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PHYSICAL OPTICS

The Role Played by Evanescent Fields in the Process of Formation of Radiation of Combined Radiating Systems

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Abstract—The problem of active controlling of the structure of fields of combined radiating systems within their near zone is studied. The characteristic size of this zone is on the order of the wavelength and is characterized by the presence of evanescent (nonpropagating) fields, which are formed, among other things, due to the interference interaction of radiators of the system. Using multipole expansions for fields and special summation formulas for such expansions allows one to obtain concise expressions convenient in carrying out numerical calculations. The results of calculations confirm that the evanescent fields' structure plays a significant part in the process of the formation of the radiation field.

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Continued interest in studying various interference effects in counterpropagating fields of plane electromagnetic waves, as well as in fields generated by systems of radiators [1, 2], has been on display for a rather long time. Together with this, there are attempts being made to more carefully study the radiation physics of isolated radiators. These attempts are based on distinguishing radiating and evanescent fields with the involvement of multipole expansions of these fields in the near zone of the radiators [3, 4]. There are many reasons to believe that the structure of evanescent fields is much more complex in the so-called combined antennas [5]. Such antennas contain at least two radiating centers separated by a distance of about 0.3–0.5 of the wavelength. The proposed new constructive solutions of such antennas [6] are still based on very general physical ideas presented in [5].

In connection with this, the study of the specificity of the formation of evanescent fields, as well as the possibility of controlling energy flows of these fields in the near zone of combined antennas, is of considerable interest. The electric and magnetic dipoles are used in this work for the simplest model of radiating centers.

In the system of spherical coordinates r, θ, φ, fields of an electric dipole with moment p^e oriented along the z axis and of a magnetic dipole with moment p^m oriented along the y axis (Fig. 1) can be represented [7] by the following multipole expansions and expressions, respectively:

$$E_r^{(1)} = -\frac{p^e Z_0}{4\pi b r}\sum_{n=1}^{\infty}(2n+1)n(n+1) \times P_n(\cos\theta)\, j_n(kr_<)\, h_n^{(2)}(kr_>),$$

$$E_\theta^{(1)} = -\frac{p^e Z_0}{4\pi b r}\sum_{n=1}^{\infty}(2n+1) \times \frac{dP_n(\cos\theta)}{d\theta}\begin{cases}\dfrac{d}{dr}[r j_n(kr)]\, h_n^{(2)}(kb), & r < b,\\ j_n(kb)\dfrac{d}{dr}[r h_n^{(2)}(kr)], & r > b,\end{cases} \tag{1}$$

$$H_\varphi^{(1)} = \frac{ikp^e}{4\pi b}\sum_{n=1}^{\infty}(2n+1)\frac{dP_n(\cos\theta)}{d\theta}\, j_n(kr_<)\, h_n^{(2)}(kr_>),$$

$$H_r^{(2)} = -\frac{kp^m}{2\pi r Z_0} h_1^{(2)}(kr)\sin\theta\sin\varphi,$$

$$H_\theta^{(2)} = -\frac{kp^m}{4\pi r Z_0}\frac{d}{dr}[r h_1^{(2)}(kr)]\cos\theta\sin\varphi, \tag{2}$$

$$H_\varphi^{(2)} = -\frac{kp^m}{4\pi r Z_0}\frac{d}{dr}[r h_1^{(2)}(kr)]\cos\varphi,$$

$$E_\theta^{(2)} = \frac{ik^2 p^m}{4\pi} h_1^{(2)}(kr)\cos\varphi,$$

$$E_\varphi^{(2)} = -\frac{ik^2 p^m}{4\pi} h_1^{(2)}(kr)\cos\theta\sin\varphi,$$

where i is an imaginary unit, k is the wavenumber, Z_0 is the wave resistance of the ambient medium, $j_n(x)$, $h_n^{(2)}(x)$ are spherical Bessel and Hankel func-

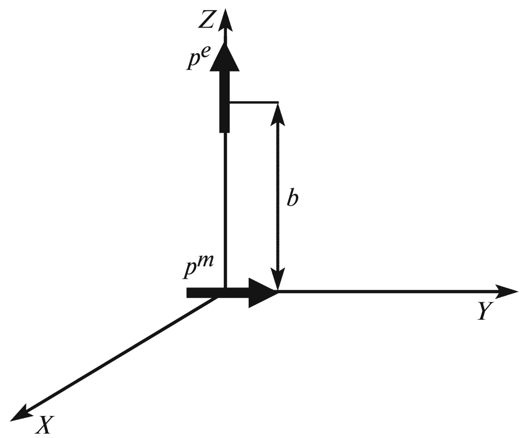

Fig. 1. Model of a combined radiating system.

tions of the second kind, $P_n(\cos\theta)$ are Legendre polynomials, and $r_>$ and $r_<$ are the largest and smallest coordinates among r and b.

