at $R = T$ (i.e., for a semitransparent layer) and reaches unity in the absence of absorption. The presence of IF in the fluxes leaving the layer can be used, e.g., to realize the flux S_j modulation due to the change in the phase difference δ caused by a change in the modulation depth m. For the flux S_1, this depth is

$$m = \frac{S_{1\max} - S_{1\min}}{S_{1\max} + S_{1\min}} = \frac{IA_1A_2}{RA_1^2 + TA_2^2}\,. \tag{19}$$

At $A_1 = A_2$, for a transparent structure, we have $m = I$, and hence m can reach $m = 1$.

A signal can also be amplified when passing through the layer, and the amplification factor for a wave with $j = 1$ is

$$K = \frac{S_2}{S_{01}} = T + I\,\frac{A_2}{A_1}\cos(\delta + \Delta)\,. \tag{20}$$

We note that when counterpropagating coherent 'illumination' is supplied to the rear side of the layer, the transmitted signal turns out to be amplified not only due to the addition of the reflected signal of the second wave. At a certain difference in the initial phases of two waves, the transmitted flux, i.e., the first-wave transmittance of the layer, can be increased. The reflected signal of the first wave and the transmittance of the second wave decrease correspondingly. In particular, counterpropagating coherent illumination with the amplitude $A_2 = A_1(R/T)^{1/2}$ turned on under the condition $\delta = \pi + \Delta$ makes the reflected flux S_1 vanish. Then, the total energy leaves the layer in the direction of the flux S_2, and it might be said that the layer, as it were, becomes transparent for a wave with $j = 1$.

To refine the role of the IF in the incident-wave energy redistribution, we represent the corresponding terms in Eqn (18) as

$$S_{j\,\mathrm{int}} = f\cos\delta \pm g\sin\delta\,, \tag{21}$$

where $f = \tau I A_1 A_2 \cos\Delta$ and $g = \tau I A_1 A_2 \sin\Delta$. At $\delta = 0, \pi$, the fluxes S_j increase or decrease simultaneously as δ changes. This behavior is explained by the fact that the terms proportional to $\cos\delta$ in Eqn (21) are related to a change in the heat release in the layer (analysis demonstrates that $\cos\Delta \neq 0$ only in the presence of losses). In turn, the terms proportional to $\sin\delta$ are related to the interference energy redistribution between the fluxes S_1 and S_2 without changing their total magnitude.

To characterize the interference heat-release effect, we introduce an absorption coefficient that is defined as the ratio of the power absorbed by the layer to the total power of two incident waves,

$$\begin{gathered} Q = 1 - \frac{S_1 + S_2}{S_{01} + S_{02}} = Q_0 - Q_{\mathrm{int}}\,, \\ Q_0 = 1 - R - T\,; \quad Q_{\mathrm{int}} = \frac{2IA_1A_2}{A_1^2 + A_2^2}\cos\Delta\cos\delta\,, \end{gathered} \tag{22}$$

where Q_0 is the absorption coefficient for a single wave and Q_{int} is the additional interference component of heat release. The interference maxima and minima of heat release respectively correspond to $\delta = 0$ and π. An analysis demonstrates that if only one type of loss (electric or magnetic) is present in the layer, the minimum value of heat release is several orders of magnitude lower than Q_0; that is, virtually nondissipative energy transfer through an absorbing layer is possible. At the same time, the maximum value of Q can approach $Q = 1$ (e.g., for microwave ferrites with a high level of magnetic losses in the ferromagnetic-resonance region). The phase difference δ also substantially affects the character of the heat release distribution across the absorbing layer.

The normal incidence of microwave waves on the opposite sides of a heated sample is widely used in the technologies of heating and heat treatment of various materials [31, 32]. Interference heat-release effects are applied here to optimize the operation of microwave devices for the elimination of nonuniform heating of samples, for instance.

The interference effects considered above were comprehensively studied for transparent dielectric layers [17], thin metallic films [7–11] (including a two-layer structure consisting of an absorbing film on a transparent substrate [20]), and magnetic gyrotropic media (microwave ferrites) [13, 14, 18]. We note that the polarization of electromagnetic waves can also be controlled in this case. For example, the resulting waves with an arbitrary elliptical polarization can be produced in a ferrite layer in the microwave region by means of a specific superposition of the magnetooptical Faraday and Kerr effects [19].

