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HOLOGRAPHY

by Yu. I. Ostrovskiy

"Nauka" Press, Leningrad Branch
Leningrad, 1970

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FROM THE AUTHOR

This book makes an attempt to give a popular account of holography which is a new and rapidly developing method, used widely in science and technology.

The reader will not find here any complicated formulas or complex arguments. The author was trying to make the book useful to a wide circle of readers, often sacrificing accuracy and completeness of exposition. However, it is hoped that the book will also be useful to those who already deal with holography or intend to do so.

I wish to give my thanks to Academician B. P. Konstantinov, Professor A. N. Zaydel', and Candidate of Technical Sciences, V. N. Sintsov, for their valuable remarks with respect to the manuscript.

Leningrad, January 1969

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Yu. I. Ostrovskiy

ABSTRACT. The book discusses holography, i.e., the interference-diffraction method of recording and reconstituting wavefronts. The method is being more and more widely applied to optics, radar, acoustics, instrumentation, and other areas of science and technology. Along with an exposition of the properties of holograms, the experimental holographic techniques and some of their applications are also described. /1*

INTRODUCTION

Holography was born in 1947. In that year, the English physicist /4
Dennis Gabor proposed his method of recording and reconstituting wavefronts which he called holography, from the Greek word holos (ὅλος), which means "whole" [1-3].

The principal difficulty in the application of this method was the lack of suitable light sources during the subsequent 15 years. These sources must have a special property; they must be coherent. It was only after the laser was invented in 1960 and found to possess the desired properties that it became possible for holography to achieve successes that it has until this day.

The first to obtain laser holograms were the American physicists Emmet Leith and Juris Upatnieks in 1963 [4]. Two years before then they had proposed

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*Numbers in the margin indicate pagination in the original foreign text.

their "two-ray" scheme [5] which was a considerable improvement over the original Gabor's idea. The first Soviet work on holography was published in 1962. Its author, Yu. N. Denisyuk proposed and developed an original method of recording a hologram in a thick-layer emulsion [6-8]. This method, that will be described below, possesses a number of unusual properties.

Holography did not just appear out of nothing; it was a predictable result of the development of optics. In this book, the reader will find the names of Fresnel and Fourier, Fraunhofer and Bragg, Lippman and Abbe, and many other outstanding scientists who at various stages made their historical contribution to this science.

How We See Objects and How We See Their Images

It is well known that the eye is an optical system with a variable focal length and a light sensitive focal surface (retina). Luminous (or illuminated by some external light sources) objects emit light waves which are bent in the crystalline body of the eye and form an image on the retina. This image is two-dimensional in contrast with the objects themselves which of course have three dimensions — height, width, and depth. Nevertheless, we obtain an impression of the three-dimensionality of objects due to the fact that the eyes can move, due to the ability to look with two eyes, and as a result of accomodation tension. By moving the point of viewing, we change the relative location of objects in their two-dimensional projection. This is called "parallax". Due to parallax, a difference also arises between the images on the retinas of the right and left eye (if a scene is not too distant) which brings about the feeling of three-dimensionality, depth of space. Fixing an eye on points which lie at different distances, we change the focal length of the crystalline body by changing the tension of the eye muscle, which is also perceived by us as a measure of the depth of space.

Looking at an ordinary two-dimensional photograph of the same scene, we do not see these effects. No matter how we change the position of our head, we always see the same thing — parallax is completely absent. Moving the eye from one object to another, we do not change the accomodative tension. The image looks flat, three-dimensionality is lacking, the "effect of immediacy" is lost. These phenomena are especially clearly observed when we look at a two-dimensional picture from an oblique angle (for example, in a /6 movie theater from the last seat in the first row). In this case, the longitudinal and lateral scales of the image are distorted which serves to emphasize the "flatness" of a picture. Thus, photography is very limited when it comes to representing the three-dimensional world.

In contrast to ordinary photography, holography makes it possible to record and reconstitute not just a two-dimensional intensity distribution but a light wave, emitted by an object, with all its details.

How Holograms are Obtained and Waves are Reconstituted

There are a number of methods for obtaining holograms and reconstituting waves. In principle they differ very little from one another, and we shall consider one of them that was suggested by Leith and Upatnieks [4, 5]. A scheme of the set-up is shown in Figure 1, a.

An object whose hologram one wants to make is illuminated by laser light. The scattered light wave falls on a photographic plate. The same plate is illuminated by a reference beam which is part of the light from the same laser, reflected from a mirror. A photoplate thus exposed upon developing and fixing is called a hologram. The photographic plate contains information about the light wave scattered by the object. How the information is stored will be explained later. On the outside, a hologram looks no different from a uniformly illuminated photographic plate. Often one can see rings and fringes on a hologram, but they are due to dust particles that had fallen on the mirrors and objectives causing diffraction of light, and do not have anything in common with the microstructure (Figure 2, b) that contains a record of a light wave scattered by an object.

In order to reconstitute the wave, the object is removed, and the hologram is placed in the same position as in the stage of formation (Figure 1, b). /7
If then a laser is turned on and one looks through the hologram as if out a window, one shall see the object in its former position as if it were never removed. The object seen seems perfectly real: we can discover parallax by moving our head; looking at its closer and more distant parts, we have to accomodate our eyes differently. If we want to photograph the image, just as in ordinary photography, we shall have to choose a diaphragm which would provide a sufficient depth of focus. If we fail to do this, certain parts of

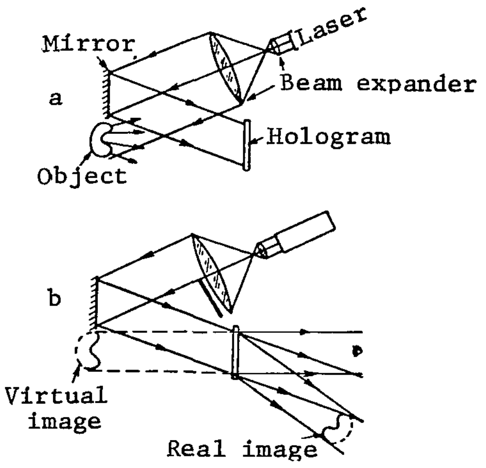

Figure 1. Set-up for obtaining holograms (a) and reconstituting wavefronts (b).

the object will look sharp on the photograph, and others — blurred. The reconstituted image seems so real that one would almost like to touch the object which is of course impossible, for a hologram restores only the light wave that was scattered by the object.

In addition to the image of the object that can be seen with our eyes (it is called a virtual image), there exists a real image of the object. It is located on the other side of the hologram (Figure 1, b). Usually it is difficult to see the real image with an unaided eye, but if one places a photographic plate or frosted glass in the plane where the real image is formed, one can obtain its two-dimensional projection.

The real image has a number of interesting properties. The most interesting of them is pseudoscopicity, i.e., a property in which the real image has a relief which is a reverse of the initial object: convex parts are replaced with concave ones — the image was "turned inside out". /8

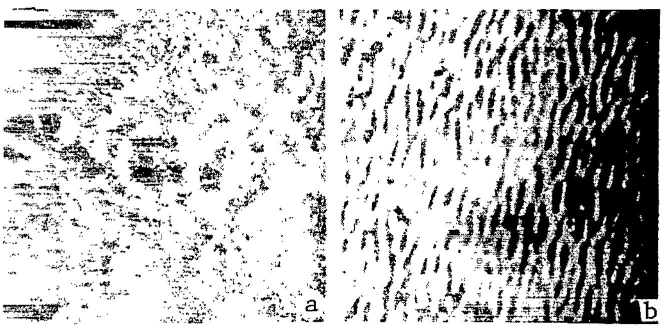

Figure 2. External view of a hologram (a) and its structure seen through a microscope (b).

A Hologram of a Point — Fresnel's Zone Plate

Let us consider how a hologram is obtained, and how the wave is reconstituted from the simplest object — a point. A point is an object whose angular dimensions are so small that its structure is undetectable. A point scatters a light wave whose front at any time is a sphere. At a sufficiently large distance from the point, the surface of the sphere may be considered plane. There is another way of transforming a spherical wave into a plane one: for this purpose, one places the luminous point at the focal point of a lens (Figure 3).

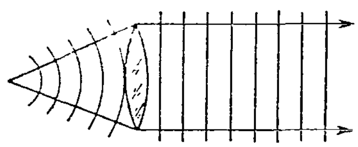

Figure 3. Transformation of a spherical wave into a plane wave by means of a lens.

The light wave scattered by any object, however complicated, may be regarded as a set of waves scattered by the individual points of the object.

Thus, let a point 0 which scatters a spherical light wave be located at a distance a from a photographic plate (Figure 4). In addition, let us assume that a normal plane reference wave is incident on the photographic plate.

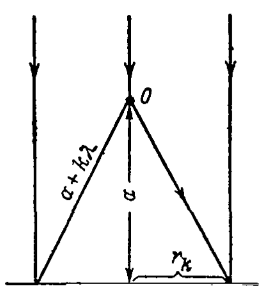

Figure 4. Formation of a hologram of a luminous point with a plane reference wave.

We require that the light wave emitted by our luminous point and the /9
light of the reference wave be coherent (see, for example, [9]). The meaning of this requirement reduces in the last analysis to a stipulation that the waves can interfere. For this purpose, they must have identical frequency (wavelength) and a constant phase difference, and the light oscillations must take place in the same plane. When

lasers are used in holography, these requirements can usually be satisfied.

The inventor of holography, Professor Dennis Gabor

If the waves incident on the photographic plate are incoherent, then simply the intensities of the waves are added. This is observed each time we illuminate a room with two or more electric bulbs.

If the waves are coherent, then the amplitudes of the light waves are summed, instead of the intensities, and the phase relationships among them are taken into account. Where waves meet in the same phase, their amplitudes are added; if the waves meet in opposite phases, the amplitudes are subtracted from each other. The law of amplitude combination has the form

$$A^2 = A_1^2 + A_2^2 + 2A_1A_2 \cos(\varphi_1 - \varphi_2). \qquad (1)$$

Here A_1 and A_2 are amplitudes, ϕ_1 and ϕ_2 are phases of the light waves.

If the phase difference $\phi_1 - \phi_2$ is equal to an even number times π (0, 2π, 4π, ...), then

$$A = A_1 + A_2. \qquad (2)$$

If the phase difference is equal to an odd number times π (π, 3π, 5π, ...)

$$A = A_1 - A_2. \quad (3)$$

A system of interference fringes is formed on the photographic plate. Condition (2) corresponds to the centers of light fringes; Condition (3) corresponds to the centers of dark fringes.

What is the form of fringes on a hologram of a luminous point obtained according to the scheme in Figure 4?

First of all, it is not hard to establish that these are concentric circles. In fact, for all points on the photographic plate, equidistant from its center, the phase relationships of the incident waves are identical.

Secondly, as one moves from one ring to the next one, the difference between the interfering waves is one wavelength (the phase difference is 2π). At the center, the difference is equal to zero. Then for the k^{th} /10
ring, it is equal to $k\lambda$; hence the radius of the k^{th} ring is (Figure 4)

$$r_k^2 = (a + k\lambda)^2 - a^2 = 2ak\lambda + k^2\lambda^2. \quad (4)$$

Thus, a hologram of a point is a system of concentric rings whose radii are subject to the relation (4). Such a system is shown in Figure 5. This is the so-called Fresnel's zone plate[1]. It must be kept in mind, however, that in this figure the transition from a dark to a light ring is discontinuous whereas in a hologram it occurs smoothly, approximately according to a sinusoidal law[2]

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[1] It is sometimes called Fresnel's zone grating as well as Sore's plate.

[2] This would be exactly true if the transmittivity of the plate depended linearly on its illumination. In reality this relationship is much more complex (see page 24 and Figure 14).

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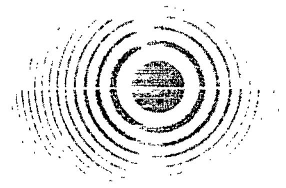

Figure 5. Fresnel's zone plate.

The distance between the neighboring rings, as is easy to show from Formula (4), is equal to

$$\Delta r_k = \frac{a\lambda + k\lambda^2}{r_k}. \qquad (5)$$

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

Now let us consider the process of reconstituting the light wave emitted by a point by using a hologram. We shall remove our luminous point, placing the hologram in the place where it was exposed, and illuminating the hologram with the same plane light wave which was used before.

Each small portion of the Fresnel zone plate may be viewed as an ordinary diffraction grating. The latter, as we know (see, for example, [9]), decomposes an incident light beam into several parts:

(a) zero-order beam which is a continuation of the incident beam;

(b) plus first-order and minus first-order beams which satisfy the condition

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

where Δr is the lattice constant (distance between the neighboring rings);

(c) plus second-order and minus second-order beams $\left(\sin\varphi_2 = \pm\frac{2\lambda}{\Delta r}\right)$, etc.

In the case of a grating with a sinusoidal distribution of transparency, beams of orders higher than one are absent.

The angles at which the plus first-order and minus first-order rays are propagated increase regularly in a transition from the center of a given grating to its edges, since the grating constant Δr_k decreases [see Formula (5)].

We shall show now that first-order rays form two spherical waves (convergent and divergent). For this purpose, it is sufficient to show that all rays of plus first order intersect at one point, and all minus first-order rays emerge from a single point. Let us consider a light ray incident on a hologram at a distance r_k from its axis (Figure 6).

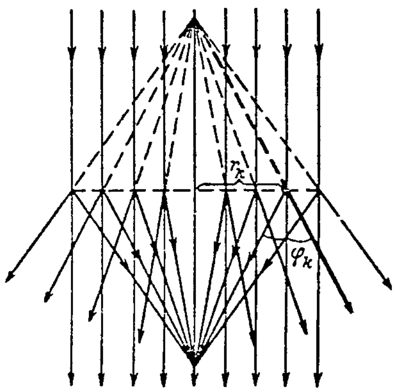

Figure 6. Reconstitution of the spherical wavefront by a Fresnel zone plate.

The plus and minus first-order rays deviate by angles $\pm\phi_k$. These rays (or their extensions in the "opposite" direction) will intersect the axis of the hologram at a distance $\pm$ x from its surface. /12

Let us find the value of x. From Figure 6, it is clear that

$$x = r_k \operatorname{ctg}\varphi_k = r_k \frac{\sqrt{1-\sin^2\varphi_k}}{\sin\varphi_k}.$$

Considering that $\sin\varphi_k = \frac{\lambda}{\Delta r} = \frac{r_k}{a+k\lambda}$, we find

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

Recalling now that $r_k^2 = 2ak\lambda + k^2\lambda^2$ [see Formula (4)], we obtain

$$x = a. \tag{6}$$

Thus, the distance at which the plus and minus first-order rays intersect the axis of the hologram is the same for rays diffracted by all sections of the hologram.

Thus, when a plane wave passes through a hologram of a point (zone plate with a sinusoidal distribution of light and dark zones) three waves are formed:

(1) spherical, which converges at a point located at a distance a from the hologram which is the same as the distance of the point when the hologram was obtained;

(2) spherical, which emerges from a point located at a distance a on the other side of the hologram, i.e., from the place at which the original point was located during holographing;

(3) along with these waves that form the real and virtual images of the point, also a plane wave, corresponding to the zero-order, emerges from the hologram.

The results that we have obtained for a point are not difficult to extend to objects of any form that consist of many points scattering light. In this case, a hologram must be viewed as a superposition of zone plates formed by every point of an object. This superposition occurs according to the laws governing the interference of light, and as a result one obtains a complex interference pattern which forms a hologram of the object (Figure 2, b). /13

In reconstitution stages, all these interference zone plates act independently — each sets up a wave from its own point of the object, and the wave is set up exactly where it was in the formation stage. To a brighter point, there corresponds a higher-contrast grating which during reconstitution gives a brighter image point.

Of course not all details of the phenomenon can be explained by this simple scheme, but still many properties of holograms become easy to understand.

Certain Important Properties of Holograms

1. Let us make a contact copy of a hologram and reconstitute the wavefront by means of a copy which is a negative of the initial hologram. We shall obtain a curious result: everything is as before — light places remain light, dark places remain dark. This is easy to explain. The dark points of the object do not produce Fresnel zone plates at all, and so the plates cannot appear in the negative copy of the hologram either. Therefore, in the reconstitution stage those points remain dark. Light points, however, do participate in the formation of a pattern on the hologram, and the diffraction properties of the pattern are not changed when dark places of a hologram are replaced by light, and light — by dark.

2. Each section of a hologram is capable of reconstituting the image of the entire object. In fact, as we have seen already, any portion of the Fresnel zone plate reconstitutes the image of a point. It is natural to expect that the same property will be shared by a hologram of a more complex object. Of course, a smaller portion of the hologram will reconstitute a correspondingly smaller portion of the wavefront. If this portion /14
is very small, the quality of the reconstituted image will worsen, fine details will be lost, a characteristic grain structure will appear (Figure 7) [10].

3. It is easy to explain the fact that real images formed by a hologram are pseudoscopic. Points that lie at larger distances from the hologram (depressions) will have a real image which is also farther from the hologram but is viewed from the opposite side. Therefore, these points form bulges in the real image (Figure 1, b). In the pseudoscopic image, the right sides of

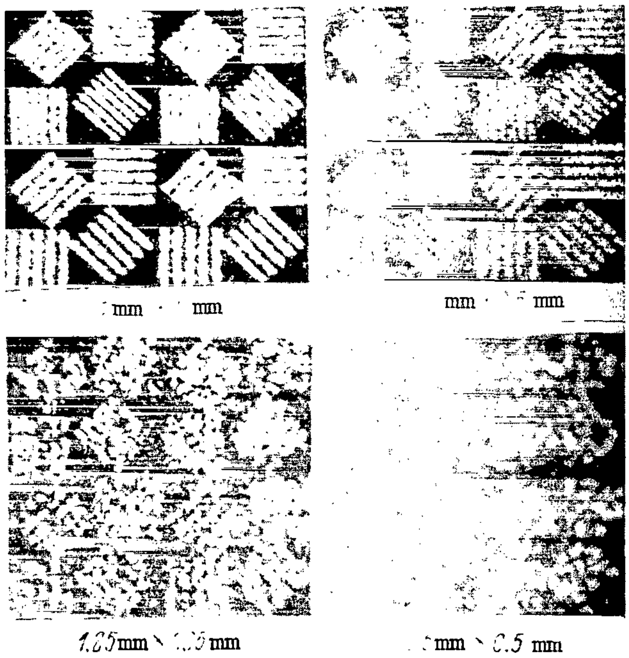

Figure 7. What happens to the reconstituted image when the size of the hologram is made smaller.

an object (with respect to the viewer) are seen as right, and the left are seen as left. Only the relief of an object is reversed.

