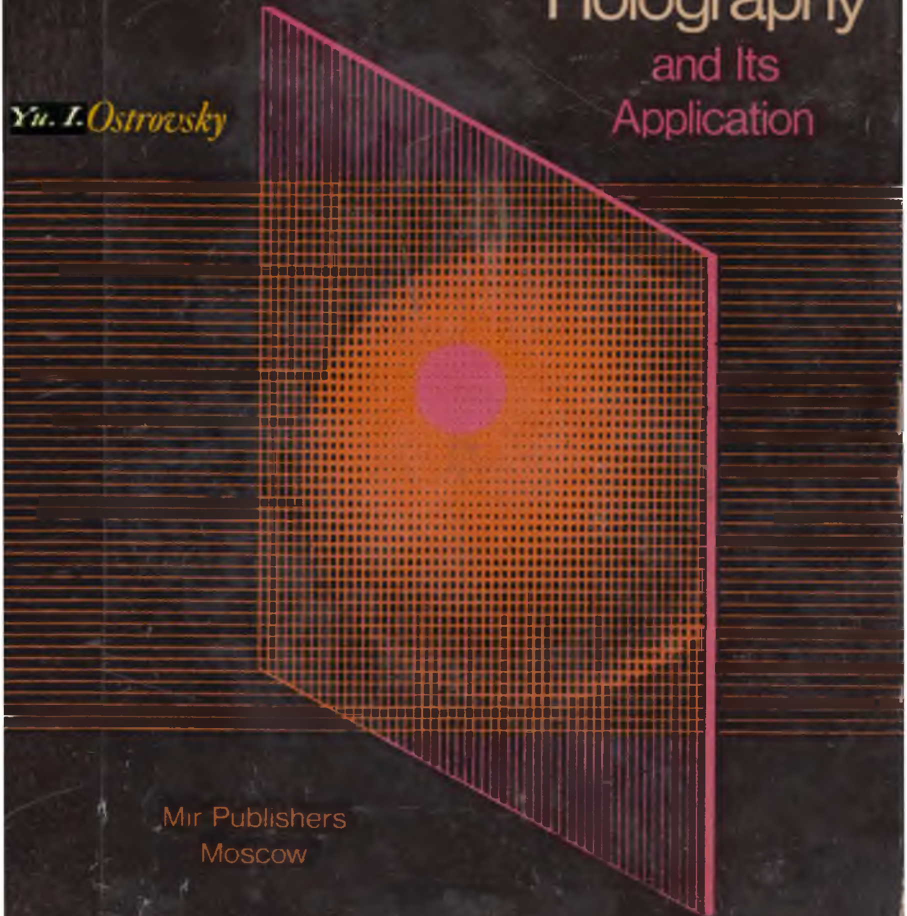
Yu. I. Ostrovsky

Holography and Its Application



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Contents

Chapter 1

A Hologram and Its Properties

1.1. The Physical Principles of Holography

Holography is a way of recording and then reconstructing waves invented by Dennis Gabor in 1948 [1-3]. The waves may be of any kind—light, sound, x-ray, corpuscular waves, etc.

The word "holography" originates from the Greek "holos" meaning "the whole". By using this word, the inventor of holography wanted to stress that it records complete information about a wave—both about its amplitude and its phase.

In conventional photography, only the distribution of the amplitude (more exactly, of its square) is recorded in a two-dimensional projection of an object onto the plane of the photograph. For this reason, when examining a photograph from various directions, we do not obtain new angles of approach, and we cannot see, for instance, what is happening behind objects in the foreground.

A hologram, on the contrary, regenerates not a two-dimensional image of an object, but the field of the wave which it scatters. By changing our point of observation within the confines of this wave field, we see the object from different angles, sensing its three-dimensional and realistic nature.

The physical foundation of holography is the science of waves, their interference and diffraction, the first steps in which date back to the 17th century—the time

Professor
Dennis Gabor, the inventor of holography, 1971 Nobel Prize winner

of C. Huygens. Already at the beginning of the 19th century, T. Young, O. Fresnel and J. von Fraunhofer had sufficient knowledge to formulate the fundamental principles of holography. This did not occur, however, up to the work of Gabor, although many scientists in the second half of the 19th and the beginning of the 20th century—G. Kirchhoff, Rayleigh

Emmet N. Leith (left) and Juris Upatnieks

(J. Strutt), E. Abbe, G. Lippmann, M. Wolfke, H. Boersch and W. L. Bragg —were very near to the principles of holography. The excuse arising in one's mind is that they did not have the technical means needed for the practical realization of holography. But this is not correct. D. Gabor, the inventor of holography, in 1947 also did not yet have a laser and ran his first experiments with a mercury-arc lamp as the source of light. And he was nevertheless able to formulate the idea of reconstructing a wavefront and indicate how to carry it out with complete definiteness. However, the difficulties connected with the preparation of holograms remained so appreciable, and holography developed so slowly that by 1963 Gabor himself "almost forgot about it" [4].

In 1963 E. Leith and J. Upatnieks prepared laser holograms for the first time [5]. A year before this they proposed their *split-beam* (also called *two-beam* or *off-axis*) method [6], which considerably improved Gabor's original arrangement. A very important stage in the development of holography was formed by the works of Yu. Denisyuk, who in 1962

Yuri N. Denisyuk

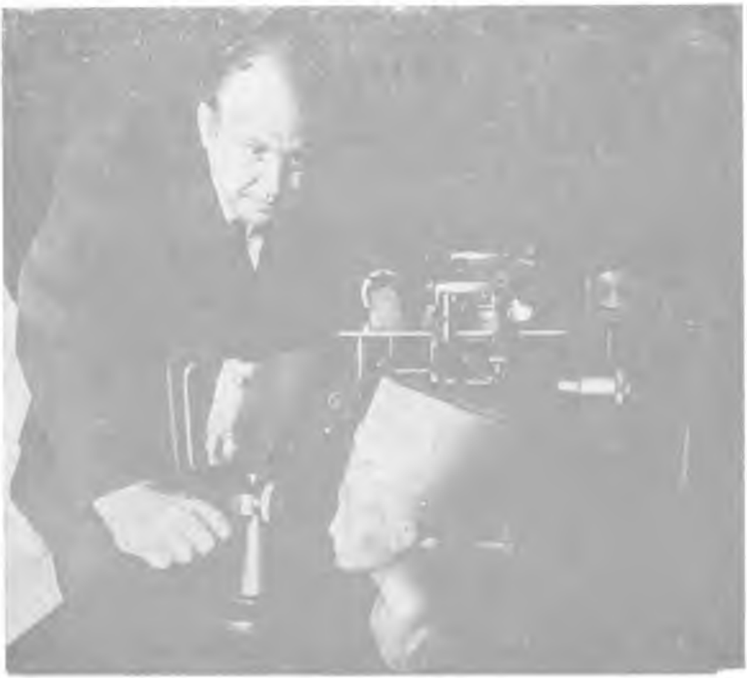
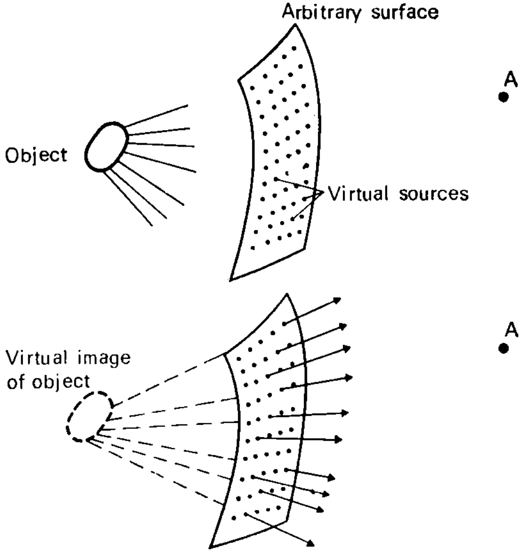


Fig. 1.
The Huygens-Fresnel principle



proposed to record holograms in three-dimensional media [7-9].

From this time, holography began to develop at a very rapid rate, and at present up to 1000 publications devoted to it appear every year.

In accordance with the Huygens-Fresnel principle, the action of an initial primary wave at arbitrary point A can be replaced with the action of virtual sources located on a sufficiently great surface at a considerable distance from point A. These sources should oscillate with the amplitude and the phase which were set by a primary wave reaching them and scattered by an object (Fig. 1). We can forget about the primary wave after a proper selection of these sources. The elementary spherical waves emitted by the secondary sources as a result of interference restore a copy of the primary wave field beyond the surface. The eye or any other receiver will not be able to distinguish this copy from the field of the wave scattered by the object itself, and the observer will thus see the virtual image of this object, even though the latter was removed a long time ago.

If we imagine a screen coated with a light-sensitive layer that reacts with its transparency to the amplitude of the primary wave and with its thickness or refractive index to the phase, then after removing the primary wave and illuminating such an amplitude and phase screen by means of a monochromatic source of light, we would reconstruct the original wave field.

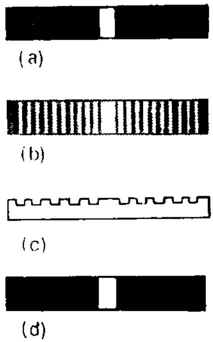


Fig. 2. Michelson's experiment

Such an experiment was conducted at the beginning of the present century by A. Michelson [10]. Its results are shown in Fig. 2. Michelson took a slit illuminated by monochromatic light as the source (Fig. 2*a*). In the far-field (Fraunhofer) band it gives a diffraction pattern of amplitude distribution described by a function of the kind $(\sin x)/x$ (Fig. 2*b*). Upon passing through zero, the phase of the wave changes by π. With this in view, Michelson made a phase plate by etching depressions of the corresponding width and depth on glass (Fig. 2*c*). Next, by placing the positive of the diffraction pattern with the distribution of the amplitude transmission of the kind shown in Fig. 2*b* combined with the phase plate in the path of the light beam, Michelson obtained a reconstructed initial image of the slot in the far-field band (Fig. 2*d*). This can be called the first experiment for recording and reproducing a light wave directly based on the Huygens-Fresnel principle.

It should be borne in mind, however, that Michelson did the right thing when he chose such a simple initial wave, i.e. a wave for which the amplitude and phase distribution is well known. The matter is that he had no phase-sensitive material and was not able to record the phase. He was forced to *draw* the phase plate, using a well-known theoretical distribution.

The question arises whether this circumstance is a technical difficulty or one of principle. Will not progress in engineering make it possible to create phase-sensitive surfaces that will be able to solve the problem in this way? The answer to this question is negative. A light-sensitive material in principle cannot by itself react to the phase of an incident wave. The phase can be "felt" only by such a medium in which an oscillating process of the same frequency as the wave being recorded, but with a known phase distribution, proceeds independently of it.

Such a "timed" photographic emulsion will be able to compare the phase of a wave being recorded at each point with that of the "internal standard" or "reference". For this purpose, it is necessary to record the distribution of the intensity in space during a time of the order of 10^{-16} second (during a fraction of the period of the light oscillations). Such a short exposure, however, is impossible not only technically, but also in principle, since in accordance with the uncertainty relation, the frequency interval occupied by a light pulse of such a short duration is tremendous, and the space and time periodicity of the light oscillations is lost.

The "instantaneous" recording of the distribution of the intensity of a wave field in space is possible with the radio and acoustic wave ranges, where the period of the oscillations is considerably greater. A different path remains for optics (which was followed by Gabor)—the sending of another, so-called *reference wave* with a known phase distribution into the recording plane. If this wave is coherent with that being recorded, an interference pattern may be formed whose contrast is determined by the distribution of the intensity of the wave being recorded, whereas the frequency and shape of the fringe are determined by the phase relief. In this way not only the amplitude, but also the phase of a light wave is recorded on a photographic plate or film—a hologram.

The reference beam can be said to "freeze" a light wave in space. The waves surrounding an object can now be recorded as long as desired, since the distribution of the intensity in space is stable in this case.

This method of recording is especially valuable because it makes a surprisingly simple reproduction of the original wave possible. It is sufficient to direct the wave which served as the reference one in recording at the structure formed to reconstruct the original wave field in the space beyond the hologram.

Interference of Light. Thus, a hologram is an interference pattern formed by a wave from an object and a reference wave. For this reason, it seems quite appropriate to give brief elementary information on the interference of light before proceeding to describe the basic properties of holograms. (For greater details on interference see [11]-[13].)

We shall first consider a very simple case—the field of interaction of light waves emerging from two point monochromatic sources O_1 and O_2 in an isotropic medium (Fig. 3). Assume that these waves are polarized in one plane (the electrical vector is perpendicular to the plane of the drawing) and have the same frequency ν and circular frequency $\omega = 2\pi\nu$. Consequently, the light oscillations at an arbitrary point M will be given by the equations

$$\left.\begin{aligned} x_1 &= A_1 \cos(\omega t + \varphi_1) \\ x_2 &= A_2 \cos(\omega t + \varphi_2) \end{aligned}\right\} \qquad (1)$$

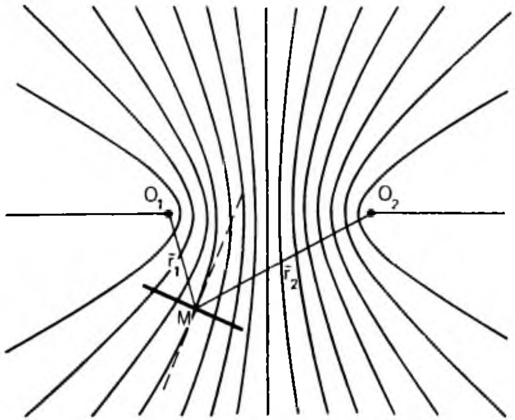


Fig. 3. Standing light waves formed in the space surrounding two point coherent sources O_1 and O_2

where A_1 = amplitude of the wave reaching point M from O_1
$\varphi_1 = \varphi_{01} - 2\pi r_1/\lambda$; here φ_{01} is the initial phase of the wave emitted by source O_1, $2\pi r_1/\lambda$ is the lag of this wave in phase along the path from source O_1 to point M, and λ is the wavelength. Similar symbols are used for the second wave (with the subscript "2").

The resultant oscillation at point M can be found by the summation of x_1 and x_2:

$$x = A_1 \cos(\omega t + \varphi_1) + A_2 \cos(\omega t + \varphi_2) = A \cos(\omega t + \varphi) \quad (2)$$

where

$$A^2 = A_1^2 + A_2^2 + 2A_1A_2 \cos(\varphi_1 - \varphi_2) \qquad (2a)$$

$$\varphi = \arctan \frac{A_1 \sin \varphi_1 + A_2 \sin \varphi_2}{A_1 \cos \varphi_1 + A_2 \cos \varphi_2} \qquad (2b)$$

Any receiver of light has inertia and can record the intensity during a time that is considerably greater than the period of the light oscillations. This is why the mean value of the intensity for a multitude of periods is always recorded. If sources O_1 and O_2 are absolutely independent, and the receiver has a high inertia, the mean value of $\cos(\varphi_1 - \varphi_2)$ during the time of recording will equal zero, and from Eq. (2a) we have

$$A^2 = A_1^2 + A_2^2 \qquad (3)$$

In this case the waves are said to be *incoherent*.

Equation (3) shows that for incoherent waves the illuminances they create are summated. We observe this every time we light a room using two or more electric lamps.

If the value of $\varphi_{01} - \varphi_{02}$ does not change with time, the waves are *coherent*. In this case, in accordance with Eq. (2a), we summate not the illuminances, but the amplitudes of the light oscillations, with account taken of the phase relation between them. When waves meet in the same phase, i.e.

$$\varphi_1 - \varphi_2 = 0, \pm 2\pi, \pm 4\pi, \ldots, \pm 2k\pi, \ldots \qquad (4)$$

where k is any integer, their amplitudes are summated, namely,

$$A = A_1 + A_2$$

When waves meet in antiphase, i.e.

$$\varphi_1 - \varphi_2 = \pm\pi, \ \pm 3\pi, \ \pm 5\pi, \ \ldots \\ \ldots, \pm (2k + 1)\pi, \ \ldots \quad (5)$$

their amplitudes are subtracted, namely,

$$A = A_1 - A_2$$

A system of stationary (standing) waves is formed in space. The maxima (antinodes) correspond to condition (4), and the minima (nodes) to condition (5).

What is the shape of the antinode and node surfaces? It is not difficult to see that when $\varphi_{01} = \varphi_{02} = 0$, condition (4) for the surfaces of antinodes can be rewritten in the form

$$r_1 - r_2 = \pm k\lambda \quad (6)$$

Equation (6) is an equation of a system of hyperboloids of revolution with the axis of rotation O_1O_2.

It is simple to calculate the total number of antinode hyperboloids N_{an}, bearing in mind that $r_1 - r_2$ does not exceed the distance a between sources O_1 and O_2. Therefore $k_{max} = a/\lambda$ and $N_{an} = 2\frac{a}{\lambda} + 1$. Similarly, the equation of the family of hyperboloids for the node surfaces is

$$r_1 - r_2 = \frac{\pm (2k+1)}{2} \lambda \quad (7)$$

and the total number of hyperboloid node surfaces $N_n = 2\frac{a}{\lambda}$. The planes tangent to the surfaces of the nodes and antinodes at each point of space divide the angle 2α between the vectors r_1 and r_2 in half, i.e. they contain the bisector of this angle. The distances between adjacent hyperboloids will be the smallest along the line joining O_1 and O_2. Here the surfaces of the antinodes are equidistant, and the distances d between them, as follows from Eq. (6), are

$$d = \frac{\lambda}{2} \tag{8}$$

The corresponding spatial frequency of the pattern will be

$$\nu = \frac{1}{d} = \frac{2}{\lambda} \tag{9}$$

In the general case

$$d = \frac{\lambda}{2 \sin \alpha} \tag{10}$$

and

$$\nu = \frac{2 \sin \alpha}{\lambda} \tag{11}$$

It is quite obvious that for the case realized along segment O_1O_2 $\left(\alpha = \frac{\pi}{2}\right)$, Eqs. (10) and (11) transform into (8) and (9).

Equations (10) and (11), determining the spatial frequency of the interference pattern, thus set the required spatial resolution of the receiver recording its structure or, conversely, at a given spatial resolution of the receiver determine the region of the interference field (Fig. 3) where its pattern can be resolved.

The contrast of the pattern will be determined by the amplitudes of the interfering waves:

$$K = \frac{E_{max} - E_{min}}{E_{max} + E_{min}} = \frac{(A_1 + A_2)^2 - (A_1 - A_2)^2}{(A_1 + A_2)^2 + (A_1 - A_2)^2} \quad (12)$$

Hence, after simple algebraic transformations, we have

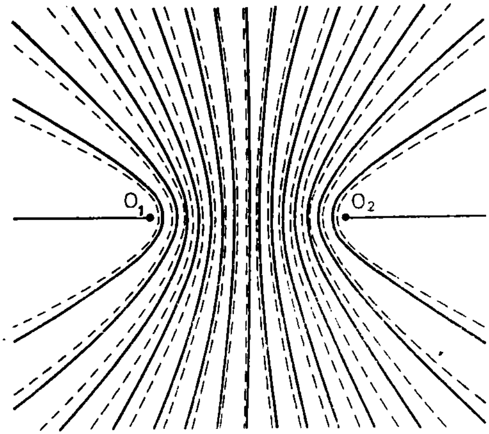
$$K = \frac{2\sqrt{p}}{1+p} \quad (13)$$

where $p = A_1^2/A_2^2$ is the ratio of the intensities of the interfering waves. It is not difficult to see that the contrast of a pattern is maximum and equals unity when $p = 1$, i.e. when the intensities of the interfering beams are equal.

Thus, for the ideal case shown in Fig. 3, certain requirements have to be met only by the spatial resolving power of the receiver when recording interference. Besides this, the power of the sources and the sensitivity of the receiver should be adequate for recording the difference between signals corresponding to the contrast of the interference pattern at a given point of the field.

It should be noted that our simplified treatment does not take into consideration the vector nature of electromagnetic

Fig. 4.
Sources emitting light at two frequencies



oscillations. Such a treatment, strictly speaking, holds only for the plane of the drawing in Fig. 3, where the directions of the electrical vectors of both waves coincide. A stricter vector consideration will not change the configuration of the interference maxima and minima, but will change the spatial distribution of the pattern contrast. In particular, the contrast of the pattern will become equal to zero where the electrical vectors are mutually perpendicular.

Let us now consider the case of non-ideal sources, O_1 and O_2. Assume that each of them emits the same quantity of light at two frequencies ν' and ν'' (the respective wavelengths are λ' and λ''). We shall meanwhile retain the other restrictions: the sources are point ones as previously, and emit light with a constant phase difference equal to zero at each of the frequencies.

It is evident that two systems of stationary hyperboloids, one corresponding to λ' and the other to λ'', will now be observed in the space surrounding O_1 and O_2 (Fig. 4). The position of only one of these surfaces of antinodes, however, will coincide for both wavelengths, namely, the one corresponding to $k = 0$. The remaining surfaces will be displaced relative to one another to an extent that grows with increasing values of k and $\Delta\lambda = \lambda' - \lambda''$ (Fig. 4). Consequently, when k grows, the contrast of the fringes observed diminishes and reaches zero when the surface of the antinodes for one wavelength coincides with the surface of the nodes for the other one. Equations (6) and (7) give for this condition

$$k\lambda' = \frac{2k+1}{2}\lambda''$$

whence

$$k = \frac{1}{2}\frac{\lambda''}{\lambda' - \lambda''} \approx \frac{1}{2}\frac{\lambda}{\Delta\lambda} \tag{14}$$

With a further growth in the difference of the path lengths, an interference pattern will once more appear, reach the maximum contrast at $k = \lambda/\Delta\lambda$, again vanish at $k = \frac{3}{2}\frac{\lambda}{\Delta\lambda}$, etc.

Condition (14) is the determining one when calculating the required monochromaticity of a light source, the maximum difference in path lengths permitted when installing a given source, and also when choosing the spectral resolution of the receiver needed for recording the interference pattern.

If we assume that the sources of light O_1 and O_2 emit a continuous spectrum of constant brightness within the interval from λ' to λ'', then the pattern of the interference field will vanish when the surfaces of the antinodes formed by the monochromatic components into which the interval from λ' to λ'' can be divided completely fill all the spaces between the surfaces of the antinodes formed by λ'. For this to occur, it is essential that the condition

$$k\lambda' = (k+1)\lambda''$$

be obeyed, whence

$$k = \frac{\lambda}{\Delta\lambda} \tag{15}$$

It is simple to find the difference in path length $r_1 - r_2$ at which the interference pattern vanishes with the aid of Eqs. (6) and (15):

$$r_1 - r_2 = \frac{\lambda^2}{\Delta\lambda} \tag{16}$$

This quantity is usually called the *coherence length* of a source.

In principle, it is no difference for observing an interference pattern whether the sources emit narrow spectral lines with a width of $\Delta\lambda$ or they emit a broad spectrum, while recording is performed with a narrow-band receiver separating the same spectral interval $\Delta\lambda$. Consequently, Eq. (16) also determines the spectral resolution of the receiver needed to record the interference field pattern,

$$R = \frac{\lambda}{\Delta\lambda} = \frac{r_1 - r_2}{\lambda} \tag{17}$$

Now assume that the point sources O_1 and O_2 emit ideal monochromatic lines of close but different frequencies—ν_1 and ν_2 (the corresponding wavelengths are λ_1 and λ_2). In this case we arrive at summation of oscillations with close frequencies, and beating is obviously observed with the frequency difference

$$\Delta\nu = \nu_1 - \nu_2 \tag{18}$$

The planes tangent to the surfaces of the nodes and antinodes will now no longer be directed along the bisector of the angle between the vectors r_1 and r_2, but will be displaced from this position by an angle that grows with increasing Δr.

The interference pattern will travel in space, covering a path equal to the distance between adjacent antinodes in the time

$$\tau = \frac{1}{\Delta\nu} \tag{19}$$

The allowable exposure in recording the pattern of an interference field should not exceed at least one-fourth of this interval. At

$$\tau = \frac{1}{4}\,\frac{1}{\Delta\nu} \tag{20}$$

the phase difference will change by $\pi/2$ during the time of recording. Although this considerably diminishes the contrast of the pattern being recorded, it does not make it indistinguishable.

Condition (20) determines the time resolving power of a receiver needed for recording the pattern of the interference field formed by sources having different frequencies. Such a case occurs, for example, upon motion of the reflecting mirror in one of the arms of a Michelson interferometer, upon the vibration or deformation of separate parts of a holographic installation, or upon holographing moving objects. The frequency of one of the interfering waves is displaced owing to the Doppler effect, and we observe the motion of the interference fringes with a velocity corresponding to Eq. (19). It should be noted, however, that the same phenomenon is explained just as convincingly by the continuous change in the difference in path length and the transition from maxima to minima in accordance with Eqs. (6) and (7).

We shall now pass over to considering the pattern of an interference field formed by extended sources. Assume that each of the point sources O_1 and O_2 consists of two independent monochromatic emitters O_1', O_1'' and O_2', O_2'' having the same power and frequency. Let the light oscillations in the pairs O_1' and O_2', and O_1'' and O_2'' be correlated in phase as previously and take place in the same plane.

As long as sources O_1 and O_2 remain point ones as previously, our assumption does not change the pattern of the resulting interference field. Both pairs of coherent sources O'_1, O'_2 and O''_1, O''_2 form completely coinciding hyperboloid patterns of the nodes and antinodes, which after summation with respect to intensity create the same pattern as up to the division of each source. Such division can be continued, and each of the point sources divided into any number of mutually incoherent sources of light, retaining here the mutual coherence of the respective pairs of elementary emitters in each of the sources.

The interference pattern formed with the aid of conventional sources of light in schemes with Fresnel mirrors, a Fresnel biprism or a Lloyd mirror is an example of exactly such a case of the interference of the light emitted by two point sources, each of which consists of an enormous number of independent emitters. The mutual coherence of the pairs of elementary emitters is obviously achieved in these schemes as a result of the circumstance that either both sources are images of the same source (the Fresnel mirrors and biprism), or one of the sources is an image of the other one (the Lloyd mirror).

We shall now proceed to define more precisely the concept "point" source. The meaning of this term should evidently be related to the task of obtaining a contrast interference pattern. The length of the source will be of no significance as long as the pattern of the field is sufficiently contrast.

To consider this question, let us imagine that sources O_1' and O_1'' coincide in space as before, while source O_2'' may move relative to its original position, when it coincided with O_2'. The displacement of source O_2'' will result in displacement and deformation of the system of nodes and antinodes formed by sources O_1'' and O_2'', which now will no longer coincide with the system of nodes and antinodes formed by emitters O_1' and O_2'. The contrast of the resulting pattern at point A (Fig. 5) will vanish when the antinode of the standing wave formed by one pair of sources is superposed on the node formed by the other pair.

It is quite obvious that any displacement of source O_2'' in the spherical layer confined between spheres with radii of $r_2' - \frac{\lambda}{2}$ and $r_2' + \frac{\lambda}{2}$ circumscribed about point of observation A does not result in complete blurring of the pattern at point A. In other words, the condition for retaining the pattern at point A is

$$|r_2'' - r_2'| < \frac{\lambda}{2} \tag{21}$$

Condition (21), however, ensures retaining of the interference pattern only at the single point A. This is naturally not enough. An interference pattern (hologram) is recorded on a certain surface having finite dimensions or in a certain volume.

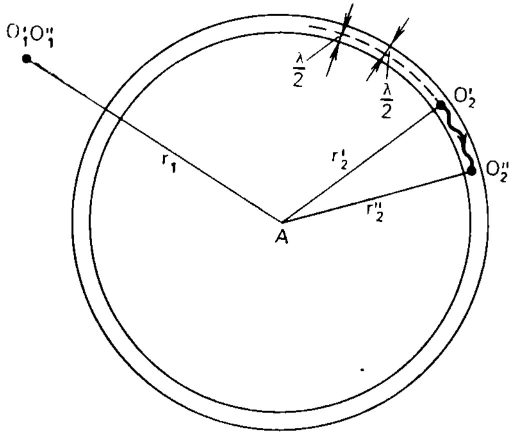


Fig. 5.
Region of permissible displacements of source O_2''

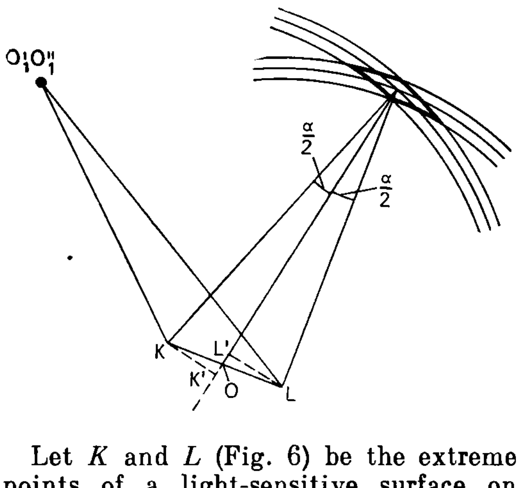


Fig. 6.
To the calculation of the permissible width of a source

Let K and L (Fig. 6) be the extreme points of a light-sensitive surface on which an interference pattern is recorded, and O be the centre of this surface. In this case, condition (21) must be simultaneously observed for the two points K and L. It will therefore also be observed for all the intermediate portions of surface KL. Examination of Fig. 6 shows that this limits the freedom of displacement of source O_2'' to the volume formed upon the intersection of two spherical layers with a thickness of λ circumscribed about points K and L.

Figure 6 shows a section of these layers by an equatorial plane (a plane containing sources O_1', O_1'' and O_2', and also point O). It can be seen from the figure that the width of the zone (the diagonal of the rhombus) is determined by the angular dimension α of the interferogram:

$$b = \frac{\lambda}{\sin\frac{\alpha}{2}} \tag{22}$$

Figure 7 depicts a section of the same spherical layers by a meridian plane passing through OO_2'. The displacement of source O_2'' permitted in a meridian plane is considerably greater than in an equatorial one. It can be shown that

$$a \approx 2\sqrt{r\lambda} \tag{23}$$

Assume, for instance, that $r = 10^2$ cm, $\sin\frac{\alpha}{2} = 5 \times 10^{-2}$ (this corresponds to a size of the interferogram of about 10 cm) and $\lambda = 5 \times 10^{-5}$ cm. Hence $b = 10^{-3}$ cm and $a = 1.4 \times 10^{-1}$ cm, i.e. the permissible displacements of source O_2'' in a meridian direction for the case being considered exceeds those in

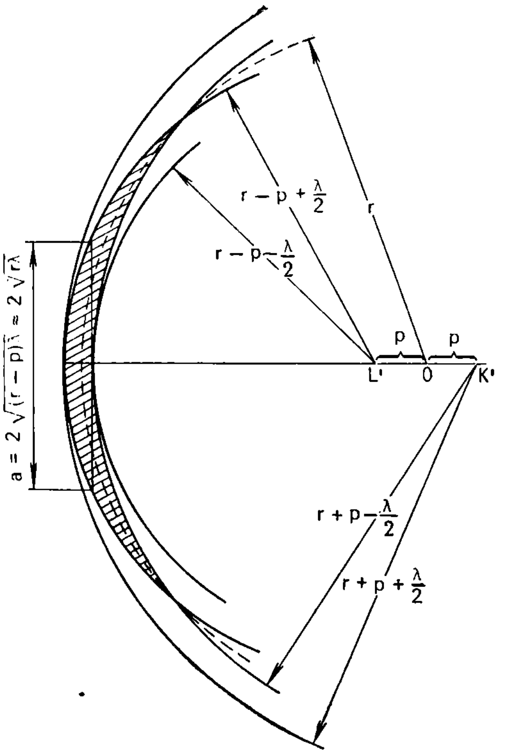


Fig. 7.
To hte calculation of the permissible height of a source

an equatorial direction by more than two orders of magnitude.

Expressions (22) and (23) approximately determine the boundaries of the region of displacements of source O_2'' at which an interference pattern is retained on section KL. The same expressions also give the maximum permissible boundaries of an extended source of light consisting of elementary independent emitters that are coherent in pairs with the respective emitters concentrated at point O_1.

Similar reasoning can be conducted for the case when O_2 is a point source and O_1 is an extended one. Our conclusions will also not change when both sources are extended ones. Indeed, this is generally the case—the length of both sources O_1 and O_2 is the same, as a rule, since they are virtual or real images of the same source of light.

In this connection, the possibility appears of obtaining a localized contrast pattern in the zones of the field where rays emitted from the corresponding points of both sources intersect. For this reason, the contrast of a pattern does not depend on the dimensions of the source in a localized zone. The depth of such a zone, however, is directly related to the length of the source.

The simple relationships considered here characterize the general circle of requirements which light sources and the schemes used to observe the interference of light waves must meet.

The time coherence depends on the degree of monochromaticity of the source (or the spectral width of the transmission band of the recording system) and determines the maximum difference in path length between interfering waves.

The spatial configuration and frequency of the interference pattern and, consequently, the spatial resolving power of the receiver needed to record it depend

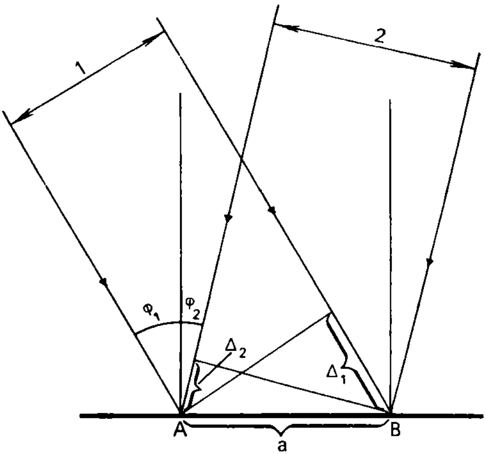


Fig. 8.
Formation of a holographic diffraction grating

on the mutual arrangement of the sources and the recording device.

The spatial coherence of waves depends on the dimensions of the sources and determines the zones of the interference field in which the contrast of the pattern exceeds a preset value.

The velocity of displacement of the interference pattern and, therefore, the time resolving power of the receiver needed for recording the fringes depend on the difference between the frequencies (wavelengths) of the light sources.

A Hologram as a Diffraction Grating. Suppose that two waves with plane wavefronts converge on a photolayer. A parallel beam of light corresponds to each of these waves. Let the angle of incidence of one of them be φ_1 and of the other φ_2 (Fig. 8).

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We shall demand that these waves be coherent. A system of interference fringes will form on the photolayer. Condition (6) corresponds to the middles of the light fringes, and condition (7) to the middles of the dark ones.

If we assume that the transmission coefficient of the photolayer with respect to its amplitude linearly depends on the intensity of the incident light, then the system of fringes obtained will have a sinusoidal distribution of transmission, as follows from Eq. (2a).

If points A and B correspond to the positions of two adjacent fringes (a is the distance between them), then the difference in the path lengths of beams *1* and *2* upon transition from A to B changes by λ. In other words, $\Delta_1 + \Delta_2 = \lambda$, and since $\Delta_1 = a \sin \varphi_1$, while $\Delta_2 = a \sin \varphi_2$, then

$$a = \frac{\lambda}{\sin \varphi_1 + \sin \varphi_2} \tag{24}$$

Let us illuminate the hologram—a diffraction grating with the period a—recorded in this way with one of the beams participating in its formation, for example *1*.

The angle of incidence of light on a diffraction grating (α) and the angle of diffraction (β) are related by the expression

$$a (\sin \alpha + \sin \beta) = k\lambda \tag{25}$$

where k is the order of the spectrum ($k = 0, \pm 1, \pm 2, \ldots$). A sinusoidal grating does not form orders above the first one. Assuming that $\alpha = \varphi_1$ and $k = 1$, we find $\sin \beta$, not forgetting that the period a is found by Eq. (24):

$$\sin \beta = \frac{\lambda}{a} - \sin \alpha = \sin \varphi_1 + \sin \varphi_2 -$$

$$- \sin \varphi_1 = \sin \varphi_2 \qquad (26)$$

i.e. $\beta = \varphi_2$.

Thus, the hologram (diffraction grating) constructed the wave participating in its formation that was absent in the reconstruction of the wavefront. If we retain beam *1*, then beam *2* is reconstructed. If we illuminate the hologram with beam *2*, then beam *1* is reconstructed, i.e. the reference and the object (subject) beams have properties of mutual convertibility.

Every wave of any degree of complexity can be represented as the superposition of plane waves. This corresponds to the breaking up of a complex wavefront into small plane areas each of which is recorded on a small section of the hologram. Thus, our conclusions can be extended to object waves of an arbitrary configuration.

It is natural to ask whether these conclusions can be applied to the case of an arbitrary reference wave. Unfortunately, the answer is no.

Let us consider this on the example of a reference wave consisting of two parallel beams striking a hologram at an angle to each other (Fig. 9*a*). In this case, two patterns corresponding to the two components of the complex reference wave

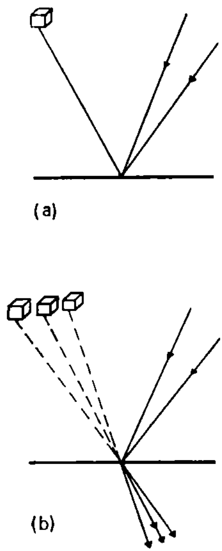


Fig. 9. Reconstruction of a wavefront by means of an extended source

will be recorded on the hologram. Let us retain the structure of the reference wave and illuminate our hologram. Each of the two beams will reconstruct one image of the object on each of the two patterns, a total of four images. Each of them will reconstruct the image of the object on its "own" pattern at the very same place where it was when the hologram was formed. These images reconstructed by the two beams coincide. Each beam reproduces the same object on the "alien" pattern, but displaced through a certain angle. We get the picture shown in Fig. 9*b*. Thus, in addition to the main virtual image of the object, two weaker images are reconstructed that are displaced relative to the main one, may be superposed on it and hinder its observation.

It is evident that if the reference wave is formed by an extended source and can be represented in the form of a superposition of a great number of parallel beams, then in reconstruction many hindering images are formed. This is why a plane or spherical reference wave is used as a rule to record holograms *.

* This is not essential, however, when special requirements to the shape of the reference source are observed. Moreover, the reconstructing wave may not coincide in shape with the reference one. It is only necessary that the function of correlation of the amplitudes of the reference and reconstructing sources be equal to the δ-function [14]. See also page 129, where it is shown that a reference source of an arbitrary structure can be used in the holography of focussed images (*image holograms*).

Summarizing what has been said above, we arrive at the following conclusion, which can be called the main law of holography:

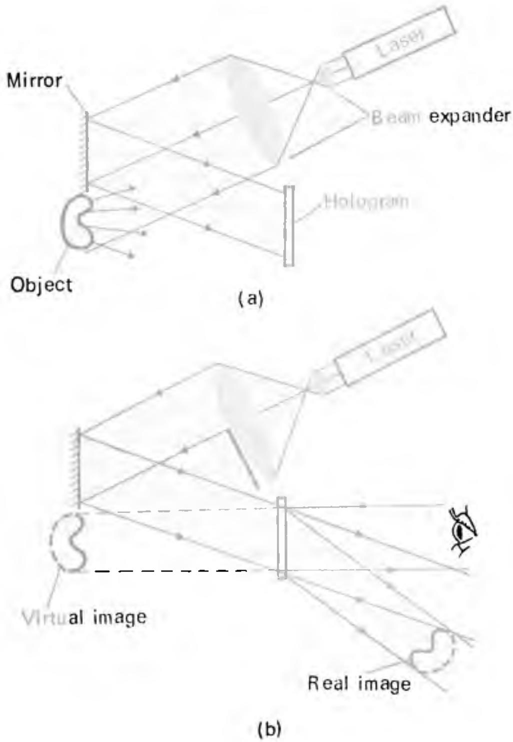
If an interference pattern formed by an arbitrary object wave and a coherent reference wave from a point source is recorded on a light-sensitive surface, and this pattern (hologram) is next illuminated by the reference wave, then diffraction of the light will cause the object wave to be reconstructed.

An interference pattern can be recorded on a hologram not only in the form of variations of the transmission coefficient (the so-called *amplitude* or *absorption* holograms), but also in the form of variations of the thickness, refraction index or reflecting relief. Such holograms are called *phase* ones.

How Holograms are Prepared and the Waves are Reconstructed. A schematic diagram showing how holograms are recorded is depicted in Fig. 10.

The object whose hologram is to be obtained is illuminated with a laser beam. The scattered light wave impinges on a photographic plate. The reference beam—part of the light from the same laser reflected from a mirror—impinges on the same plate. Since the interference pattern of a hologram is generally very fine, a developed hologram does not differ in appearance from a uniformly exposed plate. A hologram often contains rings and stripes (Fig. 11*a*). They are

Fig. 10.
Diagram
of installation
for forming
holograms (*a*) and
reconstructing the
wavefront (*b*).



due to the diffraction of light on particles of dust getting onto the mirrors and lenses, and have nothing in common with the interference microstructure (Fig. 11*b*) containing the record of the light wave scattered by the object.

To reconstruct this wave, the object is removed, and the hologram is put in the place where it was when formed

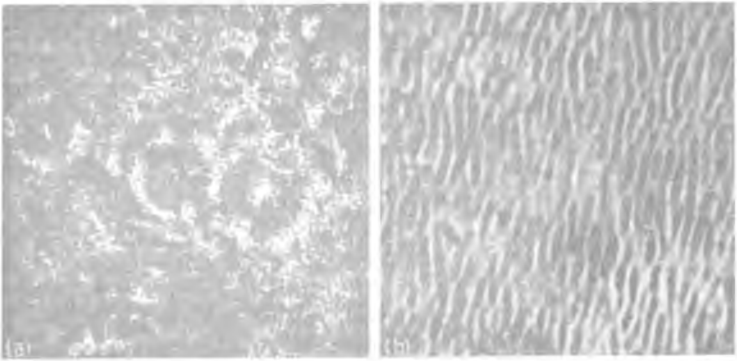


Fig. 11.
How we see a hologram (*a*) and its structure seen in a microscope (*b*)

(Fig. 10*b*). If we then switch on the laser and look through the hologram like through a window, we shall see the object at its previous place, as if it were not removed. The visible object seems so real that we can detect parallax by changing the position of our head. When looking at the near and far parts of the object, we have to accommodate our eyes differently, and if we want to photograph it, we will have to choose such an aperture, as in ordinary photography, which will ensure an adequate field depth. If this is not done, some parts of the object will be sharp on the photograph, and other ones blurred.