5. Interference effects in a system of radiating dipoles

A source of electromagnetic waves in the presence of the electromagnetic field of another coherent source emits or absorbs additional energy. The interference effect of the sources on each other is most substantial in the case where they are located in the near-field regions of each other, where the reactive components of the electromagnetic fields of the emitted waves are predominant. Their interference results in IFs that play a key role in the source energy redistribution. In the most general formulation, the problem of the interference of the electromagnetic waves of dipole radiators was solved in [23, 25], where the radiation energy fluxes were analyzed for a system consisting of several electric or magnetic dipoles arbitrarily oriented in space.

We consider two electric dipoles that are located at a distance l from each other in a vacuum and whose dipole moments change in accordance with a harmonic law $p_j = p_{0j}\exp\left[\mathrm{i}(\omega t + \varphi_j)\right]$, $j = 1,\ 2$. Let ψ be the angle between the dipole-moment directions and γ_j be the angles the dipole-moment vectors make with the segment of the straight line connecting these dipoles (Fig. 2). In the spherical coordinates $(r_j, \theta_j, \alpha_j)$, the components of the electric and magnetic field vectors of the dipoles can be written as

$$\begin{aligned} E_{rj} &= 2p_0\cos\theta_j\left(\frac{1}{r_j^3} + \frac{\mathrm{i}k}{r_j^2}\right)\exp\left[\mathrm{i}(\omega t - kr_j)\right]\,, \\ E_{\theta j} &= p_0\sin\theta_j\left(\frac{1}{r_j^3} + \frac{\mathrm{i}k}{r_j^2} - \frac{k^2}{r_j}\right)\exp\left[\mathrm{i}(\omega t - kr_j)\right]\,, \\ H_{\alpha j} &= \mathrm{i}kp_0\sin\theta_j\left(\frac{1}{r^2} + \frac{\mathrm{i}k}{r}\right)\exp\left[\mathrm{i}(\omega t - kr_j)\right]\,, \\ E_{\alpha j} &= H_{rj} = H_{\theta j} = 0\,, \end{aligned} \tag{23}$$

where $k = \omega/c$ is the wavenumber.

The total energy flux density at an arbitrary point in space is given by (1), where $\mathbf{S}_j$ are the fluxes of single dipoles and $\mathbf{S}_{\mathrm{int}}$ is the IF of the pair of dipoles. An expression for the IF through an arbitrary closed surface σ_j inside which only the dipole with index j is present was obtained in [25]:

$$\oint \mathbf{S}_{\mathrm{int}}\,\mathrm{d}\sigma_j = F\cos\delta \pm G\sin\delta\,, \tag{24}$$

where $\delta = \varphi_2 - \varphi_1$ is the difference in the initial phases of dipole-moment oscillations. The following notation is intro-

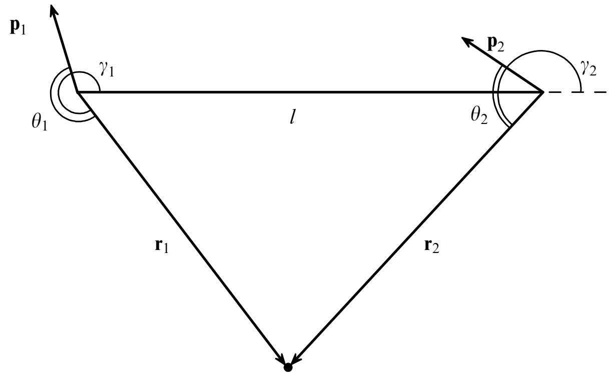

Figure 2. System of two dipole radiators arbitrarily oriented in space.

duced here:

$$F = \frac{\omega}{2l^3}\, p_1 p_2 (u \sin kl + v \cos kl)\,,$$

$$G = \frac{\omega}{2l^3}\, p_1 p_2\, (u \cos kl - v \sin kl)\,,$$

$$u = (k^2 l^2 - 1)(\cos\psi + \cos\gamma_1 \cos\gamma_2) - 2\cos\gamma_1 \cos\gamma_2\,,$$

$$v = kl\,(\cos\psi + 3\cos\gamma_1\cos\gamma_2)\,.$$

The form of Eqn (24) coincides with that of Eqns (21) for the IF of counterpropagating waves incident on a planar layered structure; moreover, analogous terms in these equations have a similar physical meaning. In Eqn (24), the first term, which is proportional to $\cos\delta$, controls the interference-induced change in the radiation power of each dipole depending on δ, and the second term, which is proportional to $\sin\delta$, controls the interference-induced power transfer from one dipole to the other. In the particular case of parallel dipoles, the second effect was studied in [1], where it was used to explain the nonradiative energy transfer from an excited to an unexcited atom.