4. Holograms of a complex /15
object may be viewed as an interference (coherent) superposition of holograms from the individual points or more complicated parts of the object. In such a superposition, there is a summation of the amplitudes of light waves with due regard given to the phase relationships among them [Formula (1)].

One can also imagine a hologram which would be an incoherent superposition of holograms of different objects or parts of the same object. In this case the photographic plate sums the intensities produced. If the number of such consecutive superpositions is not too large, the hologram will simultaneously reconstitute several consecutively recorded light waves with hardly any distortions. This property of holograms finds application in a consecutive recording on the same hologram of waves from several objects or several states of the same object. This technique is also used to obtain holograms without lasers.

Holographic Schemes

The above scheme for obtaining holograms, proposed by Gabor (Figures 4 and 8, a) has serious disadvantages. In the reconstitution stage, the rays forming the real and virtual images as well as the zero-order beam propagate in the same direction (Figure 8, b) and produce mutual disturbances.

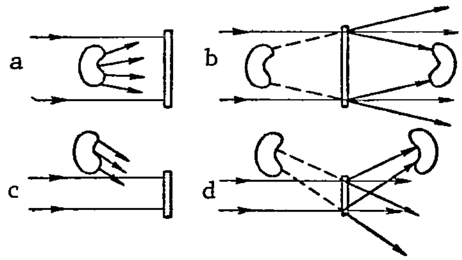

Figure 8. Obtaining a hologram and reconstitution of a wave-front according to Gabor (a, b), and according to Leith and Upatnieks (c, d).

This is one of the reasons why the reconstituted images are of poor quality.

In one of his earliest papers on holography [2], Gabor predicted that "... in light optics where the splitting of beams is allowed, new methods of using coherent radiation will be found which will improve the resolution of an object in depth and will suppress the 'associated wave' ...".

In complete agreement with these predictions, Leith and Upatnieks [5] in 1961 proposed their two-ray scheme of holography (otherwise known as a scheme with a reference beam; Figure 8, c). The scheme may be viewed as a certain modification of Gabor's scheme. In Leith and Upatnieks' scheme, only the peripheral portion of the Gabor hologram is used, and what is most important, the object is illuminated by a separate coherent light beam. This permitted them to obtain holograms of opaque and three-dimensional objects. /16
As we can see in Figure 8, d, holograms obtained according to the scheme of Leith and Upatnieks are free from the mutual disturbances between the virtual and real images. At the present time, two-ray holographic set-ups are most widespread.

It is also quite unnecessary to use a reference beam with a plane wave-front. A reference light source corresponds to such a beam; this source is infinitely removed from the hologram. If the reference source is moved toward the hologram, the quality of the hologram is not worsened, and it preserves all its properties.

The object can also be moved closer to a hologram or moved away to infinity; this can be done by means of a lens (Figure 3).

The plate on which a hologram is formed can be oriented in any direction relative to the reference beam and the object. It can even be placed between them in such a way that the light from them will fall in different directions.

In any case, if one places a hologram in the same location in which it was exposed, a virtual image of an object will appear in the same place, where the object was placed during holographing — if, of course, the location of the reference beam and its wavelength remain the same.

Figure 9 perhaps covers all possible schemes of obtaining holograms. It shows the crest surfaces of standing light waves, formed during the interference of light emerging from a point source O_1 and a reference point light source O_2. In the scheme of Figure 9, a, the reference beam is at a finite distance from the object. In Figure 9, b, it is removed to infinity, and the light wave emerging from it has a plane front. Figure 9 shows sections of interference surfaces cut by the plane of the drawing; in fact, these surfaces are figures of revolution: hyperboloids (Figure 9, a) and paraboloids (Figure 9, b). The axis of revolution passes through both point light sources. /18

Different forms of interference fringes forming the hologram of a point correspond to different holographic schemes. For all positions in which the plane of the hologram is normal to the line joining the reference source and the object (the point), the interference fringes are rings which make up the Fresnel zone lattice. If the plane of the hologram is parallel to this line, the fringes will form a family of hyperbolas[(3)].

In a gener~l case, the interference fringes are curves which represent intersections of a family of hyperboloids of revolution (Figure 9, a) or paraboloids of revolution with the plane of the hologram.

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(3) In [11] such an arrangement, first proposed in [12], was named lenseless Fourier transform holography.

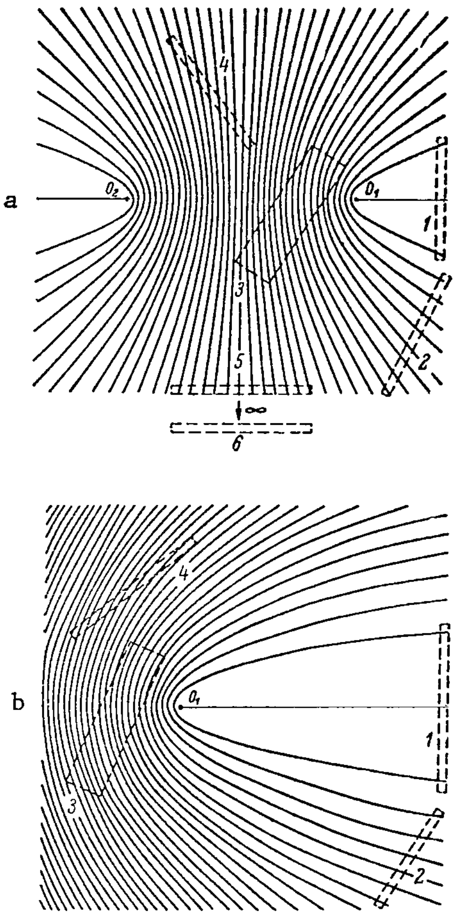

Figure 9. Crest surfaces of standing light waves formed by a point object O_1 and a point reference source O_2.

Location of the hologram: 1 - according to Gabor; 2 - scheme of Leith and Upatnieks; 3 - according to Denisyuk; 4 - two-dimensional hologram with an "inverted reference beam"; 5 - "Lens-free Fourier-hologram"; 6 - Fraunhoffer hologram.

a - two-sheet hyperboloids of revolution (axis of revolution O_1O_2); b - paraboloids of revolution.

The above schemes are realized in practice using one of the methods shown in Figure 1, 12, 20-28.

The Hologram as a Diffraction Grating

Earlier we discussed the hologram of a point obtained by means of a reference beam with a plane wavefront, as a Fresnel zone plate. Now we see that this is valid only for the particular case when the plane of photographic emulsion is normal to the line connecting the reference source and the object (a point).

Let us present a more general discussion that will explain the reconstitution process of a wavefront for any mutual location of a reference light source, object, and hologram.

Let us consider the interference of two coherent parallel beams of light rays which converge on a photographic plate at an angle to each other. Suppose that the angle of incidence of one of them is ϕ_1, /19
and that of the other is ϕ_2 (Figure 10).

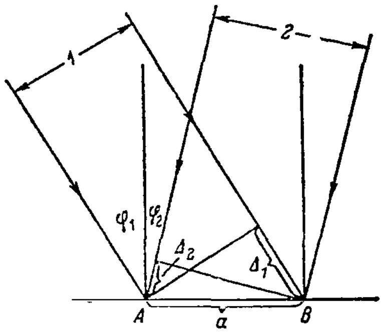

Figure 10. Formation of a holographic diffraction grating.

If points A and B correspond to the positions of two neighboring fringes (a is the distance between them), then the difference in path between beam 1 and 2 when passing from point A to point B changes by one wavelength λ. In other words, $\Delta_1 + \Delta_2 = \lambda$, and since $\Delta_1 = a \sin \phi_1$ and $\Delta_2 = a \sin \phi_2$,

$$a = \frac{\lambda}{\sin \varphi_1 + \sin \varphi_2}. \qquad (7)$$

The hologram thus obtained, which is a diffraction grating with a constant a, we shall illuminate by one of the light beams that took part in its formation — for example, by beam 1 — while beam 2 is removed. The diffraction grating produces a minimum of first order at an angle α to its normal which is related to the angle of incidence β by the expression

$$\sin \alpha + \sin \beta = \frac{\lambda}{a}. \qquad (8)$$

In our case, the angle of incidence $\beta = \phi_1$ and the constant of the grating, a, is given by Formula (7). Hence,

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

i.e., $\alpha = \phi_2$.

Thus, if we keep beam 1, then beam 2 will be reconstituted. If, however, a hologram is illuminated by beam 2, then beam 1 will be reconstituted, i.e., the reference and object beams are mutually reversible.

A light wave which propagates from a point source can be represented as a set of thin parallel light beams, to each of which a small portion of the hologram corresponds. Since, as we have seen, a hologram reconstitutes each of such beams, it becomes clear that the entire light beam which emerges from a point is reconstituted.

Similarly, instead of a parallel reference beam, one can take a number of thin beams emerging from a reference point light source located at a finite distance from the hologram. In the case of a complex object, a hologram may be viewed as an interference superposition of gratings produced by the individual points of the object. /20

By virtue of the principle of reciprocity, which was mentioned above, and referring to the reference and object beams, the reference beam may also be sent, not from the point source, but from a luminous body of any form. Naturally, a reconstitution of the wave from an object will occur only when, during reconstitution, both the structure of the reference beam and the location of the hologram are preserved[4].

Summarizing the above, we arrive at the following conclusion which may be called the basic law of holography: if a light-sensitive material which contains a recorded interference pattern of several light waves is placed in the initial position and illuminated by one of these waves, then the remaining waves will be reconstituted.

Thick-layer Holograms

Thus far we have discussed a photographic plate as a medium possessing two dimensions. This is valid only when the thickness of the light-sensitive layer is comparable with the distance between the neighboring interference fringes. If the layer is much thicker, then the peculiar features of a photographic plate as a three-dimensional medium are observed. These

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(4) When special requirements as to the form of the reference and reconstituting sources are met, they need not be identical.

features were first observed by Lippman and used by him for color photography. Yu. N. Denisyuk [6] proposed using three-dimensional media for recording holograms.

If two interference beams are directed so that they proceed opposite to each other (at an angle $\alpha = 180°$), then, as we know, standing waves are set up in space which are systems of nodal and crest planes spaced every $\frac{\lambda}{2}$. If, /21 in a more general case, $\alpha \neq 180°$, then it is not hard to see that the distance between crests (or nodes) increases by a factor of $\frac{1}{\sin \alpha/2}$, and becomes equal to $\frac{\lambda}{2 \sin \alpha/2}$. Nodal and crest planes of light waves will be directed along the bisector of the angle α, as indicated in Figure 11.

If a light-sensitive photographic emulsion is placed in the region of intersection of the light beams, then the system of nodes and crests will be recorded in it in the form of semi-transparent reflecting layers of metallic silver(5). Such a three-dimensional diffraction grating will possess the following properties: (1) the light, reflected from the layers just as /22 from a mirror, will reconstitute the wave from the object. In fact, the reflective layers, as already indicated, are directed along the bisector of the angle formed by the interfering rays, which results in the indicated property of holograms (Figure 11, c); (2) a zero-order beam as well as the real image will not be produced; (3) beams reflected from various layers will reinforce each other only when they are in phase (Lippman-Bragg condition). This leads to selectivity of holograms with respect to the wavelength of the source whose light is used to reconstitute the wavefront. The condition that the waves be in phase can be satisfied only for the wavelength which was used to produce the hologram. Therefore, it is possible that an image can

(5) To simplify the discussion, we allow certain inaccuracies here. Since the refractive index of a light-sensitive emulsion is different from the refractive index of the external medium, then both the direction of beams, and the location of crests in it, will be slightly different. If this is taken into consideration, it will not change our conclusions — only make them more complicated. Since the length of the light wave in the emulsion is n times smaller than in the air (n is the refractive index in the emulsion), the crests will be that many times closer together.

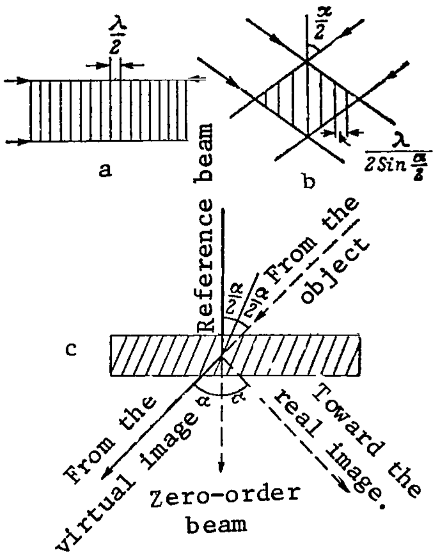

Figure 11. Formation of standing light waves by colliding beams (a) and beams that collide at an angle $\alpha \neq 180°$ (b); c - reconstitution of a light wave with the aid of a three-dimensional hologram.

be reconstituted by means of a source emitting a continuous spectrum (incandescent lamp, the sun). If the hologram were exposed in the light of several spectral lines (for example, blue, green, red), then each wavelength would form its own system of surfaces. The corresponding wavelengths will be separated /23 out of the continuous spectrum in the reconstitution stage, which results in a reconstitution of not just the structure, but also the spectral content of the light wave, i.e., the result is a color image. All this is valid if the processing of the emulsion does not change the relative location of the reflecting planes. Sometimes, due to the shrinkage of the emulsion, the wavelength of the reconstituted image is displaced toward the "blue" (shorter-wave) region.

Figure 12 shows the normally used schemes for obtaining holograms on thick-layer emulsions.

The relative location of the reference source, hologram, and the object is arbitrary, i.e., the hologram may be placed in any position in the diagrams (Figure 9). However, in order for a hologram to exhibit three-dimensional properties it is necessary that at least a few reflecting layers be placed along the emulsion thickness. For a given emulsion width, this requirement determines the zones in Figure 9 in which the hologram may be considered "three-dimensional".

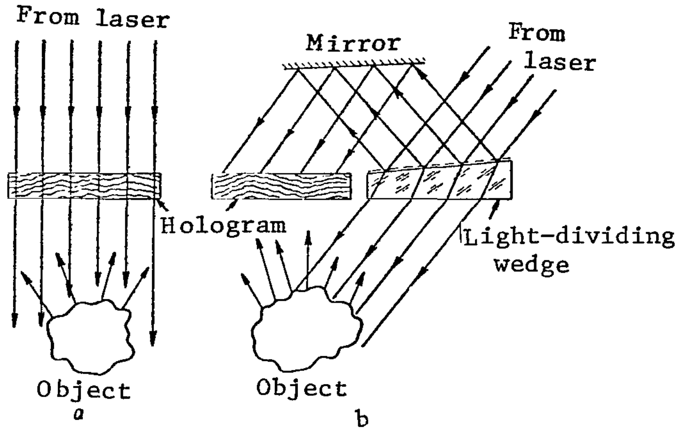

Figure 12. Scheme for obtaining holograms on thick-layer emulsions in opposed beams.

For a given position of a hologram in Figure 9, the least "three-dimensionality" will be exhibited by a hologram which is oriented normally to the dominant direction of the nodal and crest surfaces. Such a location is most convenient only when it is necessary to obtain a real image in the reconstitution of the wavefront by means of an undisplaced reference source. The unconditional requirement of such an orientation, proposed in certain papers, is apparently unjustified. Conversely, if it is necessary to obtain maximum "three-dimensionality", it is most convenient to orient the hologram along the reflecting layers (Figure 12). In this case, the brightness of the real image and the zero-order beam will be minimal.

The thickness of the holographic photographic emulsions is on the order of several microns. To exhibit the three-dimensional properties of a hologram, it is necessary that the reflecting layers lie at distances several times smaller. For example, for the emulsion Kodak 649F, the three-dimensional effects appear for the angles between the reference and object beams (λ 6328 Å) greater than 10°, i.e., when the distance between the reflecting layers is less than 4 microns.

How a Hologram Restores the Form of Objects and Their Dimensions

We have established that, if the process of holographing and reconstituting a wavefront is carried out with a reference source of the same wavelength, placed in the same location relative to the hologram, then the hologram will reconstitute the wave emerging from the virtual image, which coincides in form and location with the object itself.

If one changes the form of the reference beam, its wavelength, the orientation of the hologram and its scale, such a correspondence is disturbed. In certain cases, this results in useful combinations. For example, by changing the wavelength and the divergence of the beam, one can vary the scale of the reconstituted image of an object, and make it smaller or larger. As a rule, such a change is accompanied by an undesirable distortion of the image, called aberration, which shows up in the distortion of the longitudinal and lateral scales of the image, distortion of focus, etc.

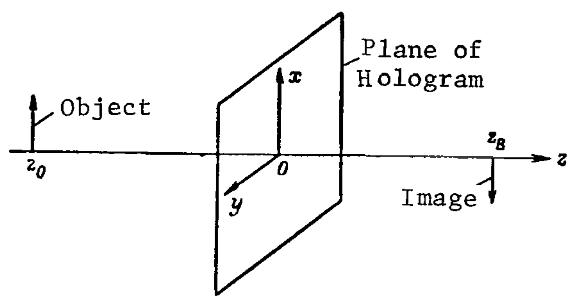

Figure 13. Explanation of the notation used in Formula (9).

We shall give the formulas [13] which enable one to compute, in an arbitrary case, the location of the reconstituted image and its magnification. Let us introduce the following notation (Figure 13): the hologram is located in the x-y plane at z = 0; the hologram is placed in the same location in both the formation and reconstitution stage; the coordinate of the object is z_0, that of the reconstructed image is z_B, that of the reference point source /25 is z_R, that of the point source, used in the reconstitution, is z_C. Suppose that before the reconstitution the hologram is magnified m times, and the wavelength of the reconstituting source is μ times greater than that of the light source used to obtain the hologram. Then

$$\frac{1}{z_B}=\frac{1}{z_C}\pm\frac{\mu}{m^2}\left(\frac{1}{z_0}-\frac{1}{z_R}\right). \qquad (9)$$

The angular magnification of a hologram is in any case independent of the quantities appearing in (9) and is equal to μ/m. Therefore, the linear lateral magnification is

$$M_{lat}=\frac{\mu}{m}\cdot\frac{z_B}{z_0}$$

and, according to (9),

$$M_{lat}=\frac{m}{1\pm\frac{m^2}{\mu}\cdot\frac{z_0}{z_C}-\frac{z_0}{z_R}}. \qquad (10)$$

The plus sign in (9) and (10) refers to the virtual, and the minus sign — to the real, image of an object. The longitudinal magnification differs from the lateral, and is equal to $M_{long} = dz_B/dz_0$, or, according to (9),

$$M_{long}=\frac{1}{\mu}M_{lat}^2. \qquad (11)$$

Formulas (9) - (11) have a universal character, and are valid for any holographic setups. Examples of their use will be found below, in Section 6.

