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Analysis of the Near Field and Radiation Field of the Dipole

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Abstract:*The electromagnetic field in the near and far zones of the oscillating atomic dipole is analyzed. It is shown that the dipole electromagnetic field has 5 components: 3 electric (~1/r, ~1/r^2, ~1/r^3) and 2 magnetic (~1/r, ~1/r^2). The article shows that at a distance λ/2π from the dipole all three components of the electric field are compared. Therefore, the line r = λ/2π should be considered as the boundary between the near and far zones. Accordingly, the region r < λ/2π is the near zone, and r > λ/2π is the far zone. A strict explanation of the difference between the concepts of "near / far zone" and "near / far field" is given. The first is geometric concepts, and the second is physical concepts. Thus, strictly speaking, the near field is the electromagnetic field in the near zone, and the far field is the electromagnetic field in the far field. But in the near zone, the far-field components proportional to 1/r are negligible, and only the near-field components are significant. At the same time, far-field components dominate in the far zone, and near-field components (~1/r^2, ~1/r^3) can be neglected. Thus, considering separately the near and far fields, their expressions can be greatly simplified. It is shown that the Poynting vector of the dipole electromagnetic field has 4 components (~1/r^2, ~1/r^3, ~1/r^4, ~1/r^5) and, with averaging over the dipole oscillation period, the Poynting vector of the reactive near field is zero, and the active radiation field is not zero. The mechanism of propagation of the radiation field wave by displacement of a crest in accordance with Maxwell's equations is described. The fundamental difference between the wave (active field with Δφ = 0) and the oscillation (the reactive field with Δφ = π/2) is shown.*
Keywords: *dipole, oscillation, near field, radiation field, Poynting vector.*

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I. Introduction

A dipole electromagnetic field is always produced in the form of a near field, after which it is transformed into a radiation field (also called a far field). The near field has unique properties[1]. Investigation of the near field and the classical radiation field is shown in a number of theoretical[2,3,4] and experimental[5,6,7] studies.

The process of converting the near field to the far field is a very subtle and not fully studied problem of electrodynamics. Because of this, researchers, as a rule, try not to go deep into the details of this problem or completely bypass it, if possible. Therefore, when reviewing the literature in many of the papers[8,9,10] that deal with the topic of converting the near field to the far field, the mechanisms of this fields transformation were not described.

In the literature, there are often confusions of near and far fields with near and far zones. Also, the definitions of near and far zones (as well as near and far fields) are very different from source to source. In this article, we will offer our definition to these concepts, which we consider to be the most correct.

II. Components of the electromagnetic field of the dipole

The electromagnetic field of a dipole in complex form can be written as follows:

$$\mathbf{E} = \left[(\hat{\mathbf{r}} \times \hat{\mathbf{p}}) \times \hat{\mathbf{r}} \frac{k^2}{r} + (3(\hat{\mathbf{p}} \cdot \hat{\mathbf{r}})\hat{\mathbf{r}} - \hat{\mathbf{p}}) \left(\frac{1}{r^3} - \frac{ik}{r^2} \right) \right] p \exp i(kr - \omega t),$$

$$\mathbf{H} = (\hat{\mathbf{r}} \times \hat{\mathbf{p}}) \left(\frac{k}{r} + \frac{i}{r^2} \right) kp \exp i(kr - \omega t),$$

where $\hat{\mathbf{r}} = \mathbf{r} / r$ is the unit vector from the dipole to the observation point, k is the wave number, p is the modulus of the electric dipole moment vector, $\hat{\mathbf{p}} = \mathbf{p} / p$ is the unit vector along the direction of the dipole moment vector, and ω is the cyclic frequency.

In real form, the electric and magnetic fields of the dipole take the following form:

$$\mathbf{E} = k^2 p(\hat{\mathbf{r}} \times \hat{\mathbf{p}}) \times \hat{\mathbf{r}} \frac{\cos(kr - \omega t)}{r} + p(3(\hat{\mathbf{p}} \cdot \hat{\mathbf{r}})\hat{\mathbf{r}} - \hat{\mathbf{p}}) \left(\frac{k \sin(kr - \omega t)}{r^2} + \frac{\cos(kr - \omega t)}{r^3} \right),$$

$$\mathbf{H} = k^2 p(\hat{\mathbf{r}} \times \hat{\mathbf{p}}) \left(\frac{\cos(kr - \omega t)}{r} - \frac{\sin(kr - \omega t)}{kr^2} \right).$$

It can be seen from the formulas that the electric field has 3 components ($\sim 1/r$, $\sim 1/r^2$, $\sim 1/r^3$), and magnetic field – 2 ($\sim 1/r$, $\sim 1/r^2$).