A hologram reconstructs not only the original wave, but also waves of the zero and minus one orders. The matter is that the process of recording a "thin" two-dimensional hologram set out above is not unambiguous. Gratings of the same shape and period are obtained in

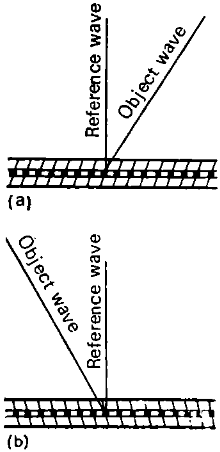


Fig. 12.
A two-dimensional hologram does not "remember" the side from which the object beam impinged on it. The arrangement of the layers inside a three-dimensional hologram, however, differs for cases (*a*) and (*b*)

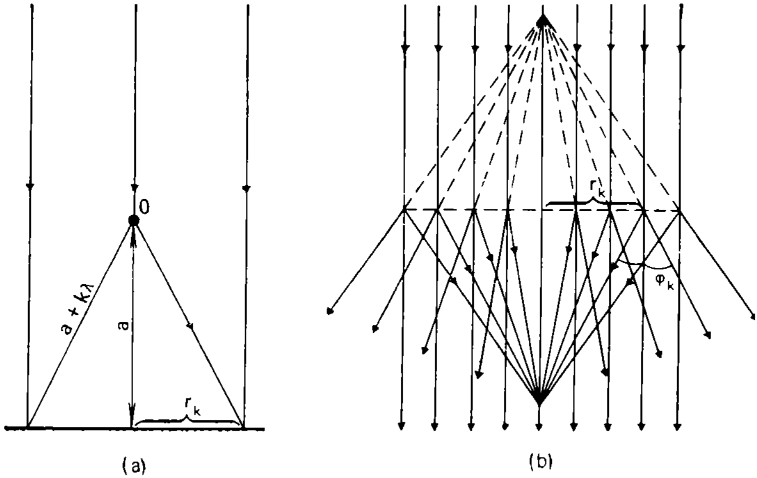
both cases shown in Fig. 12. It is natural that a hologram recorded with the use of either of these two arrangements should consequently reconstruct both object waves shown in Fig. 12*a* and *b*.

Thus, the optical arrangement shown in Fig. 12*a*, in addition to the original wave (reconstructing a virtual image of the object where it was in recording), reconstructs another conjugated wave producing a real image of the object. This image is pseudoscopic (distorted)—the depressions on it are replaced by crests and vice versa, i.e. the image is "turned inside out".

The real image, as a rule, is at the other side of the hologram (Fig. 10*b*). It is usually difficult to see it with the naked eye, but if a photographic plate or ground glass is placed in the plane where it is formed, its two-dimensional projection can be obtained.

Three-dimensional holograms, which will be discussed on a later page, "remember" the side which the object beam arrived from. For this reason, they reconstruct only one image (see Fig. 12).

Hologram of a Point—Fresnel Zone Plate. Let us see how a hologram is formed from the simplest object—a point, and how the wave is reconstructed. We shall consider that a point is an object whose angular dimensions are so small that its structure cannot be distinguished. A point scatters a light wave whose front at each moment is a sphere. At a suffi-



ciently great distance from the point, the surface of this sphere can be considered as a plane.

Fig. 13.
Formation of a hologram of a point source (*a*) and reconstruction of the spherical wavefront by it (*b*)

There is another way of converting a spherical wave into a plane one; for this end a point source is placed in the focus of a lens.

The light wave scattered by any complicated object can be considered as a complex of the waves scattered by the separate points which it consists of.

Suppose that point *O* scattering a spherical light wave is at a distance *a* from a photographic plate (Fig. 13*a*). In addition, a plane reference wave strikes the plate normal to its surface.

What will the interference fringes on the plate look like in this case? Firstly, it is not difficult to establish that they are concentric circles. Indeed, for all the points on the plate equidistant from its centre, the phase relations of the incident waves are identical. Secondly, when passing from ring to ring, the difference in path length between the interfering waves grows by one wavelength (the phase difference by 2π). Assume that the difference in path length at the centre is zero; hence for the k-th ring it is $2k\pi$, and the radius of this ring (Fig. 13a) is found from the equation

$$r_k^2 = (a + k\lambda)^2 - a^2 = 2ak\lambda + k^2\lambda^2 \qquad (27)$$

A hologram of a point is thus a system of concentric rings whose radii obey Eq. (27). Such a system, shown in Fig. 14, is called a *Fresnel zone plate* (other names are *Fresnel zone grating* and *Soret zone plate*). It should be remembered, however, that in this figure the transition from dark to bright is abrupt, whereas on a hologram it is smooth, approximately following a sine law. This would be absolutely correct if the transmission of a film depended linearly on its illumination. The actual dependence is much more complicated (see p. 61 and Fig. 21).

The distance between adjacent rings can be obtained quite simply from Eq. (27) and is

$$\Delta r_k = \frac{a\lambda + k\lambda^2}{r_k} \qquad (28)$$

Thus, a hologram of a point is a Fresnel zone plate with sinusoidal distribution of the transparency.

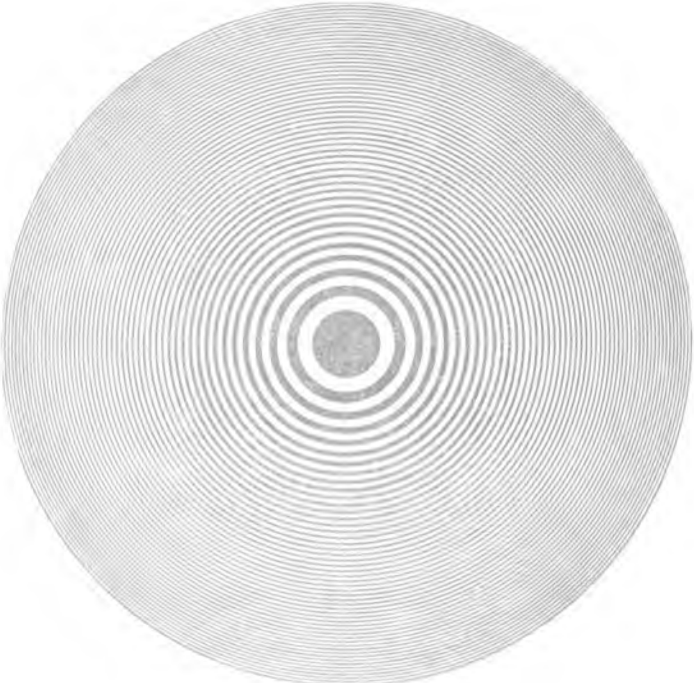


Fig. 14.
Fresnel zone plate

Let us now consider the reconstruction process with the aid of a hologram of the light wave emitted by a point. For this purpose, we remove our point source, put its hologram in the same place where it was exposed, and illuminate it with the same plane light wave which we used in recording it.

Each small section of a Fresnel zone plate can be considered as a conventional diffraction grating. It decomposes a beam of light normally impinging on it into the following parts:

(a) a beam of the zero order that is a continuation of the incident one;

(b) beams of the positive and negative first order at angles complying with the condition

$$\sin \varphi_1 = \pm \frac{\lambda}{\Delta r}$$

where Δr is the grating period (distance between adjacent rings).

The angles at which the beams of the positive and negative first orders propagate regularly increase upon transition from the centre of the given grating to its edges, since the grating period Δr diminishes [see Eq. (28)].

We shall now show that the first-order beams form two spherical waves (diverging and converging). For this purpose, it is sufficient to prove that all the beams of the negative first order intersect at one point, and all the beams of the positive first order emerge from one point. Consider a beam of light impinging on the hologram at a distance r_k from its centre (Fig. 13*b*).

The beams of the positive and negative first orders deflect by the angles $\pm\varphi_k$. These beams (or their continuations in the "opposite" direction) intersect the axis of the hologram at a distance of $\pm x$ from its surface.

Let us find the value of x. Inspection of Fig. 13*b* shows that

$$x = r_k \cot \varphi_k = r_k \frac{\sqrt{1-\sin^2 \varphi_k}}{\sin \varphi_k}$$

Taking into account that $\sin\varphi_k = \frac{\lambda}{\Delta r_k} = \frac{r_k}{a+k\lambda}$, we get

$$x = \sqrt{a^2 + 2ak\lambda + k^2\lambda^2 - r_k^2}$$

Remembering now that $r_k^2 = 2ak\lambda + k^2\lambda^2$ [see Eq. (27)], we have

$$x = a$$

Thus, the distance at which beams of the positive and negative first orders intersect the axis of the hologram is identical for beams diffracted by all the sections of the hologram.

Hence, when a plane wave passes through the hologram of a point (a zone plate with a sinusoidal distribution of the transparency), three waves are formed:

(1) A spherical wave emerging from a point at a distance a on the other side of the hologram, i.e. from the place where the point was in forming the hologram.

(2) A spherical wave converging at a point at the same distance a from the hologram which the point was placed at in forming the hologram.

(3) In addition to waves (1) and (2) forming a virtual and a real images of the point, a plane wave corresponding to the zero order also emerges from the hologram.

It is not difficult to extend the results we have obtained for a point to objects of any shape consisting of a multitude of points scattering light. In this case, a hologram should be considered as the superposition of zone plates formed by each point of the object. This superposition observes the laws of interference of light, and as a result a complex interference pattern is obtained which is a hologram of the object (Fig. 11*b*).

All these interference zone plates act independently in reconstruction—each one regenerates the wave from its point of the object at the same place where it was in forming the hologram. A more contrast zone plate corresponds to a brighter point, and in reconstruction it also gives a brighter point of the image.

Naturally, not all of the details of the phenomenon are explained by this simple scheme, but many properties of holograms become clear.

Some Important Properties of a Hologram. We shall now stop to consider some of the important properties of a hologram.

1. Let us prepare a contact print from a hologram and reconstruct the wavefront with the aid of the copy obtained in this way, which is a negative of the original hologram. We obtain a surprising result—everything remained unchanged, i.e. the bright spots remained bright and the dark ones dark. This is simple to explain. The unilluminated points of the object produce no Fresnel zone plates, and they also cannot appear on the negative copy of the hologram. Consequently, upon reconstruction these

points remain dark. The bright points of the object participate in the formation of the pattern on the hologram, and the diffraction properties of this pattern do not change at all when the dark spots of the hologram are replaced by bright ones, and the bright spots by dark ones.

2. Each section of a hologram is capable of reconstucting an image of the entire object. Indeed, as we have already seen, any section of a Fresnel zone plate reconstructs the image of a point. It is quite natural that a hologram of a more intricate object has the same property. Of course, a smaller portion of a hologram will reconstruct a correspondingly smaller section of the wavefront. If this portion is very small, the quality of the reconstructed image will become poorer, small details will vanish, and a characteristic speckled structure will appear (Fig. 15).

3. It is easy to explain the pseudoscopic nature of the real image formed by a hologram. The points of the object (depressions) that are farther from the hologram are also reconstructed farther from it in the real image, but are seen from the opposite side. This is why these points form ridges in the real image (Fig. 10*b*). In a pseudoscopic image, the right-hand parts of the object (with respect to the observer) are seen as right-hand ones, and the left-hand parts as left-hand ones. Only the relief of the object is reversed.

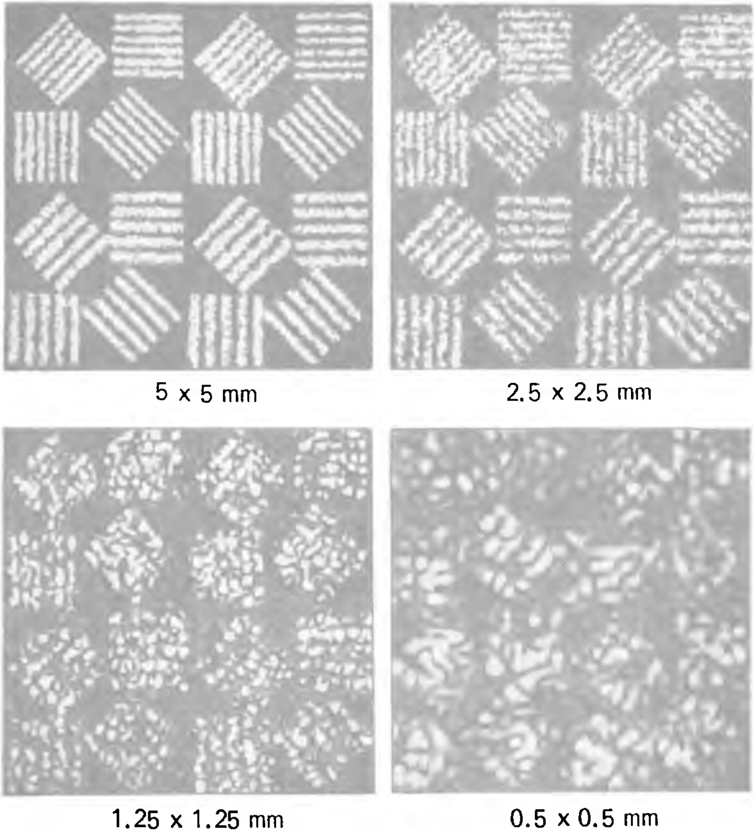


Fig. 15. Change in the structure of a reconstructed image when the area of a hologram is reduced [15]

4. A hologram of a complex object can be considered as an interference (coherent) superposition of holograms from individual points or more complex portions of the object. The amplitudes of the light waves are summated with account of the phase relations bet-

ween them in such superposition [see Eq. (2a)].

We can also imagine a hologram that is an incoherent superposition of holograms of different objects or parts of the same object. In this case, the photolayer summates the illuminations they create. If the number of such consecutive superpositions is not too great, then the hologram will simultaneously reconstruct several consecutively recorded light waves without any appreciable distortions. This property of holograms is used for the consecutive recording of the waves from several objects or several states of the same object on a single hologram.

5. The complete interval of brightnesses transmitted by a photolayer does not exceed one or two orders of magnitude, as a rule. At the same time, real objects often have much greater intervals of brightnesses. A hologram, which possesses focussing properties, uses the light impinging on its entire surface for constructing the brightest sections of the image, and it is capable of transmitting gradations of brightness up to five or six orders of magnitude.

Hologram Formation. The procedure for forming a hologram originally proposed by Gabor provided for arrangement of the light source, object and hologram along one straight line. Part of the light beam was scattered by the object and formed the object wave, while the

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unscattered part played the role of the reference wave (Fig. 16*a*). An appreciable shortcoming of this scheme is that in the reconstruction process the beams forming the real and the virtual images, and also the zero-order beam, propagate in the same direction (Fig. 16*b*) and create mutual disturbance. This is the main reason explaining the poor quality of the reconstructed images.

In one of his first works on holography [2], Gabor predicted: "It is very likely that in light optics, where beam splitters are available, methods can be found for providing the coherent background which will allow better separation of object planes, and more effective elimination of the effects of the 'twin wave'".

In complete accordance with this prediction, E. Leith and J. Upatnieks [6] in 1961 proposed their *split-beam holography*, also called *off-axis holography* (Fig. 16*c*). It can be considered as a modified version of Gabor's scheme. Leith and Upatnieks use only the peripheral portion of Gabor's hologram and, which is the most important, the object is illuminated with a separate coherent beam of light. This permitted them to prepare holograms of opaque and three-dimensional objects. A glance at Fig. 16*d* shows that holograms formed according to the arrangement proposed by Leith and Upatnieks are free of mutual disturbance of the virtual and real images. At present split-beam holography is in the greatest favour in the field.

The photosensitive layer used to form a hologram can be oriented in any way relative to the reference source and the object. It can even be placed between them so that the light from them will strike it on both sides.

In any case, if the hologram is put in the same place at which it was recorded, a virtual image of the object will be formed where it was originally, if, naturally, the arrangement of the reference source and its wavelength remain unchanged.

Figure 17 shows the most important ways of forming a hologram. It depicts the surfaces of antinodes of the standing light waves formed in the interference of light emitted from point object O_1 and point reference light source O_2. In Fig. 17*a*, the reference source is at a finite distance from the object. In Fig. 17*b*, it is removed to infinity, and the light wave arriving from it has a plane wavefront. It can be understood that Fig. 17*a* depicts sections of the interference surfaces by the plane of the drawing. These surfaces are actually bodies of revolution—hyperboloids (Fig. 17*a*) and paraboloids (Fig. 17*b*). The axis of revolution passes through both point sources of light.

Different patterns of the interference fringes forming a hologram of a point correspond to different hologram recording arrangements. For all arrangements in which the plane of the hologram is normal to the line joining the reference

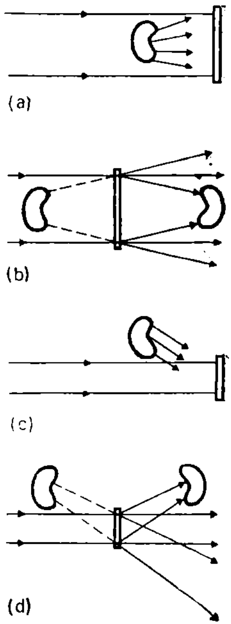


Fig. 16. Formation of a hologram and reconstruction of the wavefront according to Gabor (*a*, *b*) and Leith and Upatnieks (*c*, *d*)

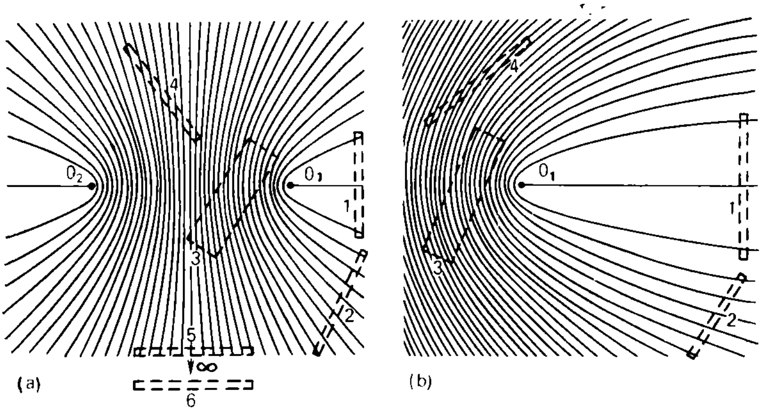


Fig. 17. Surfaces of antinodes of standing light waves formed by point object O_1 and point reference source O_2:
a—hyperboloids of revolution (axis of revolution O_1O_2);
b—paraboloids of revolution;
1—arrangement of hologram according to Gabor;
2—ditto, Leith and Upatnieks;
3—ditto, Denisyuk;
4—two-dimensional hologram with inverted reference beam;
5—lensless Fourier transform hologram;
6—Fraunhofer hologram

source and the point object, the interference fringes are rings forming a Fresnel zone plate. If the plane of the hologram is parallel to this line, then the fringes are a family of hyperbolas. Such an arrangement [16, 17] is called *lensless Fourier transform holography.*

In the general case, the interference fringes are curves formed by the plane of the hologram cutting through a family of hyperboloids or paraboloids of revolution.

The practical realization of these mechanisms is carried out in one of the ways shown in Figs. 10, 19, and 25-34.

Three-Dimensional Holograms. On the preceding pages we considered a photographic plate of film as a medium having two dimensions. This is true only as long as the thickness of the photosensitive layer is compatible with the distance between adjacent interference fringes.

If the layer is much thicker, its special properties as a three-dimensional medium manifest themselves. These properties were first noted by G. Lippmann and were used by him for color photography*. Yu. Denisyuk [7] proposed to use three-dimensional media for recording holograms and was the first to make such a record.

If two interfering beams are directed toward each other (at an angle of $\alpha = 180°$, as shown in Fig. 18*a*), then standing waves appear in space. They are systems of planes of nodes, the distance between which equals $\lambda/2$, and planes of antinodes with the same distance between them. If in a more general case we have $\alpha \neq 180°$, it is easy to see that the distance between adjacent antinodes (or nodes) of the standing waves grows $1/(\sin \alpha/2)$ times and becomes equal to $\lambda/(2 \sin \alpha/2)$. The planes of the nodes and antinodes of the light waves, as can be seen from Fig. 18*b*, will be directed along the bisector of angle α.

If a photolayer is introduced into the zone of intersection of the light beams, then the system of nodes and antinodes

---

* The opinion is frequently expressed that Lippmann's scheme of color photography is a holographic one, and, consequently, Lippmann may be considered as the inventor of holography. This is wrong, since the pattern of standing waves recorded in Lippmann's scheme carries no information on the phase of the object wave, seeing that it is recorded near the plane of symmetry (Fig. 17*a*) and is in any case a system of equidistant planes.

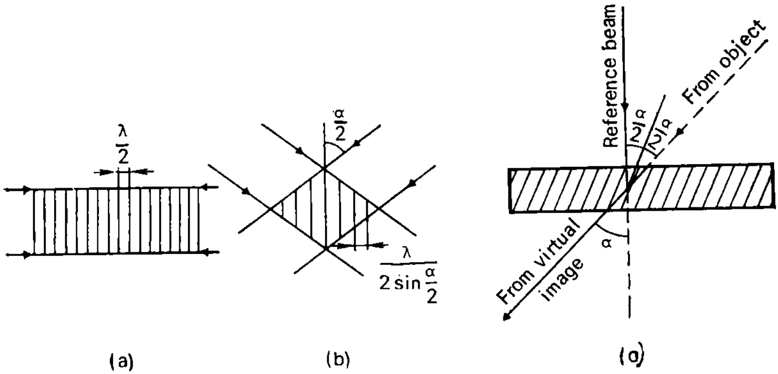


Fig. 18. Formation of standing light waves by opposed beams (a) and beams converging at an angle of $\alpha \neq 180°$ (b); c—reconstruction of light wave with the aid of a three-dimensional hologram

will be recorded in it in the form of semitransparent reflecting layers*. Such a three-dimensional diffraction grating will have the following properties: (1) the light reflected from the layers like from a mirror will reconstruct the wave from the object. Indeed, the reflecting layers, as indicated above, are directed along the bisector of the angle formed by the interfering beams, and it is exactly this which ensures the indicated

* To simplify our reasoning, we have permitted an inaccuracy here. Since the refractive index of the photolayer (n_1) usually differs from that of the surroundings (n_0), then both the direction of the beams and the arrangement of the antinodes in it will be somewhat different. The taking of this circumstance into account will not change our conclusions, but will only make them more complicated. It will be necessary, on one hand, to take into account the refraction of the light, and on the other—the change in the wavelength by n_1/n_0 times at the interface between the two media.

property of the holograms (Fig. 18*c*); (2) no zero-order beam or real image will be formed; (3) beams reflected from different layers will amplify one another only if they are in phase, in other words, the difference in their path lengths should equal a whole number of wavelengths. This condition (the Lippmann-Bragg condition) will be automatically observed only for the wavelength used to record the hologram. This results in selectivity of a hologram with respect to the wavelength of the source in whose light the wavefront is reconstructed. Consequently, the possibility appears of reconstructing an image with the aid of a source of a continuous spectrum (an incandescent lamp, the Sun). If a hologram was formed by light of several spectral lines (for example, blue, green and red), then each wavelength forms its own system of surfaces. The corresponding wavelengths will be picked out of the continuous spectrum when the hologram is illuminated, and this results in reconstruction not only of the pattern, but also of the spectral composition of the light wave, i.e. in the forming of a coloured image. All this holds if processing of the photolayer does not change the mutual arrangement of the reflecting planes. Usually, shrinkage of the photolayer causes the wavelength of the reconstructed image to be displaced toward the "blue" (short-wave) side.

Figure 19 shows how holograms with recording in a three-dimensional medium are usually obtained.

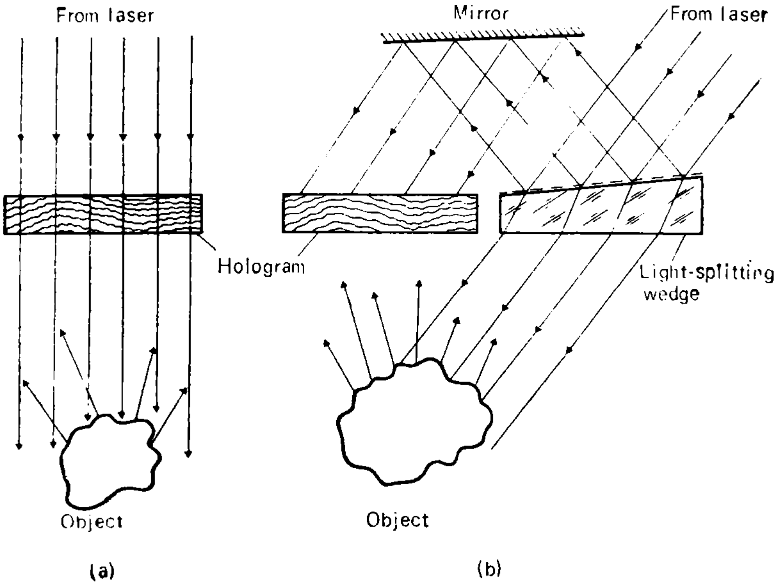


Fig. 19. Formation of holograms in thick-layer emulsions using opposed beams

The reference source, hologram and object may be arranged in any way relative to one another, i.e. the hologram can be put in any place in the schemes shown in Fig. 17. For three-dimensional properties to appear in a hologram, however, it is necessary that at least several reflecting layers be contained in the thickness of the emulsion. At a given emulsion thickness, this requirement determines the zones (Fig. 17) in which a hologram may be considered as "three-dimensional".

At a given position of a hologram, the poorest three-dimensional properties will belong to a hologram that is oriented at right angles to the predominating direction of the surfaces of the nodes and antinodes. In this case, shrinkage of the photosensitive emulsion does not lead to a change in the orientation of the layers, and thus the "blaze angle" of the hologram is retained. Conversely, if the maximum three-dimensional properties are to be obtained, it is the most advantageous to orient the hologram along the reflecting layers. In this case, the brightness of the real image and of the zero order will be minimum.

Three-dimensional holograms are often called thick-layer ones, or holograms on thick-layer emulsions. The conditional nature of this terminology is quite obvious. The thickness of the photosensitive layers of holograms actually ranges from several microns to several scores of microns, and they can be called "thick" only with great straining. The three-dimensional properties of a hologram manifest themselves when the reflecting layers are spaced apart at distances that are several times smaller than the thickness of a layer. The criterion of the transition from two-dimensional holograms to three-dimensional ones [18] is

$$T \geqslant 1.6 \frac{d^2}{\lambda'}$$

where T = thickness of a hologram
d = distance between the layers
λ' = wavelength of light in the recording medium.

Taking into account that $d \approx \lambda'/\alpha$, we can write the same criterion in the form

$$T \geqslant 1.6 \frac{\lambda'}{\alpha^2}$$

For example, for the emulsion Kodak 649F the effects of the third dimension manifest themselves at angles α between the reference and the object beams ($\lambda = 6328$ Å) exceeding 10 degrees, i.e. when the distance between reflecting layers is less than four micrometres (microns).

1.2. Properties of a Hologram

How a Hologram Reconstructs the Shape of Objects and Their Dimensions. We have established that if holograms are formed and the wavefront is reconstructed using a reference source of the same wavelength with a constant orientation relative to the hologram, then the latter will reconstruct the wave emerging from the virtual image that coincides in shape and position with the object itself.

A change in the shape of the reference beam, its wavelength, the orientation of the hologram and its scales results in violation of these features. Sometimes this produces a useful result. For example, by changing the wavelength and the divergence of a beam, we can obtain a change in the scale of the reconstructed image of an object—its reduction or enlargement. Such a change is attended,

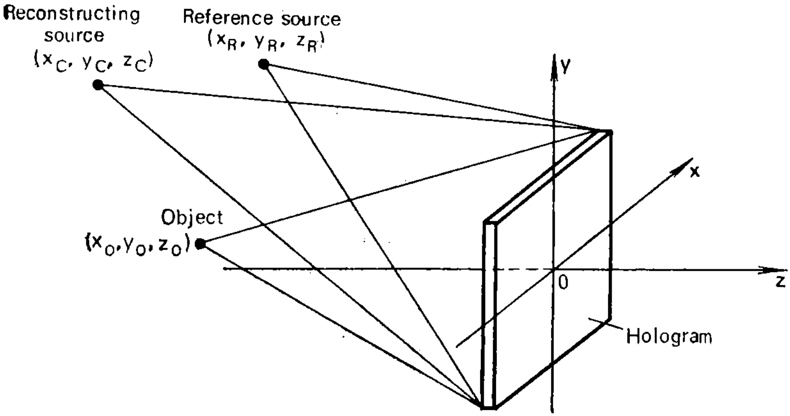


Fig. 20. Explanation of symbols used in Eqs. (30)

as a rule, with undesirable distortions of the image, so-called *aberrations*, which manifest themselves in distortion of the longitudinal and lateral scales of the image, violation of the sharpness, etc.

Below are given formulas making it possible to calculate the position of the reconstructed image and its enlargement for any case [19]. Let us introduce the following symbols (Fig. 20): the hologram is in plane x, y with $z = 0$ (it retains this position during its exposure and when the wavefront is being reconstructed); the coordinates of the object are x_O, y_O and z_O, of the reconstructed image x_B, y_B and z_B, of the point reference source—x_R, y_R and z_R, of the point source used for reconstruction—x_C, y_C and z_C. Assume that prior to reconstruction the hologram was enlarged m times, and the wavelength of the reconstructing source is μ times greater than that of the source of light used in formation of the hologram. Hence

$$\left.\begin{aligned} z_B &= \frac{m^2 z_R z_C z_O}{(m^2 z_R - \mu z_C)\, z_O + \mu z_R z_C} \\ x_B &= \frac{\mu m z_R z_C x_O + (m^2 x_C z_R - \mu m x_R z_C)\, z_O}{(m^2 z_R - \mu z_C)\, z_O + \mu z_R z_C} \\ y_B &= \frac{\mu m z_R z_C y_O + (m^2 y_C z_R - \mu m y_R z_C)\, z_O}{(m^2 z_R - \mu z_C)\, z_O + \mu z_R z_C} \end{aligned}\right\} \tag{30}$$

The angular enlargement of a hologram in any case, regardless of all the quantities in Eqs. (30), equals μ/m. Consequently, the linear lateral enlargement

$$M_{lat} = \frac{\mu}{m}\frac{z_B}{z_O}$$

and according to Eqs. (30)

$$M_{lat} = \frac{m}{1 + \frac{m^2}{\mu}\frac{z_O}{z_C} - \frac{z_O}{z_R}} \tag{31}$$

The same result can be arrived at by direct calculation of the lateral enlargement

$$M_{lat} = \frac{\partial x_B}{\partial x_O} = \frac{\partial y_B}{\partial y_O}$$

with the aid of Eqs. (30).

If a hologram is two-dimensional and simultaneously forms two images of the object, then to obtain the coordinates of the second image, $-\mu$ should be substituted for μ in Eqs. (30) and (31).

The longitudinal enlargement of a hologram, generally speaking, differs from

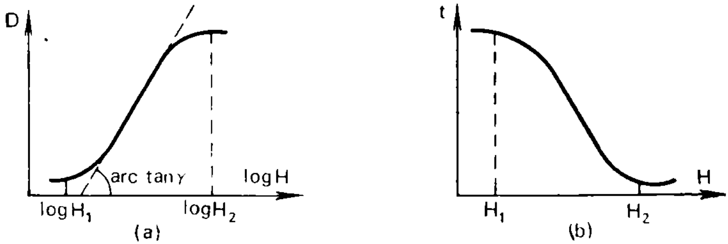


Fig. 21. Characteristic curve of photographic emulsion (*a*) and dependence of amplitude transmittance on the exposure (*b*): *D*—optical density; *H*—exposure; *t*—amplitude transmittance

the lateral one and equals

$$M_{\text{long}} = \frac{\partial z_B}{\partial z_O} = \frac{\dfrac{m^2}{\mu}}{\left(1 + \dfrac{m^2}{\mu}\dfrac{z_O}{z_C} - \dfrac{z_O}{z_R}\right)^2} =$$

$$= \frac{M_{\text{lat}}^2}{\mu} \tag{32}$$

Equations (30)-(32) are not absolutely accurate. They have been derived on the assumption that the distance from a hologram to the object is much greater than the lateral dimensions of the hologram.

How a Hologram Reconstructs the Distribution of the Brightness of an Object. In conventional photography, the distribution of the brightness in an image transmits that in the object only to a first approximation.

The photometric properties of a photographic emulsion are generally described with the aid of the so-called characteristic curve, the typical form of which is shown in Fig. 21*a*. This curve shows the dependence of the blackening of an emulsion $d = \log (1/T)$ (here T is the transmittance of the developed emulsion with respect to intensity) on the exposure (illumination $\times$ time).

The slope of the characteristic curve determines the contrast factor γ of the emulsion. For holography, it is more convenient to represent the photometric properties of an emulsion in the form of a curve showing how the amplitude transmittance of the emulsion $t = \sqrt{T}$ depends on the exposure (Fig. 21*b*).

Examination of Fig. 21 shows that the emulsion does not react at all to an exposure less than H_1. An increase of the exposure to above H_2 also does not tell on its blackening. Only within the interval from H_1 to H_2 does a photosensitive emulsion react to the distribution of the brightness of an object projected onto it and passes the less light, the greater was its illumination.

The complete interval of exposures from H_1 to H_2 does not as a rule exceed a change in this quantity by one or two orders of magnitude. At the same time, real objects have much greater intervals of brightnesses which a photographic process cannot transmit. Holography, using the same photosensitive emulsion, has from this viewpoint considerably greater (although not infinite) possibilities.

Indeed, as noted earlier, a hologram, which has focussing properties, gathers the light striking its entire surface for forming an image of a bright point of the object. Brightness gradations can be created on an ordinary photosensitive emulsion, on the other hand, only at the expense of a difference in the transmission of various sections, while the light flux striking the emulsion is not redistributed over the image.

This, of course, does not mean that a hologram does not distort the distribution of the brightness of the object no matter how it is exposed. The main thing is that a hologram can always be made to transmit the brightness without any appreciable distortions upon proper selection of the exposure, the ratio between the illuminations of the object and the reference beam, the emulsion and the conditions of developing. For this purpose, it is usually sufficient for the area of the hologram to be great, and for the exposure at the maxima of the interference fringes not to exceed H_2 and at the minima to be somewhat greater than H_1 (Fig. 21). The latter requirement corresponds to a record of the interference structure of a hologram within the limits of an approximately linear section of the curve $t = f(H)$, i.e. to linear recording of the hologram.

Figure 22*a* and *b* shows a photograph and a holographically reconstructed image of a graduated stepped attenuator—a filter with varying optical density used in photometry. A glance at this figure shows that the hologram reconstructed the gradation of brightness of the object practically without any distortion.

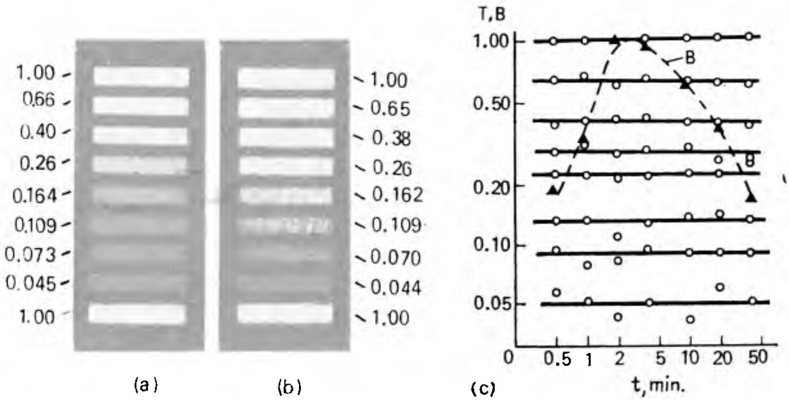


Fig. 22. Photograph of a stepped attenuator (*a*) and its holographically reconstructed image (*b*) [20] (the numbers correspond to the relative brightness of the steps);
c—result of photometering the reconstructed images of the attenuator steps upon an 80-fold change in the exposure time when forming the hologram. The latter gives the relative transmission (T) of the steps without any distortion;
B—change in brightness of reconstructed image of one of the steps. The greatest brightness of the reconstructed image was obtained within the exposure time range of 2 to 5 min

Figure 22*c* shows how a hologram retains the distribution of the brightness of an object (a stepped attenuator) with an 80-fold change in the exposure time.

Non-Linear Effects in Holography. If the values of the exposures at the maxima and minima of the interference structure appreciably extend beyond the limits of the linear portion of the dependence of the amplitude transmission on the exposure, then recording of a hologram becomes non-linear.

A linearly recorded hologram can be compared with a diffraction grating having a sinusoidal distribution of the amplitude transmittance, which forms no beams above the first order. In non-linear recording of a hologram, the latter is also a periodic grating, but the distribution of the amplitude transmittance in this case may considerably differ from a sinusoidal one owing to non-linear distortions. Such a grating, besides waves of the zero and first orders, also produces higher diffraction orders. The non-linear nature of the record of a hologram, however, manifests itself not only in the appearance of waves of higher orders, but also in distortion of the amplitudes of the first-order waves being reconstructed.

The influence of non-linearity on a first-order image boils down to amplification of the background, the appearance of haloes, distortion of the relative intensities of different points of the object, and in some cases to the appearance of false images [21].

The "images" formed by diffracted higher-order waves are complex functions (of the autoconvolution kind) of the original wave function of the object and have little in common with the object itself. In a number of cases, however (this relates, for example, to image holograms or to holograms of transparencies without diffusing screens), the higher-order waves form images [22]. The distribution of the brightness in these images is greatly distorted, as a rule, and the phase of a k-th-order image differs k times from that of a first-order one.

More detailed information on how the non-linear properties of a photosensitive emulsion affect the quality of the reconstructed images can be found in references [18, 23-25].

Resolving Power of Holograms. By *resolving power* is meant the ability of the receiver of an image or the system constructing an image to separately record (resolve) the images of close objects. This definition requires clarification. Customarily, the images of two points or lines of equal brightness are considered to be resolved with a drop in the illuminance between them equal to or greater than 20% of the maximum illuminance (the illuminance in the trough between them is less than 80%).

The concept of the *contrast of an image* is often used instead of the depth of the trough. The contrast is

$$K = \frac{E_{\max} - E_{\min}}{E_{\max} + E_{\min}} \qquad (33)$$

where $E_{\max}$ and $E_{\min}$ are respectively the maximum and minimum illuminances. The so-called Rayleigh criterion corresponds to a 20% trough (or to an 11% contrast). At the same time, the eye perceives two images having a considerably smaller contrast (1-2%) as separate ones. For this reason, visual resolution differs from the Rayleigh one.

It is customary practice to characterize the resolving power (see, for example, [11]) by the limiting angle of resolution $\delta\varphi$ or the limiting linear resolution δx. The latter quantity is usually related to the plane of the object (and not of its image). Spectral instruments characterize the quantity $\delta\lambda$—the difference in the wavelengths of the limiting resolvable absolutely monochromatic spectral lines, and also the angular ($\delta\varphi$) or linear (δy) distance between the images of these lines.

The restricted resolving power of optical instruments is to a considerable extent the result of aberrations inherent in optical components, and also of the lack of perfection in their manufacture. But even an ideal instrument has a restricted resolution owing to the diffraction of light on its aperture. For example, the resolution limit of a telescope

$$\delta\varphi = 1.22\frac{\lambda}{D} \tag{34}$$

where D is the diameter of the lens.

The resolution limit of a microscope

$$\delta x = 0.61\frac{\lambda}{A} \tag{35}$$

where A is the numerical aperture.

The resolution limit of a spectral instrument with a diffraction grating giving a first-order spectrum can be calculated according to one of the following formulas:

$$\delta\lambda = \frac{\lambda}{N} \tag{36}$$

$$\delta y = \frac{\lambda}{\alpha} \tag{37}$$

$$\delta\varphi = \frac{\lambda}{L} \tag{38}$$

where N = total number of lines
α = angular width of the grating

L = projection of grating width onto a plane perpendicular to the direction of observation.

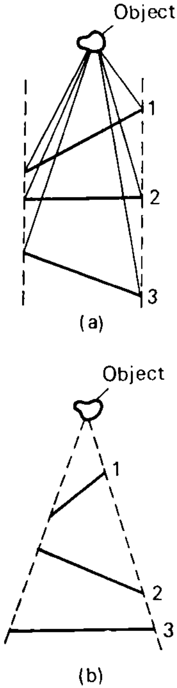


Fig. 23.
a—holograms *1-3* have the same angular resolution (their linear resolution diminishes from *1* to *3*); *b*—holograms *1-3* have the same linear resolution (the angular resolution grows from *1* to *3*). The requirements to the resolving power of the emulsion diminish from *1* to *3*, and to the sensitivity of the emulsion grow from *1* to *3*

As we already established earlier, a hologram is a diffraction grating, and for this reason its resolution can be determined by formulas (37) and (38). Thus, the angular resolution of a hologram depends only on its linear dimension, and the linear resolution—on the angular dimensions (Fig. 23). Formulas (37) and (38) are confirmed by experimental data [15]. They have a common value for any mutual arrangements of the reference source, object and hologram (see Fig. 17), i.e. for any holographic scheme.

It is not always possible, however, to use a hologram having such great dimensions as to ensure the required degree of resolution. For example, when using a reference source with a plane wavefront (removed to infinity), an increase in the dimensions of a hologram is attended by a growth in the maximum spatial frequency of its structure. After this frequency becomes equal to the limiting one permitted by the emulsion, a further increase in the dimensions of a hologram will be useless—the photosensitive emulsion will not be able to transmit its pattern. Let us consider this in greater detail.

The spatial frequency of an interference pattern can be written down on

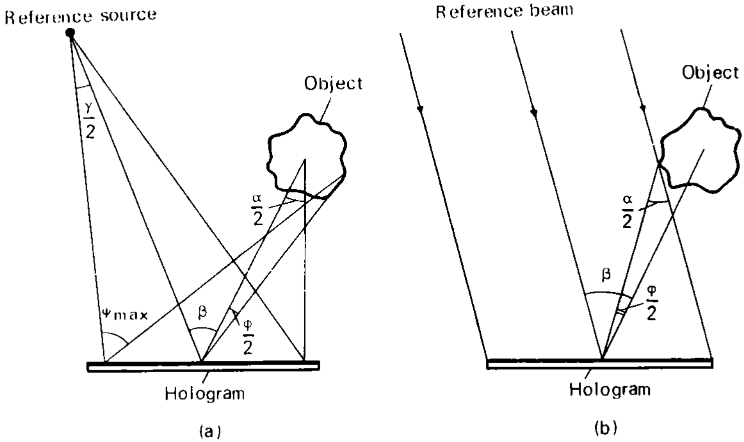


Fig. 24.
To calculation of the spatial frequency of the interference pattern on a hologram:
a—general case;
b—reference source at infinity

the basis of Eq. (24) in the form

$$\nu = \frac{\sin\varphi_1 + \sin\varphi_2}{\lambda} =$$

$$= \frac{2\sin\frac{\varphi_1+\varphi_2}{2}\cos\frac{\varphi_1-\varphi_2}{2}}{\lambda} \tag{39}$$

or, considering that $\cos\frac{\varphi_1-\varphi_2}{2} \approx 1$,

$$\nu = \frac{2\sin\frac{\psi}{2}}{\lambda} \tag{40}$$

where $\psi = \varphi_1 + \varphi_2$ is the angle between the interfering beams.

