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PHYSICS

PHOTOGRAPHIC RECONSTRUCTION OF THE OPTICAL PROPERTIES OF AN OBJECT IN ITS OWN SCATTERED RADIATION FIELD

Yu. N. Denisyuk

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To Mr Wally Edwards with the best wishes 4.08.81.

The following discussion pertains to a phenomenon discovered by the author, wherein the reflecting properties of an object are manifested with extraordinary fidelity.

We have an arbitrary object O, on which radiation from a source S is allowed to fall (see Fig. 1). In the case of Rayleigh scattering the radiation reflected by the object will combine with the radiation emanating from the source, thereby forming a stationary standing wave pattern. In Fig. 1 the loci d_1, d_2, d_3 respresent the antinodal surfaces of these waves. We assume, further, that in the space surrounding the object there is a definite volume V filled with a photosensitive emulsion (such as a Lippman emulsion). After an appropriate exposure and chemical processing, a photographic deposit will be formed in the volume, its density exactly simulating the intensity pattern in the standing wave.

It turns out that such a spatial structure is a unique kind of optical equivalent of the object. If radiation from the same source that illuminated the object during exposure is allowed to impinge on this structure, it will reflect this radiation in such fashion that the wave field of the reflected radiation will be identical to the wave field of the radiation reflected by the object. The observer $\underline{h}$ in this case will detect 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 even into the spectral composition. If the radiation incident on the object in producing the photograph is monochromatic, while the radiation incident on the photographic reconstruction during observation has a continuous spectrum, the photograph will reflect only the monochromatic component to which it was originally exposed.

Let us examine in general terms one version of the theory of this phenomenon. We will confine our discussion to the case when the amplitude a_s of the radiation incident on the object does not depend on the coordinate, and we will write the wave functions for the incident and reflected radiations as follows:

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

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

The wave function for the total field will be equal to

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

We find the intensity of this field by multiplying ψ_w by ψ_w^*:

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

We are assuming that the total wave field in the volume filled with the photosensitive emulsion acted to form a substance whose density $\underline{q}$ is proportional to I_w. We will call this structure the wave photograph. If the photographic deposit is a nonmagnetic dielectric and if $\underline{q}$ is small, then the dielectric constant of the wave photograph will have the form

$$\varepsilon = \varepsilon_{f0} + \delta\varepsilon, \quad (2)$$

where

$$\delta\varepsilon = \varkappa I_w. \quad (3)$$

Consider the image formation process. Let the same radiation that was incident on the object during the photographic reconstruction now impinge on the

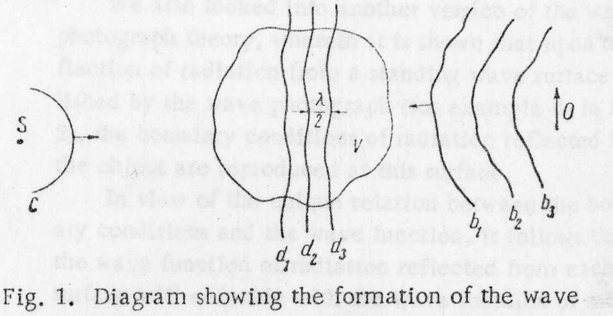

Fig. 1. Diagram showing the formation of the wave image. S is the radiation source, O the object, C the wave surface of the incident radiation; b_1, b_2, b_3 are the wave surfaces of the radiation reflected by the object; d_1, d_2, d_3 are the antinodal surfaces of the standing waves formed as the result of interference between the wave C and the waves b_1, b_2, b_3.

wave photograph. We will consider only the case of a scalar wave field, i.e., one in which ψ obeys the Helmholtz equation

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

We now make use of the fact that $\delta\varepsilon$ is small in order to determine the wave function of the radiation reflected by the photograph, solving (4) in the first approximation of perturbation theory. For this purpose we write ψ as the sum of the unperturbed function ψ_s, which satisfies Eq. (4) for $\varepsilon = \varepsilon_{f_0}$, and some small perturbation ψ_f evoked by the presence of $\delta\varepsilon$:

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

It is obvious that ψ_f is the sought-after wave function of the radiation reflected by the wave photograph.

Substituting (5) and (2) into (4) and invoking the equation for 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, the right-hand side of which contains the known quantities, is the inhomogeneous Helmholtz equation. For simplicity we will let $\varepsilon_{f_0} = 1$, whereupon

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

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

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

We analyze all the components of this expression below.