The directivity patterns (Fig. 1, a) and the graphs (Fig. 1, b) of the electric fields $\sim 1/r^3$, $\sim 1/r^2$ and $\sim 1/r$were constructed for optical radiation (λ = 532 nm).

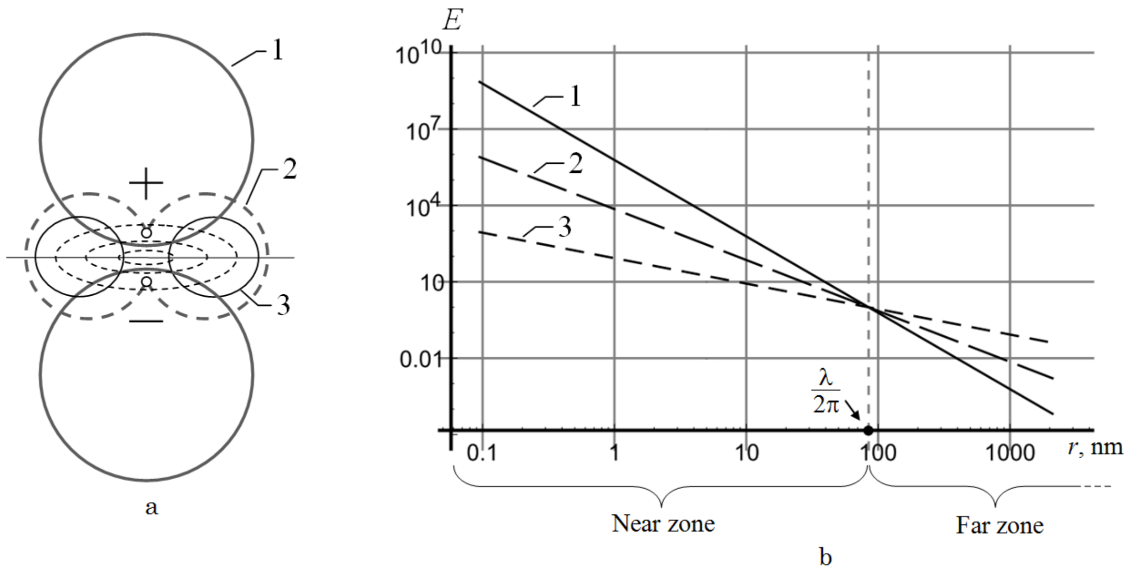

Fig. 1. Directivity diagrams (a) and corresponding graphs of the relative values of the electric field strength of optical radiation (λ = 532 nm) on the distance from the dipole (b) for three components of the electric field: $\sim 1/r^3$ (1), $\sim 1/r^2$ (2), $\sim 1/r$ (3).

Fig. 1 (b) shows that at a distance $\lambda/2\pi$ from the dipole all three components of the electric field are compared. In our opinion, it is expedient to assume that the line $r = \lambda/2\pi$ is the boundary of the near and far zones. Accordingly, the region $r < \lambda/2\pi$ is the near zone, and $r > \lambda/2\pi$ is the far zone.

Also, we should not confuse the concepts of “near zone” and “far zone” with “near field” and “far field”. The first is geometric concepts, and the second is physical concepts. Strictly speaking, the near field is the electromagnetic field in the near zone, and the far field is the electromagnetic field in the far field. But in the near zone, the far-field components, proportional to $1/r$, are negligible, and only the near-field components are significant (Fig. 1, b), therefore:

$$\mathbf{E}_{NF} = p(3(\hat{\mathbf{p}} \cdot \hat{\mathbf{r}})\hat{\mathbf{r}} - \hat{\mathbf{p}}) \left(\frac{k \sin(kr - \omega t)}{r^2} + \frac{\cos(kr - \omega t)}{r^3} \right),$$

$$\mathbf{H}_{NF} = -kp(\hat{\mathbf{r}} \times \hat{\mathbf{p}}) \frac{\sin(kr - \omega t)}{r^2}.$$