It follows from Fig. 24*a* that the highest spatial frequency will correspond to the maximum angle between beams

$$\psi_{max} = \beta + \frac{\alpha}{2} - \frac{\gamma}{2} + \frac{\varphi}{2} \tag{41}$$

where α = angular dimensions of the hologram (the apex of the angle at the centre of the object)

γ = angular divergence of the reference beam

β = angle between the axes of the reference and the object beams

φ = angular dimensions of the object.

Thus [15]

$$\nu_{max} = \frac{2 \sin \left(\frac{\beta}{2} + \frac{\alpha - \gamma + \varphi}{4} \right)}{\lambda} \tag{42}$$

Consequently, if the resolution of the emulsion ν_{lim} is given, then we can vary the angles α, β and γ only within such limits at which the following condition is observed:

$$\frac{\beta}{2} + \frac{\alpha - \gamma + \varphi}{4} \leqslant \arcsin \frac{\nu_{lim}\lambda}{2} \tag{43}$$

It should be remembered here that the linear resolution is determined by the angular dimensions of a hologram α, and it is advantageous to make this quantity the maximum one by reducing the others.

Let us first consider the case of a reference wave with a plane wavefront ($\gamma = 0$). In this case, a reference beam passing as close as possible to the object (Fig. 24*b*) corresponds to the minimum angle β. A glance at this figure shows that $\beta_{min} = \frac{\varphi}{2} + \frac{\alpha}{2}$, and condition (43) can be written down as follows:

$$\frac{\alpha+\varphi}{2} \leqslant \arc \sin \frac{\nu_{\lim}\lambda}{2} \tag{44}$$

It is simple to assess the limiting linear resolution achievable in these conditions by replacing arc sin $\frac{\nu_{\lim}\lambda}{2}$ with $\frac{\nu_{\lim}\lambda}{2}$. In this case $\alpha \leqslant \nu_{\lim}\lambda - \varphi$, and in accordance with formula (37) we have

$$\frac{1}{\delta y} \leqslant \nu_{\lim} - \frac{\varphi}{\lambda} \tag{45}$$

In other words, for a hologram formed with a parallel reference beam, the linear resolution in the plane of the object may be only worse than the linear resolution of the photosensitive emulsion.

Let us consider the other extreme case. Assume that the reference source is put in the plane of the object, i.e. that $\gamma = \alpha$ (a lensless Fourier transform hologram). Now α and γ in expression (43) cancel out, and this condition thus imposes no restrictions on the angular dimensions of the hologram α and, consequently, on the linear resolution in the plane of the object.

Thus, a lensless Fourier transform hologram in principle can give a linear resolution with respect to the object that is higher than the linear resolution of the emulsion.

In practice, however, it is difficult to form a hologram covering an angle α

exceeding one radian. For this reason, as follows from formula (37), the limit of the resolution is, as a rule, not less than the wavelength.

Lensless Fourier transform holography permits us, by bringing the reference source as close as possible to the object and leaving the remaining part of the arrangement unchanged, to reduce the spatial frequency of the interference structure by the greatest possible degree. Hence, with such an arrangement of the reference source, the requirements to the resolving power of the photosensitive emulsion may be lowered. It should be remembered, however, that the halo from the bright zero-order image of a source may spoil the edges of the reconstructed image.

Chapter 2

Holographic Experiments

2.1. Arrangements for Forming Holograms

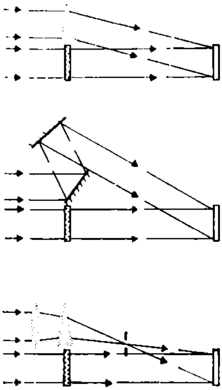


Fig. 25. Forming holograms of transparent objects, according to Leith and Upatnieks

Diagrams of Arrangements. Let us consider diagrams of arrangements used for forming holograms. Lasers are generally used as the source of light, although arrangements are possible employing conventional sources of radiation having a line spectrum which one or several lines are separated from by means of filters. A number of arrangements used for forming holograms of three-dimensional objects and transparencies are illustrated in Figs. 10, 19, 25-34. The rule is for each arrangement to have two branches, one of which illuminates the object, and the other forms the reference beam.

Expansion of Beams and Changing of Their Direction. Lasers emit narrow light beams with a diameter of several millimetres. They are expanded to the requi-

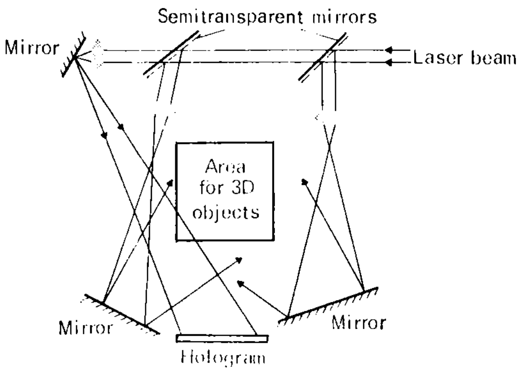


Fig. 26. Forming holograms of three-dimensional (3D) objects with illumination of the object area from two sides

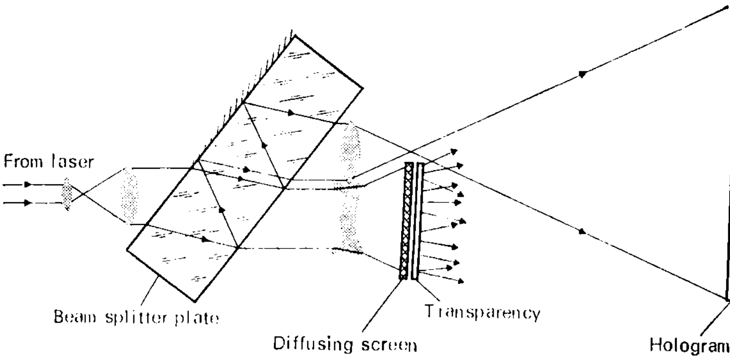


Fig. 27. Arrangement for forming lensless Fourier transform holograms of transparencies using a diffusing screen.
The focal lengths of the positive and negative lenses are the same

red diameter and divergence with the aid of lenses or their systems.

To expand a parallel light beam (Fig. 35), it is convenient to use a telescopic system consisting of a microscope objective and a long-focus lens having a large diameter. The focal points of both lenses are made to coincide. The increase in the diameter of the beam equals the ratio of the focal lengths f_2/f_1. By moving the lens along its opti-

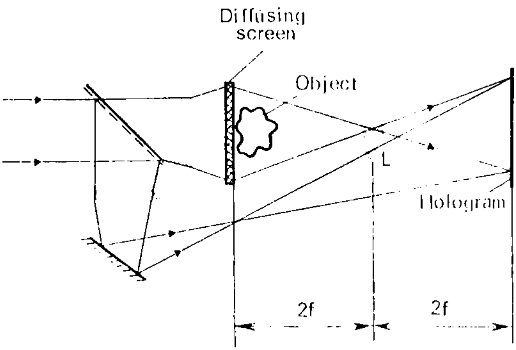


Fig. 28. Arrangement for forming holograms of transparent objects with a diffusing screen upon inadequate spatial coherence of laser radiation.
The diffusing screen is projected by the lens onto the hologram, which makes it possible to achieve coincidence of the mode structure of the reference and object beams

Fig. 29. Arrangement for forming holograms of 3D diffuse objects upon inadequate spatial coherence of laser radiation.

The object is projected by the lens onto the hologram, and this results in coincidence of the mode structures of the beams

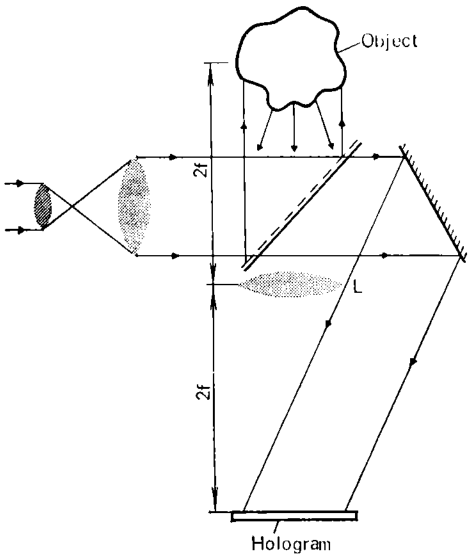
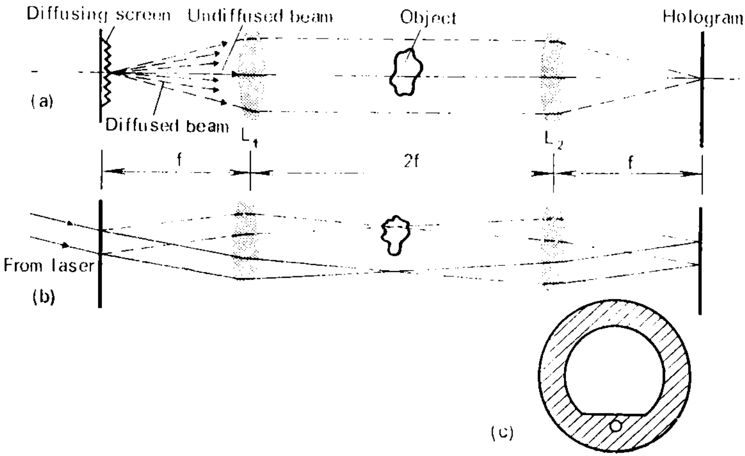


Fig. 30. Arrangement with a diffusing screen [26, 27]:

a—side view; *b*—top view. The diffusing screen is projected onto the hologram by lenses L_1 and L_2. Diaphragm *c* is introduced into the plane of the object. It has two apertures—a big one for the object beam and a small one for the reference beam. The latter is formed by the undiffused part of the light beam



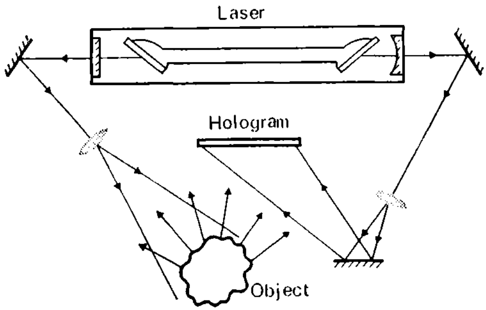


Fig. 31. Forming a hologram without beam splitters, using a second laser beam as the reference one

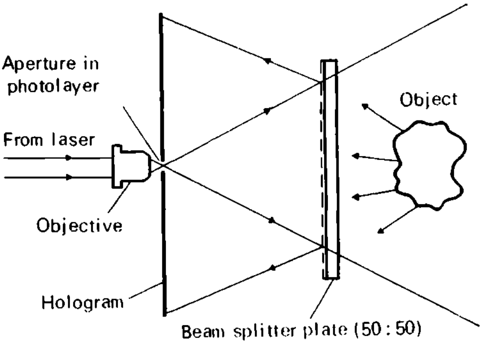


Fig. 32. Arrangement for forming Gabor holograms of opaque diffusing objects [28]

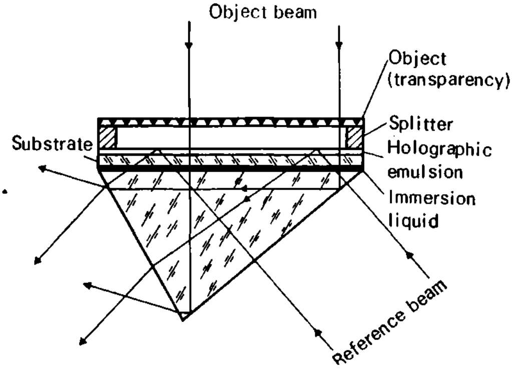
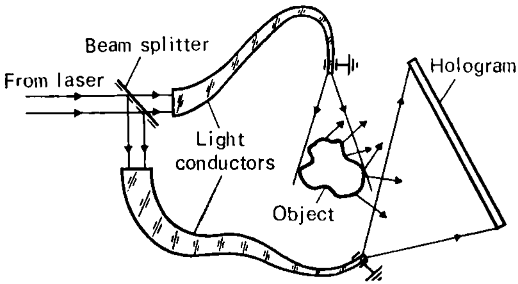


Fig. 33. Forming a hologram with a reference beam subjected to complete internal reflection at the emulsion-air interface [29].
Here actually two holograms are recorded on the emulsion: with the incident reference beam (this hologram has a high spatial frequency) and with the reflected beam (this hologram has a low spatial frequency). The wavefront is reconstructed by means of the same prism. The arrangement permits an object to be placed close to its hologram

Fig. 34. Forming holograms with fibrous light conductors [30].

The narrowing flexible light conductor with an outlet diameter of several micrometres (microns) plays the part of a microscope objective with a pinhole diaphragm and produces an ideal spherical wave at the outlet. The angular expansion of the beam equals the reduction in the diameter of the outlet aperture relative to the inlet one

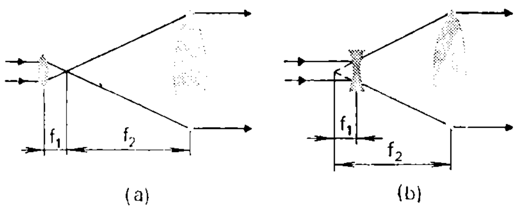


cal axis, it is possible to obtain a converging or a diverging beam of light.

Mirrors and prisms are used to change the direction of the light beams. When using prisms, account should be taken of the possibility of the origination of secondary reflections from the faces, which result in the appearance of parasite beams. The brightnesses of these beams are usually not great, but they may interfere with the main beams and produce quite contrast interference fringes detracting from the quality of the holograms.

Particles of dust that have settled on optical components forming the reference beam affect the quality of holograms in

Fig. 35. Telescopic systems for expanding parallel beam:
a—with a positive lens; *b*—with a negative one. The latter system is preferable when using a laser with a giant pulse, since a laser-induced spark in air may appear at the focal point of a positive lens



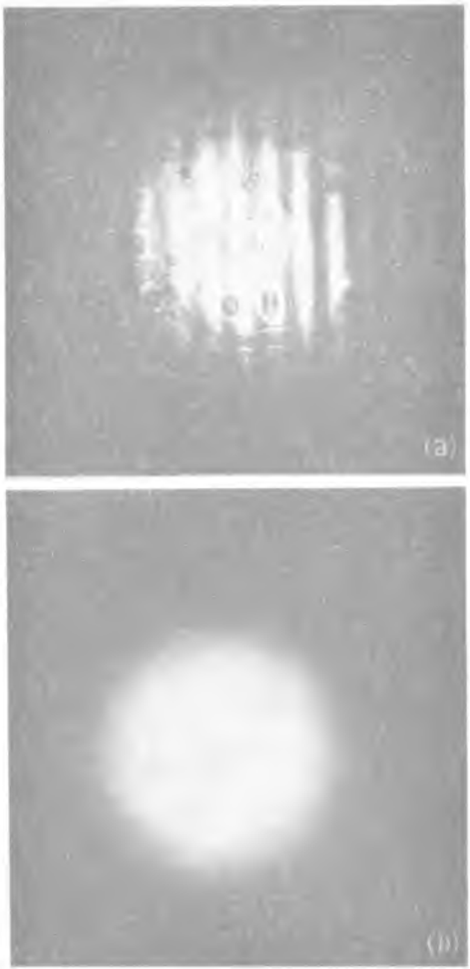


Fig. 36.
Filtration of a reference beam by a lens-pinhole system (photograph from [31]):
a—structure of original beam;
b—ditto after filtration

the same way. The spectacular rings covering the surface of a hologram (see, for instance, Fig. 11*a*) are exactly the result of diffraction of coherent light on dust particles. Here modulation of blackening of a hologram occurs: the sections corresponding to maxima are found to be overexposed, and those corresponding to minima—underexposed. The effective area of the hologram diminishes, and the quality of reconstruction becomes poorer.

A good hologram should have a uniform, visually homogeneous surface. For this purpose, a diaphragm with an aperture having a diameter of the order of 10-15 microns (a pinhole) is usually put at the focal point of the microscope objective. The pinhole adjustment plays the part of a spatial filter. An ideal spherical wave emerges from the pinhole. It is deprived of all traces of aberrations of the optical system forming the beam, of interference due to secondary reflections, and also of diffraction on dust particles and defects of the optical components (Fig. 36).

It is quite natural that the position of the pinhole must be adjusted very carefully in both the longitudinal and lateral directions. Otherwise a major portion of the radiant energy will be retained and will not pass through the pinhole.

A hole of a suitable diameter can be pierced by the point of a needle in thin aluminium foil placed on a smooth hard

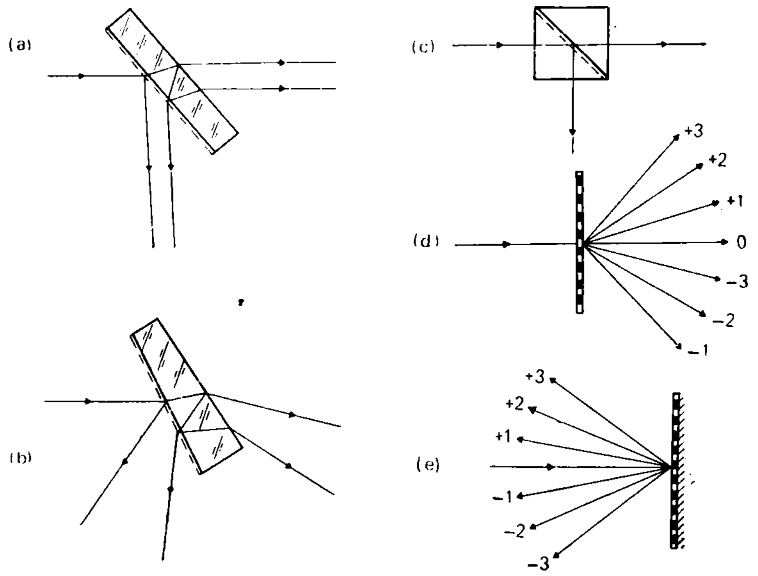


Fig. 37. Arrangements for amplitude division of light beams:
a—semitransparent mirror;
b—wedge;
c—beam splitter cube;
d—transparent grating;
e—reflecting grating

surface. The best hole is chosen under a microscope. A good pinhole can also be pierced by means of a pulsed ruby laser, focussing its radiation on the foil with the aid of a well-corrected lens.

Beam Splitting. The light beam of a laser can be split into two branches in two basic ways, namely, by amplitude division and by wavefront division.

Semitransparent mirrors, wedges or diffraction gratings are used in amplitude division. These arrangements are shown in Fig. 37.

The same purpose is also served by double refraction systems, for example a

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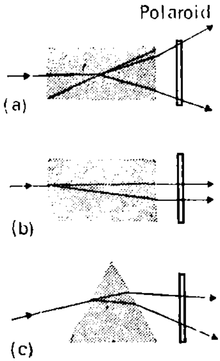

Fig. 38. Polarizing arrangements for the amplitude division of light beams:

a — Wollaston prism (Rochon and Senarmont prisms may also be used); *b* — calcite plate; *c* — calcite prism

Wollaston prism, calcite crystals or crystals of another double-refraction substance (Fig. 38). The beams emerging from such systems are polarized in mutually perpendicular planes, and to make their interference possible, they are passed through a polarizer oriented at an angle of 45 degrees to the planes of polarization of each of the beams. Half of the quantity of light is lost in this case. The beams can be brought to one plane of polarization without a loss of light by means of elements rotating the plane of polarization, for example by passing them through quartz crystal plates cut out at right angles to their optical axis. A plane of polarization is turned through 90 degrees using a quartz plate 4.8 mm thick ($\lambda = 6328$ Å).

A diffusing screen can also be used for amplitude division. The diffused radiation emerging from it illuminates the object, while the part remaining unscattered is used for the formation of the reference beam. Such an arrangement is shown in Fig. 30.

The wavefront of a light wave can also be divided with the aid of mirrors, prisms and lenses. The relevant arrangements are shown in Fig. 39.

Arrangements with wavefront division can be used only with a high spatial coherence of the beam, whereas arrangements with amplitude division can also be used with spatial incoherent radiation. Amplitude division in some cases makes it possible to make the mode struc-

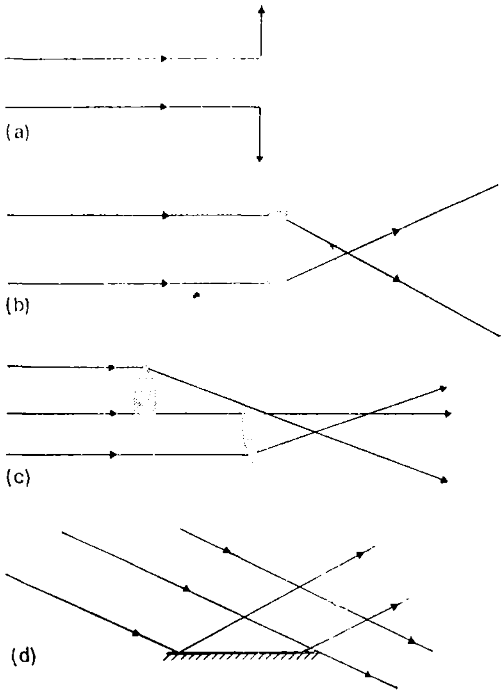

Fig. 39. Arrangements for wavefront division:
a—prism with external reflecting layer;
b—biprism;
c—split lens;
d—Lloyd mirror

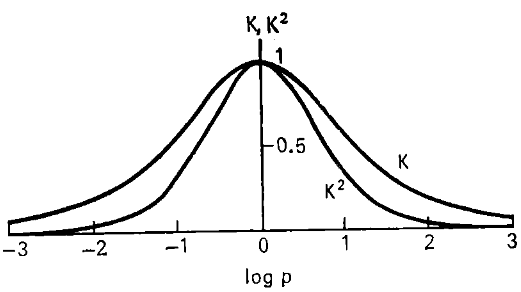

Fig. 40. Dependence of contrast K of interference pattern and its square on the ratio of the illuminations (p) created by the reference and the object beams

ture of the reference and object beams coincide (see below). Beam splitting optical components are sometimes dispensed with in holography, and a second, weaker beam emitted by the laser is used as the reference one (Fig. 31). Fibrous light-conducting elements, such as those shown in Fig. 34 [30, 32], open up broad possibilities for the construction of holographic systems.

Illumination Ratio. When recording holograms, everything possible is done to achieve the optimal ratio between the illumination created in the plane of a hologram by the reference source of light and the object. As a rule, the illumination from the reference source should be several (3-10) times greater. In this case, the exposure is practically completely determined by the illumination created by the reference source, while the contrast of the fringes diminishes somewhat in comparison with the maximum one when the illumination created by both beams is the same. This reduces the possibility of leaving the linear section of the curve in Fig. 21*b*. Figure 40 shows how the contrast K of the interference pattern depends on the ratio of the illuminations $p = E_{ref}/E_{obj}$ created by the interfering beams. The chart was plotted following the assumption of the absolute coherence of the beams according to Eq. (13).

Figure 40 also shows in relative units the dependence on p of the quantity

$K^2 = 4p/(1 + p)^2$, which the brightness of the reconstructed image is proportional to.

N. Nishida [33] used the left branch of the curve (Fig. 40) for reconstructing a negative image from a hologram. In conditions when the illumination created by the object exceeds that created by the reference beam, the brighter parts of the object projected onto the hologram create a grating having a smaller contrast and appear less bright on the reconstructed image. It is obvious that this method of producing negative images can be used for image holograms and cannot be applied to holography in diffuse light, when the radiation from different points of the object is mixed over the entire surface of a hologram.

With a weak reference beam and a correspondingly strong illumination of a hologram by the object, the mutual interference of the light waves emitted by different points of the object becomes appreciable. Each point of the object can be considered as a reference source with respect to its other points. In reconstruction, the image of the reference source is surrounded by a broad halo owing to the diffraction of light on the cross interference pattern. The halo may be superposed on the reconstructed image and spoil it. To prevent this, the angle β between the axes of the reference and object beams (Fig. 19) should be taken greater than 1.5α, where α is the angular dimension of the object. It

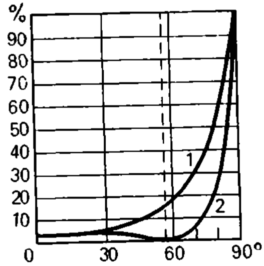

Fig. 41. Dependence of coefficient of reflection R (air-glass interface, $n = 1.52$) on the angle of incidence:
1—the light is polarized in the plane of incidence;
2—the light is polarized in a plane perpendicular to the plane of incidence

should be noted, however, that if the reference beam creates on an emulsion an illumination that is several times greater than that created by the object beam, then the cross interference pattern on the hologram is usually not noticeable. In forming holograms of objects having symmetrical properties, such a cross-interference hologram is sufficient for obtaining much important information on the object. In this case, it is possible to form holograms without a reference beam, which is especially valuable for the x-ray holography of crystals [34].

In a rationally designed arrangement, the desired ratio between the illuminations of a hologram from the reference and the object beams is achieved not by using filters, but by proper selection of the beam splitters. Here the radiant energy of the laser is utilized the most completely. It should be remembered that the losses of energy are usually much greater in the object beam branch than in the reference beam one (from 10 to 1000 times). For this reason, it is often profitable to use a simple glass wedge without a coating as a light-splitting mirror. One of the beams it reflects serves as the reference one. The ratio between the light fluxes in the beams can be varied within broad limits by inclining the light-splitting wedge, since the Fresnel reflection coefficient is known to depend on the angle of incidence (Fig. 41).

To vary the ratio of the beam intensities, it is still more convenient to use the dependence of the ratio between the reflected and passed quantities of light on the orientation of the plane of polarization. Inspection of Fig. 41 shows that if the angle of incidence of the light onto a glass plate ($n = 1.52$) equals 56°40′ (the Brewster angle), then by turning the plane of polarization of the light striking the plate through 90 degrees, it is possible to change the ratio between the beam intensities from five to infinity. At an angle of incidence of 70 degrees, the limits of the change in the intensity ratio range from 2 to 18. The smooth and controlled turning of the plane of polarization is accomplished with the aid of quartz wedges cut out at right angles to their optical axis. The rotatability of quartz is about 19 deg/mm for $\lambda = 6328$ Å and about 16 deg/mm for $\lambda = 6943$ Å.

A polarization beam splitter with a varied ratio of the beam intensities is described by R. Brown [35]. It is similar to the one shown in Fig. 38*a* and consists of a Rochon prism and a half-wave plate placed in front of it. The plate can be rotated about its optical axis. When using polarization beam splitters, it should be remembered that in the long run the directions of the electrical vector of the reference and object waves should coincide as much as possible in the plane of the hologram.

It is sometimes necessary to change the ratio of the beam intensities while entirely retaining their phase structure, For instance, this occurs when developing a hologram for obtaining an interferogram "on the spot", and the ratio of the beam intensities which was optimal in forming the hologram has to be changed for obtaining the maximum contrast of the interference fringes. Here either plane-parallel light filters are used, or high-quality polarizers rotated about the beam axis.

In the latter case, to retain the orientation of the polarization plane constant, a stationary polarizer oriented to the maximum transmission of the original beam is installed after the rotating one.

To diminish phase distortions of the wavefront, a filter or polarizer is introduced into the narrowest part of the beam, generally near a focal point.

It is essential to be able to conduct photoelectrical measurements of the illuminations in the plane of holograms. For this purpose, use is made of any sufficiently sensitive photodiode, photoresistor, photoelectric cell or photomultiplier, by means of which the desired beam intensity ratio is set, and the exposure is determined.

There have also been developed automatic photoelectric shutters which switch on an integrating circuit. The latter operates when the exposure reaches the preset value [36].

Forming Holograms of Self-Luminous Objects. When it is necessary to form a hologram of a self-luminous object, the hologram should be protected from the light emitted by the object. This is achieved by choosing filters having the maximum transparency for laser radiation and cutting out as much as possible the long-wave and short-wave parts of the spectrum.

For example, for a helium-neon laser ($\lambda = 6328$ Å), it is convenient to use a type KC-13 filter [37] which is non-transparent for $\lambda < 6150$ Å. The action of the longer waves of the spectrum is generally eliminated automatically, since emulsions have a low sensitivity to it.

If these measures are not sufficient for eliminating light-striking, then improved filtration is used, for example by means of narrow-band interference filters with a maximum transmission coinciding with the emission line of the laser. It must be borne in mind, however, that such a filter should be installed in a parallel beam of light, since the position of the maximum of its transmission depends on the angle of incidence and shifts toward the short-wave direction when the incident beam deviates from a normal. Polaroids so oriented as to pass polarized radiation of a laser can also serve to diminish light-striking. They halve the natural emission of the object. One should never be afraid of a small dose of incoherent radiation getting onto a hologram, however. It was shown [38] that even when the incoherent exposure is 50 times greater than the exposure due to the object beam (signal), the quality of the reconstructed image remains satisfactory.

Other Components of a Holographic Arrangement. Photographic plates are put into special holders or into holders for cameras or spectrographs. A film (if the size of the frame is adequate) is loaded into an ordinary camera from which the lens has been removed. The lenses, prisms, mirrors, filters and holders should be clamped in mounts having the essential adjusting degrees of freedom.

It is convenient to use components from optical bench sets ОСК-2 or ОСК-3 for the construction of a holographic arrangement. It should be noted, however, that many elements of these costly sets are superfluous for holography, while other ones are provided in an insufficient quantity.

Special sets of optical components for holography have also appeared on the market. In the Soviet Union, they include the interferometric table СИН of the Lenin Novosibirsk Instrument-Building Works, and type УИГ arrangements of the All-Union Research Institute of Opticophysical Measurements. In the United States of America, tables for holography with the required set of components are produced by the Ealing Corp., the Newport Research Corp., Karl Lambrecht Corp., etc., in Great Britain by the Optel Corp., etc.

The firm TRW Inc. (USA) manufactures the "Holocamera 1200" arrangement for pulse holographic interferometry. It includes a single mode pulsed ruby laser with an amplifier that emits double pulses with a given interval between them (from 5 μs to 10 s), a helium-neon laser for adjustment of the system and reconstruction of the wavefront, all necessary holders, mirrors, lenses, diffusing screens, etc. and also a set of the instruments needed for control and adjustment of the circuit—an autocollimator, an oscillograph, etc.

The presumed exposure should be kept in mind when designing a holographic arrangement. The shifting of any components of an arrangement during an exposure should not result in a change in the difference in the length of the path for the interfering beams exceeding $\lambda/4$. If this difference reaches $\lambda/2$, the interference pattern becomes completely blurred. This raises especially stiff requirements to stability of the position of the optical components which the light passes through or which it is reflected from after being separated into two branches. The optical components which reflect or scatter light (they may include the object of holographing) should not shift, as a rule, by over $\lambda/8$. The requirements which light-transmitting components must meet are not so stiff.

All these requirements, which are usual for interferometric arrangements, are easily complied with without any special care being taken if the holograms are recorded by means of pulsed lasers (the duration of a pulse is of the order of 1 millisecond). Giant-pulse lasers with a pulse duration of several nanoseconds or scores of nanoseconds can be used to form holograms even of moving objects.

Continuous-wave (CW) gas lasers are a different matter. When they are used, the exposure ranges from fractions of a second to several minutes, and sometimes even to scores of minutes. In these cases, special measures are taken to fasten the components of the arrangement, to eliminate vibrations, to ensure temperature stabilization, and so on. The components of an arrangement are generally set up on a massive granite, concrete or steel slab, which rests in turn on inflated motor vehicle tyres or tubes, tennis or soccer balls.

Layout slabs or plates available on the market in sizes of 2×1 m and 1.5×1 m are frequently used. The mass of such a slab is about a ton. The natural frequency of oscillations of a slab supported on two motor vehicle tyre tubes is about one hertz.

To see whether an arrangement vibrates or not, it is often enough to have a microscope with the required magnification focussed approximately to the plane which a hologram is to be in, and visually check the immobility and sharpness of the holographic pattern. It is necessary to consecutively test all the possible kinds of mechanical noise (from pumps, machine tools, persons walking in the room, conversations, etc.). This makes it possible to determine what precautions are needed, and what are not. To keep the fringes stationary upon the action of noise, various stabilizing schemes have been proposed that automatically introduce a phase shift compensating for the shift caused by the noise [39]. Arrangements of this kind, however, are very complicated and should be used only in exclusive cases, when all the remaining ways of eliminating noise do not give the desired results.

To eliminate noise or to form holograms of chaotically moving objects, an arrangement with a "local reference beam", which was proposed by a number of authors (for example, [40-42]), can sometimes be used. This arrangement is based on using part of the light reflected or scattered by the object, or the light reflected by a mirror rigidly connected to the object to form the reference beam. The frequency drift due to motion of the object occurs simultaneously in the reference and in the object beams, and the interference pattern remains stationary.

Arrangements with a local reference beam require stability of the object not in the interferometric, but only in the conventional photographic meaning.

If the speed of the object is constant, then the stability of the interference pattern can be increased by compensating for the Doppler shift of the object beam frequency with the aid of an ultrasonic cell placed in one of the beams. A beam of light undergoing diffraction on the running ultrasonic wave has a frequency differing from the original one by $\Delta\nu = \pm k\nu_{us}$, where k is the order of the spectrum and ν_{us} is the frequency of ultrasound. Taking into account that $\Delta\nu_D = \frac{v}{\lambda}\cos\theta$ and assuming that $\Delta\nu = \Delta\nu_D$, we get an equation for calculating the required frequency of the ultrasonic generator:

$$\nu_{us} = \frac{v\cos\theta}{k\lambda}$$

For example, the required frequency of the ultrasonic cell for an object, the projection of whose speed v on the object beam is $v\cos\theta = 10$ m/s, is about 16 MHz ($\lambda = 6328$ Å, $k = 1$).

If a hologram of the required area cannot be exposed owing to the limited stability of the arrangement and the insufficient power of the laser, then, as proposed in [43], it can be exposed by portions.

When it is necessary to keep a hologram in exactly the same position which it was in during the exposure, it is developed and fixed on the spot [44]. This necessity appears in holographic interferometry (see Sec. 3.2). A special photographic plate holder is used for developing on the spot. It permits a glass or flask with the developing solution to be placed under it (Fig. 42*a*). Other

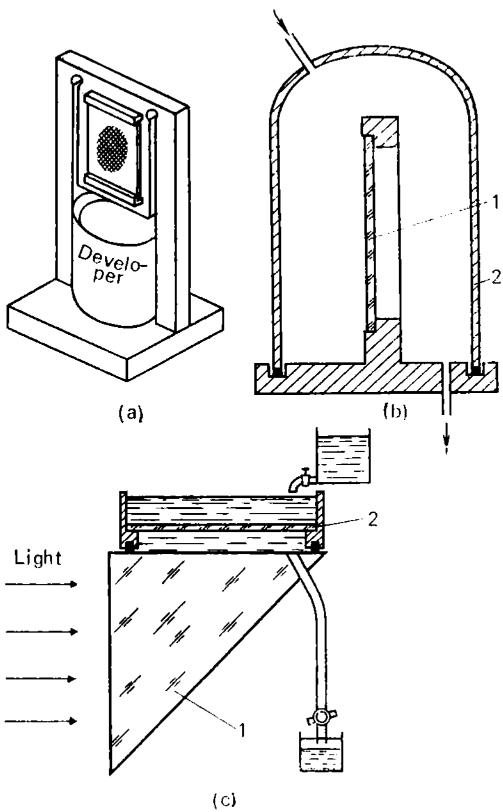

Fig. 42. Devices for developing a hologram on the spot

devices have been proposed. Figure 42*b* shows a plate holder (*1*) with a bell jar (*2*) which is fitted onto the holder for developing and washing the hologram. Figure 42*c* shows a device for developing with a 45-degree prism (*1*) [45]. An opening is made in the prism for draining off the solutions. Before exposure of a hologram and after developing and fixing it, a tray with the photographic plate (*2*) secured on the prism is filled with pure water. This is needed in order to keep the emulsion in a swollen state. In addition, the water plays the part of an immersion diminishing the losses of light due to reflection and improving the quality of the reconstructed images.

It was proposed [46] to achieve the same result by exposing a hologram on a plate preliminarily placed for several minutes in a developer. In this case, it is possible to directly observe the appearance of the reconstructed image during an exposure.

Diffusing Screens. When recording holograms of transparencies, diffusing screens are usually placed before them. The screens transform the directed radiation of a laser into diffuse radiation. A hologram of a transparency formed with a diffusing screen has all the properties considered above characteristic of holograms of three-dimensional diffuse reflecting objects. The main property among them is that the radiation from each point of the object is distributed over the entire hologram and, consequently, each small section of the hologram contains information on the entire object. As a result, a virtual image of the entire transparency can be observed directly with the eye. If a hologram of a transparency is recorded without a diffusing screen, then the hologram does not have this property, and a different section of the hologram corresponds to each section of the transparency. Diffusing screens are also used for uniform ang diffuse illumination of three-dimensional objects and scenes. The use of a diffusing screen levels out the exposure over the entire surface of a hologram and facilitates the selection of the working point on the characteristic curve when the dynamic range of the emulsion is limited. It is quite natural that the characteristics of a hologram depend to a considerable extent on the properties of the diffusing screen.

Finely ground glass or quartz is generally used as a diffusing screen. A very fine-grain screen can be obtained by processing a glass plate in hydrogen fluoride vapour. It is good practice to use milk glass as diffusing reflectors. Some glass plates of this kind have a diffusing reflectivity close to unity. Metal or glass surfaces coated with a layer of magnesium oxide are used for the same purpose.

When diffusing screens are used in holography, it should be remembered that the angular dimensions of a hologram must be coordinated with the diffusion indicatrix. If the latter is too broad, a considerable portion of the laser light will pass outside of the hologram. If, on the contrary, the diffusion indicatrix is very narrow, then this results in uneven illumination of the

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hologram. The shape of the indicatrix is mainly determined by the size of the diffusing screen grains. A Christiansen filter can be used as a diffusing screen [47]. This is a suspension of a glass powder in a liquid whose refractive index is close to that of glass. The width of the diffusion indicatrix of such a filter can easily be controlled by changing its temperature, which is very convenient in a number of cases. It is necessary, however, to keep the temperature of such a diffusing screen strictly constant during the entire exposure.

J. Gates [27] in the arrangement shown in Fig. 30 used a bleached hologram of a ground glass formed in the same arrangement as a diffusing screen. This resulted in ideal agreement between the diffusion indicatrix and the geometry of the arrangement. The zero-order beam of such a hologram served as the reference beam. About 60% of the total light flux corresponded to it. From 10 to 15% fell to each of the two diffused first-order waves.

In the reconstruction of the images of objects with diffuse reflection or of transparencies illuminated through a diffusing screen, a characteristic speckle pattern of the image appears, as was noted on an earlier page (Fig. 15). The grain size is determined by the aperture of the hologram. The speckle pattern detracts from the resolving power of holograms, especially when the aperture is small. To diminish the influence of the speckle pattern, the exposure can be divided into several parts by shifting the diffusing screen slightly each time. Several holograms will be correspondingly recorded on the emulsion, each of which will regenerate the same image of the object at the same place, but the speckle pattern of these images will be different, and it is exactly this feature that will result in its averaging.

One should obviously never try to form a hologram with the diffusing screen moving chaotically during the exposure. A hologram recorded in this way will reconstruct no image. However, if a moving film with a non-uniform thickness (for example, a disk made of tracing paper or polyethylene revolved by a small motor) is introduced into the light beam used in reconstruction, it is usually possible to considerably reduce the visible speckle pattern of the image averaged in time.

Another method of weakening the speckle pattern of the reconstructed image can be applied only to Fourier transform holograms. The spatial frequency of the interference pattern in such a hologram changes very slowly. For this reason, small translational movements of a hologram in its own plane do not practically lead to shifting of the reconstructed image. At the same time, the speckle pattern of the image at each new position of the hologram changes chaotically. Consequently, if a Fourier transform hologram is secured on a vibrating support, an appreciable improvement of the image can be achieved. The author used the diffuser of a switched on loudspeaker as such a support.

The illumination of three-dimensional phase objects through a diffusing screen provides the opportunity of reconstructing and investigating the waves which passed through the object in many directions.

This is essential for the unambiguous interpretation of the results obtained. In particular, it is possible to construct the field of the refraction index of a non-axisymmetric phase object according to a single holographic interferogram covering a sufficiently great solid angle.

To obtain contrast interference fringes, however, it is necessary to iris the hologram. This, in turn, leads to the speckle pattern of the reconstructed image becoming coarser.

C. Vest and D. Sweeney [48] propose to illuminate the object not with the aid of a diffusing screen, but through a phase diffraction grating. The holographically recorded grating with 50 lines per millimetre yielded bright beams of the first three orders at each side of a normal and thus made it possible to obtain seven interferograms deprived of a speckle pattern and covering an angle of vision of about 11 degrees (through 1.8 degrees).

2.2. Sources of Light for Forming Holograms

The main requirements to the extension and monochromatic nature of a source of light for the formation of holograms were considered in a previous section. Light waves emitted by a source in different directions should interfere with one another upon their subsequent meeting on a hologram. This property of light waves, determined by the angular dimensions of the light source, is called *spatial coherence*. Light waves that spend a different time along their path from the source to the hologram should also form contrast interference fringes when they meet one another. This property is called *time coherence*, and it is connected with the monochromatic nature of the light source.

To obtain radiation with the required time coherence, light from a conventional source (incandescent lamp, mercury-discharge lamp, etc.) can be passed through a narrow-band monochromator.

For producing a light wave with a sufficient spatial coherence, the distance from the source should be so great as to ensure its angular dimensions being sufficiently small, or its radiation should be focussed on an aperture having a sufficiently small diameter.

By meeting the requirements of spatial and time coherence in these ways, however, we lose the predominating part of the light flux.

Thus, the problem of the coherence of radiation boils down in the long run to that of the spectral brightness of the source, i.e. to the power emitted by its unit area in a unit of solid angle within a unit wavelength interval.

Lasers are superior to ordinary sources as regards their spectral brightness millions and thousands of millions of times. In contrast to ordinary sources, a laser emits light within a very small solid angle. Hence, by focussing the laser radiation on a small aperture or by removing the laser to a sufficiently great distance from the holographic arrangement, we lose practically no energy.

Laser radiation, as a rule, is highly monochromatic, which makes it possible to also meet the requirements of time coherence without any appreciable losses of light. For these reasons, the progress of holography became possible only after the invention of the laser.