How a Hologram Reconstitutes the Distribution of Brightness on an Object

In the ordinary photographic process, the brightness distribution in an image only to a first approximation reproduces the brightness distribution of an object.

The transmittivity of a plate is related to exposure (illumination x time) by a characteristic curve whose typical form is shown in Figure 14. /26

As we can see from Figure 14, the plate does not react at all to exposures less than H_{min}. An increase in exposure above H_{max} does not have any effect on the transmittivity. It is only in the interval from H_{min} to H_{max} that a photographic plate, even though nonlinearly, reacts to the brightness distribution of an object, and then, the greater the illumination, the less light it transmits.

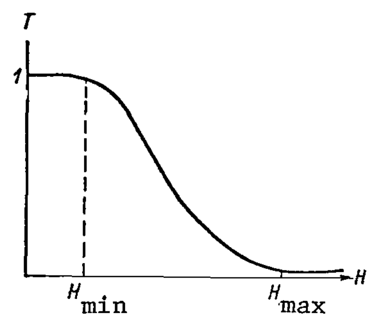

Figure 14. Characteristic curve.

T - transmission coefficient of a photographic plate,

H - exposure.

The entire interval of exposures from N_{max} to N_{min} is as a rule no greater than one or two, or something on that order. On the other hand, real objects have a much greater range of brightness which cannot be reproduced photographically. Holography, using the same emulsion, is in this sense capable of much greater (although not unlimited) range.

In fact, to construct the image of any bright point of an object, a hologram, possessing focusing properties, uses the light falling on its entire surface. However, an ordinary photographic plate can only produce gradations in the brightness if its various portions having different transmittivity, and the redistribution of the incident light flux over the image cannot be effected.

This, of course, does not mean that a hologram, no matter how it is exposed, does not distort the brightness distribution over an object. The most important thing is that, with a correct choice of exposure, the relationships between the illumination of an object and the reference beam, emulsion, and conditions of development, one can always obtain a hologram that reproduces a wide range of brightness without noticeable distortions. For this purpose, it is usually sufficient that the exposure at the maxima of interfer- /27 ence fringes be not much larger than H_{max}, and at the minima — not much less than H_{min} (Figure 14), and that the area of the hologram be sufficiently large.

This property of holograms will be easier to understand if one considers that the nonlinear distortions of a sinusoidal distribution of brightness by the emulsion result in the appearance of images of second and higher orders. A grating with a sinusoidal distribution of transmittivity does not produce images of order higher than one. Therefore, the nonlinear distortions on first-order images appear only to a slight extent, and mainly in those cases of pronounced underexposure or overexposure.

Figure 15 [14] shows a photograph and a holographically reconstituted image of a graduated stepwise attenuator, i.e., a filter of variable optical density used in photometry. As one can see in Figure 15, the hologram reproduced the gradations in the brightness of an object with hardly any distortions.

Figure 16 illustrates how a hologram preserves the distribution of /28 brightness on an object (stepwise attenuator) when the exposure changes 80 times).

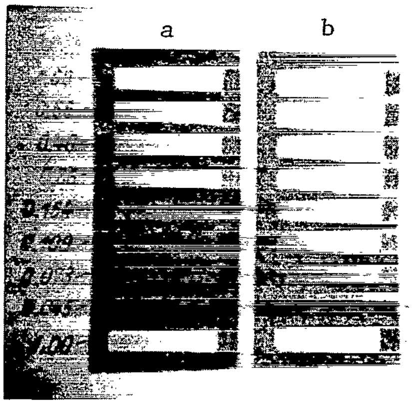

Figure 15. A photograph of a stepwise attenuator (a) and its holographically reconstituted image (b). The numbers indicate the relative brightness of the steps.

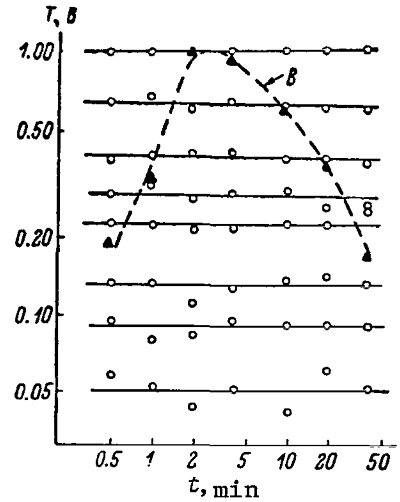

Figure 16. The result of a photometric analysis of reconstituted images of the attenuator steps for the 80-fold gradation of exposure in holographing. A hologram reproduces without distortions the relative transmittivity (T) of steps. The same graph shows the brightness variation of the reconstituted image of one of the steps (B). The largest brightness of the reconstituted image was obtained within the exposure interval t, equal to 2-5 min.

Resolving Capacity of Holograms

The resolving capacity is defined as the ability of a receiver of an image, or a system constructing an image, to record separately (resolve) the images of close objects. This definition is lacking in precision. Usually, one considers the images of two points or two lines of equal brightness as resolved when there is a brightness drop between them, equal to or greater than 20% of the maximum brightness (brightness in the gap is less than 80%).

Instead of the depth of the drop, one often uses the contrast of an image

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

where E_{max} and E_{min} are the maximum and minimum brightness, respectively. The so-called Rayleigh criterion corresponds to a 20% drop (or 11% contrast). At the same time, the eye receives separately two images with a considerably smaller contrast (1-2%). Therefore, the visual resolution differs from the Rayleigh resolution.

The resolving capacity (see, for example [9]) came to be characterized by the limiting resolving angle ($\delta\phi$) or the limiting linear resolution ($\delta\chi$). /29
Usually, the latter quantity is divided by the area of the object (and not the image). The spectral instruments are characterized by $\delta\lambda$ which is the difference between the wavelengths of limiting resolved absolutely monochromatic spectral lines, or by the angular or linear distance between the images of these lines ($\delta\phi$ or δy).

The limited resolution of optical instruments is to a considerable extent a consequence of aberrations peculiar to optical components, as well as imperfections in their fabrication. But even an ideal instrument possesses a limited resolving power due to the diffraction of light on its aperture. For example, the limit of resolution of a telescope is

$$\delta\varphi = 1.22\frac{\lambda}{D}, \quad (13)$$

where D is the diameter of the objective.

The resolving power of a microscope is

$$\delta x = 0.61\frac{\lambda}{A}, \quad (14)$$

where A is the numerical aperture.

The resolving power of a spectroscopic instrument with a sinusoidal diffraction grating can be computed using one of the following formulas:

$$\delta\lambda = \frac{\lambda}{N}, \tag{15}$$

$$\delta y = \frac{\lambda}{\alpha}, \tag{16}$$

$$\delta\varphi = \frac{\lambda}{L}, \tag{17}$$

where N is the total number of lines, α is the angular width of grating, L is the projection of the width of a grating on the plane normal to the direction of observation.

As established earlier, a hologram is a diffraction grating, and thus, its resolution can be determined using Formulas (16) and (17). Therefore, the angular resolution of a hologram depends only on its linear dimension, and the linear resolution — on its angular dimension (Figure 17). Formulas (16) and (17) have been confirmed by experimental data [10]. They have a general meaning for any relative locations of the reference source, object, and hologram (Figure 9a and b), i.e., for any holographic configuration. /30

It is, however, not always possible to use a hologram of dimensions so large that the necessary degree of resolution is obtained. For example, when using a reference source with a plane wavefront (removed to infinity), as one increases the size of the hologram, so does the maximum spacing in its structure. After the spacing becomes equal to the resolving power of the emulsion, a further increase in the size of the hologram will be useless — the photographic emulsion cannot reproduce its structure. Let us consider this question in more detail.

The spacing of the interference pattern may be written on the basis of (7) as

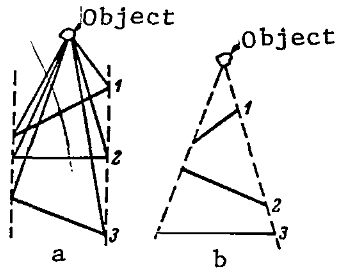

Figure 17. a - holograms 1-3 have the same angular resolution, linear resolution decreases from 1 to 3; b - holograms 1-3 have the same linear resolution, angular resolution increases from 1 to 3. Requirements on the resolving power of the emulsion are lowered from 1 to 3 in both diagrams; requirements on the sensitivity of the emulsion increase from 1 to 3 in both diagrams.

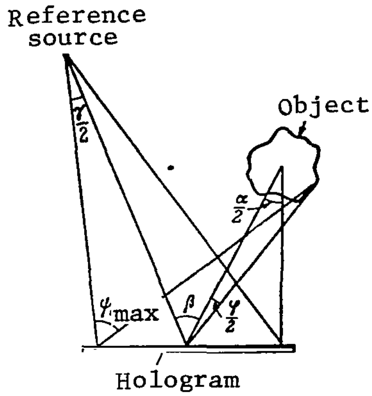

Figure 18. Calculation of the spacing of the interference structure in a hologram.

$$\nu = \frac{\sin\varphi_1 + \sin\varphi_2}{\lambda} = \frac{2\sin\frac{\varphi_1+\varphi_2}{2}\cos\frac{\varphi_1-\varphi_2}{2}}{\lambda}, \qquad (18)$$

or, assuming $\cos\frac{\varphi_1-\varphi_2}{2} \approx 1$ (6), /31

$$\nu = \frac{2\sin\frac{\Psi}{2}}{\lambda}, \qquad (19)$$

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

(6) $\cos\frac{\varphi_1-\varphi_2}{2}$ for the difference $\varphi_1 - \varphi_2$, equal to 30, 60 and 90° will be 0.97, 0.87, 0.71, respectively.

As we can see in Figure 18, the maximum spacing will correspond to the maximum angle between the beams

$$\Psi_{max}=\beta+\frac{\alpha}{2}-\frac{\gamma}{2}+\frac{\varphi}{2}. \tag{20}$$

Here, α is the angular dimension of the hologram (the vertex of the angle is at the center of the object); γ is the angular divergence of the reference beam; β is the angle between the axes of the reference and object beams; ϕ is the angular size of the object.

Thus, [10],

$$\nu=\frac{2\sin\left(\frac{\beta}{2}+\frac{\alpha-\gamma+\varphi}{4}\right)}{\lambda}. \tag{21}$$

Therefore, if we are given the resolution of the emulsion, ν_{ob}. then we can vary the angles α, β and γ only within limits such that the following condition will be satisfied

$$\frac{\beta}{2}+\frac{\alpha-\gamma+\varphi}{4}\leqslant\arcsin\frac{\nu_{ob}\lambda}{2}. \tag{22}$$

Here it must be kept in mind that the linear resolution is defined in terms of the angular size of a hologram, α, and it is convenient to increase this parameter to a maximum, while at the same time making the others smaller.

Let us first consider the case of a reference wave with a plane front, ($\gamma = 0$). To the minimum angle β in this case, there corresponds a reference beam passing close to the object (Figure 19). As we can see in this figure, $\beta_{min} = \phi/2 + \alpha/2$ and Condition (22) can be written in the following way: /32

$$\frac{\alpha+\varphi}{2}\leqslant\arcsin\frac{\nu_{ob}\lambda}{2}. \tag{23}$$

The limiting linear resolution achieved in this case is easy to estimate by replacing arc sin $\nu_{ob}\lambda/2$ with $\nu_{ob}\lambda/2$. Then $\alpha \leq \nu_{ob}\lambda - \phi$, and, in view of (16),

$$\frac{1}{\delta y} \leqslant \nu_{ob} - \frac{\varphi}{\lambda}. \tag{24}$$

In other words, the linear resolution of the object may only be worse than the linear resolution of the emulsion.

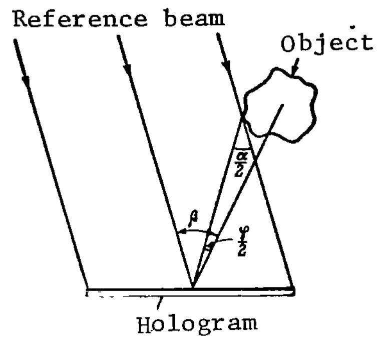

Figure 19. Calculation of the spacing of the interference pattern in the case of a plane reference wave.

Now let us consider another extreme case. Let us assume that the reference source has been placed in the plane of the object, i.e., $\gamma = \alpha$. Now α and γ in (22) are cancelled out, and thus, condition (22) does not impose any restrictions on the angular dimensions of the hologram, and, consequently, on the linear resolution in the plane of the object.

Practically, however, it is difficult to make a hologram spanning an angle α which is greater than one radian. Therefore, as implied by (16), /33
the limiting linear resolution has a magnitude on the order of one wavelength.

As already indicated, such a configuration, first proposed in [12], was named lensless Fourier transform holography (see [11]). This configuration is in many cases preferable, in particular when it is necessary to obtain a linear resolution (in the plane of the object) which is higher than the linear resolution of the emulsion. The configuration with a plane reference beam does not give us this opportunity at all. However, in using high-resolving films of the Kodak 649F or BP type in the visible part of the spectrum, this advantage cannot be achieved, since these films have a resolving power less than λ as it is. On the other hand, in the X-ray part of the spectrum the configuration will undoubtedly be most convenient.

Lensless Fourier transform holography makes it possible, by moving the reference source close to the object and leaving the remaining parts of the configuration unchanged, to minimize the spacing of the interference pattern. Therefore, in principle, with such a location of the reference source, the requirements on the resolving power of the emulsion may be slightly lower. In fact, for a parallel reference beam we have $\gamma = 0$, and $\beta_{min} = \phi/2 + \alpha/2$ (Figure 19), whence the maximum spacing of fringes on a hologram will be, in view of (21),

$$\nu_{I} = \frac{2\sin\left(\frac{\varphi}{2} + \frac{\alpha}{2}\right)}{\lambda}. \qquad (25)$$

For lensless Fourier transform holography, $\beta_{min} = \phi/2$, $\alpha = \gamma$, and, in accordance with (21),

$$\nu_{\Phi} = \frac{2\sin\frac{\varphi}{2}}{\lambda}. \qquad (26)$$

(25) and (26) imply that, in transition from a parallel reference beam to a reference source lying in the plane of an object close to it, the requirements on the resolving power of the emulsion may be lowered to

$$\frac{\nu_{I}}{\nu_{\Phi}} = \frac{\sin\left(\frac{\varphi + \alpha}{2}\right)}{\sin\frac{\varphi}{2}} \text{ times} \qquad (27)$$

Unfortunately, this configuration is practically inapplicable, since — /34
during the reconstitution — the halation from the bright zero-order beam spoils the edges of the image of an object.

§3. SET-UPS

Set-ups for Obtaining Holograms

Let us consider set-ups that are used in holography. The light sources are usually provided by lasers, although it is possible to use ordinary light sources that have a line spectrum from which one or a few lines are isolated by filters (see Section 5). A number of configurations used in holography of three-dimensional objects and transparencies are shown in Figures 20-28. As a rule, in each such configuration there are two branches, one of which illuminates the object, and the other forms the reference light source.

Expansion of Beams

Lasers emit narrow light beams several millimeters in diameter. They are expanded to the desired diameter and divergence with the help of lenses or lens systems.

To expand a parallel light beam (Figure 29) it is convenient to use a telescopic system consisting of a microobjective and a large diameter lens of long focal length. The focal points of both lenses coincide. The increase in the diameter of the beam is equal to the ratio of the focal lengths f_2/f_1. By moving the lens along the optical axis, one can get a convergent or divergent light beam. At the focus of the microscopic objective that expands the reference beam, one often places a diaphragm with a small opening, on the order of 10-15 microns. This is done to remove any aberration of the optical system as well as diffraction rings due to dust particles that fall on mirrors and lenses, since a small opening emits an ideal spherical wave. Of course, the adjustment of the position of the opening should be done very carefully /39 both in the longitudinal and lateral directions. Otherwise a large portion of the radiated energy will be blocked, and will not pass through the opening.

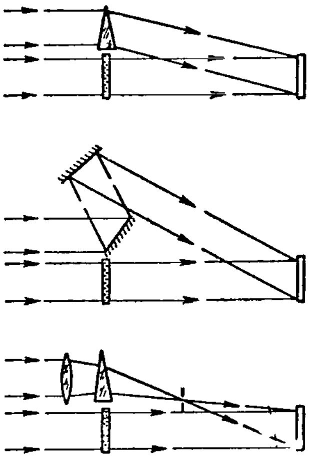

Figure 20. Configurations in holographing transparent objects according to Leith and Upatnieks.

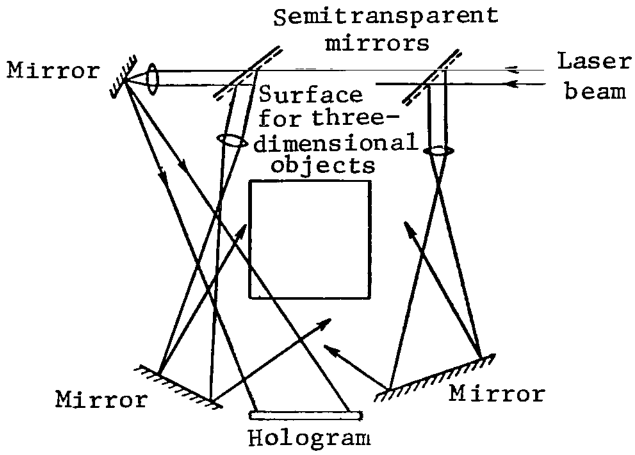

Figure 21. Configuration for obtaining holograms of three-dimensional objects with a two-sided illumination of the scene.

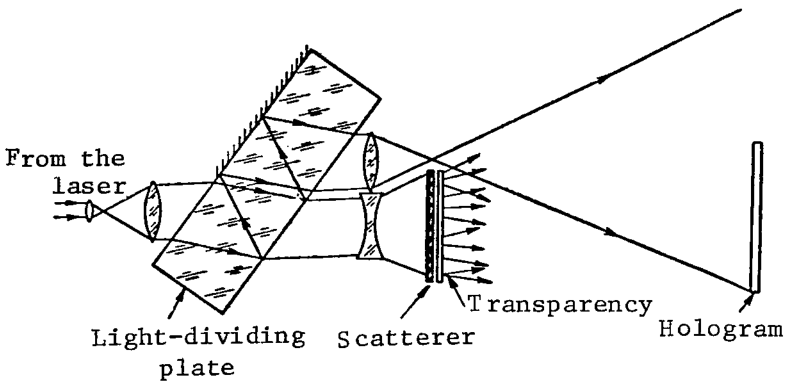

Figure 22. A configuration for obtaining lensless Fourier transform holograms of transparencies with a scatterer. The focal distances of the positive and negative lenses are identical.