At the same time, far-field components dominate in the far zone, and the near-field components ($\sim 1/r^2$, $\sim 1/r^3$) can be neglected (Fig. 1, b):

$$\mathbf{E}_{RF} = k^2 p(\hat{\mathbf{r}} \times \hat{\mathbf{p}}) \times \hat{\mathbf{r}} \frac{\cos(kr - \omega t)}{r},$$

$$\mathbf{H}_{RF} = k^2 p(\hat{\mathbf{r}} \times \hat{\mathbf{p}}) \frac{\cos(kr - \omega t)}{r}.$$

The Poynting vector, which determines the energy flux density of the electromagnetic field, is given by the following formula:

$$\mathbf{S} = \frac{c}{4\pi} \mathbf{E} \times \mathbf{H}.$$

Before inserting expressions for the dipole fields into the formula, we first go to the spherical coordinate system (where the z axis is directed along **p**, and θ is the angle between the directions of the vectors **p** and **r**):

$$\mathbf{E} = -k^2 p \sin\theta \hat{\boldsymbol{\theta}} \frac{\cos(kr - \omega t)}{r} + p(2\cos\theta \hat{\mathbf{r}} + \sin\theta \hat{\boldsymbol{\theta}}) \left(\frac{k \sin(kr - \omega t)}{r^2} + \frac{\cos(kr - \omega t)}{r^3} \right),$$

$$\mathbf{H} = k^2 p \sin\theta \hat{\boldsymbol{\phi}} \left(\frac{\sin(kr - \omega t)}{kr^2} - \frac{\cos(kr - \omega t)}{r} \right).$$

Hence the Poynting vector takes the following form:

$$\mathbf{S} = \frac{cp^2}{4\pi} \left[\sin^2\theta \hat{\mathbf{r}} \left(\frac{k^4 \cos^2(kr - \omega t)}{r^2} - \frac{k^3 \sin 2(kr - \omega t)}{r^3} \left(1 - \frac{1}{2k^2 r^2} \right) - \frac{k^2 \cos 2(kr - \omega t)}{r^4} \right) + \right.$$

$$\left. + \sin 2\theta \hat{\boldsymbol{\theta}} \left(\frac{k^3 \sin 2(kr - \omega t)}{2r^3} \left(1 - \frac{1}{k^2 r^2} \right) + \frac{k^2 \cos 2(kr - \omega t)}{r^4} \right) \right].$$

Thus, the Poynting vector has 4 components ($\sim 1/r^2$, $\sim 1/r^3$, $\sim 1/r^4$, $\sim 1/r^5$). When averaged over time $\langle \cos 2(kr - \omega t) \rangle = \langle \sin 2(kr - \omega t) \rangle = 0$. Therefore, all the near-field components become equal to zero and the energy flux density of the reactive near field during the period is equal to zero:

$$\langle \mathbf{S}_r \rangle = 0.$$

Moreover, taking into account also that in the expression for the Poyntingvector $\langle \cos^2(kr - \omega t) \rangle = 1/2$ the time-averaged energy flux density of the active radiation field will not be equal to zero:

$$\langle \mathbf{S}_a \rangle = \frac{ck^4 p^2 \sin^2\theta}{8\pi r^2} \hat{\mathbf{r}}.$$

The ratio of the amplitudes of the components $\sim 1/r^3$, $\sim 1/r^2$ and $\sim 1/r$of the electric field in the literature is usually depicted in a linear or semilogarithmic coordinate system. In the near zone, the graphs are represented by steep hyperbolic curves, for which it is difficult to estimate the amplitude ratio. Thus, it is more convenient to consider these relations in a logarithmic coordinate system (Fig. 1, b).

III. The mechanism of propagation of the radiation field wave

We give two Maxwell's equations (Ampere's circuital law and Maxwell–Faraday equation) in differential form for vacuum:

$$\operatorname{rot} \mathbf{H} = \frac{4\pi}{c} \mathbf{j} + \frac{\varepsilon_0}{c} \frac{\partial \mathbf{E}}{\partial t}, \tag{1}$$

$$\text{rot}\,\mathbf{E} = -\frac{\mu_0}{c}\frac{\partial \mathbf{H}}{\partial t}. \tag{2}$$

To find out the mechanism is propagating an electromagnetic wave, we choose the starting point, where the values of **E** and **H** are maximum (Fig. 2). This determines the behavior of the **E** vector at the next instant of time - its modulus can only decrease.