Both terms in the expression for the IF of the system of two dipoles decrease with increasing l and are significant only for $l < \lambda$, when the dipoles are located in the near-field region of each other. The IF can substantially exceed the radiation fluxes of these dipoles [23]. If we consider a closed surface that envelopes both dipoles and is located in the far-field radiation region, the term of the flux through this surface that is proportional to $\sin\delta$ becomes zero in contrast to the other term, which controls the interference-induced change in the total power radiated by the system of dipoles. This change results from the source of energy exciting the radiators (in the case of a transmitting antenna, for example, it results from a change in the transmitter power).

The authors of [23, 24] experimentally and theoretically substantiated the possibility of electromagnetic energy transfer only with an IF. The transfer efficiency increases with decreasing the frequency, which is important for decreasing the energy losses for long-wave and very-long-wave radio communication. Electromagnetic interference converters were also proposed for the electromagnetic field of radiating waves for mode conversion [24].

The authors of [21–23] comprehensively discussed a practically important particular case of the problem under study, a dipole radiator in the field of an incident plane wave (i.e., $l \to \infty$). In this case, the incident plane wave interferes with the spherical wave radiated (or scattered) by the dipole. We now consider certain interference effects that are observed in this situation and allow increasing the electromagnetic-signal detection efficiency [23, 24].

The receiver is assumed to be a dipole antenna that actively radiates at the signal frequency. The energy flux to the dipole radiator then includes an additional IF of the total field of the incident wave and the wave radiated by the dipole. The signal power received by the antenna can increase, which is characterized by the gain

$$K = 1 + \eta \sin\delta\,, \tag{25}$$

where η is the ratio of the dipole moments of the active and passive antennas. The quantity δ is the difference in the initial oscillation phases of the dipole and external field at the dipole location. The gain K is analogous to amplification factor (20) for ICWs in a parallel-sided layer.

Moreover, as a result of interference, the effective absorption cross section of the receiving antenna exceeds its geometric cross section and is of the order of the squared wavelength of the received radiation. The interference component of the effective absorption cross section, which is equal to the ratio of the IF absorbed by the dipole to the incident wave intensity, is given by [23]

$$\sigma_{\text{int}} = \frac{kp_0}{E_0} \cos\psi \sin\delta\,, \tag{26}$$

where E_0 is the electric field amplitude of the incident wave and ψ is the angle between the $\mathbf{p}$ and $\mathbf{E}_0$ vectors. In a certain range of δ, the absorption cross section of the antenna can be negative (the dipole radiates additional energy due to interference with the external field).

If a noise electromagnetic field with a chaotically changing initial phase exists in addition to the field of the received signal, then, according to Eqn (25), the noise level of the received power is lower by a factor of K because of the absence of interference of the antenna-radiated wave with the noise field. Thus, compared to the case of a passive antenna, the signal-to-noise ratio at the input of the receiver can be substantially increased and the signal threshold sensitivity can be decreased.

6. Conclusion

The interference components of fluxes and the character of their coordinate dependences are determined by the properties of the medium, the structure of the wave field, and the phase relations between electric and magnetic field components. In the general case, an interference flux is an oscillating function of a coordinate and provides local electromagnetic field energy redistribution within a spatial oscillation period.

The interference of waves from two coherent sources results in electromagnetic-energy IFs that contain two interrelated components in the general case. One of them is proportional to the sine of the difference in the source oscillation phases and provides a spatial intensity redistribution without changing the total power radiated by the sources. In a particular case, the interference-induced change in the power can be related to a change in the ('reactive') electromagnetic energy of the wave fields stored in the medium. The other component is proportional to the cosine of the phase difference and provides an interference-induced change in the total radiation power. This change requires a corresponding change in the power of the external sources of energy or a change in the internal energy of the medium (e.g., in the Joule loss power).

Because the phenomenon of wave interference is universal, the dependences described here should manifest themselves or, at least, should have appropriate counterparts for waves of another (not electromagnetic) physical nature (acoustic and spin waves, probability density waves in quantum mechanics, waves of the Bose condensate of Cooper pairs in superconductors, etc.).

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