The development of holography, in turn, resulted in the creation of arrangements in which the requirements to the coherence of light are considerably lowered. In a number of cases, this made it possible to record high-quality holograms in the light of conventional (non-laser) sources.

Lasers. The first laser holograms were obtained with the aid of a helium-neon laser having a wavelength of 6328 Å. Later the much more powerful argon laser (λ = 5145, 4880, 4765 Å) was also

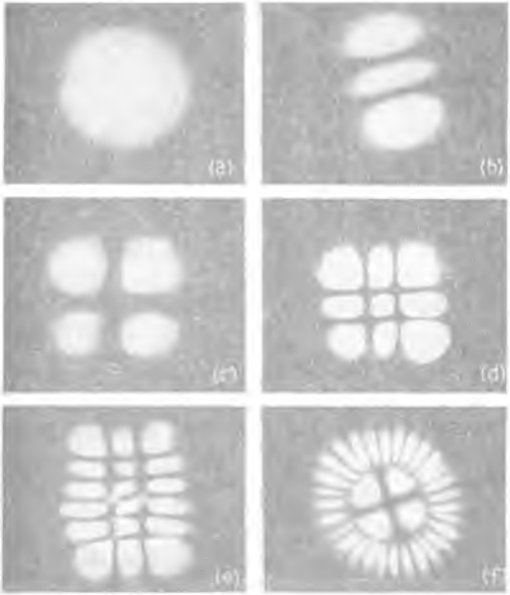


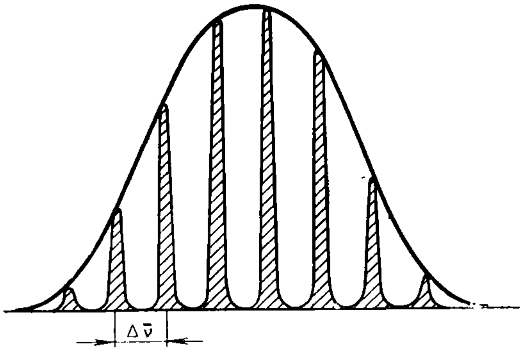
Fig. 43. Distribution of intensities over the cross section of the beam emitted by a helium-neon laser:
a—TEM_{00q};
b—TEM_{02q};
c—TEM_{11q};
d—TEM_{22q};
e—TEM_{25q};
f—complex multimode structure

used as a source of radiation. Pulsed lasers, ruby ones as a rule, are also used at present for forming holograms ($\lambda = 6943$ Å).

A number of special books (for example, [49-53]) are devoted to the operating principles of lasers and a detailed description of their properties and features. We shall stop here to consider only the coherent properties of laser radiation owing to which lasers have become indispensable sources of light for holography.

Transverse standing waves of the TEM (transverse electromagnetic) mode set in

Fig. 44
Structure
of a laser line



in a laser resonator. The mode of oscillation can be characterized by three subscripts and is designated TEM_{mnq}.

The first two subscripts (m and n) relate to the distribution of the fields in a plane perpendicular to the axis of the resonator. Modes differing in these subscripts are called *transverse*. If a laser generates only one of them, then such operating conditions are called *single-mode*. Figure 43 shows the beam cross sections when a laser generates different transverse modes. The number of simultaneously excited modes is determined by the configuration of the resonator and the nature of interaction of each mode with the active medium.

The radiation corresponding to the principal lower-order mode—TEM_{00q}—concentrates near the axis of the resonator. The angular divergence of the radiation for the mode TEM_{00q} is minimum and is determined by diffraction. An increase in the number of transverse modes leads to a growth in the angular divergence of the radiation and is equivalent to an increase in the extension of the source.

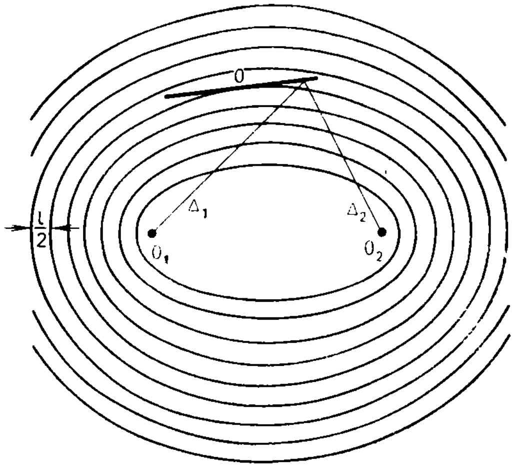
The third subscript (q) equals the number of standing waves accommodated along the length L of the resonator. The modes of oscillations differing with respect to this subscript are called *longitudinal* or *axial*.

The radiation line of a laser operating in several longitudinal modes consists of a number of equidistant lines with a spacing between them (in a wave number scale) of $\Delta\bar{\bar{\nu}} = \frac{1}{2L}$ (Fig. 44). The number of simultaneously generated longitudinal modes is determined by the width of the line of fluorescence of the active medium and the elevation of the pumping level over the threshold one. The conditions in which a laser generates only one longitudinal mode are called *single-frequency* ones. The subscript q is expressed by a number greater than m and n, and is generally omitted when designating the modes.

The coherence length is obviously maximum when a laser is operating in single-frequency conditions.

An inadequate coherence length limits the depth of a holographic scene and makes it necessary to take measures for equalizing the paths of the reference and the object beams from the point of their separation to the hologram. In this case, care should also be taken to ensure

Fig. 45. Principles of rational illumination of an object with a limited coherence length of the light source [54]



a rational arrangement of the object relative to the light source and the hologram so that the path source-object-hologram would be about the same for all the points of the object.

It is simple to understand the principles of the most rational arrangement of an object from this viewpoint [54] by examination of Fig. 45.

Let us locate the source illuminating an object at point O_1 and the centre of the hologram at point O_2. The surface for whose points the sum of the distances $b = \Delta_1 + \Delta_2$ from O_1 and O_2 is constant is an ellipsoid of revolution with the foci O_1 and O_2.

Figure 45 shows a section of a family of such ellipsoids to each of which there corresponds its own value of b, and

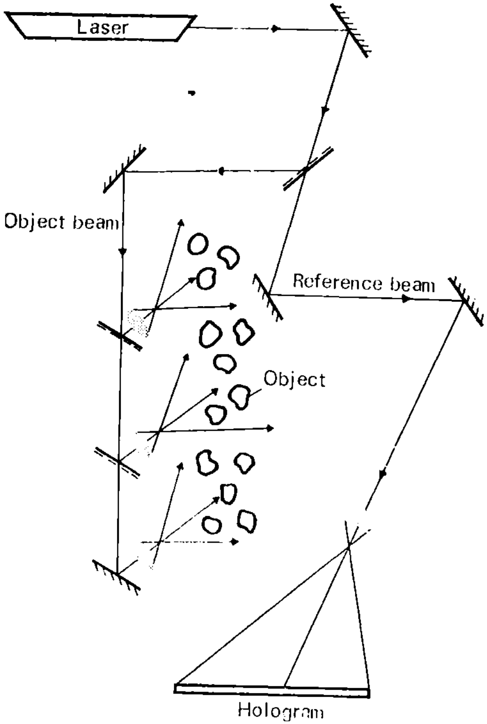


Fig. 46. Forming holograms of a scene extended in depth by means of a laser with a limited coherence length [55]

to its neighbouring ellipsoids—a change in b by l—the coherence length.

If the illuminated surface of the object (O) is so arranged that it fits into the space between two neighbouring ellipsoids (as shown in Fig. 45), then the time coherence of the source will obviously be sufficient for forming a hologram of this surface.

Extended objects can also be illuminated with the aid of the arrangement shown in Fig. 46, in which the object is illuminated by parts.

Helium-neon lasers with short discharge tubes (10-20 cm) generally operate in single-frequency conditions—only one generation line fits in the width of a fluorescent line. A drawback of such lasers is the low radiated power (from 0.1 to 0.5 mW). Helium-neon lasers with a resonator length of about 1 or 2 metres have a considerably higher power (20-150 mW), but their coherence length is not great and usually equals 10 to 20 cm.

A number of techniques have been developed for increasing the time coherence of lasers. Most of them consist in introducing into the resonator a selective element that supplies different losses for different components of the line. As a result, the quality of the resonator does not practically change for some longitudinal modes, while for others it becomes considerably poorer. The result is disruption of generation on these wavelengths: the line appreciably narrows, whereas the coherence length grows. The total radiated power diminishes only slightly.

Ruby lasers, if no measures are taken for narrowing of the line, have a coherence length not exceeding several centimetres. Selection of the longitudinal modes by means of resonance reflectors makes it possible to increase the coherence length up to several metres.

The action of the resonance reflectors formed from two or three glass, quartz or sapphire plane-parallel plates is equivalent to the complex Fabry-Perot etalon (multiplex). Its transmission spectrum has narrow peaks within whose confines generation is carried out.

The transverse modes are usually selected by introducing a stop into the resonator of the laser (Fig. 47). Such a stop is provided in the design of certain gas lasers. The generation power diminishes for gas lasers (for example, of types ЛГ-35, ЛГ-36 and ЛГ-36А) to about one-half to one-fourth of the original value when a stop is introduced. The flash energy of a ruby laser emitting a giant pulse when a stop is introduced which suppresses the generation of off-axis modes diminishes to from one-tenth to one-fiftieth of the original value. The radiation of such a laser can be amplified by placing a second laser head, excited synchronously with the master one, on its output end. The gain factor usually ranges from 3 to 5, which to a considerable extent compensates for the losses due to the introduction of a stop. Some authors used even two- and three-stage or two- and three-pass amplifiers of this kind.

There are a number of techniques making it possible to form holograms of a good quality when using multimode lasers. All of them boil down in the long run to more or less accurate coincidence of the mode structures of the reference and object beams on a hologram.

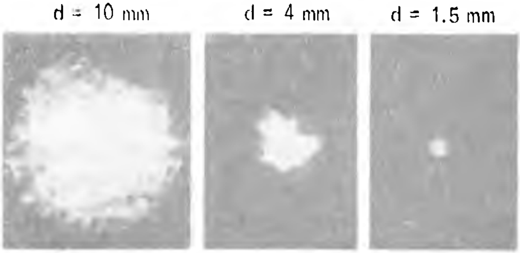


Fig. 47.
Suppression of off-axis modes by introducing a stop (d) into the resonator of a ruby laser, photo from [56].

It is generally easy to comply with this requirement when forming holograms of transparencies or weakly scattering phase objects.

The arrangement for matching the mode structure is somewhat more complicated when forming holograms of transparent objects using a diffusing screen. In this case, it is necessary to project the screen onto the hologram [57] by means of a special lens (see Figs. 28 and 30). Such an arrangement, however, is suitable only if the object itself does not appreciably mix the structure of a beam.

In forming holograms of three-dimensional scattering objects, the mode structures of the reference and object beams can be made to coincide to a certain extent by projecting the object onto the hologram, for instance, using the arrangement shown in Fig. 29.

Studying the Coherence of Radiation. The time coherence of laser radiation can be studied directly according to the visibility (contrast) of the interference fringes when observing the interference of beams that have travelled different paths, for example, with the aid of a Michelson interferometer. The time coherence of radiation can be measured according to the width of the spectral line with the aid of spectral instruments having a high resolving power (for example, the Fabry-Perot etalon).

A number of procedures have been developed for controlling the spatial coherence of radiation. All of them involve the observation of the interference of light beams emitted by a source in different directions, and measurement of the contrast of the interference fringes formed.

Such a possibility is provided, for example, by Young's classical arrangement, in which a screen with two small apertures is placed in the path of the radiation being studied, and then the interference of the light diffracted by these apertures is observed [58-60]. In the Jamin, Michelson, Mach-Zehnder and other two-beam interferometers, exact coincidence of the wavefronts from both branches takes place at the output. Absolutely contrast interference fringes are observed in the plane which such coincidence occurs in regardless of the degree of spatial coherence of the light striking the interferometer. It is called the *plane of localization* of the interference pattern. If the conditions of coincidence of the wavefronts are artificially violated, then the contrast of the observed interference pattern will be determined by the degree of spatial coherence of the light.

A number of methods of measuring spatial coherence are based on this fact. For example, one of the mirrors of a Michelson interferometer was replaced with a corner reflector [61]. Thus, the wavefront travelling along one branch of the interferometer was found to be inverted as if by a mirror relative to the wavefront travelling along the other branch.

In another method, the conditions of coincidence of the wavefronts were violated by inclining one of the interferometer mirrors [62].

A method requiring no alteration or readjustment of the interferometer is described in [63]. The spatial coherence of the radiation was measured according to the contrast of the interference pattern formed at different distances from the plane of localization of the fringes. With an increase in the distance from this plane, the contrast of the fringes diminishes the more rapidly, the lower is the degree of spatial coherence of the light (the greater is the extension of the source).

We shall now stop to briefly consider holographic methods of studying coherence. It is quite obvious that a hologram will reconstruct the true distribution of light over the surface of an object only when the entire object is illuminated with coherent light. The

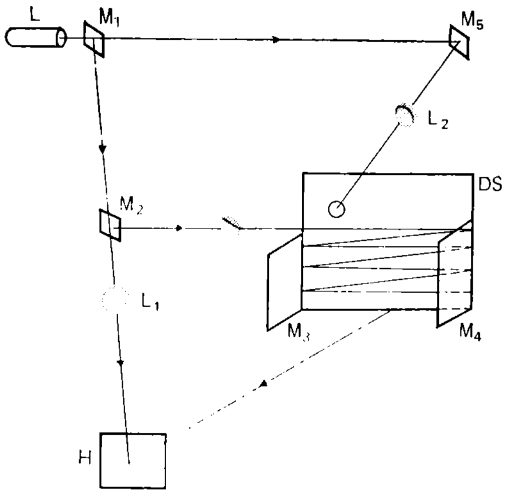


Fig. 48. Arrangement for the holographic measurement of time and space coherence of laser radiation [65, 66]:
M_1 and M_2—light-splitting mirrors;
M_3-M_5—reflecting mirrors;
L_1 and L_2—lenses;
DS—diffusing screen;
H—hologram
L—laser;
the lens in the centre is cylindrical

sections of the object illuminated with incoherent light do not contribute to the structure of the hologram, but only create a background.

Therefore, such sections will not be regenerated when reconstructing the image, and they will be dark.

Sections of an object illuminated with partly coherent light will give a pattern having a lower contrast on the hologram, and upon reconstruction will be found much darker than they should have been on the basis of their illumination. The contrast of the structure is proportional to the degree of spatial-time coherence, while the brightness of the reconstructed image is proportional to the square of the contrast of the structure (see p. 84). Thus, the true distribution of the brightness in the reconstructed image will be modulated by the square of the function of spatial-time coherence.

This underlies the holographic methods of determining coherence [64, 65]. If the object is extended in depth and is uniformly illuminated by light emerging from the source in one direction, then the distribution of the brightness in the reconstructed image of the object corresponds to a function of the time coherence.

If the depth of the object is not great, and light emerging from the source at different angles corresponds to different points of it, then the distribution of the brightness in the reconstructed image of the object corresponds to a function of the spatial coherence of the source with respect to the reference beam. The arrangement shown in Fig. 48 makes it possible, by reconstructing the image of the diffusing screen through different points of the hologram, to reveal the mode structure of the laser beam illuminating the screen [66, 67].

Changing the Wavelength. While broad possibilities exist for choosing the wavelength of a continuous laser, in pulse holography the choice is limited to a ruby laser with a wavelength of 6943 Å. Neodymium lasers ($\lambda = 1.06$ microns) are not convenient both owing to their radiation lying in a region of the spectrum difficult to record, and because of the low coherence of the radiation. The width of the radiation line of a neodymium laser is scores of angstroms, and its coherence length is fractions of a millimetre.

The methods of non-linear optics provide certain possibilities for extending the set of wavelengths of laser lines. At present, highly effective methods have been developed for generating the second and third harmonics of the radiation of a ruby laser ($\lambda = 3472$ and 2314 Å). The first of these lines was already used for forming pulse holograms [68-70].

The second harmonic of a neodymium laser ($\lambda = 5300$ Å) was also used for forming holograms of processes proceeding at a high rate [71]. The coherent properties of the original radiation are completely retained when the frequency is doubled.

The forming of holograms in the light of stimulated Raman scattering provides broad possibilities for choosing the wavelength owing to the diversity of liquids, gases and solids that can be used. A noticeable difficulty here, however, is the lowering (by more than an order) of the degree of spatial coherence of the stimulated Raman scattering in comparison with the degree of spatial coherence of the exciting laser radiation [63].

Notwithstanding this circumstance, stimulated Raman scattering was already used for the formation of holograms [72].

Semiconductor [73] and dye solution lasers were also used as the source of light for the formation of holograms. The introduction of tunable narrow-band selective elements (such as a Fabry-Perot interferometer or a diffraction grating) into the resonator of dye solution lasers makes it possible to obtain highly coherent radiation within a broad range of wavelengths [74-77].

Apart from helium-neon and argon lasers, a number of other laser sources of continuous radiation have already been used or can be used in holography. From this standpoint, the helium-cadmium lasers ($\lambda = 3250$ and 4416 Å) already available on the market are very prospective.

Carbon dioxide lasers are the most powerful sources of continuous coherent radiation. The wavelength of their radiation ($\lambda = 10.6\,\mu$), however, is in the region which it is difficult to record.

Forming Holograms without Lasers. A hologram is the interference pattern obtained when a reference wave is superposed onto the waves scattered by an object. We considered the formation of a hologram as follows: each point of an object emits a spherical wave which upon interfering with the reference one creates an interference pattern in the form of a Fresnel zone plate. The zone plates formed by each point are coherent; their coherent superposition is recorded on a hologram (the amplitudes are summated with account of the phase relations, and not of the illumination).

At the same time, holographic arrangements are possible in which the holograms are formed with spatially incoherent illumination. In these arrangements, the light from each point of an object splits into two channels and forms two spherical waves having different curvature. The waves upon interference with one another produce a Fresnel zone plate. The rings formed by different points are incoherent. They are superposed on the hologram with summation according to illumination. The quality of the hologram (its contrast) is considerably poorer than with spatially coherent illumination, it being the poorer, the more complex is the object. The quality of a hologram, however, may be sufficiently high for simple objects consisting of a small number of luminous points.

We already considered one of the ways of forming holograms with the use of spatially incoherent light in connection with the possibilities of using multimode lasers with many transverse modes of oscillations for holography (see Figs. 28-30). These arrangements provide for amplitude splitting of a wave into two parts, and then for exact coincidence of the wavefronts on the hologram as far as possible. One of them passes through the object being studied, and it is essential that it introduces only small distortions. Otherwise the coincidence of the two waves on the hologram will be inexact, and the interference pattern have a low contrast.

Another aspect of the same problem is the formation of holograms with the aid of light sources having a low time coherence. When a low-pressure mercury-discharge lamp is used with a filter separating one of the lines, the coherence length is several millimetres. Sources of light with narrower lines have a low intensity, and in this respect have no prospects (for example, atomic beams with a coherence length of the order of one metre).

High- and superhigh-pressure mercury-discharge lamps emit very bright, but very broad lines whose coherence length does not exceed tenths of a millimetre. For this reason, when forming holograms with the aid of such light sources, the optical paths of both branches of the arrangement should be equalized very carefully.

Notwithstanding the difficulties listed above, the achievements in "non-laser" holography are quite considerable. In some cases, the quality of reconstruction of the wavefront is so high that the results are practically not inferior to those obtained in "laser" holography [78, 79].

Any arrangement with Michelson, Jamin, Mach-Zehnder and other interferometers can be used to divide the wavefront into two parts and then combine them in forming a non-laser hologram. A number of other arrangements

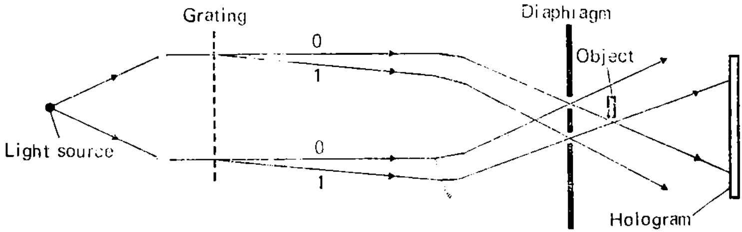


Fig. 49. Arrangement for forming achromatic holograms [79]: *0*—zero-order beam; *1*—first-order beam

for forming non-laser holograms were proposed by A. Lohmann [80]. G. Stroke and R. Restrick [81] used an interferometer with a diffraction grating, while C. Froehly and J. Pasteur [82] used one with two half-lenses.

Considerable achievements in non-laser holography were made by E. Leith and J. Upatnieks [79]. Their arrangement for recording achromatic holograms is shown in Fig. 49. The achromatization is needed to create such conditions in which the phase difference of the interfering waves does not depend on the wavelength. This is achieved by introducing an achromatizing element into the arrangement, for instance a prism, lens or diffraction grating. In the arrangement in Fig. 49, the grating forms a diffraction spectrum in the plane of the diaphragm (a complex of its monochromatic images). A zero-order beam is used to illuminate a transparency, and a spectrum of one of the first orders is used as the reference source. The parts of this spectrum having longer waves strike the hologram at greater angles than those having shorter waves do, but the spatial frequency of the fringes on the hologram remains the same for all the waves.

The use of the arrangement shown in Fig. 49 lowers the requirements not only to time, but also to spatial coherence of the source of radiation, since according to the van Cittert-Zernike theorem (see, for example, [12, 13]), the degree of mutual coherence is the maximum for the waves propagating after the grating in the direction of the diffraction peaks.

Using a superhigh-pressure mercury-discharge lamp with a filter separating one of the lines, Leith and Upatnieks [79] obtained a high-quality reconstruction of transparencies and silhouette three-dimensional scenes compatible with those obtained when using lasers.

The above arrangement makes it possible, as shown in [83], to use light sources for holography whose monochromatic properties are still lower—a mercury-discharge lamp without a filter and even an incandescent lamp without a filter. The quality of reconstruction is naturally not high.

Multicolour Holograms. We have already mentioned the possibility of forming holograms reconstructing not only the structure, but also the "colour" of a light wave (p. 55). A general arrangement for forming a multicolour two-dimensional hologram is shown in Fig. 50. Three diffraction gratings are formed on such a hologram, namely, a "blue" one

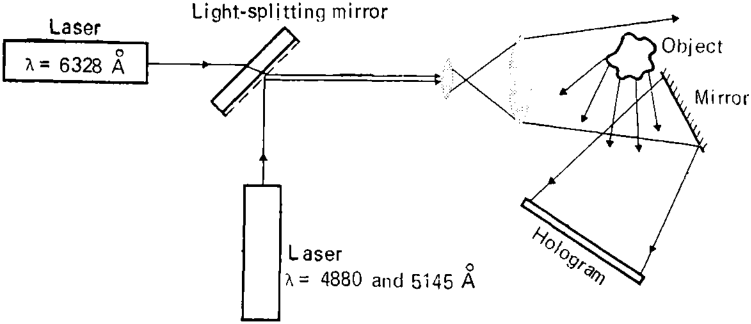


Fig. 50. Arrangement for forming a "three-colour" hologram with the aid of a helium-neon and an argon lasers

(λ = 4880 Å), a "green" one (λ = 5145 Å) and a "red" one (λ = 6328 Å).

When reconstructing the wavefront by means of a three-colour beam, diffraction of the red light on a "red" grating, of the green light on a "green" one and of the blue light on a "blue" grating gives a correct three-colour image of the object. The red light, however, also diffracts on the green and blue gratings and thus gives two images of the red light that are displaced relative to the correct three-colour image. The blue and green rays diffract in a similar way on "alien" gratings.

Thus, in addition to the correct three-colour image, six single-colour images are formed that are displaced with respect to one another and may be superposed on one another and on the correct image.

A number of investigators tried to circumvent these restrictions, but good results were obtained only when using holography with recording in a three-dimensional medium [7-9]. It was shown earlier that such holograms are selective with respect to the wavelength and therefore give reconstructed images only in the light of their "own" wavelengths. For this reason, three-dimensional multicolour holograms form no hindering auxiliary images [84, 85]. The wavefront can be reconstructed in white light. Such a hologram plays the part of an interference filter separating the needed wavelengths.

One of the most serious problems appearing here is the shifting of the wavelength in reconstruction owing to shrinkage of the emulsion. The reconstructed image "turns blue" to quite a considerable extent, since the shrinkage reaches 15-20%. The best way of combatting this phenomenon is to submerge the developed and fixed hologram in a solution of triethanol amine. The concentration of the solution and the duration of the bath are selected experimentally. It should be noted that the colour of the reconstructed image may also differ from that of the object as a result of the fact that the diffraction efficiency of a hologram determined by the contrast of the pattern recorded on it diminishes with a decreasing wavelength. This is due to two reasons: firstly, the smaller the wavelength, the greater is the spatial frequency of the interference pattern [see expression (21)] whereas the frequency-contrast characteristic (see

p. 143) of photographic materials drops with an increase in the spatial frequency; secondly, radiation having a smaller wavelength scatters to a greater extent in the emulsion, and therefore the frequency-contrast characteristic drops with a reduction in the wavelength.

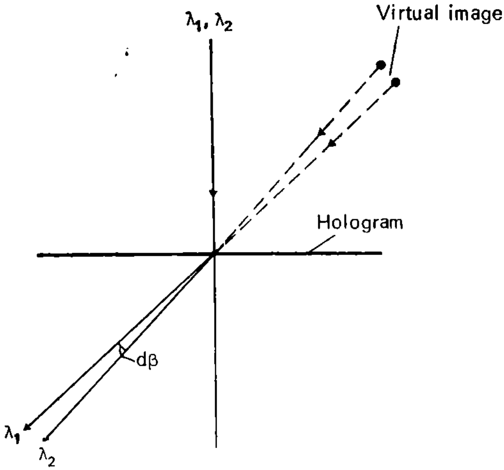
2.3. Reconstruction of Wavefront

Requirements to Time Coherence. In the reconstruction of a wavefront, the requirements to the spatial and time coherence of the radiation are as a rule considerably more lenient than in forming holograms. For this reason, conventional (non-laser) light sources are often used in reconstruction of the wavefront. The requirements to the time coherence of the radiation of such a source are determined by the fact that the images of the object obtained in the diffraction of light of various wavelengths on a hologram should not be appreciably shifted relative to one another. In other words, the angle $d\beta$ (the angular displacement of the points of an image obtained in wavelengths differing by $d\lambda$) should be less than the realized angular resolution $\delta\varphi = \delta x/r$ (Fig. 51), where δx is the linear resolution, and r is the distance from the hologram to the reconstructed image, i.e.

$$d\beta \leqslant \delta\varphi \quad \text{or} \quad \frac{d\beta}{d\lambda}\, d\lambda \leqslant \delta\varphi$$

Here $d\beta/d\lambda$ is the angular dispersion of the hologram, equal, as follows from

Fig. 51.
To determination of permissible non-monochromaticity of reconstructing light source



Eq. (25), to

$$\frac{d\beta}{d\lambda}=\frac{1}{a\cos\beta} \tag{46}$$

We finally have

$$d\lambda \leqslant a\delta\varphi\cos\beta \tag{47}$$

or

$$d\lambda \leqslant a\,\frac{dx}{r}\cos\beta \tag{48}$$

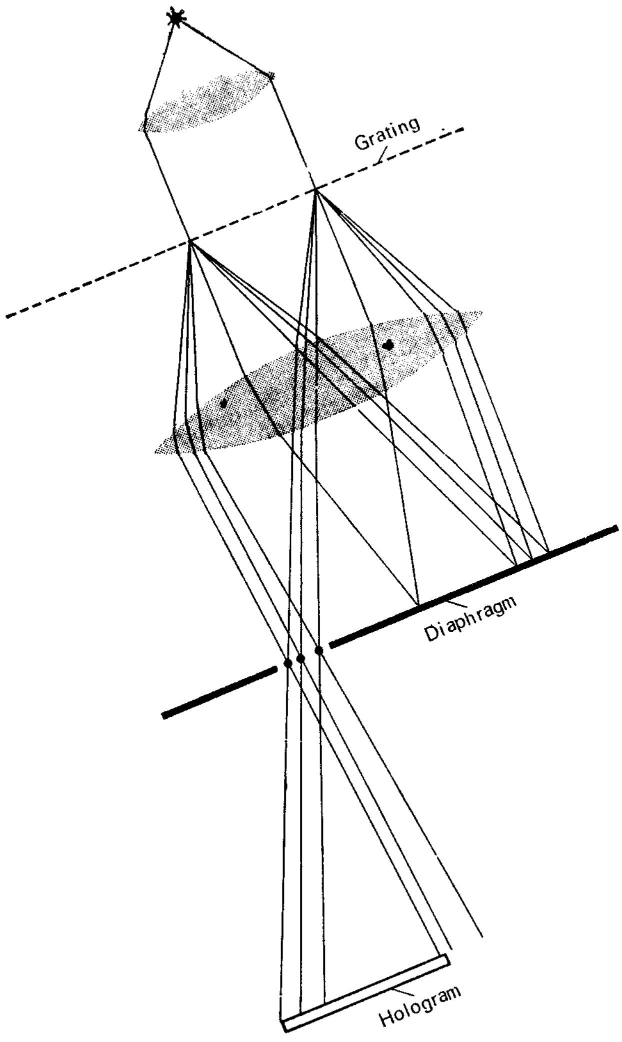
If visual reconstruction of the wavefront takes place, then $\delta\varphi \approx 2 \times 10^{-4}$ radian, which approximately corresponds to the resolving power (sharpness of vision) of a normal human eye. When $a = 10^{-4}$ cm and $\cos\beta \approx 0.7$, this gives $d\lambda \leqslant 1.4$ Å. Thus, for visual reconstruction of a wavefront, a low-pressure mercury-discharge lamp with a filter separating, for example, a green line is quite suitable. If it is necessary to reach the diffraction limit of resolution provided by a hologram, then in accordance with Eq. (38) $\delta\varphi = \lambda/L$ and we have

$$\frac{d\lambda}{\lambda} \leqslant \frac{a\cos\beta}{L} = \frac{1}{N}$$

where N is the total number of lines in a hologram. The result obtained is lawful: the width of a line should be smaller than the limit of the spectral resolution of a diffraction grating having the same number of lines as a hologram [see Eq. (36)].

Arrangements for the achromatizing of wavefront reconstruction exist, however, in which the requirements to the width of the spectral line of the source can be appreciably lowered. One possible arrangement for achromatizing a hologram [86] is given in Fig. 52. The diffraction grating decomposes the radiation striking it into a spectrum, thus producing a set of reconstructed sources of different wavelengths in the plane of the diaphragm. By properly selecting the grating and the geometry of the arrangement, we can achieve coincidence of the images of the object reconstructed by each of these sources, or at least their insignificant difference (Fig. 53). In this way, excellent results can be obtained when using reconstructing sources with a considerable width of the spectrum, for instance a bright superhigh-pressure mercury-discharge lamp ($\Delta\lambda \approx 50$ Å), and sometimes even incandescent lamps.

Fig. 52. Arrangement for achromatizing wavefront reconstruction



Requirements to Spatial Coherence. The requirements to the spatial coherence of the light used for reconstruction of a wavefront consist in that the angular dimensions of the source be sufficiently small for reconstruction of the structure of the image being regenerated. Let us consider them just as schematically and with the same lack of strictness as the requirements to the width of the line of the reconstructing source.

Assume that a hologram has been formed with the aid of an ideal point reference source of light (Fig. 54). Here *1* and *2* are the extreme points of the reconstructing source of light, and $d\alpha$—its angular dimension. Hence $d\beta$—the angle between the corresponding diffracted beams—gives the angular dimensions of each point of the reconstructed image (observed from the plane of the hologram). Considering the light source to be monochromatic, we have from Eq. (25)

$$|d\alpha| = \frac{\cos\beta}{\cos\alpha} d\beta = \frac{\cos\beta}{\cos\alpha} \frac{\delta x}{r} \tag{49}$$

Since the factor $\cos\beta/\cos\alpha$ has the order of unity and usually varies within the limits from one-half to two, we finally get that the angular dimensions of the reconstructing source should be of the order of the required angular resolution.

It is often possible to reconstruct an image by looking through its hologram and through a red glass at an electric lamp removed to a distance of several

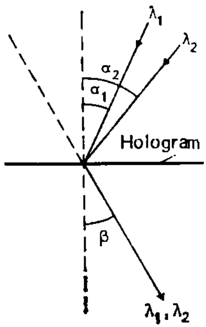


Fig. 53. Explanation of achromatizing action of arrangement shown in Fig. 52

metres. It is quite natural that a frosted lamp is less suitable in this case—its angular dimensions are too great.

Notwithstanding what has been said above, laser radiation is generally used for high-quality reconstruction. The same laser is frequently employed that was used to form the hologram.

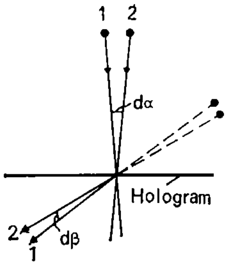


Fig. 54. Determining the permissible angular dimensions of the reconstructing light source

Image Holograms (Holograms of Focussed Images). The requirements to the spatial and time coherence of the light serving to reconstruct an image can be appreciably lowered if when forming a hologram the object was focussed onto it or was adjacent to its surface. Such holograms are called *image holograms.*

The unusual properties of these holograms are due to the fact that in contrast to conventional holograms, here we have local recording, i.e. strict conformity between the points of a hologram and those of the object. A definite point of the object corresponds to each point of the hologram, and vice versa.

The result is that an image hologram always reconstructs the image in its own plane, and this image, being "lashed" to the hologram, does not change its dimensions, shape and region of localization when the position of the reference source serving for recording the hologram is changed or when the wavelength and position of the reconstructing source are changed.

Consequently, the spectral composition and extension of the reconstructing source are unessential in image holography, and a high-quality image can be obtained even when using an extended source of white light. Different colouring of the reconstructed image is observed in this case when looking at it from different angles.

For the same reason, the configuration of the reference wave is immaterial when forming a hologram, and there is no necessity of maintaining an identical shape of the reference and reconstructing waves. An image hologram can be obtained by using an extended source of an arbitrary shape as the reference one.

It should be noted that the lowering of the requirements to the spatial and time coherence of the light of the source serving to reconstruct an image in image holography directly follows from expressions (48) and (49). For the case when $r \to 0$, these expressions impose no restrictions on the width of the radiation spectrum $d\lambda$ and on the extension $d\alpha$ of the light source. Indeed, it follows from Eq. (49) that when $r \to 0$ we have $|d\alpha| \to \infty$, i.e. the angular dimension of the reconstructing source may be as great as we wish, and this will not affect the linear resolution δx of a hologram (Fig. 54).

Whether or not the light serving to reconstruct the wavefront is monochromatic is also of no importance for image holograms. Formula (48) imposes no restrictions on the value of $d\lambda$ when

$r \to 0$. If the image is reconstructed in white light, then owing to the dispersion of the hologram, different colouring of the reconstructed image will be observed when looking at it from different angles (see Fig. 51).

Thus, image holograms permit the wavefront to be reconstructed in the light of an extended source emitting a continuous spectrum.

Thick-Layer (3D) Holograms. The requirements to the monochromatic nature of the light source used for reconstruction of the wavefront with thick-layer, three-dimensional (3D) or volume holograms are also not strict. It was shown in an earlier section that such holograms, functioning like multilayer interference filters, themselves separate monochromatic radiation whose wavelength corresponds to the Lippmann-Bragg condition from a continuous spectrum.

If a 3D hologram was recorded in direct proximity to the object, then, as for image holograms [see Eq. (49)], the angular dimensions of the reconstructing source are immaterial and the image can be observed in the light of an extended source. The isophasal reflecting surfaces in the volume of such a hologram repeat the relief of the object with an accuracy that grows when the object was closer to the hologram. The reflecting properties of such a hologram are close to those of the object itself, and the hologram can reconstruct not only the light wave scattered by the object when forming it, but also the waves appearing in different conditions of lighting [87]. When the reconstructing source is moved, the shadows and patches of light travel over the surface of the reconstructed image in the same way as if we were observing the object itself.

Geometry of Reconstruction. In Sec. 1.2 we considered the geometrical laws relating the longitudinal and lateral enlargement of an object to the position of the hologram, object, reference and reconstructing light sources [Eqs. (30)-(32)]. These relationships should be used for guidance in designing arrangements for reconstructing wavefronts. Let us consider some particular cases.

1. The original hologram is not enlarged ($m = 1$), and reconstruction is conducted in the same wavelength that was used to form the hologram ($\mu = 1$). If $x_R = x_C$, $y_R = y_C$ and $z_R = z_C$ (Fig. 55*a*), i.e. reconstruction takes place in the light of an undisplaced reference source, then from Eqs. (30)-(32) for a virtual image it follows that $x_B = x_O$, $y_B = y_O$, $z_B = z_O$ and $M_{lat} = M_{long} = 1$.

In this case the virtual image thus appears at the same place where the object was; its longitudinal and lateral scales remain unchanged.

If a hologram is two-dimensional and simultaneously with a virtual image forms a real one, then, as follows from

Eqs. (30)-(32), the latter is not symmetrical to the virtual image ($z_B \neq -z_O$), its scale will not equal unity $\left(M_{\text{lat}} = \frac{1}{1-(z_O/z_C)}\right)$, and the longitudinal and lateral scales will not be the same ($M_{\text{lat}} \neq M_{\text{long}}$).

2. To obtain an undistorted real image, the direction of the reconstructing wave should be reversed, as shown in Fig. 55*b*. Here, as in the previous case, the coordinates of the reconstructing light source also coincide with those of the reference source, but the light rays enter it instead of emerging from it. The image is formed at the same place where the object was, and its longitudinal and lateral enlargements will equal unity. Since we examine the image in the arrangements shown in Fig. 55*a* and *b* from opposite sides, however, then in the latter case we shall see the reverse relief. If the hologram is two-dimensional, then in addition to this real image a virtual one will be formed which, generally speaking, is not symmetrical to the real one and has distorted proportions.

3. There are two more possibilities for obtaining an image of the object free of aberrations with an enlargement equal to unity (no enlargement) for two-dimen-

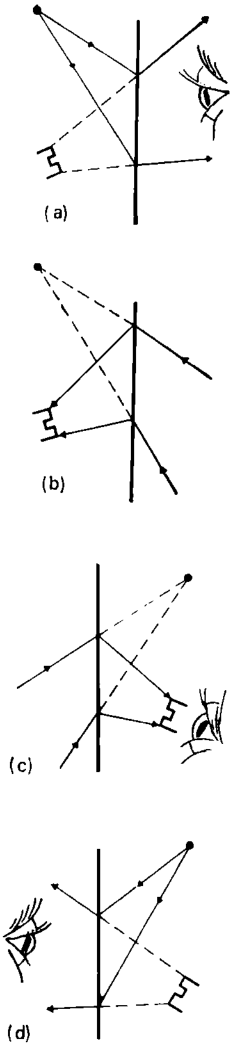


Fig. 55. Reconstruction of images free of aberrations. The reconstructing source coincides with the reference one.
Cases *c* and *d* are possible only for two-dimensional holograms

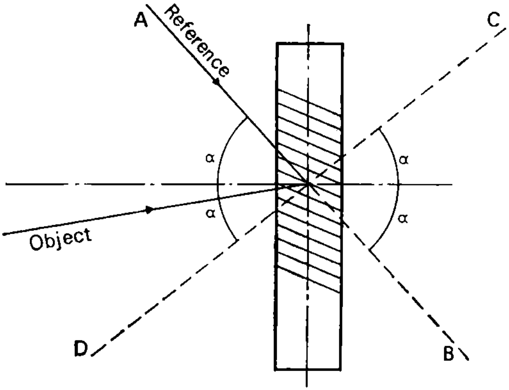


Fig. 56. Reconstruction of an image free of aberrations by means of two- and three-dimensional holograms.
The reconstructing beam should strike the hologram along one of the directions AB, BA, CD or DC. The last two arc only for a two-dimensional hologram

sional holograms. They correspond to a position of the reconstructing source at a point symmetrical to the position of the reference source for the direct and reverse path of the rays (Fig. 55*c* and *d*). Indeed, assuming in Eqs. (30)-(32) that $m = 1$, $\mu = -1$, $z_C = -z_R$, $x_C = x_R$ and $y_C = y_R$, we get $z_B = -z_O$, $x_B = x_O$, $y_B = y_O$ and $M_{lat} = M_{long} = 1$. The appearance of additional possibilities of reconstructing undistorted images with the aid of two-dimensional holograms can be explained with the aid of Fig. 56.

If a hologram is two-dimensional, then rays AB, BA, DC and CD striking it at the same angle α as the reference beam should be equivalent. Only two of these four rays, however, namely, AB and BA, corresponding to Fig. 55*a* and *b*, strike the semitransparent reflecting layers formed in the bulk of a 3D hologram at the same angle as the reference beam.

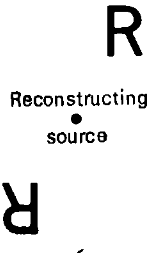


Fig. 57.
A Fourier transform hologram gives two reconstructed images localized in the plane of the reconstructing source, which is the centre of symmetry of the picture formed

Rays *CD* and *DC* corresponding to Fig. 55*c* and *d* do not satisfy the Lippmann-Bragg condition and form no images in the case of 3D holograms.

4. The reference source is in the same plane as the object. In other words, the case of a lensless Fourier transform hologram is being considered, which $z_R = z_O$ corresponds to. It follows from Eq. (30) that regardless of the values of m and μ, we have $z_B = z_C$, i.e. the image is localized in the same plane as the reconstructing source. If the hologram is two-dimensional, then a second image of the object is formed simultaneously [corresponding to a negative

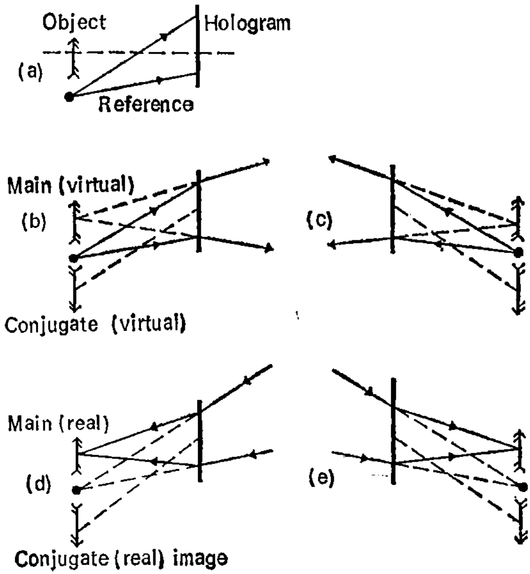


Fig. 58.
Lensless Fourier transform hologram:
a—recording of hologram;
b and *c*—obtaining of virtual image free of aberrations;
d and *e*—ditto, real image.
Arrangements *c* and *e* can be used only with two-dimensional holograms

value of μ in Eq. (30)]. Both images are localized in the plane of the reconstructing source, the latter being the centre of symmetry of the picture formed (Fig. 57). They are virtual with direct travel of the rays corresponding to Fig. 58*b* and are real with reverse travel (Fig. 58*d*)*. The enlargement of these images, as follows from Eq. (31), is

$$M_{\mathrm{lat}} = \frac{\mu}{m} \frac{z_C}{z_O} \tag{50}$$

If the scale of a hologram remains unchanged ($m = 1$), and the reconstructing source is in the same plane as the reference one ($z_C/z_O = 1$), then

$$M_{\mathrm{lat}} = M_{\mathrm{long}} = \mu$$

i.e. both images retain their three-dimensional properties and will be enlarged in proportion to the ratio of the wavelengths used in reconstruction and in forming the hologram. It should be stressed, however, that the Lippmann-Bragg condition does not permit the wavefront to be reconstructed in light whose wavelength differs from that used in forming the hologram (except for integer ratios). This makes it difficult to obtain enlarged images in the case of 3D holograms.