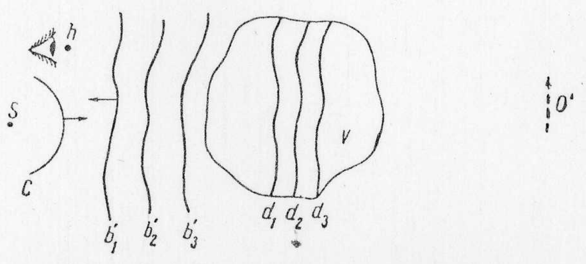

Fig. 2. Production of an image from the wave photograph. d_1, d_2, d_3 are the reflecting "mirror" layers formed at the site of the antinodal surfaces: b_1', b_2', b_3' are the wave surfaces of radiation reflected from the photograph.

It can be shown that if the region in which the function ψ_0 is considered is separated from the object by a distance R which is much greater than the linear dimensions of the object $\underline{d}$ or the radiation wavelength λ ($R \gg d$, $R \gg \lambda$), the gradients a_0 will be negligibly small in comparison with the gradients of the function ψ_0. With this in mind, it is quickly understood that the first term in (8) describes the interaction of the radiation with a medium that has a constant index of refraction. This case reduces of course to the reflection from the boundary of the volume filled by such a medium.

The second integral of Eq. (8) is also not important, for, as is readily demonstrated, its integrand oscillates and the integral goes to zero everywhere except in the region of the geometric shadow of the object.

Notice the third component of the wave function of the radiation reflected by the wave photograph. It is seen without great difficulty that this component describes radiation issuing from sources which fill the volume and fluctuate in phase with the radiation field reflected from the object. On this basis we identified the wave function corresponding to this component with the wave function of the radiation that, after reflection from the object, passed through the volume of the wave photograph as through a medium with a slight negative index of refraction [the smallness of the negative index of refraction is implied by the fact that the secondary interaction of the radiation emitted by the volume V with the active substance contained in this volume is not included in Eq. (8)].

An observer registering this radiation will see a spatial image of the object of the photograph O' (see Fig. 2), where those details of the object from which the issuing rays traverse a greater thickness of the volume V will show up more clearly than those details whose issuing rays pass through the volume V where the thickness is less.

We also looked into another version of the wave photograph theory, wherein it is shown that upon reflection of radiation from a standing wave surface established by the wave photograph (for example d_2 in Fig. 2), the boundary conditions of radiation reflected from the object are reproduced at this surface.

In view of the unique relation between the boundary conditions and the wave function, it follows that the wave function of radiation reflected from each such surface will coincide with the wave function of radiation reflected from the object. Summing the wave functions corresponding to all the standing wave surfaces, it can be shown that in the radiation reflected from the wave photograph the same rays will be present as in the radiation reflected from the object and that the amplitude of these rays will be proportional to the paths which they covered in the volume V.

Following the same line of reasoning, it can also be shown that the wave photograph will imitate the radiation even in spectral composition. In order to give a unified explanation for the wave photograph simultaneously reproducing such a wide range of the optical properties of the object, we introduced the concept of the "optical scattering operator," which is interpreted as a certain idealized scattering structure acting on the given radiation in the same manner as the real object. The wave photograph may be regarded as the model of such an operator.

In order to lend support to the postulates of the theory, we set up an experiment, the general layout of which corresponded to the diagram of Figs. 1 and 2. The incident radiation on the object in this case had a wavelength of 5460 A. The standing wave pattern was recorded by means of Lippman photosensitive plates. For the objects we used spherical mirrors of various radii of curvature and the scale of an object-micrometer. The wave photographs of the mirrors were similar in their attributes to concave diffraction gratings and exhibited the same optical strength for $\lambda = 5460$ A 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 outside the emulsion layer.

The phenomenon discussed represents a generalization of the group of phenomena which form the basis of the Lippman color photographic process [1] and the hologram method of Gabor [2]. It can be used to advantage for the development of optical imagery techniques, creating a complete illusion of reality in the reproduction of objects, as well as in structural analysis (electron structural analysis, x-ray structural analysis, etc.), sonar, radar, ultrasonic flaw detection, and in the preparation of dispersing elements of the diffraction grating type.

LITERATURE CITED

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