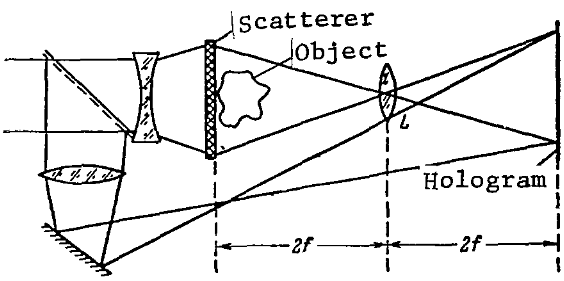

Figure 23. A configuration for obtaining holograms of transparent objects with a scatterer with an insufficient space coherence of laser radiation. The scatterer is projected by a lens on the hologram which makes the structures of the reference and object beams coincide.

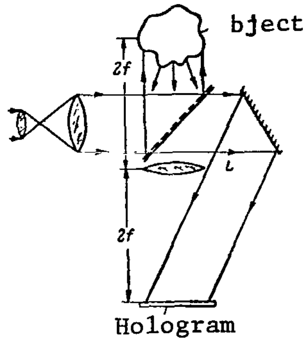

Figure 24. Configuration for obtaining holograms of three-dimensional scattering objects with insufficient space coherence of laser radiation. The object is projected by a lens L on the hologram, which results in a coincidence of the modal structures of the beams.

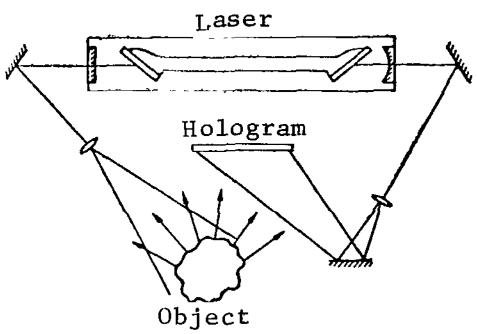

Figure 25. Configuration for obtaining holograms without light dividers, using a second laser beam as a reference beam.

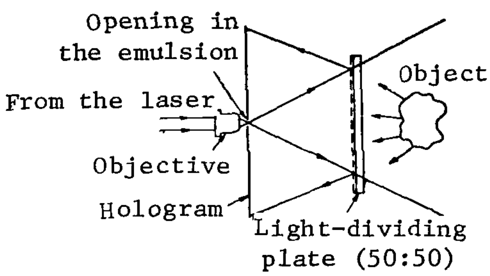

Figure 26. Configuration for obtaining Gabor holograms of opaque scattering objects [15].

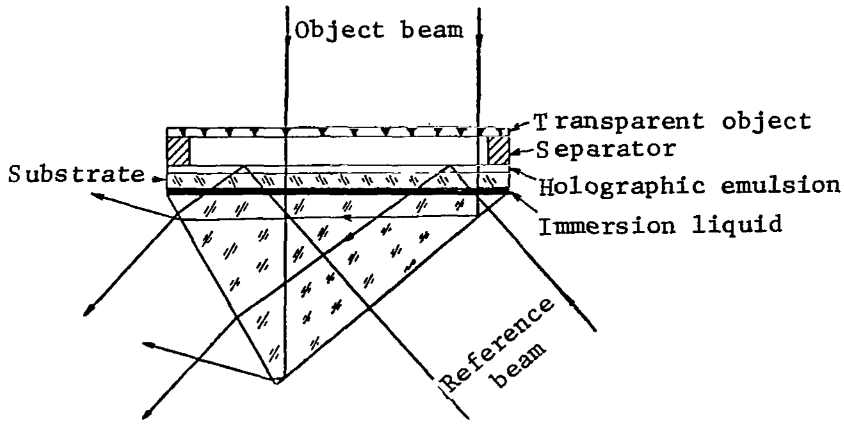

Figure 27. Configuration for holographing with a reference beam undergoing a full reflection at the photographic emulsion-air boundary [16]. Here on one plate two holograms are recorded: with the incident reference beam (this hologram has a large spacing) and with the reflected beam (this hologram has a small spacing). The reconstitution of the wavefront is achieved using the same prism. The configuration allows the object to be located close to the hologram.

Variation of the Direction of Beams

To vary the direction of light beams, one uses mirrors and prisms. When the latter are used, one has to keep in mind the possibility that secondary reflections will arise from the faces, which will result in the appearance of parasitic beams. The brightness of these beams is usually small, but they may interfere with the main beams, and result in very high-contrast interference fringes that worsen the quality of holograms.

The same effect on the quality of holograms is exerted by dust particles that fall on optical instruments, forming the reference beam. The rings covering the surface of holograms (see, for example, Figure 2, a) are nothing else but results of the diffraction of coherent light on the dust

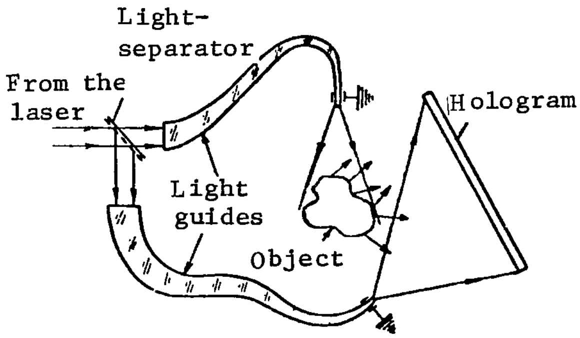

Figure 28. Configuration for obtaining holograms using fiber light guides. A convergent flexible light guide with the exit diameter of several microns plays the role of a microscopic objective with a point diaphragm and emits an ideal spherical wave at the exit. The angular expansion of the beam is equal to the reduction of the exit opening diameter divided by the entrance diameter.

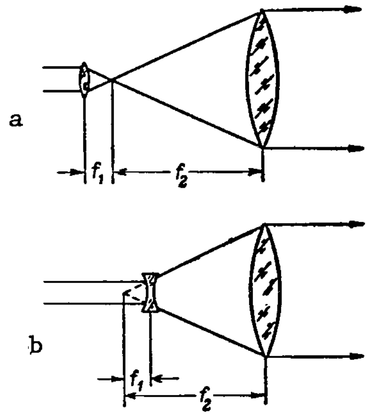

Figure 29. Telescopic systems for expanding a parallel beam.

a - with a positive lens,
b - with a negative lens.
A system with a negative lens is preferable when using a laser with a gigantic impulse, since a laser spark may arise at the focus of the positive lens.

particles. This also modifies the darkening of the hologram: portions that correspond to maxima turn out to be overexposed; those that correspond to minima are underexposed. The effective area of a hologram is reduced, and the quality of reconstitution is worsened. A good hologram should have a smooth, visually homogeneous surface.

Separation of Beams

To separate the laser light beam into two branches, one uses two basic techniques: separation of amplitude, and separation of the wavefront.

In amplitude separation, one uses semi-transparent mirrors, wedges, or diffraction gratings. Configurations of these instruments are shown in

Figure 30. For the same purpose, one uses double-refracting systems — for example, Wollaston prisms, crystals of calcite or some other birefringent substance (Figure 31). The beams emerging from such systems are polarized in mutually perpendicular planes, and in order for them to interfere they are passed through a polarizer placed at 45° angle to the planes of polarization /40 of each beam. This results in the loss of one half of the luminous energy. Beams may be brought to a single plane of polarization without any loss of light with the help of devices that can rotate the plane of polarization — for example, by passing them through quartz crystal plates cut perpendicularly to the optical axis. To rotate the plane of polarization by 90°, one needs a quartz plate 4.8 mm in thickness (λ 6328 Å). The light wavefront may also be separated with the help of mirrors, prisms, and lenses. The corresponding configurations are shown in Figure 32.

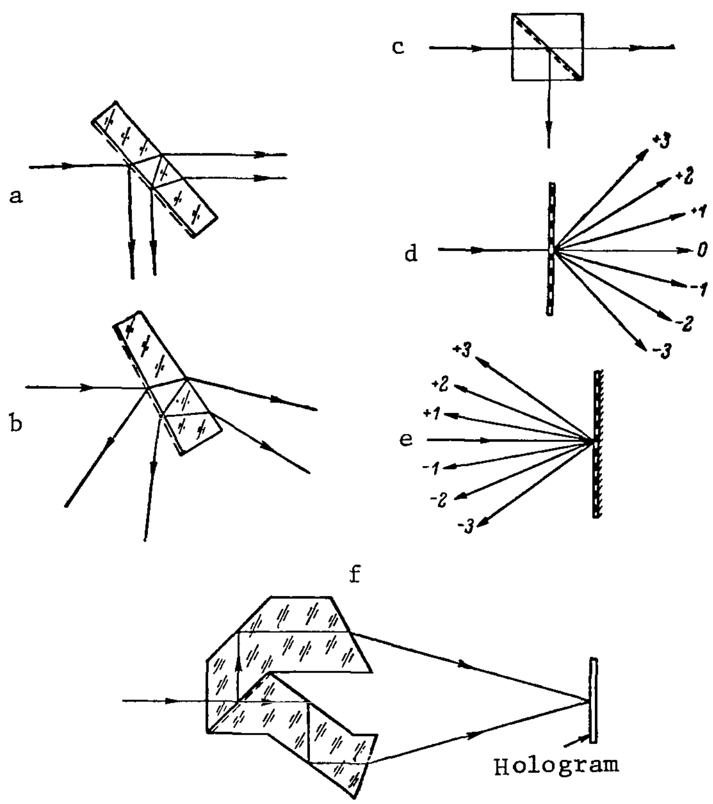

Figure 30. Devices for the amplitude separation of light beams.
a - semi-transparent mirror; b - wedge; c - light-separating cube; d - transparent grating; e - reflecting grating; f - special prism [17].

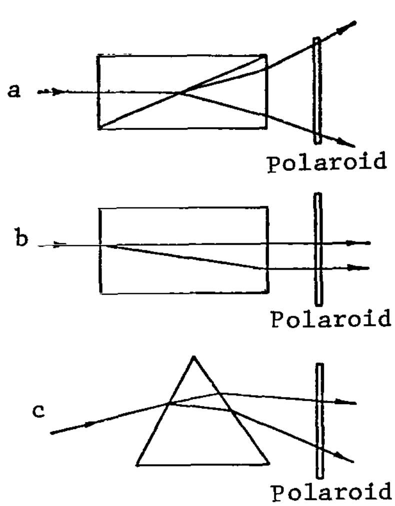

Figure 31. Polarizing devices for the amplitude separation of light beams.

a - Woolaston prism (it is also possible to use Rochon and Senermon prisms); b - calcite plate; c - calcite prism.

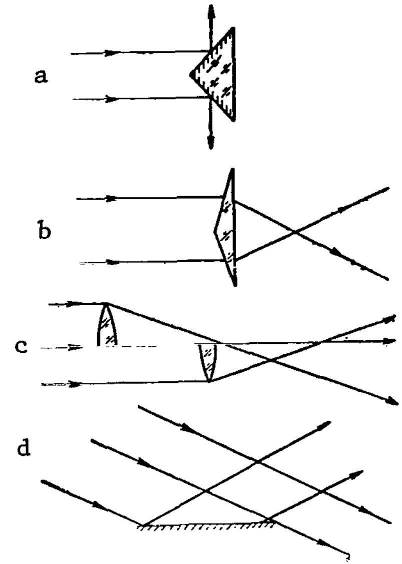

Figure 32. Devices for separating the light wavefront.

a - a prism with an outer reflecting layer; b - biprism; c - bilens; d - Lloyd mirror.

The configurations involving a subdivision of the wavefront may only be used if the beam has a full space coherence. Configurations involving subdivision of amplitudes, however, may also be used with beams that are spatially incoherent; the latter make it possible in certain cases to make the modal structures of the reference and object beams coincide (see below). Sometimes in holography one does not use light-separating optical systems, but rather a weaker laser beam as a reference beam (Figure 25). Enormous possibilities for constructing holographic systems have been created by fiber optical devices (Figure 28).

To produce a reference beam, one may also use part of the light scattered by the object itself [18]. One must only separate from this light its mirror-reflected component by placing a point diaphragm at the focus of the objective. This type of system makes it possible to holograph fast-moving objects, since the Doppler effect has the same effect on both the object and reference beams.

Relationship between Illuminations

In holography, one attempts to achieve an optimum relationship between the illuminations produced in the plane of the hologram by the reference light source and the object. As a rule, the illumination produced by the reference source must be several (5-10) times greater. In this case, the exposure is almost completely determined by the illumination produced by the reference source, and the fringe contrast is slightly reduced as compared with its maximum when the illuminations produced by both beams are identical. This lowers the chance of going out of the linear portion of the characteristic curve. Figure 33 shows the plot of the contrast of the interference pattern versus the ratio of illuminations α, produced by the interfering beams. The graph is constructed under the assumption that the beams are absolutely coherent from the formula /43

$$K = \frac{2\sqrt{\alpha}}{1+\alpha}.$$

With a weak reference beam and a correspondingly strong illumination of the hologram by the object, one begins to notice the mutual interference of light waves emitted by various points of the object. Each point of the object may be regarded as a reference source with respect to the rest of points of the object. During the reconstitution of such a hologram, the image of the source turns out to be surrounded by a wide halo due to the diffraction of light on the crossing interference structure. The halo may be superimposed on the reconstituted image, thus lowering its quality. In order to prevent this from happening, one has to select the angle β between the axes of the reference and object beams (see Figure 18) to be greater than 3/2 α, where α is the angular size of the object. However, if the reference beam produces on the plate an illumination which is several times greater than that produced by the object beam, then the cross-interference hologram is sufficient for obtaining a great deal of important information about an object. In this case it is possible to obtain holograms without the reference beam, which is especially valuable in x-ray holography of crystals [19,20].

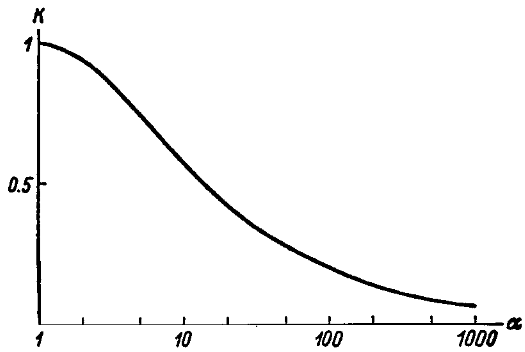

Figure 33. Dependence of the contrast of an interference pattern, K, on the ratio of illuminations, α, produced by the reference and object beams.

In an efficiently constructed set-up, the desired relation between the illumination of the hologram due to the reference and object beams is achieved not by using filters, but by the right choice of light dividers. When this is done, the energy of the laser is most fully used. One must keep in mind that usually losses of energy in the branch illuminating the object are much greater than in the branch of the set-up that produces the reference beam (10-1000 times). Therefore, it is sometimes convenient to use a simple glass wedge without coating in the role of the light-dividing mirror. The ratio of light fluxes in the beams can in this case be varied within a wide range by rotating the light-dividing wedge since, as we know, the Fresnel reflection coefficient depends on the angle of incidence (Figure 34). /44

In changing the ratio of beam intensities, it is even more convenient to use the dependence of the ratio of the reflected to the transmitted light energy on the orientation of the planes of polarization. As we can see in Figure 34, if the angle of incidence of the light on the glass plate ($n = 1.52$) is equal to 56°40' (Brewster angle), then by rotating the plane of polarization of the light incident on the plate by 90°, one can vary the ratio of beam intensities from 5 to infinity. For the angle of incidence 70°, the range of the ratio of intensities is from 2 to 18. A smooth and regulated rotation of the planes of polarization is achieved with the help of quartz wedges cut

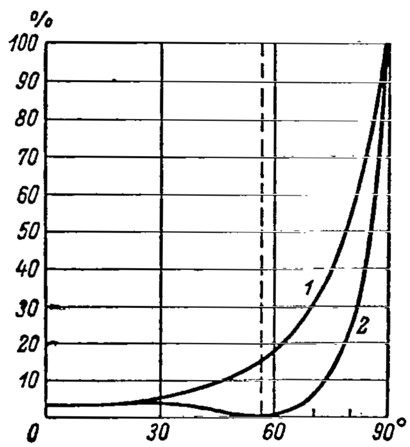

Figure 34. The reflection coefficient (air-glass boundary, n = 1.52) vs. the angle of incidence.

1 - light polarized in the plane of incidence; 2 - light polarized in the plane perpendicular to the plane of incidence.

perpendicularly to the optical axis. For approximate calculations of such a wedge, one must know that the rotational ability of quartz is equal to about 19 deg/mm for λ 6328 Å, and about 16 deg/mm for λ 6943 Å.

It is convenient to be able to make a photoelectric measurement of illumination in the plane of the hologram. For this purpose, one can use any sufficiently sensitive photodiode, photocell, or photomultiplier.

Holography of Self-Luminous Objects

When it is necessary to holograph a self-luminous object, the hologram must be protected from the light emitted by the object. This is done by using filters which are maximally transparent to laser radiation, and as far as it is possible, cutting off both long-wave and short-wave portions of the spectrum.

For example, for the helium-neon laser (λ 6328 Å) it is convenient to use the filter KS-13 [21] which is opaque to λ < 6150 Å. The influence of the longer-wave portion of the spectrum is usually eliminated automatically, since the emulsion is not very sensitive to it.

If these measures are insufficient to eliminate unwanted exposure, one can use a more complete filter system, e.g., one consisting of narrow-band interference filters with the transmission maximum coinciding with the laser line. It must, however, be kept in mind that such a filter should be placed in a parallel light beam, since the location of its transmission maximum depends on the angle of incidence, and is displaced toward the shortwave part of the spectrum as the incident ray is further and further from the normal. To lower the unwanted exposure, we can also use polaroids oriented in such a way that the polarized laser radiation will be transmitted. They reduce the natural radiation from the object by a factor of two. One should not be particularly concerned with small doses of incoherent radiation falling on a hologram. In [22] it was shown that, even when the incoherent exposure is 50 times greater than the exposure due to the object beam, the quality of the reconstituted image remains satisfactory.

Other Parts of Holographic Equipment /46

Photographic plates are put in special cassettes or cassettes for photographic cameras or spectrographs. A film (if frame size is sufficient) may be loaded into an ordinary camera with lens removed.
Lenses, prisms, mirrors, filters, and cassettes should be framed so that they have the necessary adjustable freedom of movement.

In constructing a holographic set-up, it is convenient to use parts from the optical bench OSK-2 or OSK-3. It must be noted, however, that many elements of these expensive sets are in oversupply for holography, whereas there are not enough of others. Therefore, it is necessary to manufacture special holographic sets.