5. If formation of the hologram and wavefront reconstruction were performed

* Separate fragments of Figs. 58, 59 and 62 have been taken from a review by E. Ramberg [88].

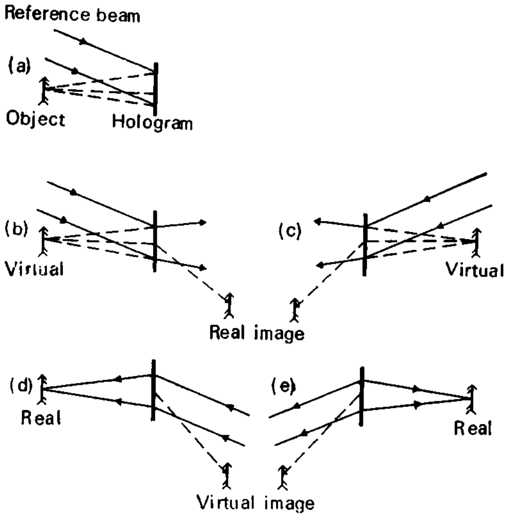


Fig. 59.
Hologram with a parallel reference beam:
a—recording of hologram;
b and *c*—obtaining of virtual image free of aberrations;
d and *e*—ditto, real image.
Arrangements *c* and *d* can be used only with two-dimensional holograms

using a reference light wave with a plane wavefront (Fig. 59)

$$|z_R| = |z_C| = \infty$$

then it follows from Eq. (30) that

$$z_B = \frac{m^2}{\mu} z_0$$

i.e. both images formed by a two-dimensional hologram and corresponding to $+\mu$ and $-\mu$ will be symmetrical relative to it. Here, as follows from Eqs. (31) and (32), we have

$$M_{lat} = m \text{ and } M_{long} = \frac{m^2}{\mu}$$

To retain the three-dimensional properties of an image, the longitudinal and

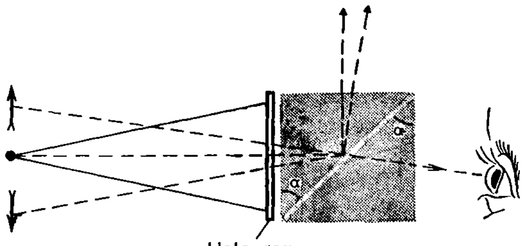


Fig. 60.
A device eliminating the zero-order beam and one of the virtual images

lateral enlargement should be the same. This is possible if $m = \mu$, i.e. the enlargement of a hologram should equal the ratio of the wavelength of the reconstructing reference source to that of the source whose light was used to form the hologram.

The cases considered above make it possible to rationally choose the layout of the elements of an arrangement for reconstructing the wavefront.

It was mentioned above that a lensless Fourier transform hologram forms two mirror-symmetrical virtual images localized in the plane of the reference source (see Fig. 57). It is convenient to look through such a hologram with the aid of the device described by L. Lin [89] which eliminates the light from the zero-order beam and from one of the images (Fig. 60). The device consists of two glass prisms with an air gap between them. The refractive index of the glass and the geometry of the prisms are so selected that the light normally striking the front face of the prism undergoes

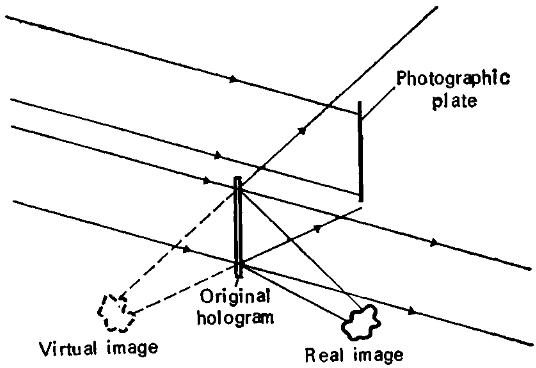


Fig. 61.
Arrangement for the contactless copying of holograms

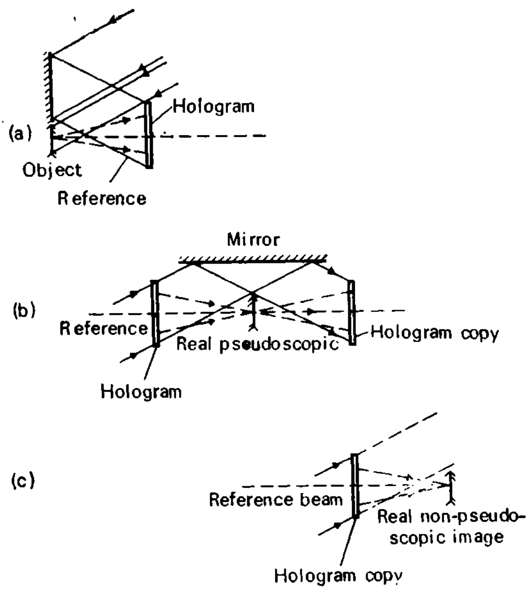


Fig. 62.
Reconstruction of real non-pseudoscopic image by hologram copy:
a—recording of original hologram;
b—recording of hologram copy;
c—reconstruction of real non-pseudoscopic image

complete internal reflection on the hypotenuse face (for kron glass $n \approx 1.51$ and $\alpha > 41°30'$), while the light from one of the virtual images passes through the air gap without hindrance.

Copying Holograms. Contact printing was used to prepare the first copies of holograms. Since the structure of a holographic pattern may have a spatial frequency exceeding 1000 lines/mm, it is easy to understand that a gap of even one micron between the original and the photographic emulsion of the plate cannot be tolerated. It was found, however, that if the light of a laser is used in the contact printing of copies, there is no need to worry about the complete elimination of the gap between the copy and the original [90].

Indeed, by illuminating a hologram with a reference beam of light, we get an exact copy of the wave scattered by the object. This wave interferes with the zero-order beam that is a copy of the reference beam and directly behind the hologram forms a pattern of the standing light waves identical to the one recorded on it. It is exactly this pattern that will be recorded on the hologram copy. If the latter is illuminated with the reference beam, we shall see both a real and a virtual images similar to the ones formed by the original hologram. The interference pattern produced by the reference beam and the beam of light travelling to the real image will be recorded at the same time when forming such a holographic copy. Upon reconstruction, this pattern also forms both a real and a virtual images.

Thus, the copy will be a double hologram. It reconstructs two virtual and two real images. If the original hologram and the photographic plate were in contact with each other in copying, then the two virtual images will coincide, otherwise their doubling will be noticeable [91]. Variants of arrangements for the contactless copying of holograms are shown in Figs. 61 and 62.

Another way of replicating holograms differing in principle is described in [92] and in [18]. It uses the relief of the photographic emulsion layer which repeats the distribution of the illumination in the plane of the hologram, while hologram copies are formed in approximately the same way as replicas of diffraction gratings. A liquid synthetic resin is poured over the surface of the matrix hologram, and after solidification it is separated from the latter.

2.4. Hologram Recording Materials

Frequency-Contrast Characteristic. Holography tendered a number of special requirements to photographic emulsions, which we shall consider below.

Firstly, these include requirements to the resolving power of an emulsion. The highest spatial frequency of a hologram pattern can be determined from Eq. (42).

It is essential that the emulsion resolve fringes of such a frequency quite well. It was previously noted (see Fig. 21) that a photographic emulsion is a non-linear receiver, and as a result the distribution of the amplitude transmittance over a hologram differs from that which the illumination had on the emulsion. In addition to these non-linear distortions, however, there also exist distortions of another kind connected with the structure of the emulsion.

Photographic emulsions consist of microcrystals of a silver halide dispersed in a transparent gelatin body. Consequently, the developed image is discrete and consists of separate black points. If the details of an image are compatible in size with the dimensions of these points or with the average distance between them, they become indistinguishable. In addition, when an emulsion is exposed, the light scatters on the microcrystals of the silver halide. This also leads to a lower contrast of the image. For the above reasons, photographic emulsions record the structure of an image the poorer, the higher is the spatial frequency of the pattern. The frequency-contrast characteristic serves for determining these properties of an emulsion.

By the *frequency-contrast characteristic* $K(\nu)$ of a photographic emulsion is meant a function describing the transformation by a photolayer of the contrast of the sinusoidal distribution of the illuminance (the exposure) impinging onto the emulsion into the contrast of the photographic image:

$$K(\nu) = \left(\frac{T_{max} - T_{min}}{T_{max} + T_{min}}\right)_{im} \times$$

$$\times \left(\frac{H_{max} - H_{min}}{H_{max} + H_{min}}\right)^{-1}_{obj} \qquad (51)$$

where the subscripts "im" and "obj" stand for "image" and "object", respectively.

In scientific photography, the frequency-contrast characteristic is determined in a different way: the characteristic curve (see Fig. 21*a*) is used to go over from the measured transmittances T_{max} and T_{min} to the "acting" exposures H_{max} and H_{min}:

$$K'_a(\nu) = \left(\frac{H_{max} - H_{min}}{H_{max} + H_{min}}\right)_{im} \times$$

$$\times \left(\frac{H_{max} - H_{min}}{H_{max} + H_{min}}\right)^{-1}_{obj} \qquad (52)$$

If the emulsion were a linear (with respect to the dependence of K on H) receiver, then both definitions would be identical. Definition (52) is convenient when the photographic emulsion is a part of an optical system, each of whose elements has its own frequency-contrast characteristic. In this case to find the total contrast transmission function, it is sufficient to determine the product of the relevant characteristics of all the elements, including the value of $K_a(\nu)$.

It is more convenient to use the frequency-contrast characteristic (51) for holography, since it is exactly this

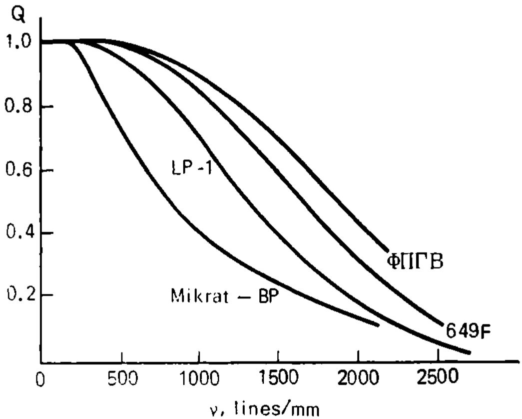


Fig. 63.
Frequency-contrast characteristics of selected photographic emulsions.
The diffraction efficiency Q assumed equal to unity at a frequency of 240 lines/mm is laid off along the axis of ordinates

quantity that determines the diffraction efficiency of the holograms.

The shape of the frequency-contrast characteristics of selected emulsions used for holography [93, 94] is shown in Fig. 63. It should be noted that the frequency-contrast characteristics may change from specimen to specimen within rather broad limits. The curves in Fig. 63 show the very conditional nature of the widely adopted concept of the resolving power of a photographic emulsion. It usually designates the maximum spatial frequency at which it is possible to distinguish the structure of an image. It is visually possible to distinguish a structure having a contrast of about 1% or even less. The emulsions BP and ФПГВ have close resolving powers, but examination of Fig. 63 shows that the emulsion ФПГВ transmits the contrast much better than the emulsion BP beginning from frequencies of 200-300 lines/mm. Consequently, to assess the suitability of a photographic material for holography, it is desirable to know its frequency-contrast characteristic. The rule is to select such a limiting spatial frequency on a hologram that the frequency-contrast characteristic will not drop to below 5-10%, although some authors recommend working in the region of higher contrasts (exceeding 30-50%).

The frequency-contrast characteristics must meet especially high requirements when forming 3D (three-dimensional) holograms. In opposing beams, the distance between adjacent nodes has the order of $\lambda/2$, i.e. a resolution of about 5000 lines/mm is needed with a high contrast (a helium-neon laser, $\lambda = 6328$ Å).* A resolving power of this magnitude is a property of such photolayers as Kodak 649F, 8E Agfa-Gevaert, plates manufactured according to the method of N. Kirillov [95], I. Protas and Yu. Denisyuk [96], or any other Lippmann emulsions.

High-quality two-dimensional holograms can also be formed on photolayers with a much lower resolving power. It is only necessary to coordinate the spatial frequency of the hologram with the possibilities of the emulsion. It is

* With account of the fact that the refractive index of the emulsion is about 1.5.

quite natural that the smaller the resolving power of an emulsion, the greater is its area needed for high-quality recording of the wavefront within the same solid angle (see Fig. 23). In this connection, it is of interest to note the successful attempts to form holograms on emulsions with a low resolving power, but a high sensitivity (P/N Polaroid [97] and Tri-X-Panfilm [98]).

G. Stroke et al. [97] formed a hologram of a transparency using a diffusing screen. The maximum spatial frequency on the hologram did not exceed 120 lines/mm, while the exposure was 1/25 s (a helium-neon laser, 10 mW, a film with a sensitivity of about 45 ASA). A similar high-quality reconstruction of the wavefront was achieved by R. Brooks [98] when using more sensitive film (about 300 ASA). The laser had a power of only 0.25 mW, but recording was performed without a diffusing screen (see the arrangement in Fig. 25). The maximum spatial frequency of the fringes in this work was 70 lines/mm. The frequency-contrast characteristic of the film used drops for this frequency to 35%.

Table 1 gives the characteristics of various holographic photolayers, and Table 2—the formulas of developing solutions.

O. Andreeva and V. Sukhanov [99] recommend a pyrogallol-ammonia developer of the following composition for obtaining unbleached 3D holograms

TABLE 1. **Characteristics of Selected Holographic Photolayers**

Photographic material	λ_{max}, Å	ν_{max}, lines/mm	θ_{max}, deg	Sensitivity, erg/cm^2 ($D = 0.5$)
Kodak 649F	7000	> 5000	180	1000 ($\lambda = 6328$) 7000 ($\lambda = 6943$)
Film ФПГВ	7000	2800	125	10-20 ($\lambda = 6328$)
Mikrat-900	6400	2800	125	50-100 ($\lambda = 6328$)
SO-243	7500	500	19	2 ($\lambda = 6328$)
Mikrat-300	6400	300	11	—
Panchrom-18	7300	250	9	0.3 ($\lambda = 6328$)
Plates ВРЛ	6400	2800	125	50-100 ($\lambda = 6328$)
Films and plates of Agfa-Gevaert:				
14 C 70	7000	1500	56	3 ($\lambda = 6328$)
14 C 75	7500	1500	62	3 ($\lambda = 6943$)
10 E 56	5600	2800	84	50 ($\lambda = 4800$)
10 E 70	7000	2800	125	50 ($\lambda = 6328$)
10 E 75	7500	2800	150	50 ($\lambda = 6943$)
8 E 56	5600	> 5000	180	200 ($\lambda = 4800$)
8 E 70	7000	> 5000	180	200 ($\lambda = 6328$)
8 E 75	7500	> 5000	180	200 ($\lambda = 6943$)

TABLE 2. **Composition of Developers for Photographic Materials Used in Holography**

	Mikrat-900, ВРЛ (developer УП-2)	Kodak 649F (developer D-19)	Agfa-Gevaert (developer Methinol-I)
Hydroquinone, g	6	8	6
Metol, g	5	2	1.5
Anhydrous sulphite, g	40	90	25
Anhydrous soda, g	31	52.5	7.75
Potassium bromide, g	4	5	4
Water, l, up to	1	1	1

having the maximum diffraction efficiency:

Solution 1		Solution 2	
Pyrogallol . . .	1 g	KBr . . .	20 g
Water	100 ml	Ammonia, 25%	30 ml
		Water	240 ml

The working solution consisting of one part of solution 1, two parts of solution 2 and 40 parts of water is prepared directly before developing.

Measuring the Resolution of Holographic Emulsions. To determine the frequency-contrast characteristics and the resolving power of a photolayer, a sinusoidal distribution of the illumination with various spatial frequencies is formed on it. Next the images thus obtained, called *resolvograms*, are studied to determine the contrast corresponding to different spatial frequencies, or the limiting frequency corresponding to the minimum contrast that can be detected at the noise level, i.e. the resolving power.

In projection resolvometers, the image of a focus target—a specially made black and white grating—is projected onto the photolayer being tested. The projection method of testing is suitable for frequencies not exceeding 600-1000 lines/mm. The matter is that the frequency-contrast characteristic of the lens projecting the focus target usually drops almost to zero toward these frequencies, and the lens, as a rule, cannot form an image with a greater spatial frequency.

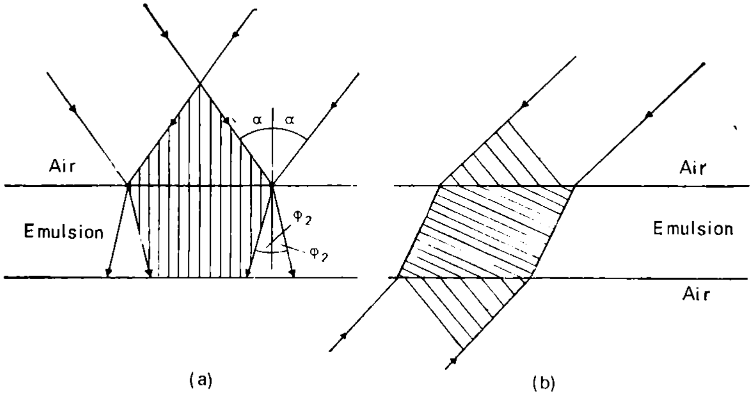


Fig. 64.
Formation of an interference structure in air and in an emulsion upon the symmetrical incidence of coherent beams on the emulsion (*a*) and upon meeting incidence from opposite sides (*b*).
In case (*a*) we have $\sin \alpha / \sin \varphi_2 = n_2/n_1$ and $\lambda_1/\lambda_2 = n_2/n_1$

Another difficulty of projection measurement of resolution is that the lines of the focus target give a stepped distribution of the illumination instead of a sinusoidal one. This difficulty can easily be surmounted, however, since methods exist for reducing the contrast of the image of a "rectangular" target to that of a "sinusoidal" one, which consist in applying correction factors close to unity to the measured contrast.

Laser interference resolution measuring has much broader possibilities [100, 101]. The maximum spatial frequency in the interference method reaches 5000 lines/mm, and the fringes have a sinusoidal distribution of the illumination. Interference fringes are obtained on an emulsion by symmetrically directing onto it two coherent beams of light forming the angle α with a normal

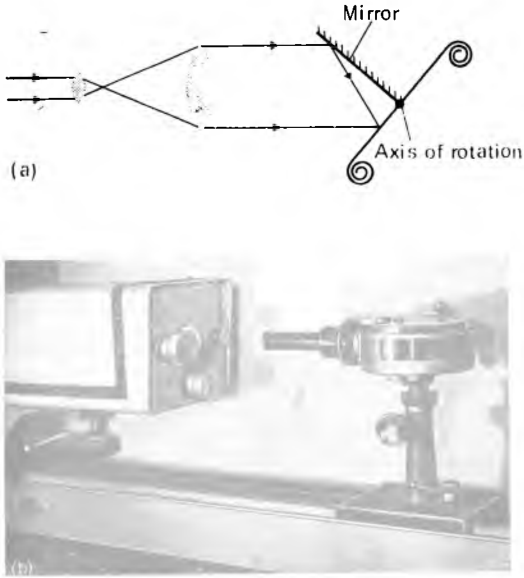


Fig. 65.
Laser interference resolvometer developed at the A. F. Joffe Physicotechnical Institute of the USSR Academy of Sciences:
a—scheme;
b—general view

(Fig. 64*a*). The spatial frequency of the interference pattern in air is determined in this case by Eq. (11):

$$\nu = \frac{2 \sin \alpha}{\lambda_{air}}$$

Refraction of light on the air-emulsion interface results in an *n*-fold decrease in the sine of the angle of incidence (*n* is the refractive index of the photolayer relative to air). The length of the light wave λ, however, will also diminish the same number of times. Hence the spatial frequency of the pattern in the body of the photolayer will be the same as in air (Fig. 64*a*).

If the angles of incidence of the beams on the photolayer are not the same, then generally speaking, the frequency of the pattern in the photolayer changes in comparison with that in air.

For example, for opposing beams impinging on a plane-parallel emulsion from opposite sides (Fig. 64*b*), by Eq. (9) we have

$$\nu = \frac{2}{\lambda_{em}} = \frac{2n}{\lambda_{air}}$$

Special interference arrangements have been developed for laser resolution measuring [102]. Following the scheme shown in Fig. 65*a*, a laser interference resolvometer whose general view is shown in Fig. 65*b* was developed at the A. F. Joffe Physicotechnical Institute of the USSR Academy of Sciences. A small batch of these instruments was manufactured for use at enterprises working out photographic emulsions for holography.

A feature of the scheme shown in Fig. 65*a* is the simplicity of changing the spatial frequency. This is done by turning the system mirror-emulsion about the edge of the two-face angle it forms. Two versions of this instrument were designed—for the resolvometric testing of 35-mm roll films and for testing photographic plates. The resolvometer is used as an attachment to a helium-neon laser.

A resolvogram can be considered as a diffraction grating [101], and the contrast of its pattern can be assessed according to the brightness of the diffraction orders. By transillumination of such a grating with the aid of a laser beam and measurement of its diffraction efficiency for different spatial frequencies, we can construct a frequency-contrast characteristic of a photographic emulsion. An automatic instrument was developed at the Physicotechnical Institute of the USSR Academy of Sciences specially for measurements of this kind. The frequency-contrast characteristics shown in Fig. 63 were obtained exactly by this method.

A resolvogram can be studied approximately by observing a bright electric lamp through fields with different spatial frequencies. The presence of diffraction orders indicates that the given frequency is resolved by the photolayer, while the brightness of the orders is a measure of the contrast of the interference structure.

Sensitivity of Photolayers (Emulsions). A second very important characteristic of photolayers for holography is their light sensitivity. It is this quantity that determines the exposure needed to record a hologram. Unfortunately, the adopted methods of testing photographic materials in the light of an incandescent lamp (for example, the one contained in USSR State Standard GOST 2817-50) and the corresponding GOST (or ASA) sensitivity units do not permit us to calculate the exposure needed in every case. The sensitivity of holographic photographic materials, which are exposed only in monochromatic light, should be determined in energy units (J/cm^2 or erg/cm^2).

The sensitivity of selected photolayers in Table 1 is given in these units. It should be remembered that a greater number of ergs per square centimetre corresponds to a lower sensitivity of the photolayer. The sensitivity indicated in the last column of Table 1 is the exposure needed to obtain an optical density of $D = 0.5$. It can be recommended to perform a number of trial exposures for every new kind of photolayer with photoelectric measurement of the illumination in the plane of the hologram each time.

The approximate exposure time required for a ВРЛ plate in forming a hologram of a 3D diffuse object having an area of about a square decimetre with the aid of a 20-mW helium-neon laser (ЛГ-36) is less than one minute.

Grade ФПГВ film has a sensitivity of about one, and Panchrom-18 of about two orders of magnitude higher.

It should be borne in mind that not only the sensitivity of a photolayer changes with the wavelength, but also its resolving power. The resolution usually diminishes quite rapidly with a drop in the wavelength owing to the greater scattering of the light in the photolayer. The change in the spectral sensitivity depends on the kind of sensitization used.

When holograms are formed with the aid of pulsed lasers, and especially of lasers generating a giant pulse, account should be taken of the deviations from the law of reciprocity, owing to which the sensitivity of photolayers diminishes when the exposure time is reduced (see, for example, [103]).

Phase and Reflection Holograms. Up to now we described the action of a photographic emulsion as a medium whose response to an exposure is a change in transparency, while a hologram was considered as an amplitude diffraction grating.

It is also possible to form a phase hologram [8, 104]—a grating in which spatial modulation of the phase of a light wave occurs. No light is absorbed in a purely phase sinusoidal grating. Therefore the brightness of images reconstructed by a phase hologram is considerably higher than that reconstructed by an amplitude one.

Phase holograms are usually obtained by bleaching a developed plate. The latter becomes transparent, and only its surface relief (thickness variation) and refractive index variation carry the information recorded on it. For bleaching, a developed and fixed plate is immersed in a solution of potassium bichromate or potassium ferricyanide.

V. Russo and S. Sottini [105] give an improved formula (for Kodak 649F plates). The bleaching solution is formed of 10 parts of solution A, 1 part of solution B and 100 parts of water.

Solution A		Solution B	
Water	500 ml	Sodium chloride	45 g
Ammonium bichromate	20 g	Water	up to 1 l
Concentrated sulphuric acid	14 ml		
Water	up to 1 l		

To form a hologram with the maximum diffraction efficiency, the exposure should be increased several times in comparison with the one needed for recording an amplitude hologram.

Reflection holograms (Fig. 66), first proposed by Yu. Denisyuk [8], are a modification of phase holograms. They are formed by spraying a thin layer of metal onto the surface of a conventional phase or amplitude hologram having an appreciable relief. Such a hologram is equivalent to a reflecting diffraction grating and also gives very bright reconstructed images.

N. Sheridan [106] succeeded in forming profiled (blazed) phase holograms having an enormous efficiency (Fig. 67). They reflect over 70% of the incident light at a spatial frequency of about 1000 lines/mm. This result, however, was obtained on a special photosensitive thermoplastic material, and not on a conventional silver halide emulsion.

Efficiency of Various Kinds of Holograms. The *diffraction efficiency* of a hologram is the ratio of the light flux in the

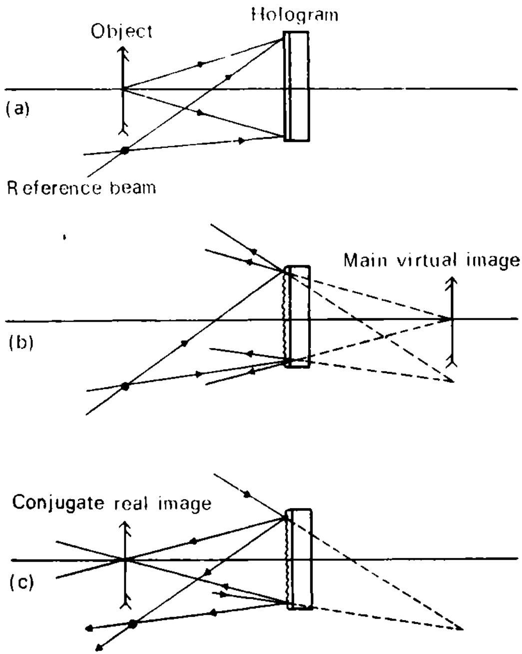


Fig. 66 Reflection hologram.
Recording (*a*) and reconstruction of mirror inverted aberration-free virtual (*b*) and pseudoscopic real (c) images

reconstructed wave to the total flux impinging on the hologram.

The theoretical values of the maximum efficiency differ for holograms of different kinds [107]. The theoretical limit for two-dimensional holograms equals 6.25% for an amplitude and 33.9% for a phase holograms, while the maximum efficiency reaches 100% for a reflection hologram (the kind shown in Fig. 67).

Three-dimensional phase holograms formed in opposing waves also have a maximum theoretical efficiency of

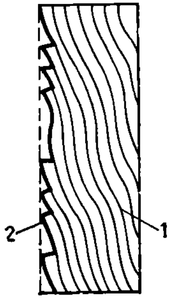


Fig. 67.
Profile of reflection hologram formed on photosensitive resist [106]:
1—wave surfaces of standing light waves;
2—aluminized surface

100%. The maximum efficiency of 3D amplitude holograms does not exceed 7.2%.

The efficiencies achieved experimentally at present are close to the theoretical ones.

Other Media for Recording Holograms. A silver halide photographic emulsion is what is most generally used for forming holograms. This is explained by the high sensitivity of the emulsion, the possibility of sensitizing it to the wavelengths of the most widespread and improved lasers, the long life and durability of the formed holograms, and also by the comparative cheapness. At the same time, photographic emulsions have a number of shortcomings, among which the following two deserve special attention: (1) in the best case several minutes elapse between the moment of completion of the exposure and that of reconstruction of the image, i.e. the time needed for chemical processing of the emulsion; and (2) a photographic emulsion cannot be used repeatedly.

Both these shortcomings result in the fact that photographic methods of recording holograms, as a rule, do not permit us to observe the dynamics of a process in "real" time.

A photographic emulsion is not the only possible light-sensitive medium for recording holograms, however. At present a number of other light-sensitive media and processes have been developed and are being used that are suitable for holography. First of all, reversible photochromic materials should be mentioned. They can be of two kinds—glass with additions of silver halides [108] and plastic or liquid films doped with organic pigments, most often spiropyrans [109].

Photochromic glass with an addition of silver chloride and bromide is sensitive to blue and ultraviolet radiation. The addition of silver iodide extends the region of sensitivity to the green part of the spectrum ($\lambda = 5500$ Å). The irradiation of exposed glass with yellow and red light accelerates its bleaching. The materials can be used repeatedly without any changes in their photochromic properties. The resolving power of a photochromic material is determined by its structure. The silver halide crystals are about 100 Å in size and are spaced from one another at about 1000 Å. Photochromic materials were already tested for recording holograms. J. Kirk [110] used an argon laser ($\lambda = 4880$ Å) having a power of several watts to form a hologram of a focus target with a diffusing screen. The image appeared in about two minutes. An exposure of over five minutes no longer increased the brightness of the reconstructed image, since equilibrium set in between the number of newly formed and perishing absorption centres. It may be assumed that such an inertia of darkening is due to the low power of the radiation, and not to the large inertia of the material itself. W. Armistead and S. Stookey observed darkening of a photochromic glass during a time of the order of 10^{-3} second when it was illuminated with a flash lamp [108].

Kirk used a photochromic silver iodide glass 6.35 mm thick [110]. The quality of the reconstructed image was very good, but the efficiency of a hologram (the brightness of the reconstructed image) is very low. The data given by Kirk show that the sensitivity of photochromic materials is by four or five orders of magnitude less than that of high-resolution photographic plates.

R. Powell and J. Hemnye [111] preliminarily exposed photochromic glass to ultraviolet light, and then used a red helium-neon laser whose radiation has a bleaching action for forming holograms. This process is less convenient, since it permits only one record to be made. To form each new image, it is necessary to subject the glass to a preliminary exposure. However, the more widespread long-wave lasers can be used in such a process.

It should be noted in passing that an arrangement with bleaching makes it possible to study the dynamics of a process if incoherent ultraviolet exposure of a hologram, its exposure with the object and reference beams and reconstruction of the wavefront using only the reference beam are alternated in a regular sequence (for instance with the aid of an obturator). Holograms were also formed using organic photochromic films [112, 113], ruby crystals [114], vitreous boric acid doped with flouresceine [115] and other photochromic substances.

Holograms can also be formed in the light of powerful pulsed lasers on thin layers of the substances used for passive Q-modulators of laser resonators, for example cryptocyanine or phthalocyanine [116, 117]. A hologram of this kind exists only during the laser pulse forming it, and the image is reconstructed by the reference beam. Such dynamic holograms were also recorded in sodium vapour, the radiation source being a dye solution laser tuned in resonance with the sodium absorption lines [118].

Thermoplastic films are another material used to form holograms. These films use the property of certain polymers to deform when heated if an electropotential relief is created on their surface. It can be formed by the cathode-ray beam of a receiving television set.

The potential relief can also be formed by introducing a photoconductor dye into the thermoplastic or applying a photoconductor layer onto (or under) it. Holograms were formed on a photoconductor-thermoplastic material by J. Urbach and R. Meier [119]. They note the higher sensitivity of the receiving layer (by about an order higher than that of Kodak 649F plates), the high resolution and practically complete absence of a discrete structure. Unlike photochromic materials, only phase holograms can be formed on thermoplastic or photoconductor-thermoplastic materials.

Alkali halide crystals are still another material used to form holograms [120-123]. When such crystals are illuminated with x-ray or ultraviolet radiation, absorption centres (so-called F-centres) are formed in them. Long-wave radiation destroys these centres and bleaches the crystals. The rate of bleaching grows with the temperature. This is why a three-dimensional interference pattern is recorded on the crystals at an elevated temperature (about 80 °C), whereas the wavefront is reconstructed at a low temperature of about 0 °C, when the rate of bleaching is very low. The resolving power of such crystalline media is at the molecular level. A tremendous number of holograms can be recorded on a single small crystal. To ensure their independent reconstruction, the reference beam must be turned through a small angle when recording each hologram. The crystal is turned similarly when reconstructing the image.

Prospective media for recording holograms also include magnetic films [124, 125], liquid crystals [126, 127], photopolymer materials [128], photosensitive resists [106, 129, 130], semiconductor layers [75, 76, 131], layers of metals [132] and silver halide [133] applied by evaporation in a vacuum, and dichromated gelatin films [134-139]. Many of these media are already being successfully used for recording holograms.

A review of "unusual" media for recording holograms is given in [140].

Chapter 3 The Main Applications of Holography

11—01562

3.1. Three-Dimensional Images

Holographic Cinematography and Television. The images observed when a wavefront is reconstructed from a hologram astonish one by their reality. Parallax, bright spots from reflecting surfaces that move over an object when the point of viewing it changes, stereoscopicity of an image, and the possibility of obtaining coloured images all make the prospects of holographic cinematography and television quite alluring. Present-day engineering, however, is making only its very first steps in this direction.

Great, but apparently surmountable difficulties stand in the way of holographic cinematography [141, 142]. The main one of them is the creation of enormous holograms through which a great number of people would be able to observe the image like through a window. These holograms should be "live", i.e. change in time in accordance with the changes occurring in the object. One possible variant is to record a multitude of images on one hologram using different inclinations of the reference beam [5]. If the hologram is turned in the same way in reconstruction, then the images will be reconstructed consecutively, creating the effect of motion. The possibility of using such systems in principle has already been proved experimentally, but at most one or two scores of frames can be recorded on a single two-dimensional hologram. Three-dimensional media, for ins-

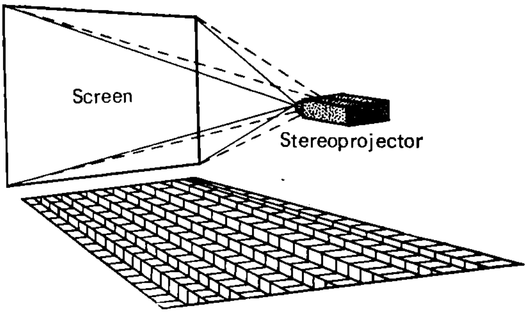


Fig. 68. Holographic stereoscreen

tance crystals, have much greater possibilities in this respect. The dimensions of crystal holograms, however, cannot be sufficiently great.

The future of holographic cinematography will evidently be determined by the achievements in the development of recording media for the formation of dynamic holograms. Such media should have a high sensitivity and resolving power, a low inertia and permit multifold (thousands of millions of times!) recording and erasing of the holograms. With such a recording medium available, it is possible to consecutively copy holographic frames on it with the aid of a powerful pulsed laser.

Holography can also render appreciable aid to "conventional" stereoscopic cinematography. The holographic stereoscreen proposed by Gabor (see, for example, [142]) can considerably improve the quality of stereoprojection. The action of a holographic screen is shown in Fig. 68. It must create alternating zones of two kinds in the auditorium: (a) one

Fig. 69.
Five-frame holographic motion picture consisting of single-beam (Gabor) holograms of a laser-induced spark.
The frames correspond to time readings of 40, 80, 120, 160 and 200 ns

in which the screen is seen illuminated by the projector of the "left-hand" frame; and (b) one in which the screen is seen illuminated by the "right-hand" frame. The distance between zones (a) and (b) is equal to the mean distance between the pupils of the human eye (about 62 mm). Such a screen can be made as a double exposed reflection hologram of a raster similar to the one shown in Fig. 68. During the first exposure, the "left-hand" zones are the object, and the reference beam is at the point where the left-hand projector is. The second exposure corresponds to the "right-hand" zones and the right-hand projector.

The prospects of scientific applications of holographic cinematography are already favourable today. An arrangement for the high-speed formation of cinematographic holograms of plasma was developed at the A. F. Joffe Physicotechnical Institute of the USSR Academy of Sciences [143, 144]. A five-frame holographic motion picture of a laser-indu-

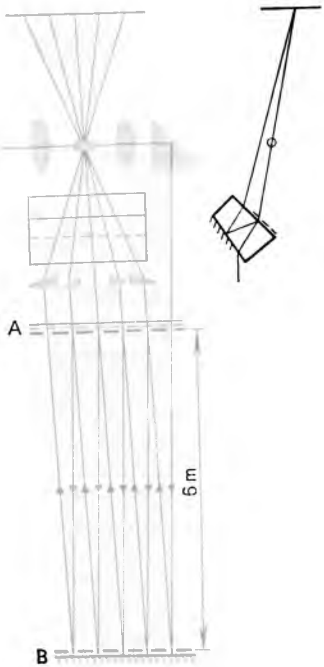


Fig. 70. Arrangement for obtaining five-frame split-beam holographic motion pictures of rapid processes with an optical delay line

ced spark [145] obtained on such an arrangement is shown in Fig. 69. The arrangement has no moving parts. Its operation is based on the use of optical delay lines [146] (Fig. 70). A light pulse with a duration of 20-30 ns from a ruby laser repeatedly passes over the 12-metre path between semitransparent mirror A and completely reflecting mirror B and back, forming upon each pass a hologram of a laser-induced spark (the plasma formed when a powerful laser beam is focussed). The interval of time between the holographic frames is thus about 40 ns. It is obvious that by bringing mirrors A and B closer together, a cinematographic hologram is formed with a greater frequency of the frames. This system can be used for the high-speed recording of other rapid processes, for instance the destruction of solids by a focussed laser ray, and the electrical explosion of small wires.

Holographic television also poses a problem that will get onto the agenda in the nearest few years. Apart from the obvious advantages of having a three-dimensional image, we must also note here the noise stability, the reliability of holographic television, the possibility of transmitting high contrasts, of coding the television broadcasts, etc. It should be borne in mind, however, that a three-dimensional scene shown on a screen of the size used in a modern television set will lead to a feeling of the "puppet-like" nature of what is shown on it. For this reason, a holographic television set will become a genuine real spectacle only when the technical possibility appears of using a holographic screen having bigger dimensions.

Holographic television is also confronted with a number of other unsolved problems. The transmission of a high-quality three-dimensional image requires a transmitting capacity (the width of the transmission band) of the television channel that is several thousand times greater than that used at present in conventional television [147]. Progress in holographic television should be expected, on one hand, in an increase in the transmitting capacity of the communication channels, and on the other in a reduction in the amount of information needed to form a hologram.

Broad-band communication channels can evidently be created on laser beams. Different procedures, both developed for television and special holographic ones, can be used to reduce the amount of information needed to form a hologram. For instance, D. De Bitetto [148] proposes to transmit not the entire hologram, but only a narrow horizontal strip of it over the television channel. This strip is multiplied at the outlet to form a complete hologram consisting of identical horizontal strips. It is quite natural that when such a hologram is used to reconstruct the wavefront, parallax remains only in a horizontal plane. It is exactly this parallax, however, that is

Fig. 71.
An image reconstructed from a hologram transmitted over a television channel

the most important for feeling the depth of a scene, since our eyes are in one horizontal plane. The same method may be useful for a holographic motion picture. The projection of a slot hologram can be achieved when it is continuously moving at a constant speed [149].

If we also "get rid" of horizontal parallax and form a hologram of identical small squares instead of strips [150], then the amount of transmitted information can be diminished by about three orders of magnitude without too great spoiling of the quality of the image. Naturally, the image on the screen will no longer be stereoscopic, and of all the advantages of holography only its noise stability remains.

The problem of recording dynamic holograms formed without inertia and immediately ready for reconstruction must be solved for both holographic television and cinematography. Already at present, however, holographic television can be useful for solving certain scientific problems, namely, the highly reliable, although comparatively slow transmission of information with a high noise stability and with the possibility of its electrical coding, filtration, feeding into computers, etc. The first still imperfect experiments in this direction have already been made (see, for example, Fig. 71 [151]).

Much better results were obtained in transmitting holograms over an interurban (Moscow-Leningrad) phototelegraph channel [152], which resolved more elements by about an order of magnitude than a standard television channel. The holograms received were used to reconstruct the images of line drawings, halftone and three-dimensional objects. The circumstance that the transmitted holograms had only two brightness gradations (which corresponds to the extreme degree of non-linearity) did not result in appreciable distortions in the transmission of the tones of an object.

Holography is also contributing to conventional television. The RCA Corporation in the USA has used it as the basis for developing a system of casset television called "Selectovision".

"Selectovision" is a holographic attachment to a television set comprising a cheap video tape recorder with replaceable holders containing holographic records of motion picture and television films. Each frame of a film is used to prepare a phase relief hologram on a photoresist. Next a layer of metal is applied to it by electroplating techniques. This metallized hologram serves as a matrix for the manufacture of relief replications on a transparent vinyl tape. One matrix can be used to prepare a great number of copies. In showing the film, the tape moves past the reconstructing beam; the real image is projected onto the target of a vidicon and is then regenerated on the screen of the television set.

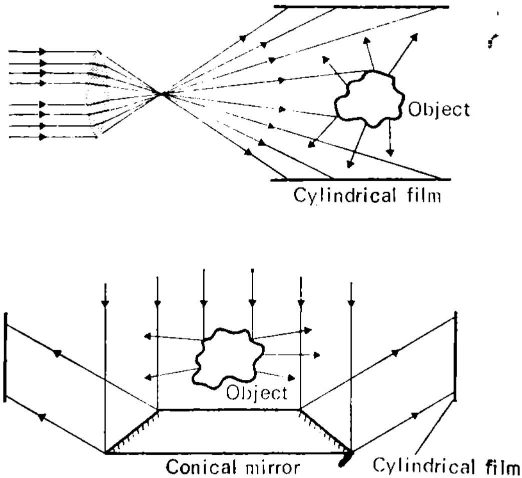
Three-Dimensional Photography. F. Perrin in his classical experiments determined the distribution in height of the most minute gum spheres performing Brownian motion in a liquid. For this end, he counted the number of spheres getting into his field of vision through a microscope by consecutively focussing it at layers of the emulsion at different heights. It would be very convenient to conduct such experiments with the aid of holography. In reconstruction of the wavefront, it is also possible to study an emulsion by layers, counting the number of now stationary spheres in each layer.

