# PHYSICS

Yu. N. DENISYUK

1962

SovietRxiv

Fig. 1. Scheme of formation of a wave image. $S$ –source of radiation; $O$ –object; $C$ –wave surface of the radiation incident on the object; $b_1, b_2, b_3$ –wave surfaces of the radiation reflected by the object; $d_1, d_2, d_3$ –surfaces of the antinodes of standing waves formed as a result of interference of wave $C$ with waves $b_1, b_2, b_3$.

Figure 1: Fig. 1. Scheme of formation of a wave image. $S$ –source of radiation; $O$ –object; $C$ –wave surface of the radiation incident on the object; $b_1, b_2, b_3$ –wave surfaces of the radiation reflected by the object; $d_1, d_2, d_3$ –surfaces of the antinodes of standing waves formed as a result of interference of wave $C$ with waves $b_1, b_2, b_3$.

## Abstract

## Full Text

PHYSICS

Yu. N. DENISYUK

# ON THE REFLECTION OF THE OPTICAL PROPERTIES OF AN OBJECT IN THE WAVE FIELD OF THE RADIATION SCATTERED BY IT

*(Presented by Academician V. P. Linnik, February 19, 1962)*

Below we consider a phenomenon discovered by the author, in which the reflecting properties of radiation appear with unusual completeness.

There is an arbitrary object $O$, on which radiation from a source $S$ is incident (see Fig. 1). In the case of Rayleigh scattering, the radiation reflected by the object, superposed on the radiation propagating from the source, forms a stationary pattern of standing waves. In Fig. 1, $d_1, d_2, d_3$ denote the surfaces of the antinodes of these waves. Let us further suppose that a volume $V$, filled with a photosensitive emulsion (for example, Lippmann' s emulsion), is introduced into the space surrounding the object. After the appropriate exposure and chemical processing, a photographic deposit is formed in this object, whose density models the distribution of intensity in the standing wave.

Fig. 1. Scheme of formation of a wave image.
$S$ –source of radiation; $O$ –object; $C$ –wave surface of the radiation incident on the object; $b_1, b_2, b_3$ –wave surfaces of the radiation reflected by the object; $d_1, d_2, d_3$ –surfaces of the antinodes of standing waves formed as a result of interference of wave $C$ with waves $b_1, b_2, b_3$.

Fig. 2

Figure 2: Fig. 2

It turns out that such a spatial structure is a kind of optical equivalent of the object. If radiation from the same source that illuminated the object during exposure is incident on this structure, then it reflects this radiation in such a way that the wave field of the reflected radiation is identical to the wave field of the radiation reflected by the object. The observer $h$ then records the appearance of a virtual spatial image of the object $O'$ (see Fig. 2).

The reflecting properties of the photographic model of the standing-wave pattern extend also to the spectral composition. If the radiation incident on the object when the photograph was obtained was monochromatic, and the radiation incident on the photograph during observation has a continuous spectrum, then the photograph will reflect only that monochromatic component to which it was exposed.

Let us consider in general terms one variant of the theory of this phenomenon. We shall restrict ourselves to the case where the amplitude $a_s$ of the radiation incident on the object,

does not depend on the coordinates, and write the wave functions of the incident and reflected radiation in the following form

$$\psi_s = a_s e^{ikL_s(r)}, \qquad \psi_0 = a_0(r) e^{ikL_0(r)},$$

where $k = 2\pi/\lambda$.

The wave function of the total wave field will be equal to:

$$\psi_w = \psi_s + \psi_0.$$

We find the intensity of this field by multiplying $\psi_w$ by $\psi_w^*$:

$$I_w = a_s^2 + \psi_0\psi_s^* + \psi_s\psi_0^* + a_0^2. \qquad (1)$$

**Fig. 2.** Obtaining an image by means of wave photography. $d_1, d_2, d_3$ are mirror layers formed at the place of surfaces of zero phase; $b_1', b_2', b_3'$ are the wave surfaces of the radiation reflected by the photograph.

Suppose that, under the action of the total wave field in a volume filled with a photosensitive emulsion, a substance has formed whose density $q$ is proportional to $I_w$. We shall call such a structure a wave photograph. If the photographic deposit is a nonmagnetic dielectric and if $q$ is small, then the dielectric constant of the wave photograph has the form

$$\varepsilon = \varepsilon_{f0} + \delta\varepsilon, \tag{2}$$

where

$$\delta\varepsilon = \chi I_w. \tag{3}$$

Let us consider the reconstruction process. Let the same radiation that was incident on the object during exposure be incident on the wave photograph. We shall restrict ourselves to the case of a scalar wave field, i.e., we shall assume that $\psi$ obeys the Helmholtz equation

$$\nabla^2\psi + \varepsilon k^2\psi_0 = 0. \tag{4}$$

Using the fact that $\delta\varepsilon$ is small, we determine the wave function of the radiation reflected by the photograph by solving (4) in the first approximation of perturbation theory. For this purpose, let us represent $\psi$ as the sum of the wave function of the unperturbed problem $\psi_s$, satisfying (4) for $\varepsilon = \varepsilon_{f0}$, and a certain small perturbation $\psi_f$ caused by the presence of $\delta\varepsilon$:

$$\psi = \psi_s + \psi_f. \tag{5}$$

Obviously, $\psi_f$ is the desired wave function of the radiation reflected by the wave photograph.