In constructing holographic set-ups, one must keep in mind the suggested length of exposure. A displacement of any portion of the equipment during exposure must not result in a difference of paths between the interfering beams that would be greater than $\lambda/4$. If the path difference amounts to $\lambda/2$, the interference pattern is completely washed out. This places especially rigid requirements on the stability of the position of those optical parts through which the light passes, or from which it is reflected upon separation into two beams. The optical parts that reflect or scatter light (these may also include the object being holographed), as a rule, should not be displaced by more than $\lambda/8$. Less rigid requirements are placed on parts transmitting the light beams.

All these requirements, which are usual for interferometric equipment, can be easily satisfied without any precautionary measures if the holograms are recorded using impulse lasers (exposure time on the order of 1 microsecond). With the aid of lasers capable of a "giant impulse" whose duration amounts to nanoseconds or dozens of nanoseconds, one can holograph even moving objects. The difficulty of holographing fast moving objects is due to the frequency shift of the scattered light as a result of the Doppler effect.

Another case is presented by gas lasers of continuous radiation. In their case, the length of exposure amounts to fractions of a second to minutes, /47 sometimes even tens of minutes. In these cases, one undertakes special measures to rigidly fasten parts of the equipment, to eliminate vibrations, to achieve thermal stability, etc. Parts of the equipment are usually placed on a massive granite, concrete, or steel slab which in turn is placed on fully inflated automobile tires or tennis or soccer balls.

To control the vibrational stability of the equipment, it is often sufficient to have a microscope capable of necessary magnification, which is focused approximately on the plane in which the hologram is going to be placed, and to check the stability and sharpness of the holographic structure visually. One should also test sequentially for any possible mechanical imperfections (due to pumps, machine-tools, walking on the floor, conversations, etc.). This will enable one to determine what precautionary measures are necessary when taking a hologram, and which ones are useless. To make fringes stationary in the presence of disturbances, various stabilizing configurations have been proposed which automatically introduce a phase shift which compensates the displacement due to the disturbance [23]. Equipment

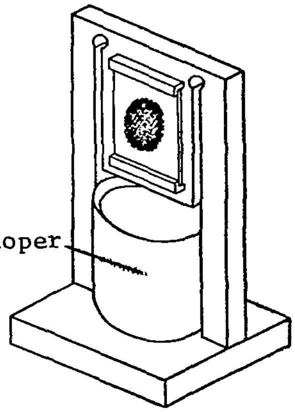

Figure 35. A device for developing a hologram in place.

of this type, however, is very complex and should be used only in the exceptional cases when all the other methods of eliminating disturbances have been tried, and did not give the desired results.

If it is necessary to hold a hologram exactly in the position in which it was during exposure, one resorts to developing and fixing on the spot [24]. Such a necessity arises in holographic interferometry (see page 35). For on-the-spot developing, one uses a photographic plate holder of special form which permits one to place underneath a container with the developing solution (Figure 35). The study [25] for the same purpose suggests exposing the hologram on the plate which has been previously placed for several minutes in the developer. In this case, one can directly /48 observe the formation of the reconstituted image during the exposure.

§4. LASERS

The first laser holograms were obtained with the aid of a helium-neon laser whose wavelength was 6328 Å. Subsequently, a number of papers reported that holograms were obtained using as the source of radiation the argon laser which gives a much greater power (λ 5145, 4880, 4765 Å). At the present time, in holography impulse lasers are also used, usually of the ruby type (λ 6943 Å)

The principle of operation of the laser, and a detailed description of its properties can be found in a number of specialized books (see, for example, [26]). We shall dwell only on the property of coherence possessed by laser radiation, which is what has made lasers the irreplaceable sources of light in holography.

The notion of coherence may have different meanings depending on the context in which it is used.

Time Coherence

Time coherence defines the ability of light waves emitted by a source at different times to interfere with one another. The time coherence may be characterized numerically by the maximum time interval (Δt) within which radiation maintains its coherent properties or by a path segment Δl traversed by the light during that time. Of course, the length of coherence Δl and the time of coherence Δt are related by $\Delta l = c\Delta t$, where c is the velocity of light.

Time coherence is uniquely related to the width of the spectral line emitted by the light source. The more monochromatic the line is, the longer and longer-lasting the wavetrain to which it corresponds, and consequently, the higher the coherence of radiation. One can show that

$$\Delta l = \frac{1}{\Delta \bar{\nu}} = \frac{\lambda^2}{\Delta \lambda}, \tag{28}$$

/49

where $\Delta\bar{\nu}$ is the width of the spectral line in the unit system of wave numbers[7], and $\Delta\lambda$ is the same quantity in the unit system of wavelengths.

The coherence length of a source is of great importance in holography. It is necessary that the path difference between any light beams meeting on a hologram not exceed the length of coherence. This circumstance sometimes limits the depth of the holographed scene, and necessitates certain measures for equalizing the paths of the light beams after their separation.

If the depth of the object is rather large, and it does not permit one to obtain a hologram with the available laser, then configurations exist in which the object is illuminated part by part [27] (Figure 36). In this case, it is possible to obtain a hologram of a deep scene using a laser that has a small length of coherence.

Helium-neon lasers with short discharge tubes radiate very narrow spectral lines; their length of coherence may reach hundreds of meters. However, the power of such lasers is extremely small (0.1-0.5 milliwatt). Helium-neon lasers whose resonator length L is about 1-2 m have a considerably greater power (20-150 milliwatt), but their length of coherence is much smaller, since their radiated line consists of many components with the spacing between the neighboring components $\Delta\bar{\nu} = 1/2L$ (Figure 37). The length of coherence of such lasers usually does not exceed 10-20 cm. /50

To increase the degree of time coherence of lasers and their resonators, one introduces selective elements, usually in the form of plane-parallel transparent plates. Such a plate is a Fabry and Perot etalon with a low reflection coefficient. Figure 38 shows a typical dependence of the transmission

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(7) Wave number is the reciprocal of the wavelength.

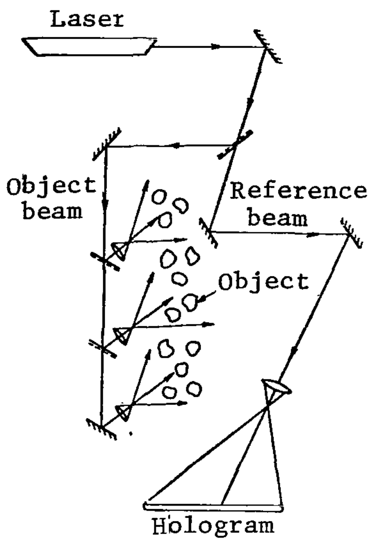

Figure 36. Holographing of a scene extended in depth with the aid of a laser with a limited length of coherence.

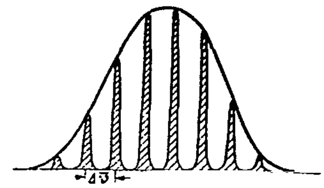

Figure 37. Structure of the laser radiation line

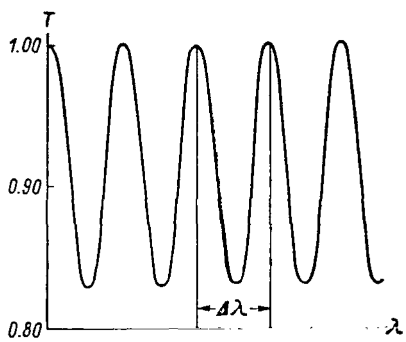

Figure 38. Dependence of the transmission coefficient of a glass plate (n = 1.5) on the wavelength.

coefficient of such an etalon (in the direction of the normal to its surface) on the wavelength. As a result, for certain longitudinal types of oscillations (modes) the Q factor of the resonator changes very little when a plate is inserted. For other modes, it becomes worse, which results in a disruption of generation on these wavelengths: the line is made much narrower, and the length of coherence is made longer. The total radiated power is only slightly reduced in this case.

If one does not take any measures to make the lines emitted by ruby lasers more narrow, their length of coherence is no greater than a few centimeters. A selection of the oscillatory modes accomplished with the help of resonance reflectors makes it possible to increase the length of coherence up to several meters.

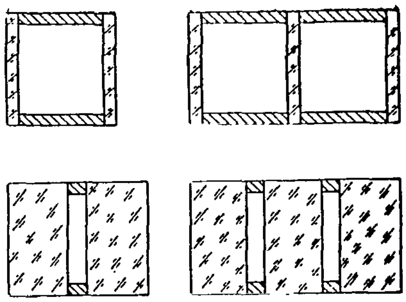

Figure 39. Resonance reflectors used in the selection of the longitudinal oscillatory modes.

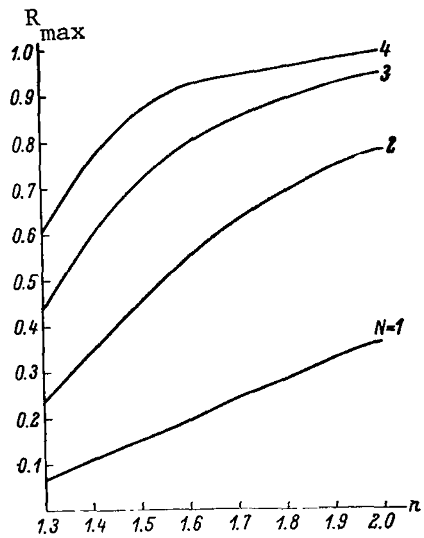

Figure 40. Dependence of the maximum reflection coefficient for a resonance reflector consisting of N plates on the refractive index

The operation of the resonance reflectors composed of 2-3 glass, quartz, or sapphire plane-parallel plates (Figure 39) is equivalent to that of the Fabry and Perot etalon which is based on reflection. If one neglects the losses due to absorption, then the reflection coefficient of one plane-parallel glass plate is a function of the wavelength, which supplements the curve in Figure 38 up to T = 1. /53

The reflection coefficient at the maximum of a resonance reflector consisting of N plates can be calculated using the formula [28]

$$R_{max} = \left[\frac{1-\left(\frac{1}{n}\right)^{2N}}{1+\left(\frac{1}{n}\right)^{2N}}\right]^2. \qquad (29)$$

Figure 40 gives a plot of R_{max}, computed according to the above formula, versus the refractive coefficient of a plate n for reflectors consisting of 1, 2, 3, and 4 plates, and Figure 41a,b shows the plots of the reflection coefficient versus the wavelength for two types of resonance reflectors computed in [29].

The time coherence of lasers can be investigated directly by an inspection of the interference fringes

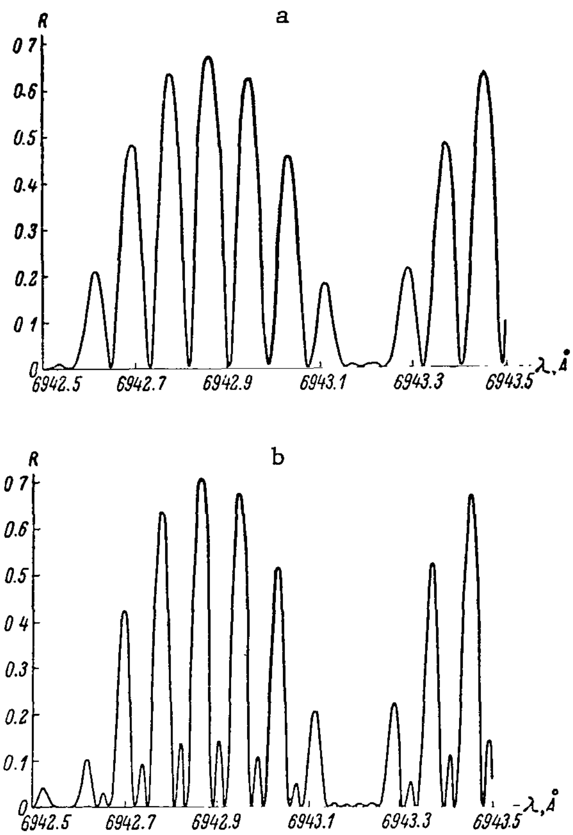

Figure 41. Reflection coefficient of a resonance reflector as a function of the wavelength (near the line radiated by a ruby laser λ 6943 Å).

a - reflector made of two two-millimeter plates (n = 1.79) with a gap of 25 mm;

b - reflector made of three two-millimeter plates (n = 1.52) with a gap of 25 mm (see Figure 39).

observed in the interference of beams that have traversed different paths — for example, with the help of the Michelson interferometer. One can measure the time coherence of radiation from the width of the spectral line with the help of high-resolution spectral instruments (for example, a Fabry-Perot interferometer).

Space Coherence

Space coherence of radiation characterizes the ability of light waves emitted by various portions of the source and at various angles to interfere with one another.

Usually, both gas and solid-state lasers emit a light beam with a complex structure in the form of characteristic dots (Figure 42). These are the so-called nonaxial modes (types of oscillations). Radiation of such a structure has a low degree of space coherence, since there are no constant phase relations between spots of this structure. This does not mean that it is impossible to /54
obtain good holograms with such lasers. It is only necessary that the modes preserve their individuality within beams in the scheme, and that the beams exactly coincide on the hologram. In holographing transparencies without a scatterer, these conditions are easy to satisfy.

Slightly more complex is the scheme for superimposing the modal structures in holographing transparent objects with a scatterer. In this case, it is necessary to project the scatterer on the hologram by means of a special objective [30] (see Figure 23). This scheme, however, is useful only if the object itself does not disturb the structure of the beam to any greater extent.

In holographing three-dimensional scattering objects, the modal structures of the reference and object beams can to some degree be superimposed simply by projecting the object on the hologram, for example, using the scheme of Figure 24. However, all these contrivances become unnecessary if it is possible to suppress the generation of nonaxial modes. The simplest way to achieve

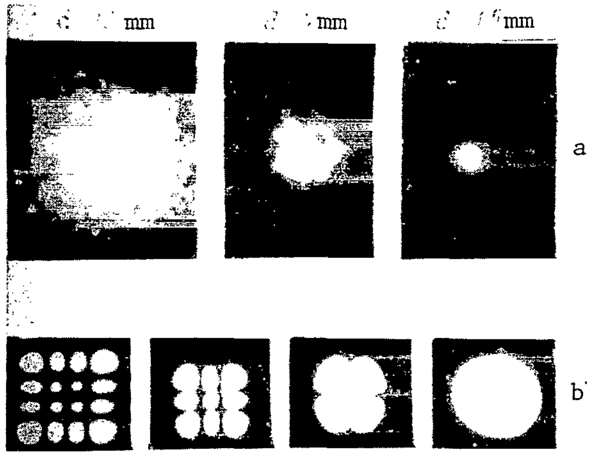

Figure 42. Suppression of nonaxial oscillatory modes by introduction of a diaphragm (d) in the resonator of the laser.

a - ruby laser; b - helium-neon laser.

this is by introducing a diaphragm into the laser resonator (see Figure 42). Such diaphragms are provided with some gas lasers. The generated power is /55 diminished with the introduction of a diaphragm in gas lasers by approximately a factor of 2-4 (for example, for the types LG-35, LG-36). The energy of burst of a ruby laser, emitting a "gigantic" impulse, is diminished by a factor of 10-50 when a diaphragm that suppresses the generation of nonaxial modes is introduced. The radiation from such a laser can be amplified by placing at its exit a second laser head that oscillates synchronously with the first. The amplification coefficient is usually about 5, and to a considerable extent this compensates for losses incurred by introducing a diaphragm. Certain authors even used two- and three-cascade or two-, three-way amplifiers of this type. To control the space coherence of lasers, one can recommend, for example,schemes proposed in [31, 32].

Variation of the Wavelength

Although there is a wide choice of the wavelength of a continuously generating laser, in impulse holography the choice is limited to a ruby laser of the wavelength 6943 Å. Neodymium lasers (λ 1.06 microns) are inconvenient, because their radiation lies in a spectral region which is difficult to record, and also due to low time coherence. The width of the radiated line from a neodymium laser amounts to dozens of angstroms, and the length of coherence is a fraction of a millimeter. Some possibilities for widening the choice of the wavelength of laser lines are presented by the techniques of nonlinear optics [33]. At the present time there have been developed highly effective methods of generating 2^{nd} and 3^{rd} harmonics of the ruby laser wavelengths (3472 Å and 2314 Å). The first of these lines has already been used for obtaining impulse holograms [34, 35].

Another possibility is to obtain holograms in the light of lines of stimulated combination radiation, but as far as we know this has not been done so far.

Both in the case when the frequency was doubled and in the case of stimulated combination radiation, the primary laser radiation retains its coherent properties to a considerable extent. The transformation coefficient in individual cases amounts to 10-30%.

Scatterers

In obtaining holograms of transparencies, one usually places scatterers in front of the latter which convert concentrated laser radiation into diffused radiation. A hologram of a transparency obtained with a scatterer possesses all the properties considered above, which are characteristic of holograms of three-dimensional objects. The main property is the fact that radiation from each point of an object is distributed over the entire hologram, and consequently each small portion of the hologram contains information about the entire object. If a transparency is holographed without a scatterer, then the hologram does not possess this property, and to each portion of the transparency there corresponds a certain portion of the hologram. Scatterers are also used to produce uniform and diffused illumination of three-dimensional objects and scenes. Of course, the quality of a hologram to a large extent depends on the properties of the scatterer used. According to the data of [36], use of fine-grain scatterers improves the quality of reconstituted images, mainly since the grain structure of the scattered laser light turns out to be slightly finer in this case (Figure 43).

Fine-polished glass or quartz are usually used as scatterers. A fine-grain scatterer can be obtained by treating glass plates with vapors of hydrogen fluoride. Frosted glass is convenient to use for diffusion reflectors. For certain types of frosted glass, the diffusion reflection coefficient is close to unity. In the same way, one can use metallic or glass surfaces coated with magnesium oxide.

When scatterers are used in holography, one must keep in mind that the angular dimensions of a hologram must agree with the scattering index. If the latter is slightly too wide, then a considerable portion of laser light will go past a hologram. If, however, conversely, the scattering index is

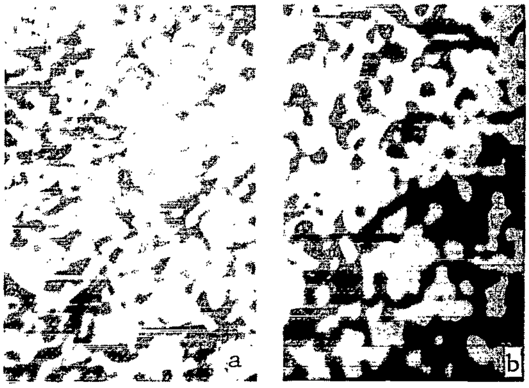

Figure 43. Grain structure of laser radiation that has passed through polished glass.

Structure a corresponds to glass polished by the emery which is finer than in case b.