A holographic disdrometer—a device for investigating moving particles such as rain drops, fog particles and snow flakes—operates in about the same way. The hologram is recorded with the aid of a pulsed laser during a time of about 20 ns. The three-dimensional distribution of the particles is examined in reconstruction with the aid of a continuous laser. Similar arrangements are used for recording the tracks of particles in bubble chambers and the Wilson chamber [153, 154]. The advantages of this method are obvious: the depth of the sharply shown space and, consequently, the output of the chamber grows, and the possibility appears of separating and filtering tracks having a shape of interest to the investigator.

The main difficulty in recording the spatial distributions of tracks and particles consists in that the particles outside of the focussing plane create a blurred background which reduces the contrast of the image. This limits the possibilities of the method in the recording of ensembles with a high concentration [155].

Holograms can record radiation scattered by an object within a broad solid angle. Figure 72 shows arrangements for recording holograms with a coverage angle of 360 degrees. A hologram with such a coverage, however, can also be formed

Fig. 72.
Arrangement for recording holograms with a coverage angle of 360 degrees



with ordinary (not from all sides) illumination. For this purpose, it is necessary to make a multitude of exposures, turning the object each time through a small angle and exposing each time a narrow vertical strip of the hologram [156].

The three-dimensional properties of images reconstructed with the aid of holograms can be used in advertizing, for illustrating lectures, in the construction of artistic panoramas, the creation of copies of works of art, museum rarities, and the recording of holographic portraits. In forming a holographic portrait of a person, it is necessary to use such short exposures that the structure of the hologram will not be blurred owing to movement of the illuminated surface.

This requires a greater power of the laser used to form the hologram. Here, however, one should never forget about the maximum permissible concentration of energy on the surface of the retina of the human eye*. A way out of this situation is to illuminate the face with the aid of diffusing screens having a large area [157-160] (Fig. 73).

Fig. 73. Photograph of an image reconstructed by means of a hologram [159]

Non-Optical Holography. The problem of visualization of acoustic fields is

* For a 30-nanosecond ruby laser, the level of energy on the surface of the retina should not exceed several hundredths of a joule per square centimetre [157].

being successfully solved with the aid of holography. This is very significant for many applications. Possible applications of acoustic holography include fault detection, studying of the relief of the sea bottom, sonar, sound navigation, prospecting for minerals, and studying the structure of the earth's crust.

Ultrasonic holography is of special importance for medical diagnostics.

Acoustical holograms are so recorded as to make optical reconstruction possible. The following methods are used for this purpose.

1. *Scanning of a sound field.* The signal from an ultrasonic receiver (microphone, piezoelectric element, etc.) modulates the light flux forming an optical hologram. Different modifications of this system are possible. Figure 74 shows an arrangement in which the signal of the scanning receiver controls the brightness of a point lamp secured on it [161].

In other arrangements, the signal from the receiver is fed to a cathode-ray tube. The ray is scanned synchronously with the motion of the transmitter, and the hologram is photographed from the screen of the tube [162, 163]. The photographs are usually made with a large reduction, since the length of a light wave is many times smaller than that of a sound one. A similar hologram can also be obtained if the space is scanned by a source of ultrasound with a stationary receiver [162, 164].

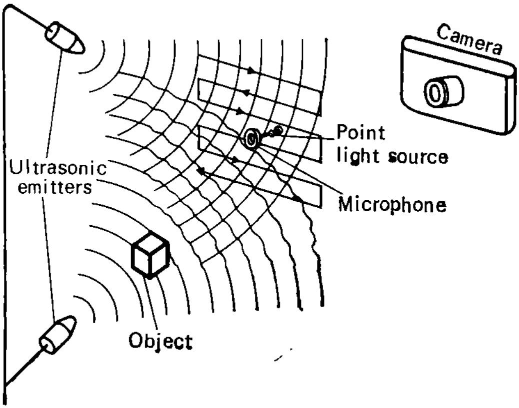


Fig. 74. Arrangement for forming acoustic holograms with a scanning receiver

Both single-beam and off-axis variants of acoustical holography are possible. It should be noted that the part of the reference sound beam can be played by the electrical signal from a sound generator added to the signal of the transmitter [163] (Fig. 75).

2. *Photography.* An ultrasonic field can be directly recorded on a photographic emulsion by making use of the fact that ultrasound intensifies the chemical reactions proceeding in the development or fixing of the photolayer. P. Greguss [165] placed a preliminarily uniformly exposed but undeveloped photographic plate in a bath with a weak solution of sodium thiosulphate. An ultrasonic field was created in it, and the silver halide rapidly dissolved at the antinodes of the sound waves. After 20 to 30 seconds of "sound recording", the plate was

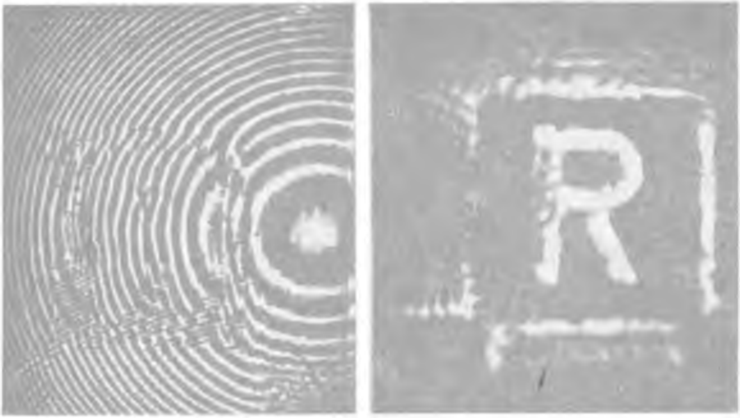


Fig. 75.
Ultrasonic
hologram formed
in scanning a
receiver, and the
image of the
letter R
reconstructed
from it.
The reference
signal is from the
emitter [162]

developed in the light. The acoustic hologram formed in this way reconstructed the image in a light beam. A photographic emulsion can be exposed in exactly the same way in a weak developing solution. The emulsion should preliminarily be exposed to light. Developing proceeds much faster in the antinodes of the sound waves than in the nodes.

3. *Deformation of the surface of a liquid under the action of sound pressure* (Fig. 76). The advantage of this process is that optical reconstruction of the reflection hologram obtained can be carried out as it is formed and a process observed in real time [166]. Another variant is described in [167]. The surface of a liquid was covered with a thermoplastic film which was deformed by an ultrasonic wave, cooled and subsequently used as a phase optical hologram.

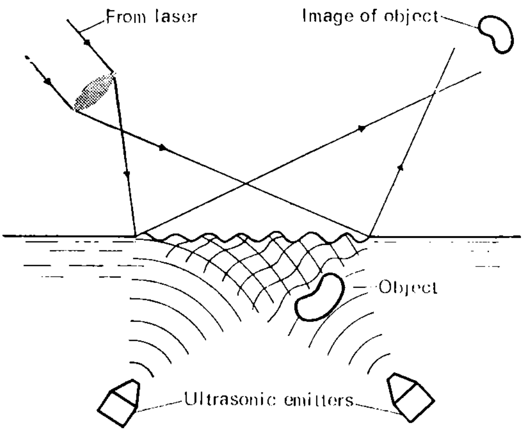


Fig. 76. Arrangement for forming ultrasonic holograms using the surface relief of a liquid

A piezoelectric ceramic mosaic was also used for recording ultrasonic holograms in conjunction with reading of the signal by a scanning cathode ray by elements.

4. *A running or standing ultrasonic wave in a liquid* can itself be used as a volume hologram. The compactions and rarefactions of the liquid are attended by changes in its refractive index. A sound wave is thus a 3D phase hologram. An optical copy of an ultrasonic wave can be obtained in real time as a result of Bragg diffraction of a laser beam on such a hologram [168, 169] (Fig. 77).

The main investigations in acoustical holography are collected in the annually published editions of "Acoustical Holography" [170].

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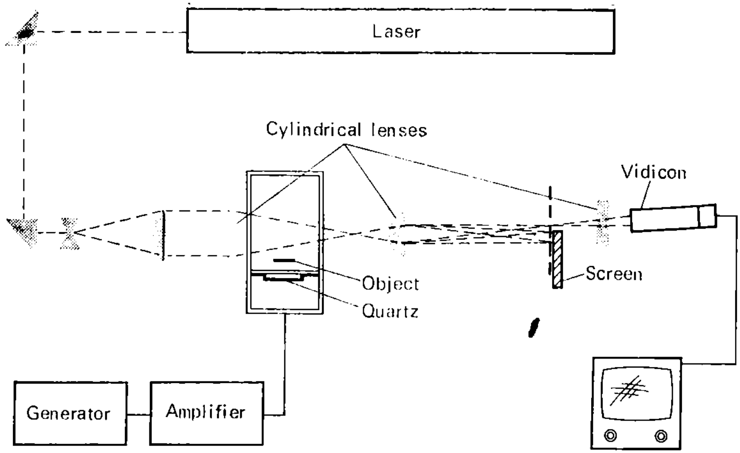


Fig. 77.
Arrangement for reconstruction of an image formed by Bragg diffraction of light on an ultrasonic hologram [169]

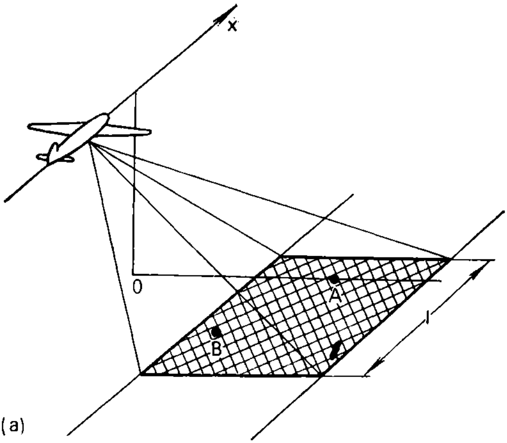
Already in the fifties of the present century, the first successful experiments were run for recording holograms and optically reconstructing the images in the centimetre and millimetre ranges of electromagnetic waves. Such experiments are of great importance for radar. The conventional radar methods, as a rule, do not make it possible to record the shape and dimensions of objects, but only permit the observer to judge whether they are present or absent in his field of vision. Radioholographic methods make it possible to observe both the shape and the dimensions of objects, which is very important for their identification. Other applications of microwave holography have also been proposed, namely, investigation of the surface of the Earth and the planets from satellites, and the optical modelling and investigation of radio antennas [171].

The methods of recording microwave holograms are similar to those for recording acoustical holograms with scanning. For example, the signal from the transmitter was fed to the screen of a television system whose scanning was synchronized with the motion of the transmitter [172]. The hologram was photographed from the screen, and the image was reconstructed in laser light. In another investigation [173], the arrangement for recording a microwave hologram was similar to that shown in Fig. 74. The hologram was recorded on an area of 2×2 m (the wavelength was 3 cm). The field was scanned by a crystal diode that controlled the brightness of a point lamp moving together with it and projected onto a photographic film. The hologram was reduced 1000 times (to dimensions of 2×2 mm), and the image was reconstructed with the aid of a helium-neon laser ($\lambda = 0.63\ \mu$).

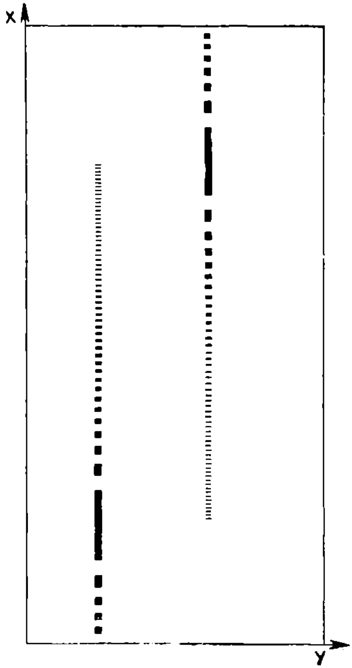
Liquid crystals, which change their colour when heated by microwaves, were also used for forming microwave holograms [174].

A unique method of recording a microwave hologram was proposed by K. Iizuka [175]. The microwave interference field was recorded by an absorbing plate (paraffin mixed with a carbon powder). Local heating of the plate at the antinodes of the field resulted in a relief appearing on its surface, a contour map

Fig. 78. Geometry of hologram recording using a radar with a synthetic aperture:
a—diagram of recording,
b—hologram of two points [the film moves along the *x*-axis (azimuth), the path of the cathode ray along the *y*-axis (distance)]



(a)



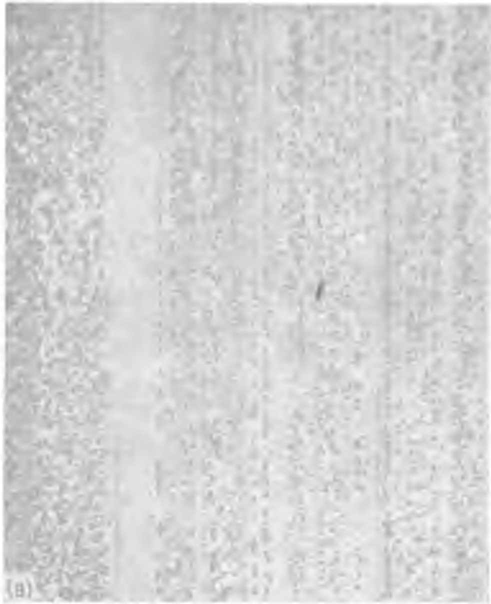
(b)

of which was recorded by the method of optical holographic interferometry. It is exactly this contour map that is a microwave hologram.

It should be noted that methods of holography in radiowaves began to be developed long before the "holographic explosion" of 1964-1965. They are mainly related to radar systems using a synthetic aperture (a side-looking radar) [176-179]. The principles of operation of such a system are shown for a simplified one in Fig. 78. The aircraft travels along a straight route in direction x, continuously emitting short pulses of microwaves, each time "illuminating" the area cross-hatched in the figure. The signals reflected from the terrain enter the receiving antenna and are mixed with the continuous signal from the same microwave emitter playing the part of a plane reference wave. The resulting signal modulates a cathode ray with respect to intensity. Scanning of the cathode ray is started by the pulses of the emitter. Signals from remote points of the terrain are received later and are recorded at the end of each path of the ray. The beginning of scanning corresponds to closer points of the terrain. The screen of the cathode-ray tube is continuously photographed on a moving film, forming a hologram like the one shown in Fig. 79.

Since the signals from each point of the terrain are received for a long time, during many pulses, and during this time the aircraft, accumulating these signals,

Fig. 79. Hologram of terrain recorded with the aid of a radar having a synthetic aperture (*a*), and the reconstructed (*b*) image (the shore of Lake Erie to the south of Detroit, the USA [178])



travels a considerable distance l, the resolving power with respect to the azimuth will now be determined by the direction diagram of the "synthetic" antenna whose length (and, consequently, angular resolution) is determined by the distance l. The resolving power with respect to distance will be determined, as in a conventional radar, by the duration of the pulses.

Consider first of all the very simple case when there is only one point object A on the terrain (Fig. 78*a*). This object will scatter a spherical wave, while the frequency of the signal received by the

aircraft will change as a result of the Doppler effect owing to the motion of both the emitting and the receiving antennas. As long as the aircraft has not reached line OA, the frequency of the received signal will be greater than that of the reference one, but the difference between the frequencies will diminish and become equal to zero when the aircraft flies over line OA. Now the aircraft will travel away from point A and, consequently, the Doppler shift of frequency will reverse its sign. The mixing of signals of different frequencies will result in beating whose frequency will decrease as the aircraft approaches line OA, will become equal to zero when the aircraft crosses this line and will then grow. As a result, a unidimensional zone plate will appear on the hologram whose centre corresponds to the moment when the aircraft flies over line OA (Fig. 78*b*). For point B, which is nearer to the course of the aircraft, there will be a different unidimensional zone plate nearer to the beginning of the path of the cathode ray and having a correspondingly displaced centre (Fig. 78*b*).

A hologram of a complex terrain will be a coherent superposition of such unidimensional plates corresponding to different points. Thus, correspondence between the points of the terrain and the hologram is observed only along the y-axis, and the hologram formed is equivalent to an optical hologram of the same locality focussed on its surface with a cylindrical lens having its axis directed along x. Reconstruction of the image of the terrain formed on such a hologram should naturally be performed also using a cylindrical lens. An image of terrain reconstructed in this way from a hologram of the kind shown in Fig. 79*a* is depicted in Fig. 79*b*.

Indeed, since during motion of the aircraft the distance from it to the points of the zone being recorded changes somewhat, a slightly curved zone plate will correspond to each point of the terrain instead of a linear one.

A side-looking radar is of great practical significance in geology, mineralogy, cartography and geophysical investigations with the aid of artificial satellites of the earth.

The development of holographic investigations in short-wave radiation (x- and gamma-rays, and also in corpuscular streams) is held back by the difficulties in obtaining coherent sources.

3.2. Holographic Interferometry

General Principles. If a hologram is placed at the same spot where it was exposed and the object removed, then, as we already know quite well, the light wave that was scattered by the object during the exposure will be reconstructed. If the object is not removed, then two waves can be observed: one coming from it directly through the hologram and the other one reconstructed by the hologram. These waves are coherent and can interfere. If changes, for example strains (deformations), occurred in the object during the time that elapsed between the recording of the hologram and observation, this will immediately be noted on the picture observed—the image of the object will be cut by interference fringes equal to the difference in the path length.

It thus becomes possible to make two light waves existing at different times interfere. This was impossible before the invention of holography. In a conventional non-holographic interferometer, the object of investigations must have a perfect optical surface deprived of a microstructure to remove the obstacles in the way of creating a reference beam having a wavefront of exactly the same shape. For example, in the Twyman-Green interferometer (which is a modification of the well-known Michelson instrument), the lens or prism being investigated is placed in one of the interfering beams and a standard lens or prism in the other. The interference pattern obtained is used to assess the difference between the part being investigated and the standard one.

Holographic interferometry makes it possible to investigate objects having an irregular shape and even with scattering reflection. Deviations from a regular shape of the surface of an object will not affect the interference pattern, since both interfering waves will be distorted to the same extent by them because the standard wave is created by the object being investigated itself in its initial state. The interference pattern will be determined only by the geometrical or phase changes that occurred with the object.

The above method of holographic interferometry, called the *real-time* one, is very convenient, since it permits a single hologram of an object formed in its initial (unexcited) or undisturbed) state to be used to obtain interferograms of it in many states or investigate the dynamics of a process occurring in it in real time. This method, however, requires returning of the hologram to exactly the same position which it was in during its exposure. To achieve this, a photographic plate or film is sometimes processed on the spot, for which purpose special devices are needed (see Fig. 42).

The *double-exposure* method is much simpler. Two holograms of an object in two different states are consecutively recorded on a single photolayer. Now care only has to be taken to see that the photolayer does not move during the interval between the two exposures. This interval can be made very small, for example R. Brooks et al. [180, 181] used a laser to generate a double giant pulse consisting of two peaks displaced by several microseconds, and a holographic interferometer recorded the phase changes that occurred with the object during this time.

It should be noted that the requirements to the quality of the optical elements, which are so strict for conventional interferometry, are as a rule of no importance for its holographic counterpart. Both interfering waves are distorted in the same way by defects in the optical elements. This makes it possible to conduct interference investigations of large objects without an enormous outlay for high-quality mirrors, windows and light splitting plates.

Thus, holographic interferometry has to do with interference patterns formed by waves of which at least one is reconstructed with the aid of a hologram. This method was proposed independently and almost simultaneously by several authors at the end of 1965 [180-187].

Holographic Investigations of Strains. It was already noted that holographic interferometry made it possible to compare different states of the same object even if it has a random microstructure and diffusely reflects or transmits light. This wonderful property of holographic interferometry is due to the reference wave reconstructed by a hologram being scattered by the same object in its initial state. If the microstructure of the object underwent no appreciable changes, we observe a regular interference pattern corresponding to the macroscopic changes that occurred with it. If the microstructure of the object also changed appreciably, we shall see no interference fringes, since the difference in path length from point to point changes randomly, and the interference pattern will accordingly have an irregular structure and a high spatial frequency. For this reason, holographic interferometry does not allow us to compare different diffusely transparent or reflecting objects*. It is also powerless if in the two states of an object being compared its microstructure noticeably

* To form a holographic interferogram when comparing different diffusely reflecting objects, they should be so positioned as to reflect like a mirror, i.e. they should be observed with glancing incidence of the light [188] (Fig. 80).

changed, for example if its surface was painted or subjected to chemical etching. The diminishing of the contrast of the fringes when the microstructure of an object changes can be used, however, to assess the nature of these changes—for example to watch processes of corrosion [189] or sedimentation and diffusion of turbid suspensions [190].

The investigation of strains of diffusely reflecting objects was one of the first applications of holographic interferometry [191].

The observation and deciphering of the fringes obtained is not at all a trivial task [192]. The matter is that the fringes are formed owing to the interference of waves scattered by the "corresponding" points of the object and its holographic copy (Fig. 81), and the difference in path lengths of these waves determining the configuration of the fringes depends not only on the strain Δr, but also on the direction of illumination and observation. For example, with parallel displacement of the object when it is illuminated by a plane wave (Fig. 81), the difference in path lengths Δ for all the points of the object is

$$\Delta = \Delta x (\cos \varphi + \cos \psi) - \Delta y (\sin \varphi + \sin \psi) \quad (53)$$

We observe a system of parallel fringes localized at infinity. In the case of pure turning, the fringes are localized near the surface of the object.

Fig. 80.
Interference fringes obtained in comparing the inner surfaces of two similar cylinders [188]. Glancing incidence of the light on the inner surfaces of the cylinders being compared was used

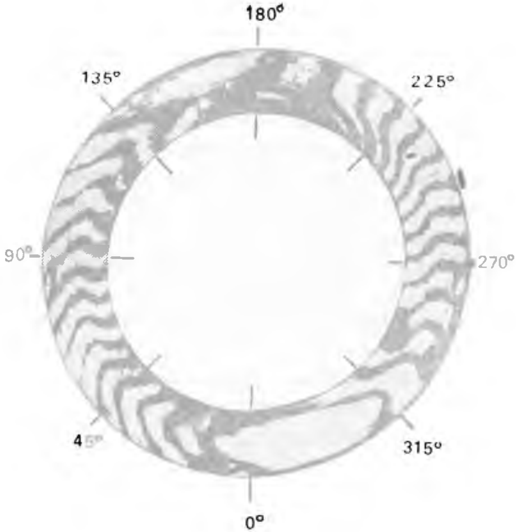


Fig. 81.
To calculation of the difference in path lengths with parallel displacement of a surface.
A and *A'* are the consecutive positions of the same point

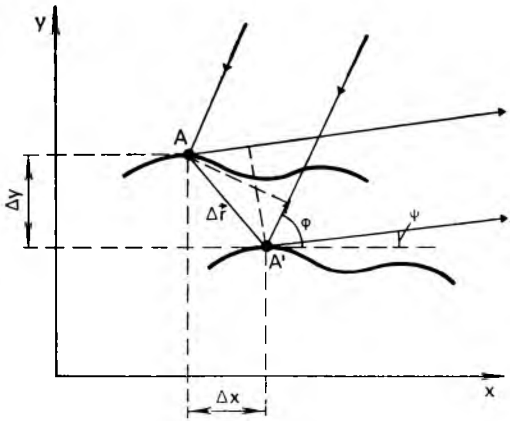


Figure 82 shows interferograms reconstructed from a double-exposed hologram of an elastic plate strained by a force applied to its upper right-hand corner and normal to the plane of the figure. The lower edge of the plate is gripped in a vise. The two interferograms (Fig. 82*a* and *b*) were reconstructed from different sections of the hologram, i.e. they correspond to different directions of observation. It can be seen that the arrangement of the fringes on the two interferograms differs somewhat. This feature of holographic interferometry hinders the observation and photography of the fringes with a great aperture. A reduction of the aperture increases the contrast of the fringes, but also results in a coarser speckle structure of the reconstructed interferogram.

A variety of methods for calculating strains according to observed interferograms are described by a number of authors [191-197]. Special notice should be given to the "holodiagram" method proposed by N. Abramson [54, 197]. This method makes it possible to consider from general positions the geometry of a holographic arrangement (Fig. 83), the orientation and localization of the fringes at a preset strain and, conversely, to determine the strain from the interference pattern.

To date a great number of publications have appeared devoted to the use of holographic interferometry for studying strains. Many of them were published in

Fig. 82.
Holographic interferograms of a strained elastic plate reconstructed from different sections of the same hologram

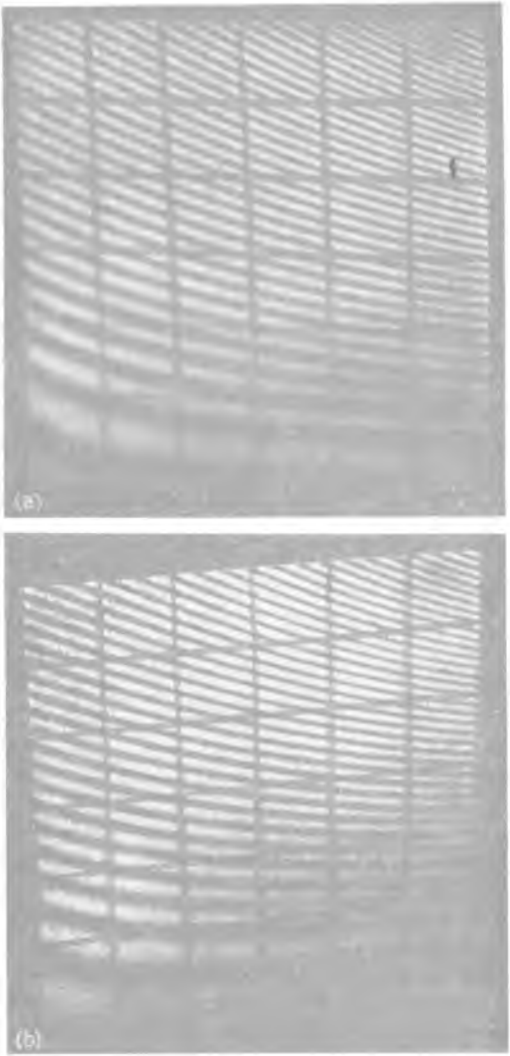


Fig. 83. Interference fringes obtained by the double-exposure method for the straining of a beam 195 cm long [54].
The layout of the beam relative to the parts of the arrangement was chosen in accordance with Fig. 45

the proceedings of two international conferences on the applications of holography [198, 199]. Holographic interferometry was used to investigate the process of crystal growth from a melt [200], and also the shape of the meniscus on the surface of a liquid [201]. It was also used to control the quality of motor vehicle tyres according to the deformation of their surface upon a small change in the pressure [202] (Fig. 84). The double-exposure method was used to study the strain of cylindrical shafts [203], turbine blades [204, 205], etc.

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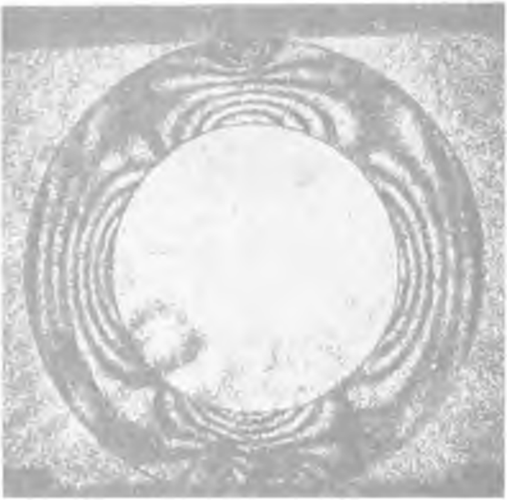
Fig. 84.
Interference fringes obtained in testing tyres.
The regions of a high concentration of the fringes (shown by arrows) indicate weakened spots. The object was simultaneously recorded on the hologram from three directions with the aid of two mirrors placed at an angle of 45 degrees

Fig. 85.
Holographic interferogram of a loaded ring made of an epoxide resin [210]



T. Tsuruta and Y. Itoh [206] described the holographic investigation of the strains of a revolving disk. To exclude the influence of rotation, an arrangement was used in which the hologram was fastened on the same shaft as the object and revolved together with it. Many applications of holographic interferometry are also described in [207-209].

Close to the studying of strains is the application of holographic interferometry for studying the changes in the refractive index of transparent liquids and solids as a result of various action on them such as stresses (holographic photoelastometry [210-212] (see Fig. 85), heating [213], etc).

Holographing a Uniformly Moving Object. It was shown on a previous page that the motion of an object during an exposure is, generally speaking, impermissible. In some cases, however, a hologram of a moving object can be formed and, moreover, the hologram can be used to reach an opinion on the nature of its motion.

Consider the very simple case schematically shown in Fig. 86*a*. The object is a diffusely reflecting plate which during exposure is rotated toward the hologram at a constant angular velocity through the small angle α_0. Assume that the plate is illuminated by a parallel beam of light from the side of the hologram. In this case, the points of the plate directly adjoining the axis of rotation

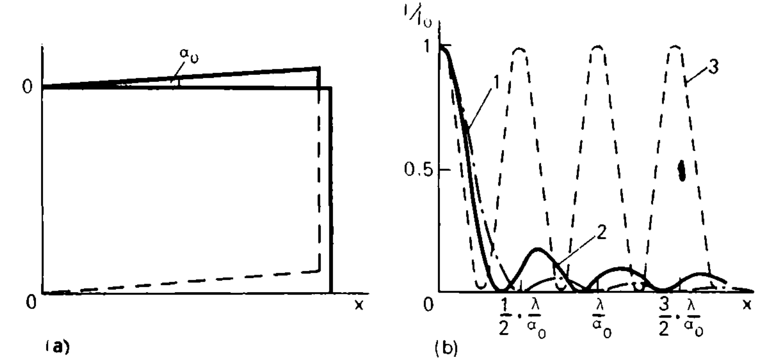


Fig. 86.
Turning of the plate (a) and distribution of the intensities over the reconstructed image (b) for different kinds of motion of the plate and methods of recording the hologram:
1—rotation at a constant speed (a single continuous exposure);
2—with sinusoidal oscillations having an amplitude of $\alpha_0/2$;
3—method of double exposures at the beginning and end of motion, or the stroboscopic method

and remaining stationary will form a stationary interference pattern on the hologram and will be the brightest when the image is reconstructed. The points which during the exposure approached the hologram by $\alpha_0 x = \lambda/2$ will not contribute to the interference pattern. Indeed, for these points, the quantity $(\varphi_1 - \varphi_2)$—the difference between the phases of the object and the reference waves—will change during the exposure time by 2π. Since the mean value of the cosine upon a uniform change in the argument by 2π equals zero, then in accordance with Eq. (2a) we get $A^2 = A_1^2 + A_2^2$, i.e. the reference and the object waves will be summated as regards their intensity and will create no interference pattern on the hologram.

Points for which $\alpha_0 x$ equals any whole number of half-waves also form no interference pattern in exactly the same way. Equidistant dark fringes between which bright fringes sharply diminishing in intensity are arranged will cut across the reconstructed image of the plate.

The origin of the bright fringes and the sharp diminishing of their intensity can be explained as follows. Let us conditionally divide the duration of the exposure for points approaching the hologram by a distance not equal to a whole number of half-waves into two parts. In the first part, a point approaching the hologram by a whole number of half-waves does not contribute to its pattern. The second part of the exposure corresponding to displacement of the point over a distance less than $\lambda/2$ results in the appearance of a holographic pattern* whose contrast, however, will be the smaller, the smaller is the fraction of the total exposure which this second part forms. Calculations show that the law governing the change in intensity over the surface of the plate will have the form

$$I = I_0 \left(\frac{\sin \frac{2\pi\alpha_0 x}{\lambda}}{\frac{2\pi\alpha_0 x}{\lambda}} \right)^2 \tag{54}$$

Curve *1* in Fig. 86*b* is a plot of this function.

Thus it is possible to form holograms of objects moving during the exposure [214-216]. Figure 87 shows reconstructed

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* The mean value of $\cos(\varphi_1 - \varphi_2)$ upon a uniform change in $\varphi_1 - \varphi_2$ less than 2π does not equal zero.

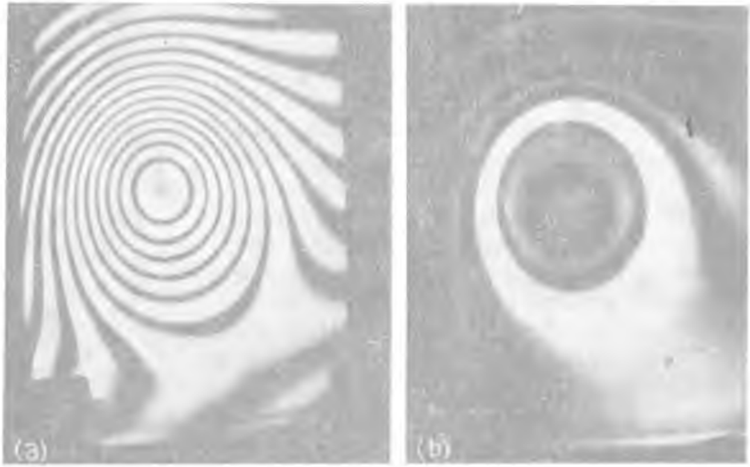


Fig. 87.
Holographic interferogram of a strained object:
a—formed by the double-exposure method;
b—formed by a single continuous exposure

interferograms of the thermal strains of a plate 60 $\times$ 60 cm in size formed by the double-exposure (*a*) and real-time (single continuous exposure) (*b*) methods [216]. The figure shows that the latter method allows us to separate the zero-order interference fringe, which appreciably facilitates calculation of the strains.

Holographic Analysis of Vibrations. Now imagine that the plate shown in Fig. 86 performs angular vibrations with an amplitude of $\alpha_0/2$ according to a sine law during the exposure. Let the duration of the exposure be much greater than the period of the vibrations. Here, as in the previous case, the pattern of the hologram will be determined by the mean value of $\cos(\varphi_1 - \varphi_2)$ during the exposure.

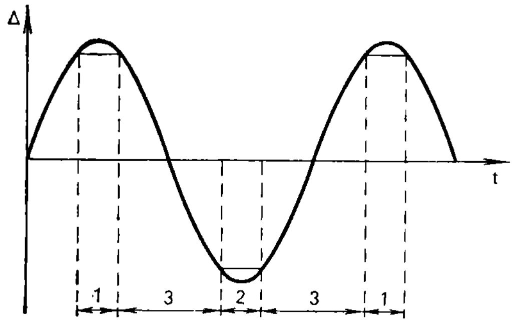


Fig. 88. "Useful" (*1*, *2*) and "harmful" (*3*) exposure time parts in the continuous exposure of a vibrating object.

Δ—difference in path lengths between the wave reflected from the object and the reference wave

Now, however, the points of the object travel over different sections of their paths with different velocities—they travel the slowest near their extreme (amplitude) positions. It is exactly these positions that make the main contribution to the pattern of the hologram. Each period of vibrations of the object can thus be divided into three parts (Fig. 88): (1) the duration of stopping in one of the extreme positions (we can assume this interval to equal the time during which the path length difference Δ changes by less than $\lambda/4$); (2) the same duration of stopping in the other extreme position; (3) the duration of rapid motion.

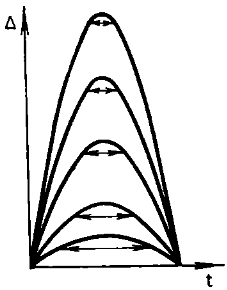


Fig. 89. Reduction in "useful" exposure when the amplitude is increased

During intervals (1) and (2), the object is exposed in turn in its two amplitude positions, and we get an interference hologram similar to one obtained by the double-exposure method. The third part of the exposure does not contribute to the pattern of the hologram, but only reduces its contrast. The latter, therefore, becomes higher with a growth in the fraction of the total period falling to the "useful" exposure, i.e. the time during which the object stops in its extreme positions. It is quite obvious that the fraction falling to the useful exposure grows with diminishing of the amplitude of the vibrations (Fig. 89).

In this connection, the intensity of the bright fringes also drops with a growth in the amplitude of the vibrations, although not so rapidly for the turning of a plate with a constant velocity. Calculations show that the law of the change in intensity over the surface of the plate will have the following form in this case:

$$I = I_0 J_0^2 \left(\frac{2\pi\alpha_0 x}{\lambda} \right) \tag{55}$$

where J_0 is a zero-order Bessel function. Curve *2* in Fig. 86*b* is a plot of this function.

The reconstructed image of a vibrating object is thus cut across by interference fringes. The brightest of them is arranged along the node line, and each following one diminishing in brightness combines the points of the object vibrating with the same amplitude (Fig. 90).

The above method of vibration analysis was proposed by R. Powell and K. Stetson in 1965 [185]. It is very convenient and simple, its drawback, however, being the impossibility of observing a vibrating object in real time. In addition, this method is limited to small amplitudes, since usually only from 10 to 15 fringes can be observed because their brightness rapidly diminishes.

The strobohologiaphic method proposed by a number of authors [217-221] is deprived of such drawbacks. A strobohologram is exposed only at the moments of time corresponding to the amplitude positions of a vibrating body. The result is an improved brightness of the interference fringes and a corresponding increase in the maximum amplitude of vibrations at which the method can be used (Fig. 91). By exposing a hologram only at the extreme positions of the object, we arrive at complete identity of the strobohologiaphic and double-exposure methods. For the case shown in Fig. 86*a*, the latter method is characterized by a distribution of the intensities in the interference pattern according to the law

$$I = I_0 \cos^2 \left(\frac{2\pi\alpha_0 x}{\lambda} \right) \tag{56}$$

Curve *3* in Fig. 86*b* is a plot of this function (fringes having a constant intensity).

The stroboscopic pulses actually have a finite duration—the brightness of the fringes drops with an increasing amplitude, but much more slowly than with continuous illumination. The theory of the strobohologiaphic method is considered in [222].

The stroboscopic method makes it possible to observe interference fringes of

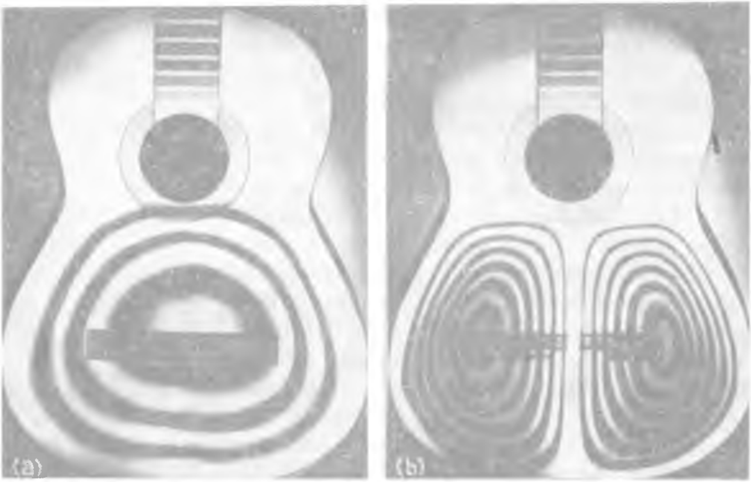
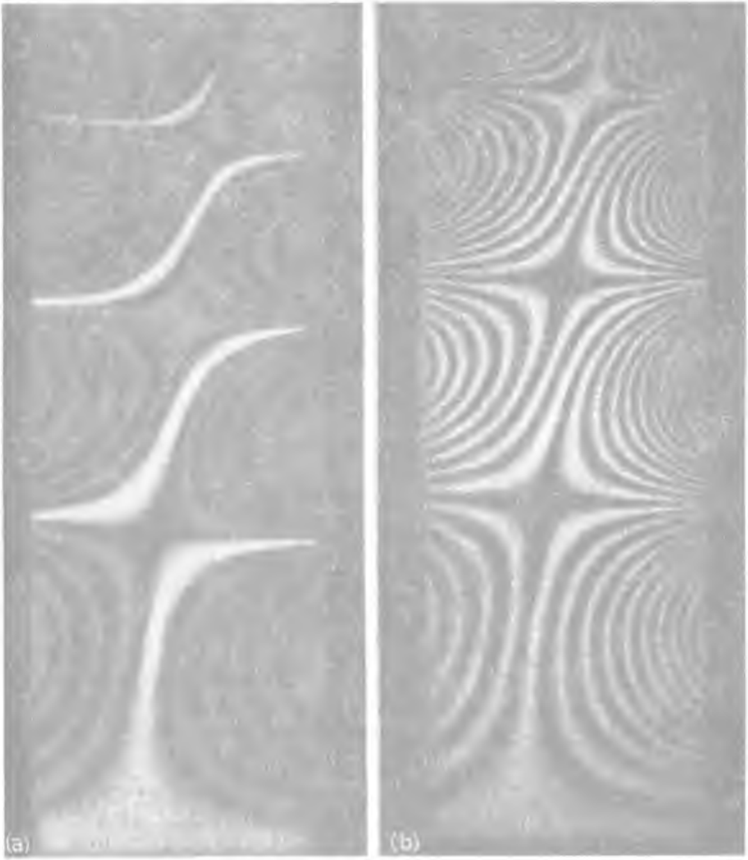


Fig. 90.
Images of a vibrating guitar formed by the Powell-Stetson method [217]:
a—185 Hz;
b—285 Hz

equal amplitudes in real time [218, 219]. For this purpose, the hologram of a stationary object is developed on the spot, and then the vibrating object is observed through it with stroboscopic illumination (one flash during a period of vibration).

A block diagram of an arrangement for the holographic investigation of vibrations is shown in Fig. 92.

Holographic methods can be used to study the vibrations of components and instruments, for example acoustic convertors, ultrasonic emitters, vibration stands, and also to investigate surface waves. Methods have been proposed for detecting internal defects of components according to the distribution of the nodes and antinodes on their surfaces. The



holographic analysis of vibrations has been considered by a number of authors, for example, in [223-227].