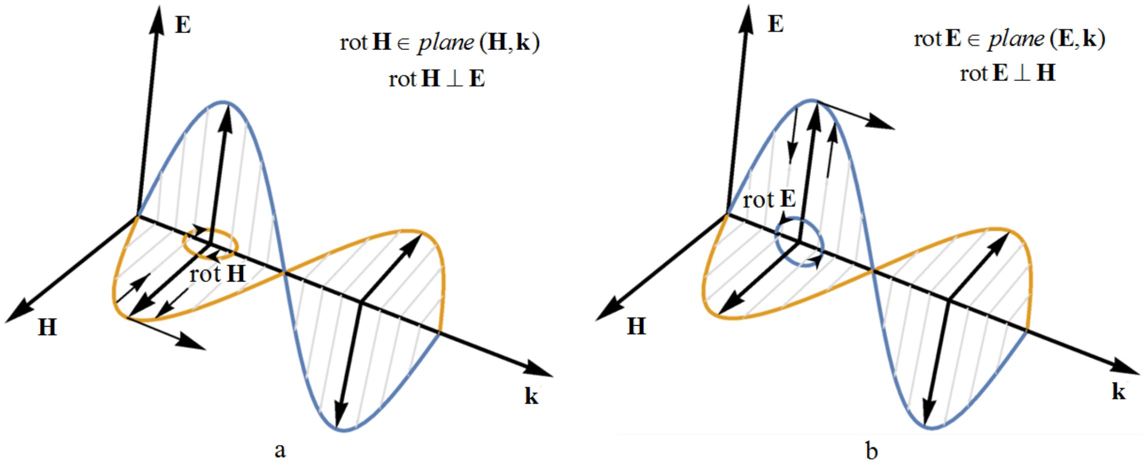

Fig. 2. Vector representation of the active electromagnetic wave of the radiation field with the image of the rot **H** (a) and the rot **E** (b). The amplitudes **E** and **H** are in phase (Δφ = 0).

A decrease in **E**, according to (1), will cause rot **H**. The vortex of the magnetic field at this point lies in the (H, k) plane (Fig. 2, a). The magnetic field of the vortex is summed with the value of **H** of the wavefront and subtracted from the backwave front. Consequently, the maximum of **H** is displaced forward (in the direction of k), and, therefore, at the initial point, **H** decreases.

In accordance with (2), a decrease in **H** at the initial point will cause in the orthogonal plane (**E**, **k**) a rot **E** (Fig. 2, b), the value of which will be added to the wavefront**E** and subtracted from the backwave front. The maximum of **E** will move forward (in the direction of **k**), and at the initial point **E** decreases. This again will cause such a rot **H**, which again will move the maximum **H** forward, and so on.

Thus, the entire wave by moving its crests will spread forward (in the direction of **k**).

The wave is not propagating oscillations, as erroneously it is sometimes said. Any electromagnetic field can be decomposed into active and reactive components. In oscillations Δφ = π/2 and therefore when the amplitude of one of the fields is maximal, the amplitude of the second is zero and vice versa. And in the waves Δφ = 0 − the amplitudes are in phase.Hence, the energies of the reactive fields are completely pumped into each other in the entire region of oscillations. This does not happen in waves in which the amplitudes **E** and **H**are never zeroed − they simply move the ridges of each other in the propagation direction (**k**).

IV. Conclusion

The dipole electromagnetic field has 5 components: 3 electric ($\sim 1/r$, $\sim 1/r^2$, $\sim 1/r^3$) and 2 magnetic ($\sim 1/r$, $\sim 1/r^2$). The article shows that at a distance λ/2π from the dipole all three components of the electric field are compared. Therefore, the line $r = \lambda/2\pi$ should be considered as the boundary between the near and far zones. Accordingly, the region $r< \lambda/2\pi$ is the near zone, and $r > \lambda/2\pi$ is the far zone.

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It is shown that the Poynting vector of the dipole electromagnetic field has 4 components ($\sim 1/r^2$, $\sim 1/r^3$, $\sim 1/r^4$, $\sim 1/r^5$) and, with averaging over the dipole oscillation period, the Poynting vector of the reactive near field is zero, and the active radiation field is not zero.

The mechanism of propagation of the radiation field wave by displacement of a crest in accordance with Maxwell's equations is described. The fundamental difference between the wave (active field with Δφ = 0) and the oscillation (the reactive field with Δφ = π/2) is shown.

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