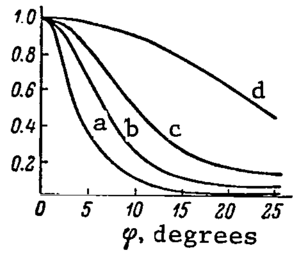

Figure 44. Scattering indices of laser radiation for various scatterers [36].

a - glass polished with an abrasive with grains of a mean size of seven microns;
b - as above, grain size - 28 microns;
c - as above, grain size - 80 microns;
d - frosted glass.

slightly too long, this will result in a nonuniform illumination of the hologram. Figure 44 shows the scattering indices for several specimens of polished /57 and frosted glass. In [36] a Christiansen filter was used as the scatterer. The filter is a suspension of glass powder in a liquid, close to glass in its refractive index. The width of the scattering index of such a filter can be easily regulated by changing its temperature, which in a number of cases is very convenient. However, one must maintain a strictly constant temperature for such a scatterer during the entire time of exposure.

In the reconstitution of images of diffusively reflecting objects or transparencies, illuminated through a scatterer, there is, as already indicated, a characteristic grain structure in the images (Figure 7). The size of the grains is determined by the aperture of the hologram. The graininess lowers the resolving capacity of a hologram, particularly in those cases when the aperture is small. To reduce the effect of graininess, one can separate the exposure into several parts, each time moving the scatterer slightly. Then the photographic plate will accordingly register several holograms, each of which will reconstitute the same image of the object in the same location. However, the grain structure of these images will be different, which will /58 result in its averaging. Of course, one must not attempt to take a hologram with the scatterer chaotically moving around during exposure. A hologram thus obtained will not form any image.

Another method of weakening the graininess of the reconstituted image is applicable only to Fourier transform holograms. The spacing of the interferency structure in such holograms changes very slowly. Therefore, small translational movements of the hologram in its plane will not lead to a shift of the reconstituted image. At the same time, the grain structure of the image changes a great deal with each new position of the hologram. Therefore, if one attaches a Fourier transform hologram to a vibrating support, a considerable improvement of the image may be the result. The diffuser of a switched-on loudspeaker can be used as a support.

Holography Without Lasers

A hologram is an interference pattern obtained when the reference beam is superimposed on the waves scattered by an object. We described the formation of a hologram in the following way: each point of the object emits a spherical wave which, upon interfering with the reference wave, forms an interference pattern in the form of a Fresnel zone grating. Zone gratings produced by each point are coherent; a hologram registers their coherent superposition (amplitudes are added, taking into consideration the phase relations, and not intensities).

Holographic techniques are possible in which holograms are formed with spatially incoherent intensity. In those techniques the light from each point on the object, upon separation into two channels, forms two spherical waves of different curvature. These waves upon interference produce a Fresnel zone grating. Gratings formed by different points are incoherent. On a hologram they are superimposed with their intensities added. The quality of a hologram (contrast) is in this case much worse than with spatially coherent light, and the more complicated the object, the worse the quality. But for simple objects, consisting of a small number of luminous points, the quality of the hologram may be sufficiently high. /59

One of the techniques of obtaining holograms used with spatially incoherent light was already mentioned above in connection with the possibility of using lasers with many lateral oscillatory modes for holography (see Figures 23 and 24). These techniques involve amplitude separation of the wave into two parts, and then as precise as possible superposition of wavefronts on a hologram. One of them passes throught the object under investigation, where it is necessary that the distortions introduced by it be small. Otherwise, the structures of both waves will not be superimposed accurately on the hologram, and the interference pattern will have low contrast.

Another aspect of the same problem is to obtain holograms with the aid of light sources having small time coherence. When a low-pressure mercury lamp is used with a filter transmitting one of the lines, the length of coherence is several millimeters. Light sources with more narrow lines have low intensity, and thus have no future (for example, atomic beams whose length of coherence is on the order of 1 m).

High- and super-high pressure mercury lamps emit very bright, but at the same time very wide lines, whose length of coherence does not exceed tenths of a millimeter. Therefore, in obtaining holograms with such light sources, one must carefully equalize the optical paths of both branches of the configuration.

This is possible only when obtaining holograms of transparencies, silhouette scenes, or phase objects that do not distort the wavefront very greatly.

Regardless of the difficulties enumerated above, "non-laser" holography /60 has already achieved considerable success. In individual instances, the quality of reconstitution of a wavefront is so high that the results are practically no worse than those achieved in "laser" holography [37, 38].

In the separation of the wavefront into two parts, followed by their subsequent superpostion in obtaining a non-laser hologram, one can use any setup involving Michelson, Jamin, Mach-Zehnder, or other interferometers. A number of other techniques for obtaining "non-laser" holograms were suggested in [39]. Stroke and Restrick [40] used an interferometer with a diffraction grating, and Froehly and Pasteur [41] used an interferometer with two semi-lenses.

Considerable success was achieved by Leith and Upatnieks in non-laser holography [38]. A scheme, proposed by them, to obtain achromatized holograms is shown in Figure 45. The meaning of achromatization involves creating conditions for which the phase difference of interfering waves does not depend on the wavelength. This is achieved by introducing into the scheme an achromatizing element, for example, a prism, lens, or diffraction grating. In the setup shown in Figure 45, the grating forms a diffraction spectrum of the source (the set of its monochromatic images) in the diaphragm plane. To illuminate a transparency, the zero-order beam is used, and as the reference source — the spectrum of one of the first-order beams. Longer-wave portions of this spectrum fall onto the hologram at greater angles α, and the shorter- /61 wave ones — at smaller angles, but the spacing of the fringes on the hologram remains the same for all wavelengths:

$$\nu \approx \frac{\sin \alpha}{\lambda}.$$

Using a mercury lamp of superhigh pressure with a filter transmitting one of the lines, the authors of [38] obtained a high-quality reconstitution

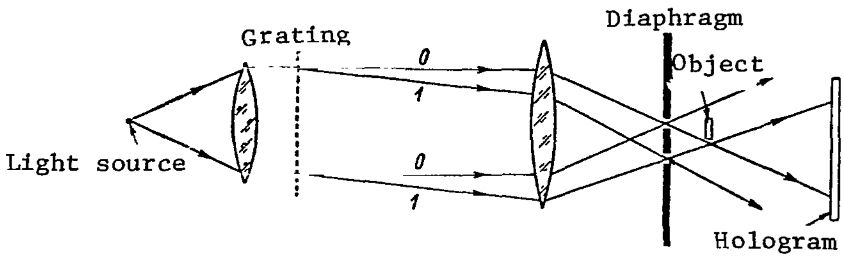

Figure 45. A scheme for obtaining achromatized holograms [38].
0 - zero-order; 1 - first-order.

of transparencies and silhouette-like, three-dimensional scenes, which is comparable with "laser" holograms.

The scheme proposed by Leith and Upatnieks makes it possible, as shown in [42], to use in holography even some of the less monochromatic light sources such as a mercury lamp without filter, and even an incandescent lamp without filter. Of course, the quality of reconstitution is then low.

Multicolor Holograms

The possibility of obtaining holograms that would reproduce not only the structure but also the "color" of a light wave, was already mentioned (p. 19). A general scheme for obtaining multicolor two-dimensional holograms is given in Figure 46. A hologram produced according to this scheme contains three diffraction gratings: "blue" (λ 4880 Å), "green" (λ 5145 Å), and "red" (λ 6328 Å).

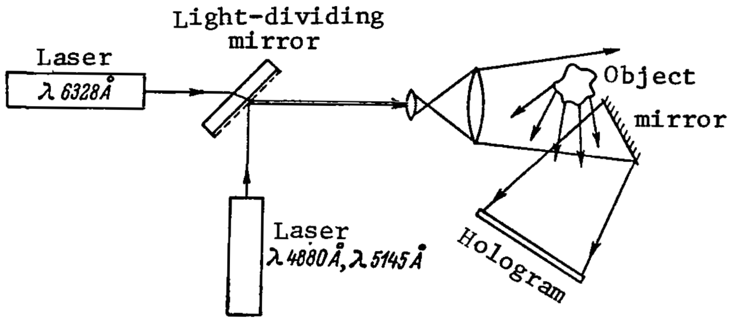

Figure 46. A scheme for obtaining "three-color" holograms with the aid of helium-neon and argon lasers.

During the reconstitution of a wavefront by a three-color beam, the diffraction of red light on the "red" grating, green — on the "green" one, and blue — on the "blue" one, gives a correct three-color image of the object. However, red light is diffracted also on the "green" and "blue" gratings, and thus produces two images of red light which are displaced relative to the correct three-dimensional image. Similarly, blue and green rays are diffracted on "wrong" gratings. /62

Let us consider the case when a reference beam is incident normally on the hologram (angle of incidence is equal to 0). Then, according to Equation (18), the spacings of the gratings produced — the holograms of a point object — will be the following:

$$\nu_1 = \frac{\sin\alpha}{\lambda_1}, \quad \nu_2 = \frac{\sin\alpha}{\lambda_2}, \quad \nu_3 = \frac{\sin\alpha}{\lambda_3}.$$

Here α is the angle of incidence on the hologram of the light from the object; λ_1 - λ_3 are the wavelengths of the blue, green, and red beams, respectively.

During diffraction of light having the wavelength λ_1, on all these gratings images of the point are formed at the angles

$$\left.\begin{aligned} \sin\alpha_{11} &= \sin\alpha, \\ \sin\alpha_{12} &= \frac{\lambda_1}{\lambda_2}\sin\alpha, \\ \sin\alpha_{13} &= \frac{\lambda_1}{\lambda_3}\sin\alpha. \end{aligned}\right\} \tag{30}$$

Similarly, the diffraction of light with the wavelengths λ_2 and λ_3 will give the image of the object at angles

$$\left.\begin{aligned} \sin\alpha_{21} &= \frac{\lambda_2}{\lambda_1}\sin\alpha, \\ \sin\alpha_{22} &= \sin\alpha, \\ \sin\alpha_{23} &= \frac{\lambda_2}{\lambda_3}\sin\alpha, \end{aligned}\right\} \tag{31}$$

$$\left.\begin{aligned} \sin\alpha_{31} &= \frac{\lambda_3}{\lambda_1}\sin\alpha, \\ \sin\alpha_{32} &= \frac{\lambda_3}{\lambda_2}\sin\alpha, \\ \sin\alpha_{33} &= \sin\alpha. \end{aligned}\right\} \tag{32}$$

The angular region which is free from superpositions is, as we can see in Figure 47, located between α_{12} and α_{21}, i.e., for λ_1 4880 Å and λ_2 5145 Å it makes about 4° for the angle of incidence $\alpha = 30°$, and about 7° for $\alpha = 45°$. The outer angular size of the object is thus two times smaller.

A number of authors (see, for example, [43]) attempted to circumvent these restrictions. However, it was possible to obtain good results only by using the technique of thick-layer holography [6-8]. As shown earlier, such holograms are selective as to the wavelength, and thus give reconstituted images only in the light of "their" wavelengths. For this reason, troublesome extraneous images are not produced during reconstitution of three-dimensional multicolor holograms [44, 45]. Thick-layer multicolor holograms can be reproduced in white light. Such holograms also play the role of an interference filter that passes only the desired wavelengths.

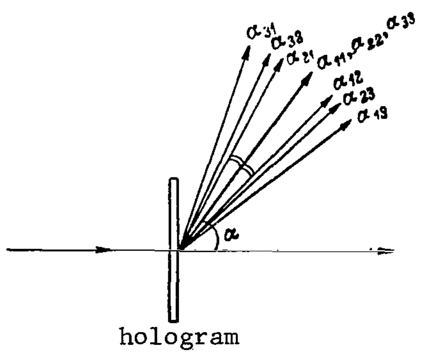

Figure 47. Calculation of a region free from superpositions in obtaining three-dimensional holograms.

One of the most serious problems that arise in this case is a shift of the wavelength in the reconstitution due to the shrinkage of the emulsion. The "bluing" of the reconstituted image is quite significant, since the shrinkage amounts to 15-20%. The best way to deal with shrinkage is to bathe a developed and fixed hologram in a solution of tri-ethanolamine. The concentration of the solution and the duration of the bath are chosen experimentally. It must be noted that the color of a reconstituted image may differ from the color of the object also /64
because of the fact that the diffraction efficiency of a hologram, defined in terms of the contrast of the recorded structure, falls off in the direction of the "blue" portion of the spectrum. This occurs for two reasons: first of all, the smaller the wavelength, the larger the spacing of the interference pattern [see Formula (18)]. Secondly, the shorter-wave radiation is scattered

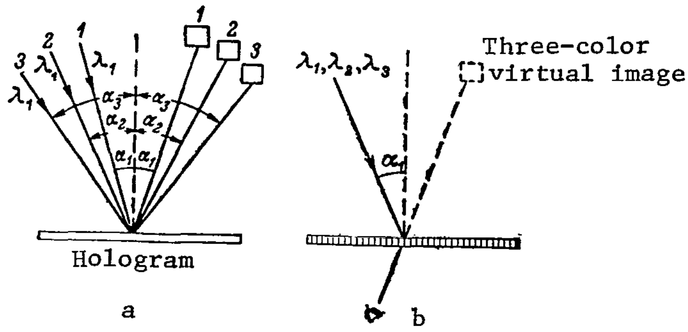

Figure 48. A scheme for obtaining (a) and reconstituting (b) "synthetic" multicolor holograms.

more in the emulsion, and the frequency-contrast characteristic of photographic materials becomes worse as the wavelength grows smaller.

Reference [45] describes an original method of obtaining multicolor thick-layer holograms with the aid of a single-color laser. The method consists in a three-fold exposure of the hologram at the same wavelength, but for different locations of the object and the reference beam (Figure 48). In such a hologram three systems of parallel reflecting surfaces are formed, and in the reconstitution stage, using white light, the hologram will produce a three-color image with the wavelengths satisfying the relation

$$\sin\alpha_1 : \sin\alpha_2 : \sin\alpha_3 = \frac{1}{\lambda_1} : \frac{1}{\lambda_2} : \frac{1}{\lambda_3}. \qquad (33)$$

§6. RECONSTITUTION OF THE WAVEFRONT

Requirement on the Time Coherence of a Source

In the reconstitution of a wavefront, the requirements on both the space and the time coherence of radiation are less strict than in the formation stage. Therefore, in the reconstitution of a wavefront one often uses ordinary (non-laser) light sources. The requirements on the time coherence of such a source result from the restriction that the images of the object obtained during diffraction of light of various wavelengths should not be noticeably displaced relative to one another on the hologram. In other words, the angle $d\alpha$ (the angular shift of image points obtained with wavelengths differing by $d\lambda$) must be less than the realizable angular resolution $\delta\phi$ (Figure 49), i.e.,

$$d\alpha \leqslant \delta\varphi \quad \text{or} \quad \frac{d\alpha}{d\lambda} d\lambda \leqslant \delta\varphi.$$

Here $\frac{d\alpha}{d\lambda}$ is the angular dispersion of the grating, equal as implied by Equation (8) to

$$\frac{d\alpha}{d\lambda} = \frac{1}{a\cos\alpha}. \tag{34}$$

We finally have /66

$$d\lambda \leqslant a\cos\alpha\,\delta\varphi. \tag{35}$$

If a visual reconstitution of the wavefront occurs, then $\delta\varphi \geqslant 2\cdot 10^{-4}$ radians, which corresponds approximately to the resolving power (sharpness of vision) of the normal human eye. This gives for $a=10^{-4}$ cm and $\cos\alpha \approx 0.7$ $d\lambda \leqslant 1.4$ Å. Thus, to visually reconstruct a wavefront, it is sufficient to use a low-pressure mercury lamp with a filter passing, for example, a green line. If it is necessary to achieve the diffraction limit of resolution, which is given by a hologram, then in accordance with Formula (17) $\delta\varphi = \frac{\lambda}{l}$, and we have $\frac{d\lambda}{\lambda} \leqslant \frac{a\cos\alpha}{L} = \frac{1}{N}$. Here N is the full number of lines in a hologram. The obtained result is regular: the line width must be less than the limit of the spectral resolution of a diffraction grating having the same number of lines as the hologram [see Formula (15)]. However, there are schemes for the achromatization of wavefront reconstitution in which the requirements on the width of the spectral line of a source may be significantly reduced[8].

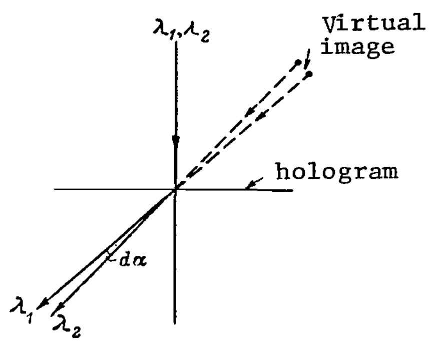

Figure 49. Calculation of the permissible nonmonochromaticity of the reconstituting light source.

One of the possible schemes of achromatization of a hologram [46] is given in Figure 50. /67

A diffraction grating decomposes the incident radiation into a spectrum, thus producing in the plane of the diaphragm a set of reconstituting sources of various wavelengths. By properly selecting a grating and the geometry of the setup, one can achieve a situation in which the images of an object reconstituted by each of these sources of various wavelengths coincide or at least differ very little (Figure 51). Thus, one can obtain different results by using reconstituting sources having a very wide spectrum, for example, bright superhigh pressure mercury lamps ($\Delta\lambda \approx 50$ Å), sometimes even using the light of incandescent lamps.

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(8) We do not consider here the cases when an object lies very close to the hologram or is focused on its surface (focused holograms). In those cases, the reconstituted virtual image of the object is also close to the hologram, and, as can be seen in Figures 49 and 52, to reconstitute a wavefront, it is not necessary to have either a monochromatic or a point light source.

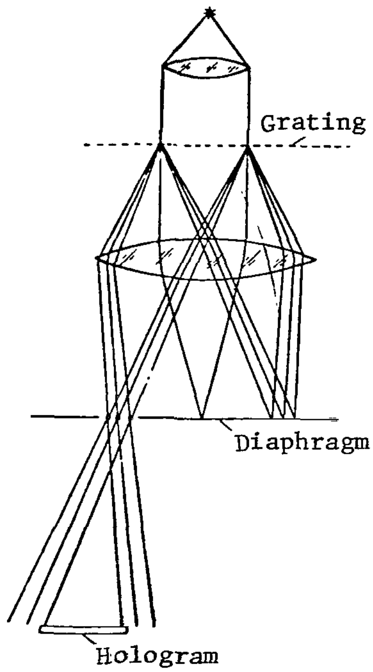

Figure 50. Scheme for the achromatization of the wavefront reconstitution

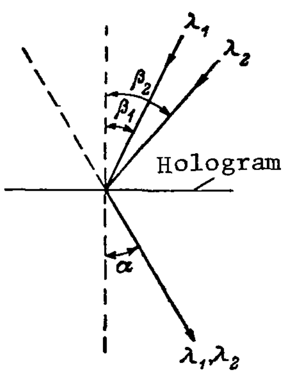

Figure 51. Explanation of the achromatizing action of the scheme in Figure 50.