Fig. 91. Images of a turbine blade 15 cm high vibrating with a frequency of 3800 Hz: *a*—Powell-Stetson method; *b*—strobo-holographic method

Studying the Relief of Intricate Surfaces. Holographic interferometry makes it pos-

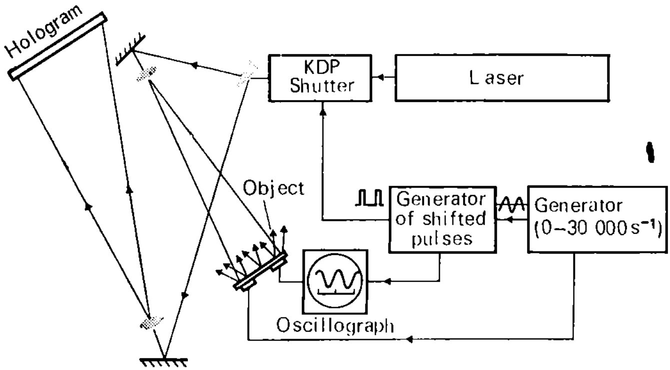


Fig. 92.
Block diagram of arrangement for the holographic investigation of vibrations [222]

sible to study the topography of objects having an intricate shape. B. Hildebrand and K. Haines [228] proposed two methods for this purpose. The first one consists in forming an interference pattern by waves scattered by the object in two different conditions of illumination. For this purpose the hologram is exposed twice, but before the second exposure the source of light illuminating the object is shifted. The second method consists in the interferential comparison of the wave scattered by the object with an identical wave, but with its scale changed slightly. For this purpose, Hildebrand and Haines exposed the hologram twice, or only once, but using a source of light with two wavelengths.

To obtain the same result, it was proposed [229] to change the refractive index of the medium in which the body being studied is immersed (for example, by changing the pressure of the gas or the composition of the immersion liquid) before the second exposure.

Figure 93 shows contours of equal depths for objects having an intricate shape formed by the two-wave method [230]. The difference in depth Δh between adjacent lines in this case equals $\lambda^2/2\Delta\lambda$ (with the object illuminated from the side of the hologram). The photograph shown in Fig. 93 was obtained with the aid of a pulsed ruby laser generating a double line ($\Delta\lambda \approx \frac{1}{8}$ Å, $\Delta h = 23$ mm).

It should be noted that in essence the two-wave method for determining the contours of equal depths of objects does not differ from the holographic method for determining the time coherence of radiation [64] (see Fig. 48). Here the known splitting of a spectral line is used to determine the relief of an object, while in determining the time coherence the known relief of an object (a plane placed at an angle to the beam) was used to determine the structure of the line.

The immersion method is also used for contour generation. It can produce holographic contour patterns of dies for manufacturing turbine blades and similar components. The width of one fringe is about 2 mm.

Holographic methods of determining the relief make it possible to control components having an intricate shape, for example turbine blades (see also [231-232]).

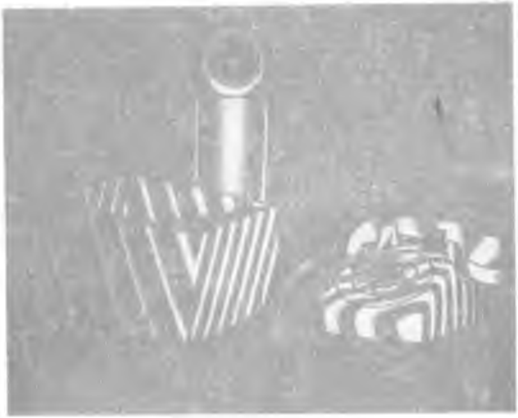


Fig. 93. Holographic contours of equal depths formed by the two-wavelength method

Holographic Investigation of Phase (Transparent) Objects. Holographic interferometry provides many new possibilities for studying pulsed and stationary phase heterogeneities—gas streams, flames, explosions, shock waves [48, 57, 180, 181, 233, 234] (Fig. 94), plasma [20, 56, 69, 70, 72, 143-145, 235-241]. The main one of them is the recording of interferograms of phase heterogeneities confined in vessels with optically imperfect walls (Fig. 95). Conventional interferometric methods do not make it possible to conduct such investigations: the space being studied has to be closed with plane-parallel (at least with an accuracy of $\lambda/2$) windows.

A single hologram of a phase object recorded using a diffusing screen can cover a large solid angle. Upon reconstruction of the wavefront at different

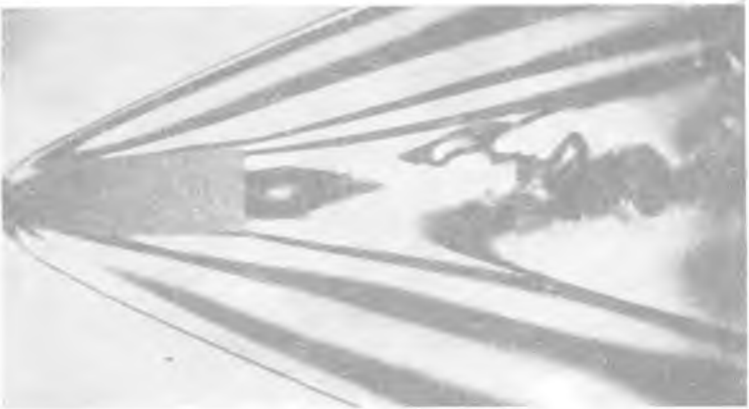


Fig. 94. Holographic interferogram of the shock wave produced by a bullet in flight [180, 181]

angles, information can be obtained on the spatial distribution of the phase heterogeneities having no axis of symmetry [233].

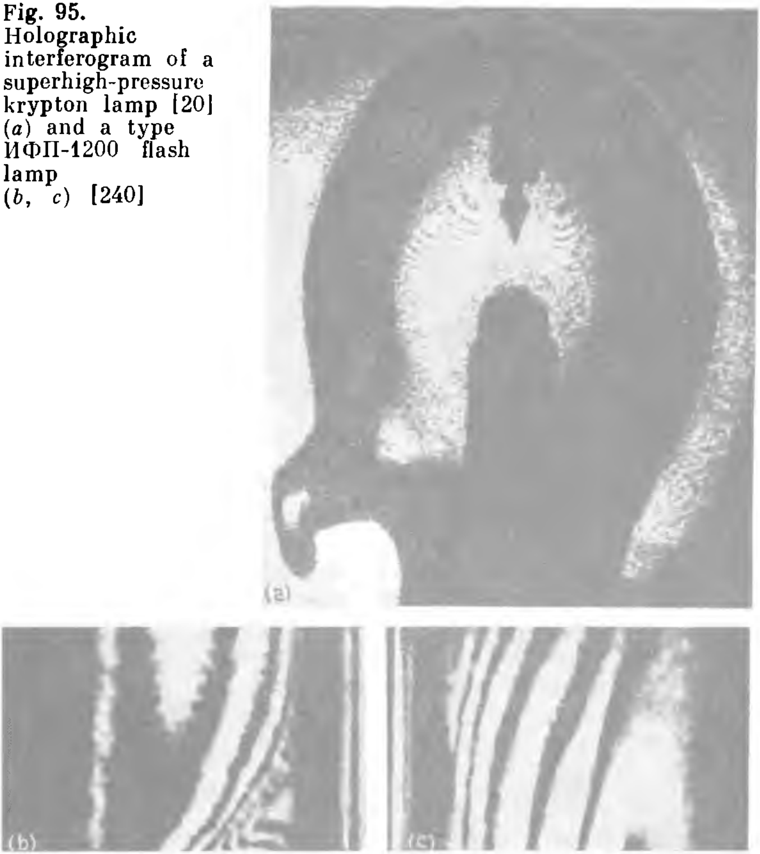
Holographic interferometry, owing to its differentiating nature, is unpretentious to the quality of the optics, which is especially significant in gas dynamics and the investigation of plasma in the transillumination of large sections (Figs. 96, 97).

One hologram allows us to study the phase heterogeneity by different methods, namely, by the interference, shadow and schlieren ones.

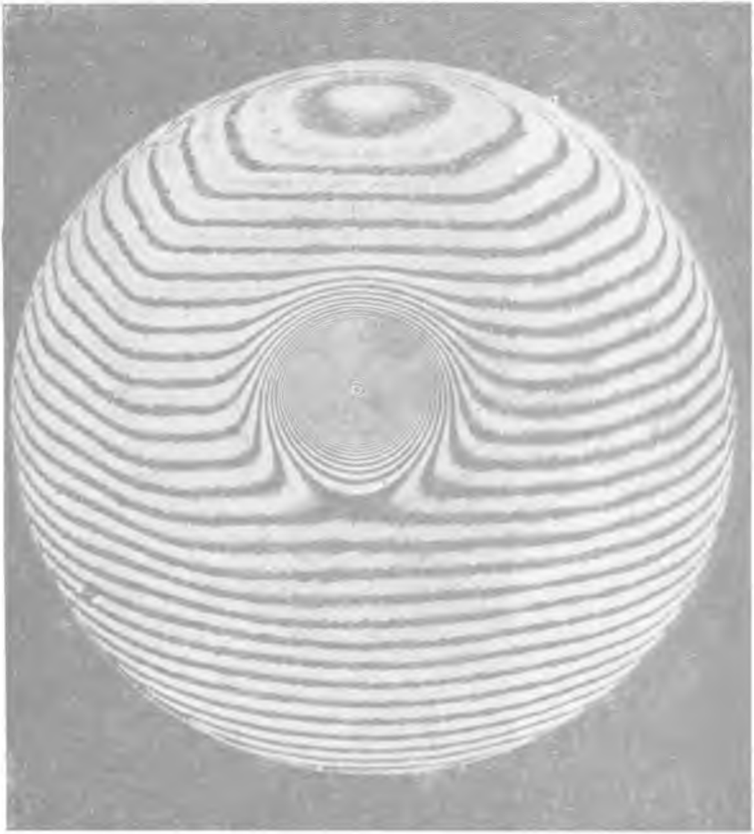
A number of methods have been proposed to increase the sensitivity of holographic interferometry of phase objects, some of which are described below.

1. The use of an emitted wavelength close to the resonance line of the gas

Fig. 95.
Holographic interferogram of a superhigh-pressure krypton lamp [20] (*a*) and a type ИФП-1200 flash lamp (*b*, *c*) [240]



being studied [20]. In the vicinity of the absorption line (λ_0) the refraction of a gas ($n - 1$) depends on the wavelength according to the law $(n - 1) \propto 1/(\lambda - \lambda_0)$ and rapidly grows when the line is ap-



proached. This method permits a gain in sensitivity of several orders of magnitude to be obtained. G. Dreiden et al. [242] used this method for studying the distribution of potassium vapour in

Fig. 96. Holographic interferogram of theta-pinch plasma 10 cm in diameter [241]

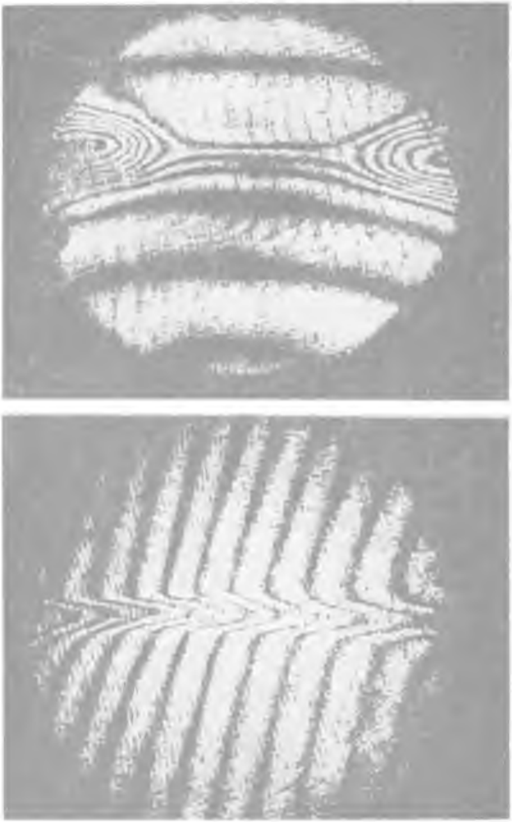
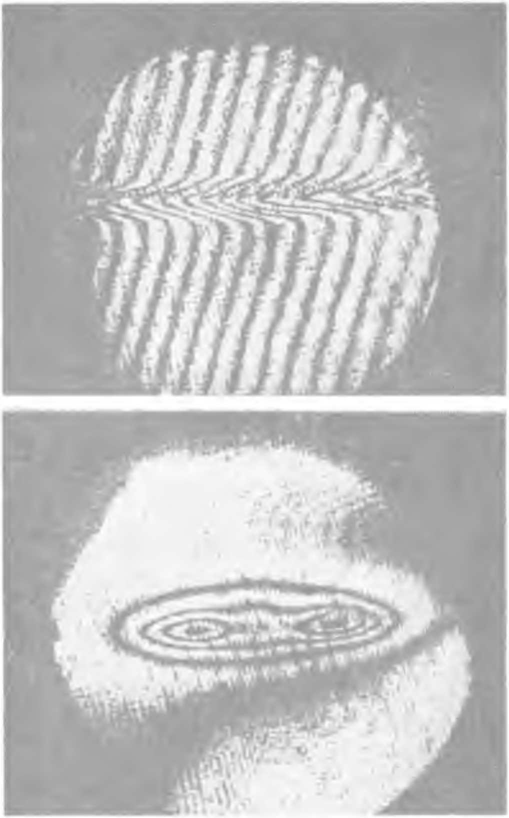


Fig. 97. Holographic interferograms of a neutral current layer [242]. The plasma section was 10 cm

plasma (see Fig. 98). The light source employed here was stimulated Raman scattering on a nitrobenzene cell with pumping by a ruby laser. The wavelength of the latter ($\lambda = 7658$ Å) is close to the resonance line of potassium ($\lambda = 7665$ Å).



It should be noted that in addition to its high sensitivity, this method has selectivity: the interference pattern records the distribution of practically only one component of a mixture.

2. The use of multiple-path arrangements. F. Weigl et al. [243] placed the

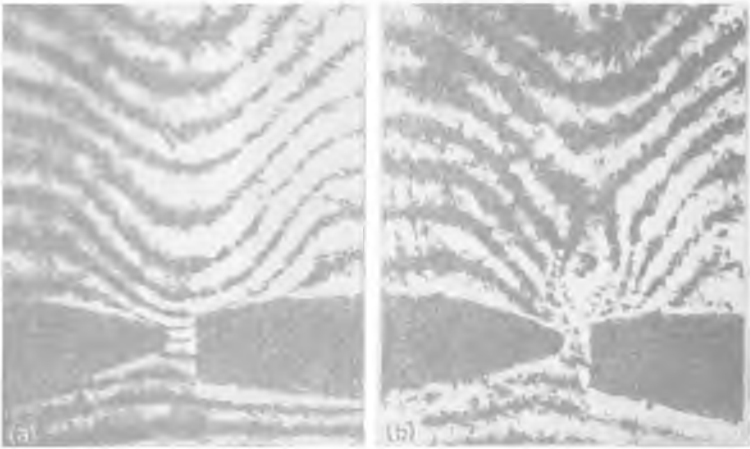


Fig. 98. Holographic interferograms of the plasma of a d-c carbon arc with potassium packing: $a - \lambda = 6943$ Å; $b - \lambda = 7658$ Å [72]

transparent optical heterogeneity being studied between two parallel semitransparent mirrors. The light beams that passed 1, 3, 5, . . . times through the heterogeneity were recorded at the outlet from this system. Only one of these beams, however, interfered with the reference beam, since the coherent length of the laser was less than the double distance between the mirrors. T. Tsuruta and Y. Itoh [244] used a similar method for testing the mirrors of a Fabry-Perot interferometer. The mirrors were placed at a small angle to one another to separate the beams undergoing a different number of reflections. As a result, these beams emerged from the system of mirrors at different angles.

3. The phase disturbances introduced by a heterogeneiy being studied into

a plane wave can be increased by reconstructing this wave with the aid of a hologram in the second, third and so on orders of diffraction ([245, 24], Fig. 99). For this purpose, it is necessary that the non-linear properties of the photolayer manifest themselves when recording the hologram. This is achieved by correspondingly choosing the exposures and the ratio of the intensities of the reference and object beams.

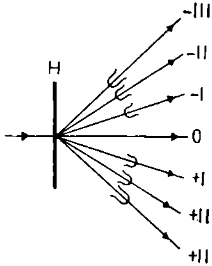


Fig. 99.
The phase distortions of a plane wave reconstructed in the n-th order are increased n times

The sensitivity can be increased still more by utilizing the fact that the phase distortions in the reconstructed beams have different signs at different sides of the zero-order beam. The sensitivity of holographic interferograms was increased in this way up to 14 times [246] (the seventh diffraction orders were used).

If radiation of several wavelengths was simultaneously used for recording a hologram, then this single hologram can be used to reconstruct separately the images of interferograms corresponding to these wavelengths.

This possibility was found to be very valuable for the holographic diagnostics of plasma. The refraction of plasma is determined by the presence of both electrons and heavy particles (atoms and ions). While electron refraction is proportional to the square of the wavelength, the refraction of heavy particles depends very slightly on the wavelength. For this reason to separate the contribution of the two kinds of particles to refraction,

$\lambda\,6943\,Å$

$\lambda\,3472\,Å$

Fig. 100. Interferograms of a laser spark reconstructed from a single two-wavelength double-exposure hologram

an interferogram of the plasma must be obtained in light of at least two wavelengths.

This method was used to study the distribution of the electron concentration in the plasma of a laser spark [69]

(Fig. 100), a plasmatron [235], and an exploding wire [247].

Holographic methods can be used to make light waves having different frequencies interfere. This possibility should naturally not be understood literally. Two waves of the same frequency actually interfere, but they are both holographic replicas of the original waves of a different frequency.

G. Ostrovskaya and the author [248] proposed an interference method in which a hologram of plasma is formed in light of two wavelengths differing by exactly two times (the first and second harmonics of ruby laser radiation). In reconstruction of the wavefront, the first-order diffraction beam corresponding to λ_1 coincides with the second-order beam corresponding to λ_2. The interference pattern created by these beams is determined only by the dispersion of the refractive index of the plasma being studied.

In this way, the two-wavelength hologram recorded during one exposure forms interference fringes that give a spatial distribution of the electron gas without the need to take into consideration the refraction of the heavy particles (see also [249]).

Interpretation of holographic interferograms of phase heterogeneities will be facilitated somewhat if the angle of incidence of the object beam on the hologram is slightly changed during one of the exposures. This is achieved by introducing a thin glass wedge into the beam [144], which results in the appearance of interference fringes parallel to a rib of the wedge (in the absence of disturbance from the phase heterogeneity being studied). The shape of the fringes formed as a result of the summary action of the wedge and a heterogeneity is shown in Figs. 98 and 100. The same results can be obtained by turning the wedge through a small angle about the optical axis of the object beam during one of the exposures [20] or by changing the pressure of the gas in a hollow wedge [250].

Holographic three-beam [251, 252] and multiple-beam [253, 254] interference methods, holographic shearing interferometers [255, 256], and also various ways of increasing and reducing the sensitivity [257-259] have been developed for studying phase objects.

Holographic interferometry is already being used for solving the most diverse problems—determining the rate of growth of plants [260], testing the homogeneity of glass blocks [261] and glass fibres in the process of their drawing [262], and establishing the quality of flat and spherical surfaces [263, 264]. A synthesized (calculated by a computer) hologram of an aspherical surface can serve to control the closeness of a surface to the designed shape [265-267].

3.3. Spatial Filtration and Character Recognition

In different fields of science and engineering, it often becomes necessary to resort to the separation of a definite signal from a complex of signals more or less differing from it. Such a problem is solved, for instance, by a radio operator when he separates the waves emitted by one definite radio station from the thousands of waves filling ether, by a specialist in spectroscopy when he searches for lines belonging to a definite element in the intricate paling of spectral lines of a sample being analysed, by a bibliographer who finds an article dealing with the problem of interest to a reader among the boundless ocean of books and articles, or by a criminalist comparing the fingerprints at the place of a crime with the ones in his file.

A general method exists for the optimal solution of such problems. Let us first consider it as applied to what confronts a radio operator or a spectrochemical analyst. These problems are united by the fact that the electromagnetic radiation of various radio stations, like the optical radiation of various elements, differs in the spectrum of its frequencies. Every radio receiver has an element called a frequency filter that passes only radiation of definite frequencies.

Such filters are also used sometimes in spectral analysis. But since it is difficult to manufacture them with a sufficiently narrow transmission band, filtration is often performed as follows. First the radiation being studied is decomposed into a spectrum, i.e. light waves of various frequencies are directed at different angles and, therefore, to different points of the focal plane. This operation is usually performed with the aid of a spectrograph provided with a prism or diffraction grating. Then the spectrum obtained in this way is compared with those of known elements and the coinciding spectral lines are found in them. This process can be automated by installing outlet slits at the places where the lines of different elements are located and watching the signals of photomultipliers installed behind these slits.

The drawback of this method is that not all the spectral lines of each element are separated out, but only one. This is attended by a high probability of noise—a line of a different element may get into the band of the spectrum cut out by the slit, and the signal recorded by the photomultiplier will be false.

A more improved method of filtration has also been proposed. A positive of the spectrum of the element being sought obtained using the same spectrograph is placed in its focal plane. A light collector and a photomultiplier are placed behind the plate. The signal of the photomultiplier will now be determined by the degree of correlation of the entire spectrum being analysed (and not of one line) with the spectrum of the given element. This system is a matched filter. The influence of noise and random coincidences on the signal is minimum in this case.

We have described this process in such detail because the operation of image filtration is conducted by means of holograms in absolutely the same way. The only difference is that an image is decomposed into a spectrum of spatial (and not time) frequencies, decomposition (and filtration) being simultaneously conducted in two coordinates.

It should be noted that the fundamentals of the ideas set out below were established by the German optician E. Abbe about a hundred years ago. They were further developed by a number of authors [268-271].

Every two-dimensional image can be dispersed into a two-dimensional spectrum of spatial frequencies. This operation corresponds to the notion of an image having the form of a set of sinusoidal diffraction gratings of different periods and orientations, in the same way as in radio engineering or spectroscopy, when a signal dispersed into a spectrum is represented in the form of a set of sinusoidal oscillations having different frequencies.

The resolution of the image of a transparency into a spectrum by spatial frequencies is usually carried out with the aid of a lens (the left-hand part of Fig. 101). Each of the sinusoidal gratings which the image can be resolved into functions independently. A grating of

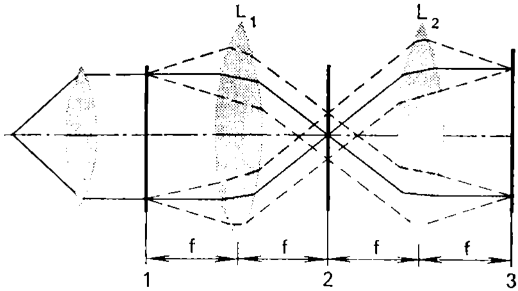


Fig. 101.
Formation
of a matched filter
and filtration of
images

a higher spatial frequency deviates the rays of the first orders over greater angles. These rays are focussed by lens L_1 at a point that is remote from the centre of plane *2*. Gratings having a greater period create illuminated points on plane *2* that are not so far from the centre. Examples of spectra obtained in this way are given in Fig. 102 [272]. We shall not stop to consider the mathematical aspect of the question, but shall only mention that the operation performed with an image in such an arrangement is called the Fourier transform.

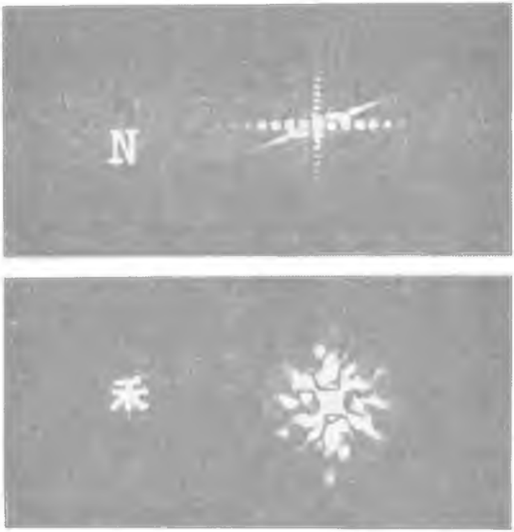
Note the important properties of the arrangement shown in Fig. 101. Rotation of the transparency about the optical axis will be attended by rotation of the spectrum. The latter also changes when the scale of the transparency is changed, namely, it broadens when the scale is reduced and narrows when it is increased. Translational motion of the transparency in plane *1* will not affect the spectrum. The zero-order beam creates a bright point at the centre of plane 2 that corresponds to the constant term in the expansion of the image into a Fourier series.

Now consider the whole of Fig. 101 (including its right-hand part). It is not difficult to see that the cofocal lenses L_1 and L_2 will construct an inverted image of the transparency in plane *3*. By placing various filters or masks in plane *2*, we can pass certain portions of the spatial spectrum of the object to form an image. This procedure is used, for example, to correct an image by weakening or stressing the high and low spatial frequencies [268]. It is possible to separate out definite details from an entire image, for instance only the letter N from a page of text. For this purpose, a transparency of the page of text being analysed should be placed in plane *1* (Fig. 101), and its image will be seen in plane *3*. If we now introduce a filter of the spatial frequencies of the letter N (Fig. 102) into plane *2*, then all the details will vanish from the page except for this letter.

A specially prepared filter placed in this plane can also improve the quality of an image by excluding the distortions previously introduced by aberrations of the optical system, heterogeneities of the atmosphere or unfavourable conditions of photography (blurring of the image owing to motion of the object during the exposure) [273, 274].

A Fourier transform of the transparency placed in plane *1* will be formed in

Fig. 102. Spatial spectra of letters. The letters are to the left, their spectra to the right



plane *2*. The second Fourier transformation performed by lens L_2 with this Fourier transform results in an image of the transparency appearing in plane *3*. The transmission of the transparency, however, is a convolution of the true distribution of the transmission of the object (f) and the apparatus function of the optical system used to obtain this transparency (h):

$$g = f \otimes h \tag{57}$$

The correction of an image boils down to excluding the apparatus function, i.e. to finding f according to the recorded g and the known h.

Since the Fourier transform of the convolution of two functions equals the product of the Fourier transforms of these functions, the distribution of the transmissions in plane *2* will be

$$G = FH \tag{58}$$

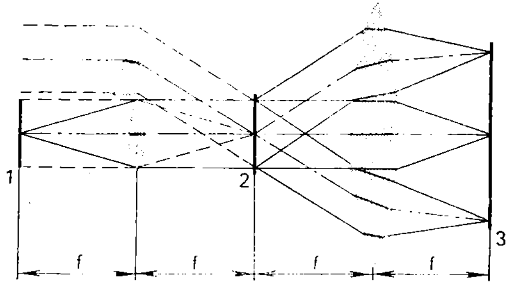
where G, F and H are the Fourier transforms of the functions g, f and h, respectively. It is easy to see that if we introduce into plane *2* a filter whose transmission is determined by the function $1/H$, the distribution of the amplitude in plane *2* will be expressed by the function F, and in plane *3* we get a Fourier transform of this function, i.e. the corrected function f.

The task, consequently, consists in preparing a filter with an amplitude transmission of $1/H$. Such a filter can be obtained in plane *2* of the same installation by introducing into plane *1* a transparency corresponding to the apparatus function of the optical system (an image of a point constructed by the same system).

The above method of spatial filtration of an image has an appreciable drawback: the filter contains not all the information on the object according to which it was made, and phase information is lost during the recording. For this reason, the light signal at the output of the system contains parasite components superposed on the images being recognized and hindering interpretation of the results.

In the holographic method of preparing a matched spatial filter [271], the phase information about the object is

Fig. 103.
Formation of a holographic filter and recognition of characters



retained, and the noise is sharply diminished. An arrangement for the formation of a holographic matched filter of spatial frequencies is shown in the left-hand part of Fig. 103. A Fourier transform of a transparency placed in plane *1* is formed as previously in plane *2*, but interference with the coherent background produced by the wedge results in a holographic diffraction grating, the so-called Fourier transform hologram, being formed in plane *2*. It is now no longer necessary to make a positive replica of the filter—we know that this will not change any properties of the hologram.

If we place an object in plane *1* and a holographic filter of a part of it in plane *2*, we will continue to see the image in the middle of plane *3* at the expense of the zero order—the filter does not practically distort it, but only weakens it somewhat. In the first-order image, we shall see bright recognition points whose coordinates correspond to the distribution over the object of its parts used to make the holographic filter.

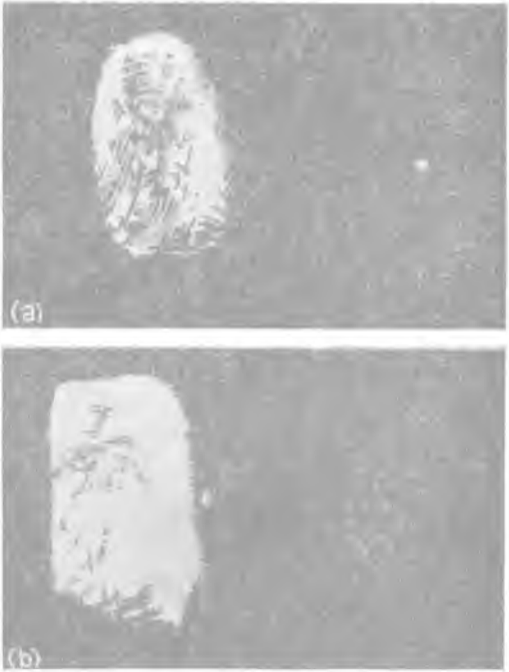


Fig. 104.
Images of
the output of an
identification
device [276]:
a—coincidence of the tendered fingerprint; *b*—no coincidence. At the left—a direct image of the fingerprint; at the right—the recognition point

The character recognition method described here is the more reliable, the more intricate is the shape of the object to be recognized. Satisfactory results were obtained, for example, in the identification of fingerprints [275, 276] (Fig. 104). Even when only an insignificant part of the fingerprint remained, the brightness of the recognition point was sufficiently high. The arrangement shown in Fig. 103 gave birth to a number of installations, including automatic readers, devices for

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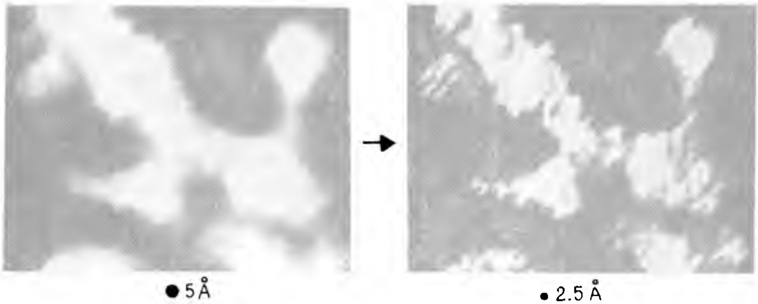
separating out the objects of a definite shape or direction on aerial photographs, and for processing geophysical data.

It is easy to understand the filtering properties of a hologram if we recall the reversibility of the reference and the object waves noted previously. If a hologram formed when exposing a plate with light from objects A and B is now illuminated with the wave from A, then the wave from object B will be reconstructed. Conversely, if the same hologram is illuminated by object B, then the wave scattered by A will be reconstructed. If A is a point source, then the hologram will reconstruct its image only when the illuminating object is B. The hologram thus performs the operation of recognizing "its own" object [277]. The same principle can be used for reconstructing a whole image according to its parts. We already mentioned that any part of an object can be considered as the reference source of light with respect to all its remaining parts (and to the reference source, if it was used in forming the hologram). For this reason, when a hologram is illuminated by a part of the object, "ghost" images of all the lacking parts are reconstructed (see, for example, [278]). Usually a halo due to the extension of the "reference source" is superposed on these images (see p. 35).

The same principles underlie the holographic methods of correcting images by excluding the apparatus function. A filter hologram is prepared by placing a trans-



parency with an image of a point constructed by the optical system (its apparatus function) in plane *1* (Fig. 103). The hologram as previously is recorded in plane *2* and is left in place after development. Next the transparency to be corrected is placed in plane *1*, and the beam which served as the reference one in recording the filter hologram is shielded or screened. An improved image of the transparency will be formed in plane *3*. The functioning of this system can be explained by considering an undistorted transparency as a complex of points emitting light, and the image distorted by the optical system and to be corrected as the superposition of the spots of confusion (apparatus functions) of this optical system. The filter hologram transforms each of such spots into a recognition point, the distribution of which corresponds to the distribution of the points emitting light over the object, and thus an improved image is constructed. Figure 105 illustrates the results obtained in this way [279].

Fig. 105. Holographic improvement of the quality of an image [279]:
To the left—the initial electron microscope photograph of a virus, to the right—the same holographically deblurred photograph (after exclusion of the apparatus function). The circles at the bottom show the resolution limit achieved in both cases

3.4. Other Applications of Holography

We shall limit ourselves here to a very brief consideration of several, from our viewpoint, most interesting problems: the applications of holography in spectroscopy, production processes and optical engineering. Such interesting and important problems as machine holography, microscopy, communication engineering and the storage of information have been left out of this book. The reader who is interested in them can find much useful information in the books by M. Françon [280], R. Collier, C. Burckhardt and L. Lin [28], in the materials of the All-Union schools on holography [281] and in the proceedings of international conferences and symposiums [198, 199].

Spectroscopy. Imagine a Michelson interferometer illuminated by a source of light whose spectrum we want to investigate. By inclining one of the opaque mirrors through a small angle φ, we get an interference pattern consisting of rectilinear fringes oriented parallel to the axis of rotation of the mirror in such a way that their period will be

$$a = \frac{\lambda}{2 \sin \varphi} \tag{59}$$

Inspection of this expression shows that the spatial frequency of the fringes is different for different wavelengths:

if the spectrum of the source contains several spectral lines, then each of them forms a pattern with its own spatial frequency. By photographing this pattern, we get a diffraction grating consisting of several (in accordance with the number of lines in the spectrum) gratings of different frequencies incoherently superposed on one another. Using the complex diffraction grating obtained as the dispersing element in a conventional arrangement of the spectral instrument and illuminating it with monochromatic light having the wavelength λ_0, we shall have in the first order of diffraction in accordance with Eqs. (25) and (59) on each of the "simple" gratings

$$\sin\beta = \frac{\lambda_0}{a} - \sin\alpha = 2\frac{\lambda_0}{\lambda}\sin\varphi - \sin\alpha \quad (60)$$

It follows from Eq. (60) that a grating obtained in the light of a line having a greater wavelength deflects the light through a smaller angle. If the gratings function independently, then in the focal plane of the spectrograph we shall see the spectrum of the original source. The method described here in a simplified way is a holographic variety of Fourier-transform spectroscopy [282]: the first step is the forming of a Fourier-transform interferogram, and the second one is reconstruction of the spectrum of the source.

In conventional Fourier-transform spectroscopy (see, for example, [283]), the first step is also conducted with the aid of an interferometer by consecutively recording the interference fringes during motion of a mirror; in the second step, as a rule, electronic computers are used.

Holographic Fourier-transform spectroscopy is still in its infancy and has not yet reached the level of the conventional non-holographic methods. The prospects of its development and improvement, however, make further investigations in this field very desirable.

A brief review of literature on holographic Fourier-transform spectroscopy is given by P. Parshin and A. Chumachenko [284] (see also [285-289]).

Application of Holography in Production Processes and Optical Engineering. The real images formed by holograms can be used in a number of production processes. Intricate patterns can be applied to surfaces being processed by the trans-illumination of holograms with a powerful laser. In particular, holograms were already used for the contactless application of microelectronic circuits [290-292]. The main advantages of holographic methods over conventional ones—contact or projection—is the possibility of obtaining an image with practically no aberrations on a large field. The maximum resolution of a hologram is determined by Eq. (37) and may reach fractions of the length of a

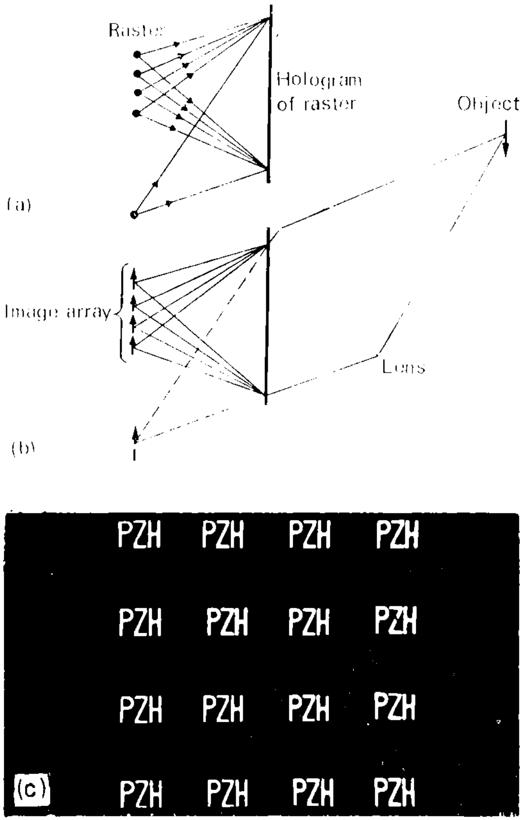
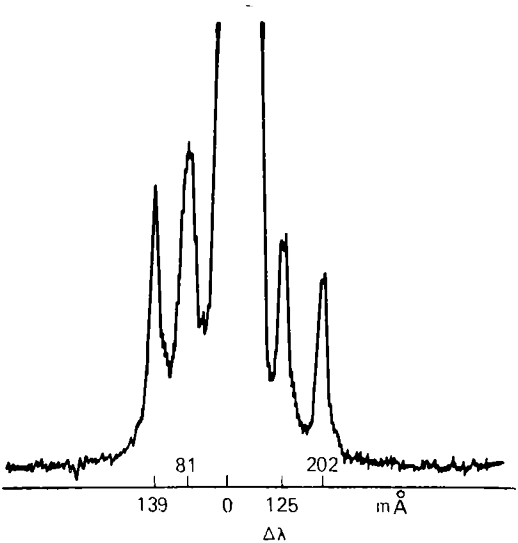


Fig. 106. Arrangement for forming a multiplying hologram (*a*) and multiplication of images (*b*); a multiplied image (*c*) obtained using this arrangement [294]

light wave. The image is practically not affected by dust particles settling on the hologram, scratches and other defects, whereas this results in rejection for contact or projection photographic patterns.

Another application of holograms in production processes is their use as len-

Fig. 107. Contour of isotopic fine structure of the mercury line ($\lambda = 4358$ Å) recorded by a holographic grating (90×60 mm, 840 lines/mm) [295]



ses. The focussing properties of zone plates were known long ago. The use of the plates, however, was limited by the difficulties encountered in manufacturing them. Holographic zone plates—holograms of a point source—are simple to fabricate and will undoubtedly be quite useful in laser production processes. For instance, holographic lenses were used to obtain holes with a diameter up to 14 microns in a tantalum film applied to glass [293]. A still greater effect in this field can be obtained by using a hologram of several pinholes—it can serve as a multiplying lens [291, 294] (Fig. 106). The aperture of each zone plate forming such a hologram is determined by the size of the entire hologram. One should not forget, however, about the great chromatism of zone plates—they can be used only in monochromatic light.

In some cases, it is precisely the great chromatism of holograms that is used. For example, compensation for the chromatic aberration of optical devices with lenses is based on the fact that the chromatic aberrations of a lens and a zone plate are opposite in sign. The chromatism of holograms is used in the fabrication of diffraction gratings [7, 295-297] (Fig. 107). We have already seen that the diffraction efficiency of holograms, especially of phase and reflection ones, may be very high. Holographic gratings never produce "ghosts", since in principle they do not have the errors of fabrication inherent in the conventional gratings marked in a ruling machine. This is why holographic gratings will evidently replace machine-made ones in the not too distant future. (Such gratings are already being manufactured by the French firm "Jobin-Yvon" [296].) In forming a holographic grating, it can be given any focussing properties. For example, it is possible to form plane or concave holograms similar in their action to a concave grating, but deprived of the astigmatism inherent in the latter. Reflection gratings with a sinusoidal profile of the lines do not produce spectra above the first order. This property is very valuable for application in the vacuum ultraviolet region of the spectrum, where there are no ways of separating superimposed spectral orders. In principle, however, it is possible to form holographic gratings with any distribution of their efficiency by diffraction orders. An ingenious method proposed for this purpose by O. Bryngdahl [298] consists in installing a holographic grating in plane *1* of the spatial filtration arrangement (see Fig. 101). The secondary grating with a corrected shape of the lines is photographed in plane *3*. Filters separating beams of the required diffraction orders and establishing the desired ratio of their intensities are placed in plane *2*.

Another interesting application of holographic methods is the formation of optical elements similar in their properties to the ones used in fibre optics [299]. For this purpose, two systems of nodes and antinodes crossing at right angles (according to the arrangement shown in Fig. 64*a*) are exposed in a thick layer of a light-sensitive material (polymethyl methacrylate). The gradients of the refractive index formed in the layer behave like regularly laid optical fibres.

Holographic elements are also used in laser engineering. Holographic gratings introduced into a laser resonator serve as excellent radiation wavelength selectors for dye solution lasers [300]. A hologram can be used as an amplitude and phase correcting element conver-

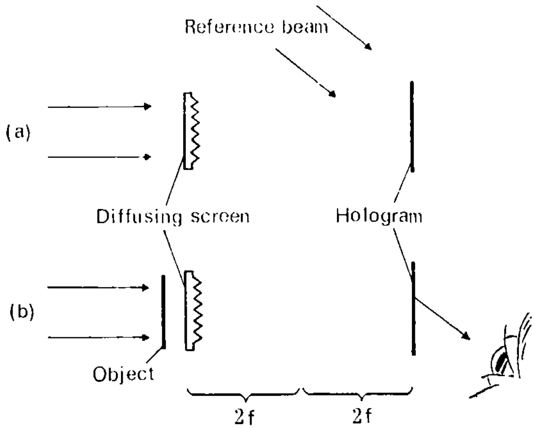


Fig. 108. Arrangement for viewing object through a diffusing screen:
a—forming hologram of diffusing screen;
b—viewing object

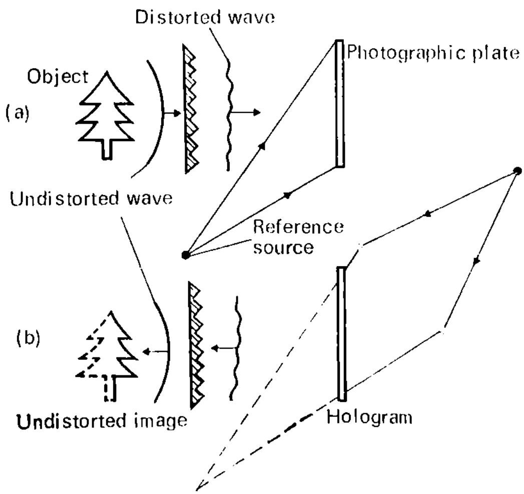


Fig. 109. Arrangement for holographic compensation of distortions:
a—forming hologram of object and distorting medium;
b—forming undistorted real image

ting the complex wavefront generated by a multimode laser into a plane wave [301]. Such conversion can evidently be especially effective when a dynamic hologram is placed in a resonator.