Substituting (5) and (2) into (4), and also using the equation of the unperturbed problem, we obtain:

$$\nabla^2\psi_f + \varepsilon_{f0}k^2\psi_f = -\delta\varepsilon k^2\psi_s. \tag{6}$$

This equation, whose right-hand side contains known quantities, is an inhomogeneous Helmholtz equation. For simplicity of exposition, let us put

$\varepsilon_{f_0} = 1$, then

$$\psi_f = \frac{1}{4\pi}\int_V \frac{\delta\varepsilon k^2\psi_s\, e^{ikr}}{r}\, dV, \tag{7}$$

where $V$ is the volume of the wave photograph. Substituting into (7) the value of $\delta\varepsilon$ from (3), into which, in turn, the value of $I_\omega$ from (1) has been substituted, and carrying out the necessary transformations, we find:

$$\psi_f = \frac{\chi k^2}{4\pi}\int_V \frac{(a_s^2 + a_0^2)\psi_s e^{ikr}}{r}\,dV + \frac{\chi k^2}{4\pi}\int_V \frac{\psi_s^2\psi_0^* e^{ikr}}{r}\,dV + \frac{\chi k^2}{4\pi}a_s^2\int_V \frac{\psi_0 e^{ikr}}{r}\,dV. \tag{8}$$

Let us analyze all the terms of this expression.

It can be shown that if the region in which the function $\psi_0$ is considered is separated from the object by a distance $R$ much greater than its linear dimensions $d$ and the radiation wavelength $\lambda$ ($R \gg d,\ R \gg \lambda$), then the gradients $a_0$ are negligibly small in comparison with the gradients of the function $\psi_0$ itself. Taking this into account, it is not difficult to see that the first term of (8) describes the interaction of the radiation with a medium having a constant refractive index. This case reduces, as is known, to reflection of radiation from the boundaries of the volume filled by such a medium.

The second integral in (8) likewise plays no essential role, since, as is not difficult to prove, its integrand oscillates and makes the integral vanish everywhere except in the region of the geometrical shadow of the object.

Let us consider the third component of the wave function of the radiation reflected by the wave photograph. It is not difficult to note that this component describes radiation emitted by sources that fill the volume and oscillate in phase with the radiation field reflected from the object. On this basis we have identified the wave function corresponding to this component with the wave function of such radiation which, having been reflected from the object, has passed through the volume of the wave photograph as through a medium with a weak negative absorption coefficient (the smallness of the negative absorption coefficient indicates that the secondary interaction of the radiation emitted by the volume $V$ with the active substance filling this volume is not taken into account in (8)).

An observer registering such radiation will see a spatial image of the object being photographed $O'$ (see Fig. 2); moreover, those details of the object whose rays pass through the volume $V$ where it has a large thickness will appear brighter than details whose rays have passed through the volume $V$ at a place where its thickness is small.

We also considered another version of the theory of wave photography, in which it is shown that, upon reflection of radiation from the surface of a standing wave recorded by a wave photograph (for example $d_2$, see Fig. 2), the boundary conditions of the radiation reflected from the object are reproduced on this surface.

By virtue of the one-to-one correspondence between the boundary conditions and the wave function, it follows that the wave function of the radiation reflected by each such surface coincides with the wave function of the radiation reflected from the object. Summing the wave functions corresponding to all the surfaces of standing waves, one can prove that, in the radiation reflected from the wave photograph, the same rays are represented as in the radiation reflected from the object, and that the amplitude of these rays is proportional to the path they have traversed in the volume $V$.

Using this method of consideration, one can also show that wave photography reproduces radiation in its spectral composition as well.

In order to give a unified explanation of the simultaneous reproduction by wave photography of such a broad range of optical properties of an object, we introduced the concept of an "optical scattering operator," by which is meant a certain idealized scattering structure,

acting on the given radiation in the same way as the real object. Wave photography may be regarded as a model of such an operator.

To confirm the propositions of the theory, an experiment was carried out, the general arrangement of which corresponded to the scheme shown in Figs. 1 and 2. The radiation incident on the object in this case had a wavelength of 5460 Å. The pattern of standing waves was recorded by means of Lippmann photographic plates. Spherical mirrors of various radii of curvature and the scale of an object micrometer were used as objects. The wave photographs of the mirrors were similar in their properties to concave diffraction gratings and, with respect to radiation of $\lambda = 5460$ Å, exhibited the same optical power as the original mirror. The radiation reflected by the wave photograph of the object-micrometer scale, in accordance with the theory, formed a spatial image of this scale located outside the emulsion layer.

This phenomenon generalizes the range of phenomena underlying Lippmann color photography ([1]) and Gabor' s hologram method ([2]). It may prove useful for the development of imaging techniques that create a complete illusion of the reality of the objects depicted, in structural analysis (electron-structure analysis, X-ray-structure analysis, etc.), hydrolocation, radiolocation, ultrasonic defectoscopy, and also for the fabrication of dispersing elements of the diffraction-grating type.

Received
4 II 1962

## CITED LITERATURE

[1] G. Lippmann, J. de Phys., **3**, 97 (1894).
[2] D. Gabor, Proc. Roy. Soc. London, A **197**, 454 (1949).

*Note: Figure translations are in progress. See original paper for figures.*

*Source: Math-Net.Ru and CyberLeninka. Machine translation. Verify with the original.*