Requirements on the Space Coherence

Requirements on the space coherence of a light source used to reconstitute a wavefront reduce to the restriction that its angular size be sufficiently small to reconstruct the structure of the reconstituted image. Let us consider these requirements as schematically and loosely as the requirements on the width of the line of the reconstituting source. Let us /68 assume that a hologram is obtained with an ideal point reference light source. 1 and 2 are extreme points of the reconstituting light source; $d\beta$ are its angular dimensions (Figure 52). Then $d\alpha$ is the angle between the corresponding diffracted rays, and it gives the angular size of each point of the reconstituted image. Considering the light source to be monochromatic, we have from (8)

$$|d\beta| = \frac{\cos\alpha}{\cos\beta} d\alpha. \qquad (36)$$

Considering that the multiplier $\frac{\cos\alpha}{\cos\beta}$ is on the order of unity, and normally ranges from 1/2 to 2, we finally find that the angular size of the reconstituted image must be on the order of

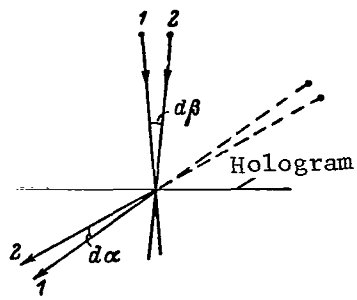

Figure 52. Determination of the permissible angular size of the reconstituting light source.

the required angular resolution of the hologram.

It is often possible to reconstruct an image, looking through a hologram and through a red glass at an electric lamp several meters away. Of course, a frosted lamp is in this case inconvenient; its angular size is slightly too large. Nevertheless, for high-quality reconstruction, one normally uses laser light, often emitted by the same laser as the one used in the formation stage.

Geometry of Reconstitution

In the preceding sections, we have considered geometrical relations that connect the longitudinal and lateral magnification of an object with the location of the hologram, object, reference and reconstituting light sources [Formulas (9) - (11)]. In constructing the setups for the reconstitution of the wavefront, one must use these relations. Let us consider certain particular cases.

a) Suppose that a hologram is not magnified ($m = 1$), and the reconstitution is achieved using the same wavelength as in the formation stage ($\mu = 1$). If in this case $Z_R = Z_C$, i.e., a reconstitution is achieved using the light of an undisplaced reference light source, then Formulas (9) - (11) imply that for a virtual image (plus sign) we have $Z_B = Z_0$, $M_{lat} = M_{long} = 1$.

Thus, in this case, a virtual image will be produced at the previous location of the object, and both its longitudinal and lateral scales remain the same as before. The real image [the minus sign in Formulas (9) - (11)] /69 is in this case produced asymmetrically relative to the virtual image $(Z_B \neq -Z_O)$. Its magnification is not equal to unity $(M_{lat} = 1/1 - 2\frac{Z_O}{Z_C})$, and the longitudinal scale is distorted $(M_{lat} \neq M_{long})$.

b) To obtain an undistorted real image of an object under the same assumptions $(m = \mu = 1)$, it is necessary that $Z_R = -Z_C$. In other words, a reconstituting source must be located on the other side of the hologram at the same distance from it as the distance of the reference source from the hologram[9].

c) Assume that the reference source is in the same plane as the object; in other words, let us consider the case of lensless Fourier transform holography to which $Z_O = Z_R$ corresponds. Formula (9) implies that $Z_B = Z_C$, i.e., both images are virtual and localized in the plane of the reference source. For the same case, (10) implies that

$$M_{lat} = \frac{\mu}{m} \cdot \frac{z_C}{z_O}. \quad (37)$$

If, in addition, the reference source is used in reconstituting images, and the scale of the hologram remains unchanged, m = 1, then

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

i.e., both images preserve their three-dimensional properties and will be free of aberrations.

d) If the holographing and the reconstitution were achieved with a plane light wave /70

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[9] Our coordinate system is rigidly attached to the hologram. Therefore, to obtain an undistorted real image, in the reconstitution stage, one can use a reference source in the previous place, and the hologram must be rotated by 180°.

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

then (9) implies that

$$z_B = \pm \frac{m^2}{\mu} z_O,$$

i.e., both the virtual and real images are located symmetrically relative to the hologram. In this case, as implied by (10) and (11),

$$M_{lat} = m, \quad M_{long} = \frac{m^2}{\mu}.$$

To preserve the three-dimensional properties of an image, it is necessary that the longitudinal and lateral magnifications be identical, and this is possible if m = μ, i.e., the hologram must be magnified as many times as the number of changes of the wavelength of the reconstituting reference source, as compared with the source whose light is used to produce the hologram.

The above examples make it possible to choose efficiently the location of the setup elements to reconstruct a wavefront. Certain cases are illustrated in Figures 53 - 55 that were reproduced from the survey by Ramberg [47].

As already indicated, in the reconstitution stage a lenseless Fourier transform hologram forms two mirror virtual images localized in the plane of the reference source (Figure 54). Such a hologram may be analyzed for overexposure using a device described in [48], which eliminates the light from the zero-order beam and from one of the images (Figure 56). The device consists of two glass prisms with an air layer between them. The refractive index of glass, and the geometry of the prisms, are selected in such a way that the light incident on the front face normally undergoes total inner reflection at the hypotenuse face (for glass K-8 $n \approx 1.51$, $\alpha > 41°30'$), and the light coming from one of the virtual images passes through the air gap without hindrance.

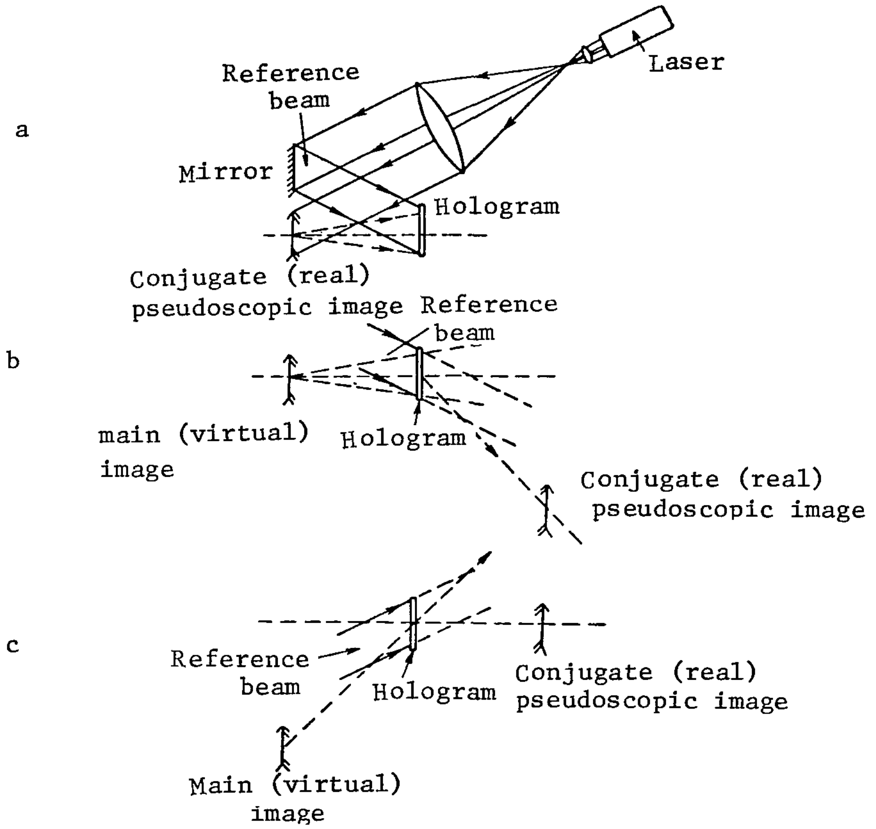


Figure 53. A hologram with a parallel reference beam.

a - formation of the hologram; b - reconstitution of a virtual image free from aberrations; c - reconstitution of a real image free from aberrations.

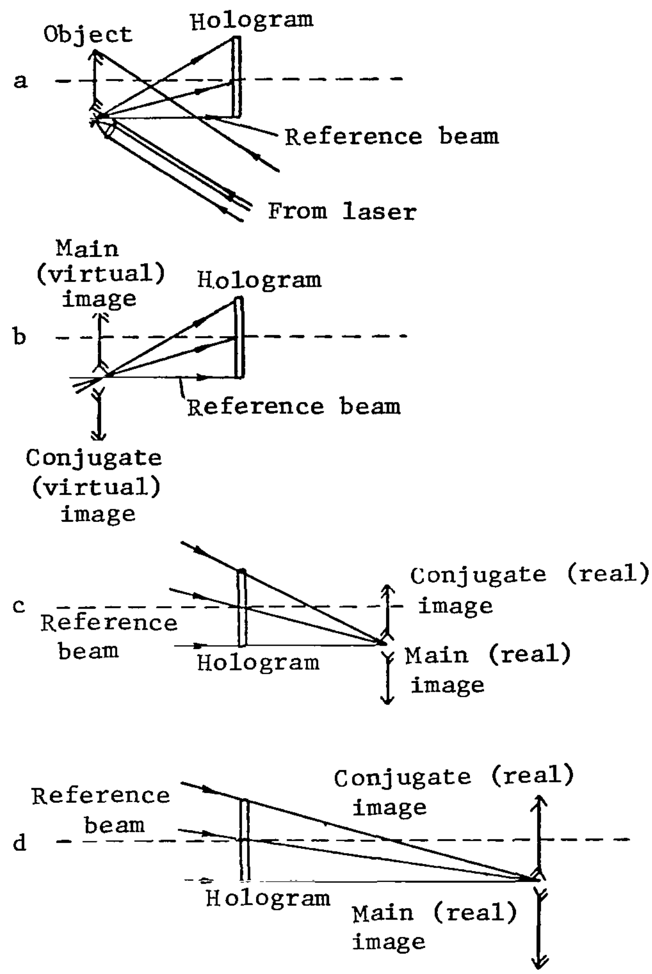


Figure 54. Lensless Fourier transform hologram.

a - recording; b - reconstruction of a virtual image free from aberrations; c - reconstruction of a real image free from aberrations; d - reconstruction of a magnified real image.

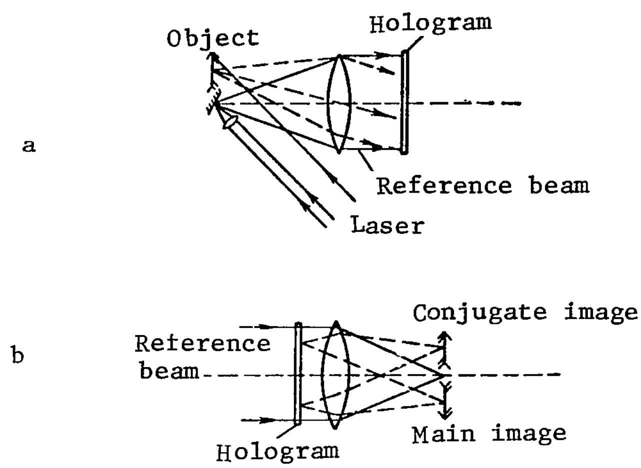


Figure 55. Fraunhoffer hologram

a - recording; b - reconstruction of an image.

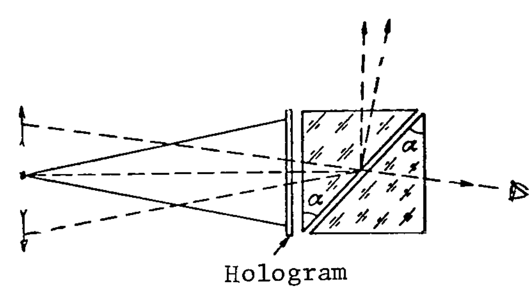


Figure 56. Device eliminating the zero-order beam and one of the virtual images.

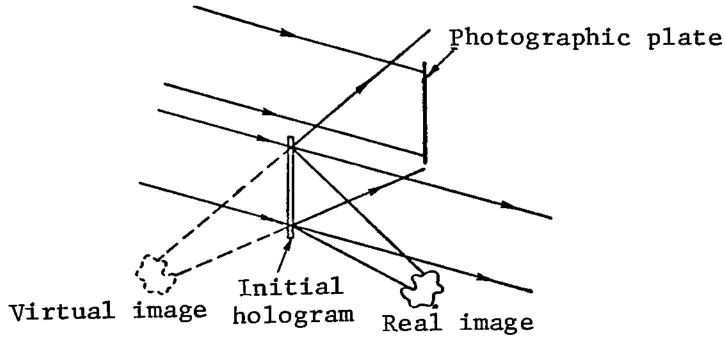


Figure 57. Scheme for contact-free copying of holograms.

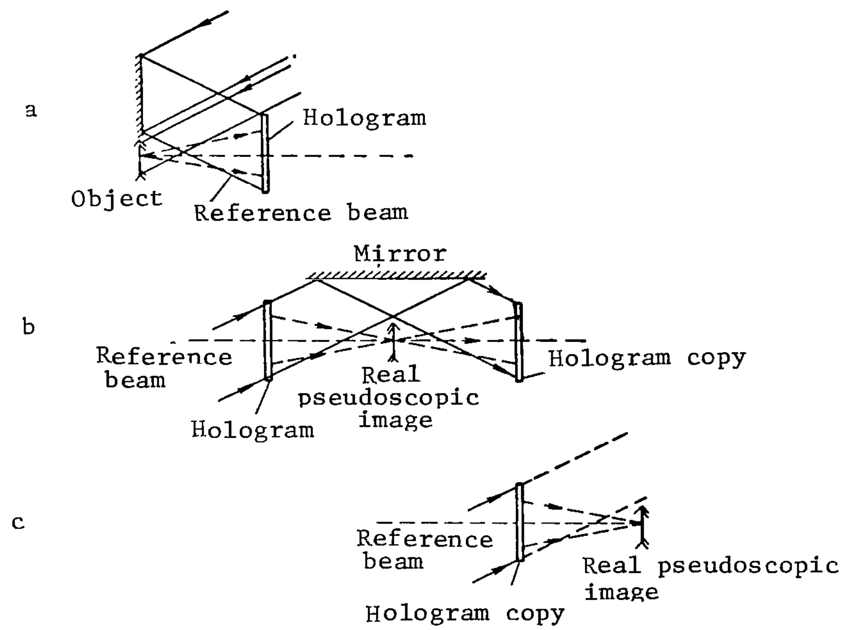


Figure 58. Reconstitution of real pseudoscopic images.

a - recording of first hologram; b - recording of second hologram; c - reconstitution of the pseudoscopic real image.

Copying of Holograms /74

The first papers on obtaining copies of holograms made use of contact printing. Considering that the structure of a holographic pattern may have the spatial frequency of more than 1000 lines/mm, it is easy to understand that even a micron-size gap between the original and a photographic plate is inadmissible. However, it has been found that, if in contact copying one uses laser light, then there is no necessity to eliminate the gap between the copy and the original completely [49].

In fact, by illuminating a hologram with a reference light beam, we shall obtain an exact copy of the wave scattered by the object. Interfering with the zero-order beam, which is an exact copy of the reference beam, the wave produces an image of standing light waves right behind the hologram, which is identical with the image recorded on the hologram. It is this structure that will be recorded on the hologram copy. If the latter is illuminated with a reference beam, we shall see both the real and the virtual images, similar to those given by the initial hologram. In obtaining such a holographic copy, one simultaneously records the interference structure which is produced by the reference beam and the light beam going toward the real image. This structure will also give in the reconstitution stage both the real and the /75
virtual image.

Thus, a hologram copy will be a double hologram. It reconstitutes two virtual and two real images. If, in copying, the original and the photographic plate are close to each other, then both virtual images will coincide. Otherwise, their doubling will be observed [50]. Schemes of other versions of noncontact copying of holograms are given in Figures 57 and 58.

§7. ON WHAT ARE HOLOGRAMS RECORDED?

Frequency-Contrast Characteristic

Holography imposed a whole series of special requirements on photographic emulsions that now will be considered here. /76

First of all, there are requirements on the resolving power. The highest spatial frequency of a hologram structure may be determined from Formula (21). It is necessary that the photolayer resolve fringes of this frequency very well. As already noted (p. 26, Figure 14), the photographic emulsion is a nonlinear receiver, and thus the distribution of the transmission coefficient over a hologram differs from the illumination distribution on the photographic plate. However, in addition to these nonlinear distortions, there are distortions of another type related to the structure of the photolayer. Photographic emulsions consist of fine grains of silver halide suspended in a transparent gelatine mass. Therefore, a developed image is discrete, and consists of individual black dots. If details of an image are comparable in magnitude with the dimensions of these points, they become unintelligible. In addition, during the exposure of the emulsion, the light is scattered by silver halide grains. This also leads to a reduction of the image contrast. For the reasons enumerated above, the photographic layers do not reproduce the structure of an image as well, if its spatial frequency is higher. The frequency-contrast characteristic is used to determine these properties of photolayers.

The frequency-contrast characteristic $T(\nu)$ of a photographic material will be defined as a function describing the transformation by the emulsion layer of the contrast of the sinusoidal distribution of the exposure superimposed on the photographic material, into the contrast of the photographic image

$$T(\nu) = \left[\frac{T_{max} - T_{min}}{T_{max} + T_{min}}\right] \text{image} \left[\frac{H_{max} - H_{min}}{H_{max} - H_{min}}\right] \text{object} \quad (38)$$

In scientific photography the frequency-contrast characteristic is defined in a somewhat different way: from the measured transmissivities T_{max} /77
and T_{min} with the help of the characteristic curve (see Figure 14) one passes to "real" exposures H_{max} and H_{min}:

$$T_{\phi}(\nu) = \left[\frac{H_{max} - H_{min}}{H_{max} + H_{min}}\right] \text{image} \left[\frac{H_{max} - H_{min}}{H_{max} + H_{min}}\right] \text{object} \quad (39)$$

If the emulsion were a linear receiver, then both definitions would be identical. The definition (39) is more convenient in those cases when the photographic layer is part of an optical system each element of which has its frequency-contrast characteristic. Then to find the complete function of *contrast transmission, it is enough to multiply the corresponding character*istics of all elements together, including the quantity $T_{\Phi}(\nu)$ as well.