Special mention should be made of the holographic methods of image correction. One of them, based on exclusion of the apparatus function with the aid of a filter placed in the Fourier-transform plane was already considered. Another method uses the conjugated wave forming the real image of the object [302, 303]. When the real image of the distorting element is made to coincide with the element itself, the original shape of the light wave is reconstructed, and an undistorted image of the object is formed. A lens or even a diffusing screen such as a ground glass plate is used as the distorting element. One of the possible arrangements for correcting images and viewing through a diffusing screen is shown in Fig. 108. The first step is to form a hologram of the diffusing screen which is focussed on the hologram. The second step is to view the undistorted image of the transparency beyond the diffusing screen through this hologram. It is not difficult to explain the functioning of this arrangement on the basis of the principle of reversibility of the reference and object waves. If we illuminate the hologram formed in the arrangement shown in Fig. 108*a* by the object wave (a plane wave distorted by the diffusing screen and the lens), then the

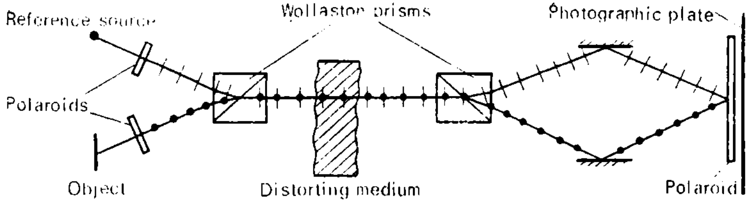


Fig. 110. Arrangement for compensation of distortions when the reference and object waves follow the same path [309]

reference plane wave will be reconstructed. If the object wave is additionally distorted by the object placed behind the diffusing screen, then the same distortions will be introduced into the reconstructed plane wave, and the observer will see the object. In another version of the same method (Fig. 109), a hologram of the wave from the object that has passed through a distorting medium is recorded [303] (see also [304-306]).

These methods of correcting images are not suitable, however, if the distorting element is not stationary, for example if it is necessary to exclude distortions caused by turbulence of the atmosphere. Methods have been developed for this case in which both the reference and the object beams are distorted to an equal degree, since they are passed along practically the same path [307-309]. A possible arrangement for this case is shown in Fig. 110.

A procedure was proposed differing in principle and based on the averaging of wavefronts by methods of holography [310]. Photographic methods of averaging cannot exclude random alternating phase distortions introduced by a heterogeneous and non-stationary medium, since they appreciably average the positive intensity. Holographic methods record both the amplitude and phase, and non-stationary random distortions should weaken in averaging, thus determining the useful stationary signal.

Epilogue

The object of the present book is to explain only the main ideas, principles and applications of holography. At present, a great number of books have been published in which our readers will be able to find sufficient material to deepen their knowledge in this field.

The mathematical background and the theory of holography are set out in a number of books [14, 18, 23, 311-313]. The experimental technique and the applications of optical holography are dealt with in [18, 31, 314]. The proceedings of the annual All-Union schools on holography also contain a variety of materials on holography and its applications [281].

The list of references on the following pages contains only a small fraction of all the works on holography published to date. We limited our choice only to those of them which were used to some extent in writing this book.

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References*

1. Gabor, D. *Nature*, **161**: 777 (1948).
2. Gabor, D. *Proc. Roy. Soc.* (London), **A197**: 454 (1949).
3. Gabor, D. *Proc. Phys. Soc.*, **B64**: 449 (1951).
4. An Interview with "The Father of Holography". In: *Optical Spectra*, Oct., 1970, p. 32.
5. Leith, E. and Upatnieks, J. *J. Opt. Soc. Amer.*, **53**: 1377 (1963); **54**: 1295 (1964).
6. Leith, E. and Upatnieks, J. *J. Opt. Soc. Amer.*, **51**: 1469 (1961); **52**: 1123 (1962).
7. Denisyuk, Yu. N. *DAN SSSR*, **144**: 1275 (1962).
8. Denisyuk, Yu. N. *Opt. i spektr.*, **15**: 522 (1963).
9. Denisyuk, Yu. N. *Opt. i spektr.*, **18**: 275 (1965).
10. Michelson, A. A. *Studies in Optics*. Univ. of Chicago Press (1927).
11. Landsberg, G. S. *Optika* (Optics). Moscow, Gostekhizdat (1957).
12. Born, M. and Wolf, E. *Principles of Optics*, 3rd ed. Pergamon Press, Oxford (1965).
13. Françon, M. and Slansky, S. *Cohérence en optique*. Paris, Editions du centre National de la recherche scientific (1965).
14. Stroke, G. W. *An Introduction to Coherent Optics and Holography*, 2nd ed. New York, Academic Press (1969).

* Most of the cited Soviet journals are published in English by the American Institute of Physics, New York, under the following titles:
Opt. i spektr.—Optics and Spectroscopy
Zh. eksp. i teor. fiziki—Soviet Physics—JETP
DAN SSSR—Soviet Physics—Doklady
Uspekhi fiz. nauk—Soviet Physics—Uspekhi
Zh. tekhn. fiziki—Soviet Physics—Technical Physics
Optikomekh. prom.—Soviet Journal of Optical Technology

15. Konstantinov, B. P., Zaidel, A. N., Konstantinov, V. B. and Ostrovsky, Yu. I. *Zh. tekhn. fiziki*, **36**: 1718 (1966).
16. Stroke, G. W. *Appl. Phys. Lett.*, **6**: 201 (1965).
17. Winthrop, J. T. and Worthington, C. R. *Phys. Lett.*, **15**: 124 (1965).
18. Collier, R. J., Burckhardt, C. B. and Lin, L. H. *Optical Holography*. New York, Academic Press (1971).
19. Meier, R. W. *J. Opt. Soc. Amer.*, **56**: 219 (1966).
20. Zaidel, A. N., Ostrovskaya, G. V. and Ostrovsky, Yu. I. *Zh. tekhn. fiziki*, **38**: 1405 (1968).
21. Friesem, A. A. and Zelenka, J. S. *Appl. Opt.*, **6**: 1755 (1967).
22. Bryngdahl, O. and Lohmann, A. W. *J. Opt. Soc. Amer.*, **58**: 1325 (1968).
23. Goodman, J. W. *Introduction to Fourier Optics*. New York, McGraw-Hill (1968).
24. Ostrovskaya, G. V. Non-Linear Effects in Holography. In: *Materialy IV Vsesoyuznoi shkoly po golografii* (Materials of the 4th All-Union School on Holography). Leningrad (1973).
25. Kozma, A., Jull, G. W. and Hill, K. O. *Appl. Opt.*, 9: 721 (1970).
26. Burch, J. M., Gates, J. W., Hall, R. J. and Tanner, L. H. *Nature*, **212**: 1347 (1966).
27. Gates, J. W. C. *J. Sci. Instr.*, **1**: 989 (1968).
28. Vandewarker, R. and Snow, K. *Appl. Phys. Lett.*, **10**: 35 (1967).
29. Stetson, K. A. *Appl. Phys. Lett.*, **11**: 225 (1967).
30. Ostrovsky, Yu. I. *Golografiya* (Holography). Leningrad, Nauka (1970).
31. Kiemle, H. and Röss, D. *Einführung in die Technik der Holographie*. Frankfurt/M., Akademische Verlagsgesellschaft (1969).
32. Hsu, T. R. and Moyer, R. G. *Appl. Opt.*, **10**: 669 (1971).
33. Nishida, N. *Appl. Opt.*, 7: 1862 (1968).
34. Aristov, V. V., Broude, V. L., Kovals-

16—01562

ky, L. V., Polyansky, V. K., Timofeev, V. B. and Shekhtman, V. Sh. *DAN SSSR*, **177**: 65 (1967).
35. Brown, R. M. *Appl. Opt.*, 9: 1726 (1970).
36. Lin, L. H. and Beauchamp, H. L. *Rev. Sci. Instr.*, **41**: 1438 (1970).
37. *Katalog tsvetnogo stekla* (A Catalogue of Coloured Glass). Compiled by T .I. Weinberg. Moscow, Mashinostroenie (1967).
38. Hamasaki, J. *Appl. Opt.*, **7**: 1613 (1968).
39. Neumann, D. B. and Rose, H. W. *Appl. Opt.*, **6**: 1097 (1967).
40. Cathey, W. T., Jr. U. S. Patent No. 3 415 587, Dec., 1965.
41. Caulfield, H. J., Harris, J. L., Hemstreet, H. W., Jr. and Cobb., J. G. *Proc. IEEE* (London), **55**: 1758 (1967).
42. Caulfield, H. J. *Appl. Phys. Lett.*, **16**: 234 (1970).
43. Palais, J. C. *Appl. Opt.*, 9: 709 (1970).
44. Bolstad, J. O. *Appl. Opt.*, 6: 170 (1967).
45. Butusov, M. M. and Turkevich, Yu. G. *Zh. nauchn. i prikl. fotogr. i kinematogr.*, **16**: 303 (1971).
46. Casler, D. H. and Pruett, H. D. *Appl. Phys. Lett.*, **10**: 341 (1967).
47. Gusev, O. B. and Konstantinov, V. B. *Zh. tekhn. fiziki*, **39**: 354 (1969).
48. Vest, C. M. and Sweeney, D. W. *Appl. Opt.*, 9: 2321 (1970).
49. Ishchenko, E. F. and Klimkov, Yu. M. *Opticheskie kvantovye generatory* (Lasers). Moscow, Sov. radio (1968).
50. Belostotsky, B. R., Lyubavsky, Yu. V. and Ovchinnikov, V. M. *Osnovy lazernoi tekhniki* (Fundamentals of Laser Techniques). Moscow, Machinostroenie (1972).
51. Mikaelian, A. L., Ter-Mikaelian, M. L. and Turkov, Yu. G. *Opticheskie generatory na tverdom tele* (Solid-State Lasers). Moscow, Sov. radio (1967).
52. Heard, H. G. *Laser Parameter Measurements Handbook.* New York, Wiley (1968).
53. Allen, L. and Jones, D.G.C. *Principles of Gas Lasers.* London, Butterworths (1967).

54. Abramson, N. H. In: Robertson, E.R. and Harvey, J. M. (Eds.). *Engineering Uses of Holography*, pp. 45-55. Cambridge, Univ. Press (1970).
55. Melroy, D. O. *Appl. Opt.*, 6: 2005 (1967).
56. Ashcheulov, Yu. V., Dymnikov, A. D., Ostrovsky, Yu. I. and Zaidel, A. N. *Phys. Lett.*, **25A**: 61 (1967).
57. Brooks, R. E., Heflinger, L. O. and Wuerker, R. F. *IEEE J. Quantum Electron.* **Q.E-2**: 275 (1966).
58. Javan, A., Bennet, W. and Herriot, D. *Phys. Rev. Lett.*, 6: 106 (1961).
59. Nazarova, L. G. *Opt. i spektr.*, 29: 757 (1970).
60. Young, M. and Drewes, P. *Opt. Commun.*, 2: 253 (1970).
61. Gerke, R. R., Denisyuk, Yu. N. and Lokshin, V. I. *Optikomekh. prom.*, 7: 22 (1958).
62. Janossy, M., Csillag, L. and Kantor, K. *Phys. Lett.*, 18: 124 (1965).
63. Dreiden, G. V., Ostrovsky, Yu. I. and Shedova, E. N. *Opt. i spektr.*, **32**: 367 (1972).
64. Staselko, D. I., Denisyuk, Yu. N. and Smirnov, A. G. *Opt. i spektr.*, **26**: 413 (1969).
65. Staselko, D. I. and Denisyuk, Yu. N. *Opt. i spektr.*, 28: 323 (1970).
66. Gerke, R., Denisyuk, Yu. and Staselko, D. I. *Optikomekh. prom.*, 7: 19 (1971).
67. Aleksoff, C. C. *J. Opt. Soc. Amer.*, **61**: 1426 (1971).
68. Brooks, R. E., Heflinger, L. O. and Wuerker, R. F. *Appl. Phys. Lett.*, **12**: 302 (1968).
69. Komissarova, I. I., Ostrovskaya, G. V., Shapiro, L. L. and Zaidel, A. N., *Phys. Lett.*, **29A**: 262 (1969).
70. Komissarova, I. I., Ostrovskaya, G. V. and Shapiro, L. L. *Zh. tekhn. fiziki*, **40**: 1072 (1970).
71. Gates, J. W., Hall, R. J. and Ross, I. N. *J. Sci. Instr.*, 3: 89 (1970).
72. Dreiden, G. V., Ostrovsky, Yu. I., Shedova, E. N. and Zaidel, A. N. *Opt. Commun.*, 4: 209 (1971).

73. Minami, M., Unno, Y. and Mizobuchi, Y. *Appl. Opt.*, 10: 1629 (1971).
74. Schmidt, W. and Fercher, A. F. *Opt. Commun.*, 3: 363 (1971).
75. Schäfer, F. (Ed.). *Dye Lasers.* Berlin, Springer-Verlag (1973).
76. Schmidt, W., Vogel, A. and Pressler, D. *Appl. Phys.*, 1: 103 (1973).
77. Ostrovsky, Yu. I. and Tanin, L. V. *Zh. tekhn. fiziki*, 45: 1756 (1975).
78. Worthington, H. R., Jr. *J. Opt. Soc. Amer.*, 56: 1397 (1966).
79. Leith, E. N. and Upatnieks, J. *J. Opt. Soc. Amer.*, 57: 975 (1967).
80. Lohmann, A. W., *J. Opt. Soc. Amer.*, 55: 1555 (1965).
81. Stroke, G. W. and Restrick, R. C. *Appl. Phys. Lett.*, 7: 229 (1965).
82. Froehly, C. and Pasteur, J. *Rev. opt.*, 46: 241 (1967).
83. Rukman, G. I. and Filenko, Yu. I. *Pis'ma v zh. eksper. i teor. fiz.*, 8: 538 (1968).
84. Friesem A. A. and Fedorowicz, R. J. *Appl. Opt.*, 6: 529 (1967).
85. Lin, L. H. and LoBianco, C. V. *Appl. Opt.*, 6: 1255 (1967).
86. Paques, H. *Proc. IEEE*, 54: 1195 (1966).
87. Denisyuk, Yu. N. and Sukhanov, V. I. *Opt. i spektr.*, 25: 308 (1968).
88. Ramberg, E. G. *RCA Rev.*, 27: 467 (1966).
89. Lin, L. H. *Appl. Opt.*, 6: 2004 (1967).
90. Brumm, D. B. *Appl. Opt.*, 5: 1946 (1966).
91. Brumm, D. B. *Appl. Opt.*, 6: 588 (1967).
92. Beinarovich, L. N., Larionov, N. P., Lukin, A. V. and Mustafin, K. S. *Opt. i spektr.*, 30: 345 (1971).
93. Vagin, L. N., Vanin, V. A. and Nazarova, L. G. The Properties of Photographic Plates for Holography. In: *Trudy I Vsesoyuznoi konferentsii po golografii* (Proceedings of the 1st All-Union Conference on Holography). Tbilisi (1972).
94. Konstantinov, V. B. and Maurer, I. A. Investigation of the Frequency-Contrast Characteristic of Photographic Materials. In: *Trudy I Vsesoyuznoi konferentsii po*

golografii (Proceedings of the 1st All-Union Conference on Holography). Tbilisi (1972).
95. Kirillov, N. I., Vasileva, N. V. and Zelikman, V. L. *Zh. nauchn. i prikl. fotogr. i kinematogr.*, 15: 441 (1970).
96. Denisyuk, Yu. N. and Protas, I. R. *Opt. i spektr.*, 14: 721 (1963).
97. Stroke, G. W., Funkhouser, A., Leonard, C., Indebetouw, G. and Zech, R. G. *J. Opt. Soc. Amer.*, 57: 110 (1967).
98. Brooks, R. E. *Appl. Opt.*, 6: 1418 (1967).
99. Andreeva, O. V. and Sukhanov, V. I. *Opt. i spektr.*, 30: 786 (1971).
100. Royer, H. *Compt. Rend.*, 261: 5024 (1965).
101. Zaidel, A. N., Konstantinov, V. B. and Ostrovsky, Yu. I. *Zh. nauchn. i prikl. fotogr. i kinematogr.*, 11: 381 (1966).
102. Ostrovsky, Yu. I. Inventor's Certificate No. 199 659, 1966—*Byull. izobr.*, 15 (1967); Inv. Cert. No. 212 751, 1967—*Byull. izobr.*, 9 (1968); Inv. Cert. No. 207 018, 1967—*Byull. izobr.*, 1 (1968).
103. Staselko, D. I. and Smirnov, A. G. *Zh. nauchn. i prikl. fotogr. i kinematogr.*, 15: 66 (1970).
104. Cathey, W. T., Jr. *J. Opt. Soc. Amer.*, 55: 457 (1965).
105. Russo, V. and Sottini, S. *Appl. Opt.*, 7: 202 (1968).
106. Sheridan, N. K. *Appl. Phys. Lett.*, 12: 316 (1968).
107. Kogelnik, H. W. *Microwaves*, 6: 68 (1967).
108. Armistead, W. and Stookey, S. *Science*, 144: 150 (1964).
109. Savostyanova, M. V. *Optikomekh. prom.*, 4 : 9 (1966); 5: 31 (1966).
110. Kirk, J. P. *Appl. Opt.*, 5: 1684 (1966).
111. Powell, R. L. and Hemnye, J. *J. Opt. Soc. Amer.*, 56: 23 (1966).
112. Mikaelian, A. L., Bobrinev, V. I., Aksenchikov, A. P., Shatun, V. V. and Gulanian, E. Kh. *DAN SSSR*, 181: 1105 (1968).
113. Lo, D. C., Manikowski, D. M. and Hanson, M. M. *Appl. Opt.*, 10: 978 (1971).
114. Hill, K. O. *Appl. Opt.*, 10: 1695 (1971).

115. Shankoff, T. A. *Appl. Opt.*, 8: 2282 (1969).
116. Gerritsen, H. J. *Appl. Phys. Lett.*, **10**: 239 (1967).
117. Stepanov, B. I., Ivakin, E. V. and Rubanov, A. S. *DAN SSSR*, **196**: 567 (1971).
118. Ostrovsky, Yu. I. and Tanin, L. V. *Pis'ma v Zh. tekhn. fiziki*, **1**: 1030 (1975).
119. Urbach, J. C. and Meier, R. W. *Appl. Opt.*, 5: 666 (1966).
120. Bosomworth, D. R. and Gerritsen, H. J. *Appl. Opt.*, 7: 95 (1968).
121. Lanzl, F., Röder, U. and Waidelich, W. *Appl. Phys. Lett.*, **18**: 56 (1971).
122. Aristov, V. V., Lysenko, V. G., Timofeev, V. B. and Shekhtman, V. Sh. *DAN SSSR*, **183**: 1039 (1968).
123. Aristov, V. V. and Shekhtman, V. Sh. *Uspekhi fiz. nauk*, **104**: 51 (1971).
124. Klimov, L. M., Pomerantsev, N. M. and Fabrikov, V. A. *Izv. AN SSSR, ser. fiz.*, **31**: 386 (1967).
125. Mezrich, R. S. *Appl. Opt.*, 9: 2275 (1970).
126. Kiemle, H. and Wolff, U. *Opt. Commun.*, 3: 26 (1971).
127. Sakusabe, T. and Kobayashi, S. *Jap. J. Appl. Phys.*, **10**: 758 (1971).
128. Jenney, J. A. *J. Opt. Soc. Amer.*, **60**: 1155 (1970); **61**: 1116 (1971).
129. Gerritsen, H. J., Hannan, W. J. and Ramberg, E. G. *Appl. Opt.*, 7: 2301 (1968).
130. Beesley, M. J. and Castledine, J. G. *Appl. Opt.*, 9: 2720 (1970).
131. Woerdman, J. P. *Opt. Commun.*, 2: 212 (1970).
132. Komar, A. P., Stabnikov, M. V. and Turukhano, B. G. *Opt. i spektr.*, **23**: 827 (1967).
133. Hashiue, M. *Opt. Commun.*, 3: 53 (1971).
134. Shankoff, T. A. *Appl. Opt.*, 7: 2101 (1968).
135. Lin, L. H. *Appl. Opt.*, 8: 963 (1969).
136. Brandes, R. G., Francois, E. E. and Shankoff, T. A. *Appl. Opt.*, 8: 2346 (1969).
137. Curran, R. K. and Shankoff, T. A. *Appl. Opt.*, 9: 1651 (1970).
138. Meyerhofer, D. *Appl. Opt.*, **10**: 416 (1971).

139. Pennington, K. S., Harper, J. S. and Laming, F. P. *Appl. Phys. Lett.*, 18: 80 (1971).
140. Sintsov, V. N. *Zh. nauchn. i prikl. fotogr. i kinematogr.*, **15**: 298 (1970).
141. Konstantinov, B. P. *Uspekhi fiz. nauk*, **100**: 185 (1970).
142. Gabor, D. *Proc. IEEE*, 60: 655 (1972).
143. Zaidel, A. N., Ostrovskaya, G. V., Ostrovsky, Yu. I. and Chelidze, T. Ya. *Zh. tekhn. fiziki*, **36**: 2208 (1966).
144. Kakos, A., Ostrovskaya, G., Ostrovsky, Yu. and Zaidel, A. *Phys. Lett.*, **23**: 81 (1966).
145. Komissarova, I. I., Ostrovskaya, G. V. and Shapiro, L. L. *Zh. tekhn. fiziki*, **38**: 1369 (1968).
146. Ostrovsky, Yu. I. Inventor's Certificate No. 179 188, 1963—*Byull. isobr.*, 4 (1966); *Opt. i spektr.*, **21**: 620 (1966).
147. Leith, E., Upatnieks, J., Kozma, A. and Massey, N. *J. Soc. Motion Pict. and Telev. Engrs.*, **75**: 323 (1966).
148. De Bitetto, D. J. *Appl. Phys. Lett.*, **12**: 176 (1968).
149. De Bitetto, D. J. *Appl. Phys. Lett.*, **12**: 295 (1968).
150. Lin, L. H. *Appl. Opt.*, **7**: 545 (1968).
151. Gurevich, S. B., Gavrilov, G. A., Konstantinov, A. B., Konstantinov, V. B., Ostrovsky, Yu. I. and Chernykh, D. F. *Zh. tekhn. fiziki*, **38**: 513 (1968).
152. Konstantinov, B. P., Gurevich, S. B., Gavrilov, G. A., Kolesnikov, A. A., Konstantinov, V. B., Konstantinov, A. B., Rizkina, A. A. and Chernykh, D. F. *Zh. tekhn. fiziki*, **39**: 347 (1969).
153. Welford, W. T. *Appl. Opt.*, 5: 872 (1966).
154. Turukhano, B. G. *Zh. tekhn. fiziki*, **40**: 181 (1970).
155. Staselko, D. I., Kosnikovsky, V. A. *Opt. i spektr.*, **33**: 365 (1973).
156. King, M. C. *Appl. Opt.*, **7**: 1641 (1968).
157. Ansley, D. A. *Appl. Opt.*, 9: 815 (1970).
158. Siebert, L. D. *Proc. IEEE*, **56**: 1242 (1968).

159. Staselko, D. I., Denisyuk, Yu. N. and Smirnov, A. G. *Zh. nauchn. i prikl. fotogr. i kinematogr.*, 15: 147 (1970).
160. McClung, F. J., Jacobson, A. D. and Close, D. H. *Appl. Opt.*, 9: 103 (1970).
161. Aoki, Y. *Appl. Opt.*, 7: 1402 (1968).
162. Metherell, A. F. and Spinak, S. *Appl. Phys. Lett.*, 13: 22 (1968).
163. Metherell, A. F. and El Sum, H. M. A. *Appl. Phys. Lett.*, 11: 20 (1967).
164. Denisyuk, Yu. N. and Parkhomenko, M. M. *Opt. i spektr.*, 26: 775 (1968).
165. Creguss, P. *Forschungsfilm*, 5: 330 (1965).
166. Mueller, R. K. and Sheridan, N. K. *Appl. Phys. Lett.*, 9: 328 (1966).
167. Young, J. and Wolf, J. *Appl. Phys. Lett.*, 11: 294 (1967).
168. Korpel, A. *Appl. Phys. Lett.*, 9: 425 (1966).
169. Landry, J., Powers, J. and Wade, G. *Appl. Phys. Lett.*, 15: 186 (1969).
170. *Acoustical Holography.* New York, Plenum Press, 1 (1969); 2 (1970); 3 (1971); 4 (1972).
171. Bakhrakh, L. D. and Kurochkin, A. P. *DAN SSSR*, 171: 1309 (1966).
172. Dooley, R. P. *Proc. IEEE*, 53: 1733 (1965).
173. Aoki, Y. *Appl. Opt.*, 6: 1943 (1967).
174. Gregoris, L. G. and Iizuka, K. *Proc. IEEE*, 58: 791 (1970).
175. Iizuka, K. *Appl. Phys. Lett.*, 17: 99 (1970).
176. Catrona, L. J., Leith, E. N., Porcello, L. J. and Vivian, W. E. *Proc. IEEE*, 54: 1026 (1966).
177. Kock, W. E. Radar and Microwave Application of Holography. In: *Applications of Holography. Proceedings of the United States-Japan Seminar on Information Processing by Holography*, p. 323. New York, Plenum Press (1971).
178. Leith, E. N. *Proc. IEEE*, 59: 1305 (1971).
179. Safronov, G. S. and Safronova, A. P. *Vvedenie v radiogolografiyu* (Introduction to Radioholography). Moscow, Sovetskoe radio (1973).
180. Brooks, R. E., Heflinger, L. O. and Wuerker, R. F. *Appl. Phys. Lett.*, 7: 248 (1965).

181. Heflinger, L. O., Wuerker, R. F. and Brooks, R. E. *J. Appl. Phys.*, 37: 642 (1966).
182. Burch, J. M. *Prod. Eng.*, 44: 431 (1965).
183. Horman, M. H. *J. Opt. Soc. Amer.*, 55: 615 (1965).
184. Collier, R. J., Doherty, E. T. and Pennington, K. S. *Appl. Phys. Lett.*, 7: 223 (1965).
185. Powell, R. L. and Stetson, K. A. *J. Opt. Soc. Amer.*, 55: 1593 (1965).
186. Haines, K. A. and Hildebrand, B. P. *Phys. Lett.*, 19: 10 (1965).
187. Stroke, G. W. and Labeyrie, A. E. *Appl. Phys. Lett.*, 8: 42 (1966).
188. Archbold, E., Burch, J. M. and Ennos, A. E. *J. Sci. Instr.*, 44: 489 (1967).
189. Ashton, R. A., Slovin, D. and Gerritsen, H. J. *Appl. Opt.*, 10: 440 (1971).
190. Gurari, M. L., Magomedov, A. A., Nikashin, V. A., Rukman, G. I., Sakharov, V. K. and Stepanov, B. M. *DAN SSSR*, 201: 50 (1971).
191. Haines, K. A. and Hildebrand, B. P. *Appl. Opt.*, 5: 595 (1966).
192. Aleksandrov, E. B. and Bonch-Bruevich, A. M. *Zh. tekhn. fiziki*, 37: 360 (1967).
193. Sollid, J. E. *Appl. Opt.*, 8: 1587 (1969).
194. Sollid, J. E. *Opt. Commun.*, 2: 282 (1970).
195. Molin, N. E. and Stetson, K. A. *Ark. Fys.*, 31: 3 (1970).
196. Walles, S. *Ark. Fys.*, 40: 299 (1969).
197. Abramson, N. H. *Appl. Opt.*, 8: 1235 (1969); 9: 97, 2311 (1970).
198. Robertson, E. R. and Harvey, J. M. (Eds.). *The Engineering Uses of Holography*. Cambridge, Univ. Press (1970).
199. *Applications of Holography*. Proc. of the International Symposium. Besançon (1971).
200. McFee, R. H. *Appl. Opt.*, 9: 1834 (1970).
201. Wardle, M. W. and Gerritsen, H. J. *Appl. Opt.*, 9: 2093 (1970).
202. *Laser Focus*, Feb., 1969, p. 16.
203. Wilson, A. D. *Appl. Opt.*, 9: 2093 (1970).
204. Hockley, B. S. and Butters, J. N. *J. of Phot. Sci.*, 18: 16 (1970).

205. Vasilev, A. M., Gik, L. D., Kozachok, A. G., Nekuryashchev, V. N., Nesterikhin, Yu. E. and Solodkin, Yu. N. *Avtometriya*, 1: 57 (1971).
206. Tsuruta, T. and Itoh, Y. *Appl. Phys. Lett.*, 17: 85 (1970).
207. Viénot, J. Ch. *Nouv. Rev. d'Optique appl.*, 1: 91 (1970).
208. Ennos, A. E. *Quant. Electr.*, 1, 4: 199 (1970).
209. Ginzburg, V. M. and Stepanov, B. M. (Eds.) *Golografiya. Metody i apparatura* (Holography. Methods and Apparatus). Moscow, Sov. radio (1974).
210. Pelzer-Bawin, G. and De Lamotte, F. *Interpretation geometrique de l'holographie applications en photoelastometrie*. Liege (1970).
211. Clark, J. A. and Durelli, A. J. *Exp. Mech.*, Dec., 1970, p. 1.
212. Zaidel, A. N., Listovets, V. S. and Ostrovsky, Yu. I. *Zh. tekhn. fiziki*, 39: 2225 (1970).
213. Hussman, E. K. *Appl. Opt.*, 10: 182 (1971).
214. Neumann, D. B. *J. Opt. Soc. Amer.*, 58: 447 (1968).
215. Zambuto, M. and Lurie, M. *Appl. Opt.*, 9: 2066 (1970).
216. Bogomolov, A. S., Vlasov, N. G. and Solovev, E. G. *Opt. i. spektr.*, 31: 481 (1971).
217. Ågren, C. and Stetson, K. A. *J. Acoust. Soc. Amer.*, 46: 120 (1969).
218. Archbold, E. and Ennos, A. E. *Nature*, 217: 942 (1968).
219. Zaidel, A. N., Malkhasian, L. G., Markova, G. V. and Ostrovsky, Yu. I. *Zh. tekhn. fiziki*, 38: 1824 (1968).
220. Shajenko, P. and Johnson, C. D. *Appl. Phys. Lett.*, 13: 44 (1968).
221. Watrasiewicz, B. M. and Spicer, P. *Nature*, 217: 1142 (1968).
222. Listovets, V. S. and Ostrovsky, Yu. I. *Zh. tekhn. fiziki*, 44: 1345 (1975).
223. Wilson, A. D. *J. Opt. Soc. Amer.*, 60: 1068 (1970); 61: 924 (1971).

224. Wilson, A. D. and Strope, D. H. *J. Opt. Soc. Amer.*, **60**: 1162 (1970).
225. Kiemle, H. and Ost, J. *Opt. Commun.*, **2**: 107 (1970).
226. Neumann, D. B., Jacobson, C. F. and Brown, G. M. *Appl. Opt.*, 9: 1357 (1970).
227. Aprahamian, R. and Evenesen, D. A. *J. Appl. Mech.*, June, 1970, p. 287.
228. Hildebrand, B. P., and Haines K. A. *J. Opt. Soc. Amer.*, **57**: 155 (1967).
229. Shiotake, N., Tsuruta, T., Itoh, Y., Tsujiuchi, J., Takeya, N. and Matsuda, K. *Jap. J. Appl. Phys.*, **7**: 904 (1968)
230. Heflinger, L. O. and Wuerker, R. F. *Appl. Phys. Lett.*, 15: 28 (1969).
231. Zelenka, J. S. and Varner, J. R. *Appl. Opt.*, **7**: 2107 (1968); **8**: 1431 (1969).
232. Varner, J. R. *Appl. Opt.*, **10**: 212 (1971).
233. Matulka, R. D. and Collins, D. J. *J. Appl. Phys.*, **42**: 1109 (1971).
234. Tanner, L. H. *J. Sci. Instr.*, **43**: 81, 353, 346 (1966); **44**: 1011 (1967).
235. Mustafin, K. S., Protasevich, V. I. and Rzhevsky, V. N. *Opt. i spektr.*, **30**: 406 (1971).
236. Burmakov, A. P. and Ostrovskaya, G. V. *Zh. tekhn. fiziki*, **40**: 660 (1970).
237. Sigel, R. *Phys. Lett.*, **30A**: 103 (1969).
238. Nikashin, V. A., Rukman, G. I., Sakharov, V. K. and Tarasov, V. K. *Teplofizika vysokikh temperatur*, **7**: 1198 (1969).
239. Ignatov, A. B., Komissarova, I. I., Ostrovskaya, G. V. and Shapiro, L. L. *Zh. tekhn. fiziki*, **41**: 701 (1971).
240. Ginzburg, V. M., Rukman, G. I. and Stepanov, B. M. In: *Ispol'zovanie OKG v sovremennoi tekhnike i meditsine* (Use of Lasers in Modern Engineering and Medicine). Pts. 2 and 3, p. 51. Leningrad (1971).
241. Gribble, R. F., Quinn, W. E. and Siemon, R. E. *Phys. Fluids*, **14**: 2042 (1971); **15**: 1666 (1972).
242. Dreiden, G. V., Zaidel, A. N., Mirzabekov, V. S., Ostrovskaya, G. V., Ostrovsky, Yu. I., Tokarevskaya, N. P., Frank, A. G.,

Khodzhaev, A. Z. and Shedova, E. N. *Pis'ma v. Zh. tekhn. fiziki*, 1: 141 (1975).
243. Weigl, F., Friedrich, O. and Dougal, A. *IEEE J. Quantum Electron.*, QE-5: 360 (1969); QE-6: 41 (1970).
244. Tsuruta, T. and Itoh, Y. *Appl. Opt.*, 8: 2033 (1969).
245. Bryngdahl, O. and Lohmann, A. W. *J. Opt. Soc. Amer.*, 58: 141 (1968).
246. Matsumoto, K. and Takashima, M. *J. Opt. Soc. Amer.*, 60: 30 (1970).
247. Jeffries, R. A. *Phys. Fluids*, 13: 210 (1970).
248. Ostrovskaya, G. V. and Ostrovsky, Yu. I. *Zh. tekhn. fiziki*, 40: 2419 (1970).
249. Ignatov, A. B., Komissarova, I. I., Ostrovskaya, G. V. and Shapiro, L. L. *Zh. tekhn. fiziki*, 41: 417 (1971).
250. Jahoda, F. C., Jeffries, R. A. and Sawyer, G. A. *Appl. Opt.*, 6: 1407 (1967).
251. De, M. and Sevigny, L. *Appl. Opt.*, 6: 1665 (1967).
252. Tsuruta, T., Shiotake, N. and Itoh, Y. *Jap. J. Appl. Phys.*, 7: 1092 (1968).
253. Matsumoto, K. *J. Opt. Soc. Amer.*, 59: 777 (1969).
254. Bryngdahl, O. *J. Opt. Soc. Amer.*, 59: 1171 (1969).
255. Belozerov, A. F. and Chernykh, V. T. *Opt. i spektr.*, 27: 355 (1969).
256. Vest, C. M. and Sweeney, D. W. *Appl. Opt.*, 9: 2810 (1970).
257. Varner, J. R. *Appl. Opt.*, 9: 2098 (1970).
258. Weigl, F. *Appl. Opt.*, 10: 187 (1971).
259. Weigl, F. *Appl. Opt.*, 10: 1083 (1971).
260. Martienssen, W. In: Nilsson, N. R. and Högberg, L. (Eds.). *High-Speed Photography. Proceedings of the 8-th International Congress on High-Speed Photography*, p. 289. New York, Wiley (1968).
261. Masumura, A., Matsukawa, M. and Asakura, T. *Optics and Laser Technology*, Febr., 1971, p. 36.
262. Lomas, G. M. *Appl. Opt.*, 10: 2037 (1969).
263. Snow, K. and Vandewarker, R. *Appl. Opt.*, 9: 822 (1970).

264. Dukhopel, I. I. and Simonenko, T. V. *Optikomekh. prom.*, 8: 44 (1971).
265. Pastor, J. *Appl. Opt.*, 8: 525 (1969).
266. MacGovern, A. J. and Wyant, J. C. *Appl. Opt.*, 10: 619 (1971).
267. Buinov, G. N., Larionov, N. P., Lukin, A. V., Mustafin, K. S. and Rafikov, R. A. *Optikomekh. prom.*, 4: 6 (1971).
268. Marechal, A. and Françon, M. *Diffraction. Structure des images*. Paris, Revue d'Optique (1960).
269. O'Neill, E. L. *Introduction to Statistical Optics*. Reading, Mass. Addison-Wesley (1963).
270. Cutrona, L. J., Leith, E. N., Palermo, C. J. and Porcello, L. J. *IRE Trans. Inform. Theory*, IT-6: 386 (1960).
271. Vander Lugt, A. *IEEE Trans. Inform. Theory*, IT-10: 139 (1964).
272. Pernick, B., Bartolotta, C. and Vustein, D. *Appl. Opt.*, 6: 1421 (1967).
273. Tsujiuchi, J. and Stroke, G. W. Optical Image Deblurring Methods. In: *Applications of Holography. Proceedings of the United States-Japan Seminar on Information Processing by Holography*, p. 259. New York, Plenum Press (1971).
274. Khalfin, L. A., Pavlichuk, T. A. and Shulman, M. Ya. *Opt. i spektr.*, 35: 766 (1973).
275. Horvath, V. V., Holeman, J. M. and Lemmond, C. Q. *Laser Focus*, 3, 11: 18 (1967).
276. Tsujiuchi, J., Matsuda, K. and Takeya, N. Correlation Techniques by Holography and its Application to Fingerprint Identification. In: *Applications of Holography. Proceedings of the United States-Japan Seminar on Information Processing by Holography*, p. 247. New York, Plenum Press (1971).
277. Gabor, D. *Nature*, 208: 422 (1965).
278. Collier, R. J. and Pennington, K. S. *Appl. Phys. Lett.*, 8: 44 (1966).
279. Stroke, G. W. *New Scientist*, 51, 770: 671 (1971).
280. Françon, M. *Holographie*. Paris, Masson (1969).

281. *Materialy I-VI Vsesoyuznykh shkol po golografii* (Materials of the 1st-6th All-Union Schools on Holography. Leningrad (1971-1975).
282. Stroke, G. W. and Funkhouser, A. *Phys. Lett.*, **16**: 272 (1965).
283. Zaidel, A. N., Ostrovskaya, G. V. and Ostrovsky, Yu. I. *Tekhnika i praktika spektroskopii* (Technique and Practice of Spectroscopy). Moscow, Nauka (1972).
284. Parshin, P. F. and Chumachenko, A. A. *Uspekhi fiz. nauk*, **103**: 553 (1971).
285. Yoshihara, K. and Kitade, A. *Jap. J. Appl. Phys.*, **6**: 116 (1967).
286. Dohi, T. and Suzuki, T. *Appl. Opt.*, **10**: 1137 (1971).
287. Lowenthal, S., Froehly, C. and Serres, J. *Compt. Rend. Acad. Sci. Paris*, **268**: 1481 (1969).
288. Antikidis, J. P. and Gires, F. *Compt. Rend. Acad. Sci. Paris*, **270**: 1210 (1970).
289. Lowenthal, S. and Aspect, A. In: *Applications de l'Holographie*. Besançon (1971).
290. Kiemle, H. In: Robertson, E. R. and Harvey, T. M. (Eds.). *Engineering Uses of Holography*. Cambridge, England, University Press (1970).
291. Lowenthal, S., Werts, A. and Rembault, M. *Compt. Rend. Acad. Sci. Paris*, **267**, Ser. B: 120 (1968).
292. Nalimov, I. P. Fundamentals of Holographic Technology. In: *Materialy I Vsesoyuznoi shkoly po golografii* (Materials of the 1st All-Union School on Holography), pp. 295-321. Leningrad (1971).
293. Moran, J. M. *Appl. Opt.*, **10**: 412 (1971).
294. Groh, G. *Appl. Opt.*, **7**: 1643 (1968).
295. Rudolph, D. and Schmahl, G. *Optik*, **30**: 475 (1970).
296. Cordelle, J., Laude, J. P., Petit, R. and Pienchard, G. *Nouv. Rev. d'Optique appliqúe*, **1**: 149 (1970).
297. Chang, M. and George, N. *Appl. Opt.*, 9: 713 (1970).
298. Bryngdahl, O. *J. Opt. Soc. Amer.*, **60**: 140 (1970).

299. Rosenberg, R. L. and Chandross, E. A. *Appl. Opt.*, **10**: 1986 (1971).
300. Kogelnik, H., Shank, C. V., Sosnowski, T. P. and Dienes, A. *Appl. Phys. Lett.*, **16**: 140 (1970).
301. Bondarenko, M. D., Gnatovsky, A. V. and Soskin, M. S. *DAN SSSR*, **187**: 538 (1969): *Ukr. fiz. zhurn.*, **14**: 303, 1930 (1969): *Pis'ma v Zh. eksp. i teor. fiziki*, **14**: 27 (1971).
302. Kogelnik, H. W. *Bell Syst. Tech. J.*, **44**: 2451 (1965).
303. Upatnieks, J., Vander Lugt, A. and Leith, E. N. *Appl. Opt.*, **5**: 589 (1966).
304. Leith, E. N. and Upatnieks, J. *J. Opt. Soc. Amer.*, **56**: 523 (1966).
305. Tsuruta, T. and Itoh, Y. *Appl. Opt.*, **7**: 2139 (1968).
306. Denisyuk, Yu. N. and Soskin, S. I. *Opt. i spektr.*, **31**: 992 (1971).
307. Goodman, J. W., Huntley, W. H., Jr., Jackson, D. W. and Lehmann, M. *Appl. Phys. Lett.*, **8**: 311 (1966).
308. Goodman, J. W., Jackson, D. W., Lehmann, M. and Knotts, J. *Appl. Opt.*, **8**: 1581 (1969).
309. Ose, T., Noguchi, M. and Kubota, T. Correction of Lens Aberration by Holography. In: *Applications of Holography. Proceedings of the United States-Japan Seminar on Information Processing by Holography*, p. 57. New York, Plenum Press (1971).
310. Denisyuk, Yu. N. and Davydova, I. N. *Opt. i spektr.*, **28**: 331 (1970).
311. Lowenthal, S. and Belvaux, Y. *Rev. d'Optique* **1** : 1 (1967).
312. Soroko, L. M. *Osnovy kogerentnoi optiki i golografii* (Fundamentals of Coherent Optics and Holography). Moscow, Nauka (1971).
313. Papoulis, A. *Systems and Transforms with Applications in Optics*. New York, McGraw-Hill (1968).
314. Viénot, J. Ch., Smigelski, P. and Royer, H. *Holographie optique*. Paris (1971).

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