NEAR-FIELD EFFECT IN SURFACE OPTICS

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In recent years various optical phenomena in microscopic volumes such as cavities of arbitrary shape and waveguides and phenomena taking place in the vicinity of surfaces of various media have attracted considerable attention. Consideration of these phenomena is based on the important statement that the spatial distribution of the photon field within a microscopic volume or in the vicinity of a surface can be calculated from classical electromagnetic theory. In this case Fresnel’s formulas for reflection and refraction of photons by the surface of a metal, dielectric, etc. are used in calculations of the corresponding mode functions.

We state in this article that application of the known relationships of classical optics which are correct in macroscopic volumes is not always possible in the case of microscopic volumes or in the vicinity of a surface at distances less than or comparable with the photon wavelength. We will show that at such distances a near-field effect emerges that leads to non-Fresnelian reflection and refraction laws. For definiteness, we will consider in this article the boundary problem of linear classical optics in which reflection and refraction of light take place in the near zone of the surface of a nonresonant semi-infinite dielectric. A detailed consideration of these processes will enable us to investigate the role of the near-field effect in boundary problems of quantum and nonlinear optics.

1. Continuous Medium and Mathematical Boundary. We will solve the posed boundary problem starting from the following integrodifferential equation for the strength of the effective field of the light wave $E(r, t)$ at the observation point $r$:

$$
E'(r, t) = E_i(r, t) + \int \text{rot} \text{rot} \frac{1}{R} E\left(r', t - \frac{R}{c}\right) dV',
$$

(1.1)

where $E_i(r, t)$ is the electric-field strength of the incident light wave; $N$ is the concentration of dipoles in the medium; $\alpha$ is the polarizability of atoms of the medium; $R = |r - r'|$; $r'$ is a point within the medium or on its surface; differentiation in Eq. (1.1) is carried out over coordinates of the observation point. The polarization vector $P = NaE'$ depends linearly on the effective field $E'$ within the medium. If the observation point $r$ is situated outside the medium under consideration, the integral is taken over the entire medium. If the point is situated within the medium then one should first exclude the small region occupied by an atom. We will consider this region to be a small sphere of radius $a$. Finally, when considering the continuous medium we will in the usual manner pass to the limit $a \to 0$. The concentration $N$ in Eq. (1.1) is considered to be a constant quantity at all points $r'$.

Equation (1.1) relates in a rather complicated manner the effective field with the electric field of the incident wave. In this case solving the boundary problem posed implies calculation of the field $E'(r, t)$ at various observation points $r$.

Equation (1.1) can be derived within the framework of classical electrodynamics by calculating the field of an electric dipole [1]. In [2-5] Eq. (1.1) was derived by means of a detailed investigation of the resonant interaction of two hydrogen-like atoms as a second-order quantum-electrodynamic effect. We have obtained a generalized Breit operator of the interaction energy of two atoms situated at arbitrary distances from one another. By separating the

orbital degrees of freedom of atomic electrons one can obtain within an electric-dipole approximation an explicit expression for the strength of the electric field created by one of the atoms at the location of the other atom. In doing so, we separate the Coulomb field, which is independent of the light velocity $c$, and the retarded field, which depends differently on the interatomic distance. The interaction of two atoms with consideration for emission and absorption of real photons was considered a third-order quantum-electrodynamic effect. In doing so, we obtained formulas for the polarizing fields and presented various schemes of quantum transitions for their formation. We discriminate between the electron and positron polarizing fields, which are determined by intermediate states in the spectrum of interacting atoms with positive and negative frequencies, respectively. It was shown that in optics one should, as a rule, take into account the electron polarizing field that leads to Eq. (1.1).

We will assume that the field $E_I(r, t)$ is created by an incident monochromatic wave with frequency $\omega$ and constant amplitude $E_{0l}$, i.e.,

$$E_I(r, t) = E_{0l} \exp \left\{ i \left[ k_0 (rs_I) - \omega t \right] \right\},$$  \hspace{1cm} (1.2)

where $k_0 = \omega/c$; $s_I$ is a unit vector along the propagation direction with the components (Fig. 1)

$$s_{zl} = - \sin \Theta_I, \quad s_{yl} = 0, \quad s_{zl} = - \cos \Theta_I.$$  \hspace{1cm} (1.3)

We will follow the Ewald-Oseen procedure [1] to satisfy the following conditions for the polarization vector:

$$P = (n^2 - 1) k_0^2 Q(r) e^{-i\omega t},$$  \hspace{1cm} (1.4)

$$\nabla^2 Q + n^2 k_0^2 Q = 0, \quad \text{div} Q = 0,$$  \hspace{1cm} (1.5)

where $n$ is the refractive index of the medium. Then we obtain instead of Eq. (1.1) the local and the nonlocal equations

$$\frac{4\pi}{3} N = \frac{n^2 - 1}{n^2 + 2},$$  \hspace{1cm} (1.6)

$$E_I(r) + \text{rot rot} \int_S \left[ Q \frac{\partial G}{\partial \nu} - G \frac{\partial Q}{\partial \nu} \right] dS' = 0,$$  \hspace{1cm} (1.7)

where $G(R) = \exp (ik_0 R)/R$ is Green's function, and the symbol $\partial / \partial \nu'$ denotes differentiation over the outer normal to the surface $\Sigma$. Expression (1.7) comprises the Ewald-Oseen annihilation theorem. It should be noted that Eqs. (1.6) and (1.7) were derived rigorously. It can also be shown that in a similar manner one can derive the formula in the case of the complex-valued refractive index of a resonant dielectric medium. By omitting the condition $\text{div} Q = 0$ one can investigate surface waves on the basis of Eq. (1.1). Moreover, from Eq. (1.1) one can derive the generalized Lorentz-Lorenz formula for an arbitrary dependence of the polarization vector $P$ on the field $E$ [2]. All these facts are evidence that the method of integral equations is efficient in solving boundary optical problems, with the boundary conditions being incorporated into the annihilation theorem (1.7) where the quantity $Q$ determines the character of field-matter interaction [2]. Equation (1.6) determines the constant value of the refractive index of the medium. The origin of this equation involves selection of an observation point within the medium, which is circumscribed by a sphere $\sigma$ of radius $a$. If the observation point is on the surface or in the immediate vicinity of the surface at a distance less than $a$, formula (1.6) should be modified, and in this case a dependence of the refractive index on the depth of the observation point emerges [2]. In the present article we will consider these situations in order not to confuse our results with Drude's transition layer theory [6].