In the case under consideration, components of the complex Poynting vector are represented as a sum of corresponding components of isolated dipoles and an interference component:

$$S_r = S_r^{(1)} + S_r^{(2)} + S_r^{\text{int}}, \quad S_\theta = S_\theta^{(1)} + S_\theta^{(2)} + S_\theta^{\text{int}}, \quad S_\varphi = S_\varphi^{(2)} + S_\varphi^{\text{int}}. \tag{3}$$

Here, in spite of the rather complicated form of multipole expansions (1), it turns out to be possible to represent all quantities entering in (3) in a concise form using the three special summation formulas determined in the work. In particular, especially interesting components of the interference component of the Poynting vector are determined by the following expressions:

$$S_r^{\text{int}} = i\frac{|p^e||p^m|}{32\pi^2 b}\cos\varphi \times \left\{\exp i(\varphi_e - \varphi_m)\frac{1}{r^2}\frac{d}{dr}[rh_1^{(1)}(kr)]\frac{\partial^2}{\partial r\partial\theta}\left[r\frac{e^{-ikR}}{R}\right] - \exp i(\varphi_m - \varphi_e)k^2 h_1^{(2)}(kr)\frac{\partial}{\partial\theta}\left[\frac{e^{ikR}}{R}\right]\right\}, \tag{4}$$

$$S_\theta^{\text{int}} = -i\frac{|p^e||p^m|}{32\pi^2 br^2}\exp i(\varphi_e - \varphi_m)\cos\varphi \times \frac{d}{dr}[rh_1^{(1)}(kr)]\left\{\frac{d}{dr}\left[r^2\frac{d}{dr}\left[\frac{e^{-ikR}}{R}\right]\right] + k^2r^2\frac{e^{-ikR}}{R}\right\}, \tag{5}$$

$$S_\varphi^{\text{int}} = i\frac{|p^e||p^m|}{32\pi^2 br^2}\exp i(\varphi_e - \varphi_m)\sin\varphi \times \left\{\frac{d}{dr}[rh_1^{(1)}(kr)]\cos\theta\left\{\frac{d}{dr}\left[r^2\frac{d}{dr}\left[\frac{e^{-ikR}}{R}\right]\right] + k^2r^2\frac{e^{-ikR}}{R}\right\} - 2h_1^{(1)}(kr)\sin\theta\frac{\partial^2}{\partial r\partial\theta}\left[r\frac{e^{-ikR}}{R}\right]\right\}, \tag{6}$$

$$R = \sqrt{r^2 + b^2 - 2rb\cos\theta},$$

where φ_e and φ_m are initial phases of currents in dipoles.

Figures 2a and 2b illustrate the behavior of $\text{Re}[S_r^{\text{int}}]$, $\text{Re}[S_\theta^{\text{int}}]$, and $\text{Re}[S_\varphi^{\text{int}}]$ in the field of orthogonally oriented electric and magnetic dipoles as the observation point moves away in the direction $\theta = \varphi = \pi/4$. The electric distance between the dipoles is $kb = 2$, and the absolute values of dipole moments are numerically equal. Normalization to the real part of the radial component of the Poynting vector of the isolated magnetic dipole was also carried out.

When the phase difference is zero, the behaviors of $\text{Re}[S_r^{\text{int}}]$ and $\text{Re}[S_\varphi^{\text{int}}]$ are similar. Both the components rapidly increase for $kr < 0.5$. In the interval

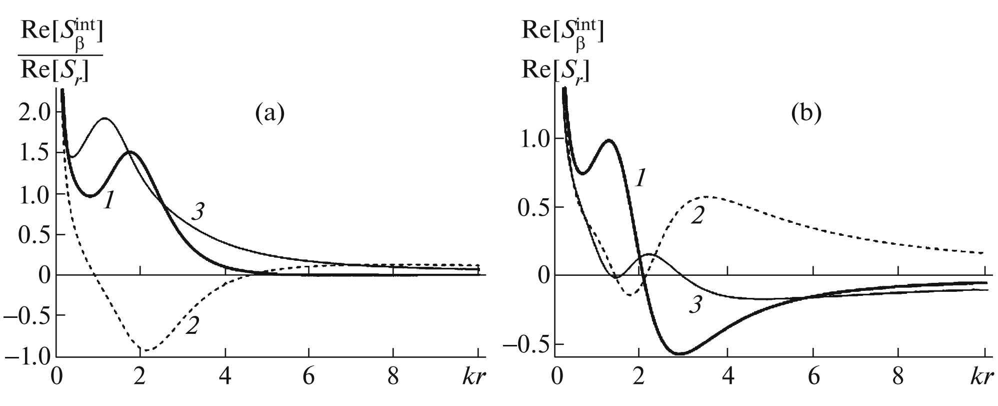

Fig. 2. Dependence of $\text{Re}[S_\beta^{\text{int}}]$ on kr at $\theta = \varphi = \pi/4$, $\beta =$ (*1*) r, (*2*) θ, and (*3*) φ; $\Delta\psi =$(a) 0 and (b) $\pi/2$.

$0.5 < kr < 2$, their behavior is of oscillating character; for $kr > 2$, it is followed by a monotone decrease. As is seen from Fig. 2a, $\mathrm{Re}[S_\theta^{\mathrm{int}}]$ is characterized by a different behavior.

When the phase difference equals $\pi/2$, the behavior of interference energy flows in the evanescent field of the system of electric and magnetic dipoles changes radically (Fig. 2b). In this case, the near-field interaction of the dipoles turns out to be minimum and the contribution of the interference component to the radiation power is maximum.

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