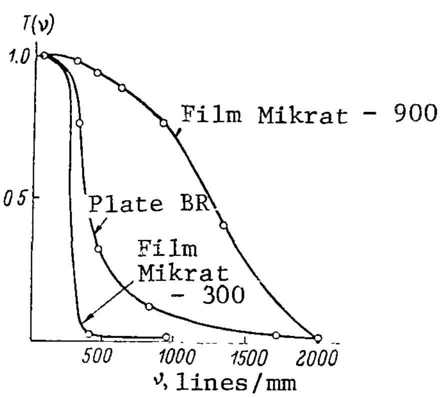


Figure 59. Frequency-contrast characteristics of certain Soviet photographic materials.

In holography it is more convenient to use the frequency-contrast characteristics, defined by Formula (38), since the brightness of the reconstituted holograms of images depends on this quantity.

The form of the frequency-contrast characteristics of certain photolayers, used in holography [51], is shown in Figure 59. It must be noted that the frequency-contrast characteristics may change from specimen to specimen within a fairly wide range. An inspection of these curves shows how relative is the widely accepted notion of the resolving ability of a photographic layer. The notion usually denotes the limiting spatial frequency for which it is possible to resolve the structure of an image. Visually one can resolve a structure if the contrast is about 1% or even less. The photolayer VR and Mikrat-900 have close resolving abilities, but as we can see in Figure 59, Mikrat-900 provides much better contrast than VR beginning with spacing of 200-300 lines/mm. Therefore, in /78 order to estimate the usefulness of any photographic material in holography, it is desirable to determine its frequency-contrast characteristic. As a rule, the limiting spatial frequency of a hologram is chosen so that the frequency-contrast characteristic will not drop below 5-10%, although certain authors recommend working in a region of higher contrasts (exceeding 30-50%).

Particularly high requirements are made on the frequency-contrast characteristics when it is desired to obtain thick-layer (three-dimensional) holograms. In the case of oppositely directed beams the distance between the neighboring beams is on the order of $\lambda/2$, i.e., a resolution of about 5000 lines/mm is required for high contrast (helium-neon laser λ 6238 Å)[(10)]. Such a resolving ability is possessed by photographic layers of the type KODAK 649F or any Lippman photographic layers.

High-quality two-dimensional holograms may also be obtained on photographic materials of much smaller resolving ability. It is only necessary to match the spatial frequency of a hologram with the capacities of a photographic layer. It is natural that the lower the resolving ability of a photographic material, the greater is the area required for a high-quality recording of a wavefront in the same solid angle (see Figure 17). In this

[(10)] Considering the fact that the refractive index of photographic gelatin is about 1.5.

connection one should keep in mind the successful attempts at obtaining holograms on low-resolution,but highly-sensitive photographic layers (P/N Polaroid [52] and Tri X-Panfilm [53]).

In [52] a holograph was made of a transparency using a scatterer. The maximum spatial frequency on the hologram was no greater than 120 lines/mm, and the exposure amounted to 1/25 sec (helium-neon laser, 10 milliwatt, a film of sensitivity about 45 GOST units). Of similarly high-quality was a reconstitution of a wavefront achieved in [53] with a more sensitive film (about 400 units according to GOST). The power of the laser was only 0.25 milliwatt,but the recording was done without a scatterer (see the scheme in Figure 20). Therefore, to make the exposure longer than 1/400 sec (shorter exposures were not possible with the shutter used in [53]), the beam had to be weakened by a factor of 1000. The maximum spatial frequency of fringes /79
was 70 lines/mm. The frequency-contrast characteristic for the film used falls off for this frequency to 35%. Table 1 gives the characteristics of /80
various holographic emulsions, and Table 2 gives the formulas for the developing solutions.

Resolvometry of Holographic Photolayers

To determine the frequency-contrast characteristics and the resolving ability of a layer, we produce in it a sinusoidal distribution of illumination with different spatial frequencies. Then the images thus obtained, called resolvograms, are studied, and as a result, one determines the contrast corresponding to a minimum contrast which may be obtained at the noise level, i.e., the resolving ability.

In projection resolvometers, on the photolayer under investigation one projects the image of a test slide which is a specially prepared black-and-white grating. The projection method is convenient for frequencies less than 600-1000 lines/mm. The problem is that the frequency-contrast characteristic of the lens which projects the test slide decreases practically to zero for

TABLE 1. CHARACTERISTICS OF CERTAIN HOLOGRAPHIC EMULSIONS

Photographic material	Object, Å	Object, lines/mm	Object, degrees	Sensitivity, erg/cm^2 (D = 0.5)
Kodak 649F	7000	5000	180	300 (λ 6328)
Mikrat 700	6400	2800	125	50—100 (λ 6328)
Plates VR	6400	2000	70—80	50—100 (λ 6328)
Film SO-243	7500	500	19	2 (λ 6328)
Film Mikrat-300	6400	300	11	—
Film Panchrom-18	7300	250	9	0.3 (λ 6328)
Diapositive plates Panchrom	7000	100	3.5	—
Films of the firm "Agfa Gevert" Sayntia				
14 C 70	7000	1500	56	3 (λ 6328)
14 C 75	7500	1500	62	3 (λ 6942)
10 E 56	5600	2800	84	50 (λ 4800)
10 E 70	7000	2800	125	50 (λ 6328)
10 E 75	7500	2800	150	50 (λ 6943)
8 E 56	5600	3000	180	200 (λ 4800)
8 E 70	7000	3000	180	200 (λ 6328)
8 E 75	7500	3000	180	200 (λ 6943)
Agfa Agepan FF Plan-Film	7000	500	19	—

these frequencies, and the lens as a rule cannot produce an image with a high spatial frequency.

Another difficulty involved in projection resolvometry is that the lines of the test slide do not give sinusoidal but, instead, stepwise intensities. However, this is easy to overcome. There are methods of converting the contrast

TABLE 2. COMPOSITION OF DEVELOPERS FOR PHOTOGRAPHIC MATERIALS USED IN HOLOGRAPH [59]

	Mikrat-900 VR (developer UP-2)	Kodak 649F (developer D-19)	Sayntia (developer Metinol-I)
Hydroquinone, g	6	8	6
Metol,* g	5	2	1.5
Dehydrated sulfite, g	40	90	25
Dehydrated soda, g	31	52.5	7.75
Potassium bromide, g	4	5	4
Water, l up to	up to 1	up to 1	up to 1

of an image of a "rectangular" test slide to a sinusoidal one [54]. These methods reduce to introducing correcting coefficients with values close to unity into the measured contrast.

Laser interference resolvometry [55, 56] offers much greater possibilities. The limiting spatial frequency of the interference method is 5000 lines/mm, and the fringes exhibit a sinusoidal intensity distribution. To obtain interference fringes, two coherent light beams are directed onto the photolayer at different angles. The spatial fringe frequency is determined from Formula (18). Special optical schemes have also been constructed for laser resolvometry [57, 58].

Using the scheme in Figure 60a [57], the workers at the A. F. Ioffe Physico-Technical Institute of the Academy of Sciences of the USSR have developed and built a laser interference resolvometer whose general form is shown in Figure 60b. /81

*Translator's Note: This is the trade mark for a photographic developer, N-methyl-p-aminophenol sulfate.

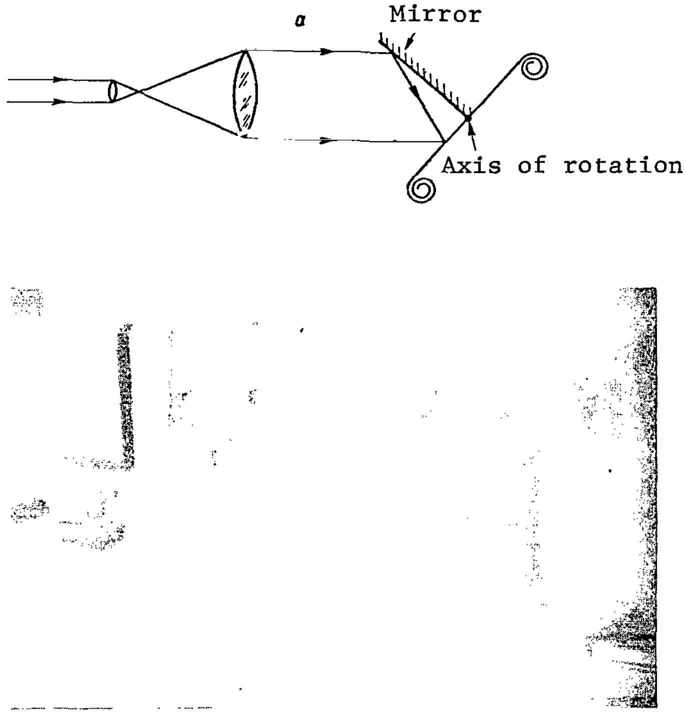


Figure 60. A laser interference resolvometer of the A. F. Ioffe Physico-Technical Institute of the Academy of Sciences of the USSR.

A characteristic feature of the scheme in Figure 60a is the simplicity of the variation of spatial frequency. This is done by rotating the mirror-photolayer system about the axis of the dihedral angle formed by the system. The design of the instrument was developed in two versions: for resolvometric testing of a 35 mm movie film and for testing photographic plates. The resolvometer is used as an adjunct to the LG-36 laser. When testing the Mikrat-900 films, the exposure was about 1/500 sec (with a preliminary weak- /82
ening of the laser beam by a filter by a factor of 3-5). A less sensitive photographic material Kodak 649F is tested with the same exposure but without a preliminary weakening of the beam.

In [56] it was shown that a resolvogram may be considered as a diffraction grating, and the contrast of its structure may be judged from the brightness of diffraction fringes. By illuminating such a grating with a laser beam, and measuring the ratio of intensities of the first and zero-order fringes for various spatial frequencies, one can construct a frequency-contrast characteristic of a photographic emulsion layer. This method was used to obtain the frequency-contrast characteristics shown in Figure 59 [51].

A rough investigation of a resolvogram can be achieved by looking at a bright electric lamp through fields with various spatial densities. A presence of diffraction fringes indicates that a given density is resolved by the emulsion, and the brightness of the fringes is a measure of the contrast of the interference structure.

Sensitivity of Photographic Layers

In holography the photosensitivity of a photographic layer is of great importance. It is precisely this quantity that defines the exposure necessary to obtain a hologram. Unfortunately, our conventional methods of testing photographic materials in the light of an incandescent lamp (GOST 2817-50) and the corresponding GOST units do not permit us to calculate the exposure which is necessary in each case. The sensitivity of holographic photographic materials which are exposed only in monochromatic light should be defined using energy units (Joule/cm^2 or ergs/cm^2).

These units are used in Table 1 to indicate the sensitivity of some photographic layers [59, 60]. One must keep in mind that the greater the number of ergs per 1 cm^2, the less sensitive the emulsion is. The number of ergs per cm^2 given in Table 1 specifies the exposure necessary to obtain the optical density D = 0.5. One can recommend that for each new photographic emulsion a number of test exposures should be made and accompanied by a photo- /83
electric measurement of the illumination in the plane of the hologram.

For orientation we can say that Kodak 649F plates need to be exposed for about one minute when holographing a three-dimensional object about 1 dcm^2 in area, using a 20 milliwatt helium-neon laser (LG-36). The VR plates and Mikrat-900 films have a sensitivity which is several times greater, and thus need correspondingly shorter exposures. The film Panchrom-18 has a sensitivity which is approximately two orders greater than the sensitivity of Mikrat-900.

It must be kept in mind that not only the sensitivity of the emulsion, but also its resolving power are dependent on the wavelength. The resolution usually falls off rapidly toward the "blue" region due to the scattering of light in the emulsion. The variation of the spectral sensitivity depends on the type of the sensitizing process.

Phase and Reflection Holograms

Thus far we have described the action of a photographic plate as a medium whose response to exposure is a change in the transparency, and holograms were considered as amplitude diffraction gratings.

One can also make a phase hologram [7, 61] which is a grating in which the phase of a light wave is spatially modulated. A purely phase sinusoidal grating does not absorb light. In addition, this type of grating does not produce a zero-order fringe. Therefore, the brightness of the images reconstituted by a phase hologram is considerably higher than that of an amplitude hologram.

Phase holograms are usually obtained by bleaching a developed plate. In this process the plate becomes transparent, and only a relief of its surface and variations in the refractive index carry the information contained in them. In order to bleach a plate, after it is developed and fixed, we immerse it in a solution of calcium bichromate or potassium ferricyanide.

A better formula (for Kodak 649F plates) is given in [62]. This bleaching solution is composed of ten parts of solution A, one part of solution B, and 100 parts of water.

/84

Solution A		Solution B	
Water	— 500 ml	Sodium chloride	— 45 g
Ammonium bichromate	— 20 g	Water	— up to 1 liter
Concentrated sulfuric acid	— 14 ml		
Water	— up to 1 liter		

To produce a hologram with a higher relief, the exposure must be increased several times as compared with the exposure necessary for producing an amplitude hologram.

Reflection holograms [63] (Figure 61) are a different form of phase holograms. They were first proposed in [7]. Reflection holograms are obtained by depositing a thin metal layer on the surface of an ordinary phase or amplitude hologram possessing a noticeable relief. Such a hologram is equivalent to a reflection diffraction grating, and also gives very bright reconstituted images.

In [64] it was possible to obtain profiled phase holograms that are capable of great efficiency (Figure 62). Such a hologram reflects in one of the first few orders more than 70% of the incident light with the spatial density of about 1000 lines/mm. However, this result was obtained on a special photographic thermoplastic, and not on an ordinary silver halide photolayer.

Other Media for Recording Holograms

A silver halide photographic emulsion is at the present time the most widely used photosensitive medium for obtaining holograms. This is due to the high sensitivity of the emulsion, the possibility of sensitizing them

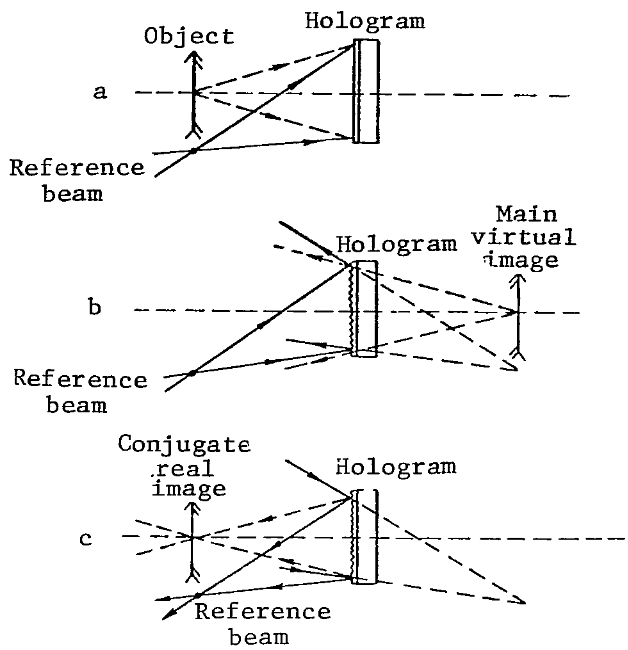


Figure 61. A reflection hologram

a - recording; b - reconstitution of a mirror virtual image free of aberrations; c - reconstitution of a mirror pseudoscopic real image, free of aberrations.

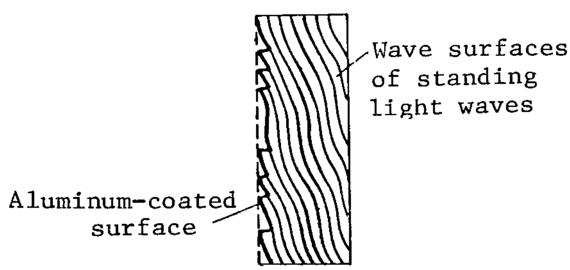


Figure 62. A profile of a phase hologram obtained on a photoconductor [64].

to the wavelengths of the most widely used and perfected lasers, longevity, and the strength of the holograms obtained, as well as comparatively low prices. At the same time, though, a photographic emulsion possesses a number of disadvantages the main of which are: 1) Between the end of exposure and the reconstitution of the image there are at least several minutes which is the time necessary for the chemical treatment of the emulsion; 2) a photographic emulsion does not permit multiple use.

Both of these shortcomings mean that as a rule the photographic methods /86 of recording holograms do not permit one to follow the dynamics of the process in "real time".

However, the photographic emulsion is not the only possible photosensitive medium for the recording of holograms. At the present time there have already been developed and applied a number of other photosensitive media and processes which are useful in holography. In the first place, we must mention reversible photochromatic materials. They are of two types — glasses with admixtures of silver halides [65] and plastic or liquid films with organic color agents, mostly spiropyrans, added [66].

Photochromatic glasses with an admixture of silver chloride and bromide are sensitive to blue and ultraviolet radiation. An admixture of silver iodide extends the sensitivity region to include the green portion of the spectrum (λ 5500 A). An irradiation of colored glass with yellow-red light accelerates their exposure. Glass can be used many times without any change of its photochromatic properties. The resolving ability of photochromatic glass is determined by its structure. Silver halide crystals are about 100 Å in size and are spaced about 1000 Å from one another. Photochromatic glasses were already tested for hologram recording abilities. In [67] an argon laser was used (power of several watts, λ 4880 Å) to obtain holograms of a target with a scatterer. The image was developed for approximately two minutes. The exposure of more than five minutes did not increase the brightness of the reconstituted image any more, since there was an equilibrium between the number of the reappearing and disappearing centers of absorption. However, one can assume that such an inertia of darkening is due to the low power of irradiation, and not to the large time constant of the glass itself. In [65] the darkening of photochromatic glass was observed during an interval on the order of 10^{-3} sec, the glass being illuminated with an impulse flash lamp.

The author of [67] has used photochromatic silver iodide glass 6.35 mm in thickness. The quality of the reconstituted image was very good, but the effectiveness of the hologram (brightness of the reconstituted image) was very small. The data given in this paper indicate that the sensitivity of photochromatic glass is by 4-5 orders of magnitude smaller than the sensitivity of high-resolution photographic plates. /87

In [68] photochromatic glass was subjected to a preliminary ultraviolet illumination, and the holograms were produced with a red helium-neon laser, whose radiation has bleaching properties. Such a process is less convenient since it allows only a single recording. To obtain each new image,it is necessary to subject the glass to a preliminary irradiation. However, in this process one makes use of the presently more widespread long-wave lasers.

However, the scheme involving decoloration makes it possible to follow the dynamics of the process if one alternates in a regular sequence (for example, with the help of shutters) an incoherent ultraviolet illumination of a hologram, an exposure of the hologram by the object and reference beams, /88
and a reconstitution of the wavefront with only one reference beam.

Photochromatic organic materials have also found use in recording holograms [69] (Figure 63). The time constants of such materials are measured in microseconds, the resolution is on the molecular level, the spectral region of the sensitivity is usually about 0.3 - 0.5 microns.

Using the light of powerful impluse lasers, holograms can also be obtained on thin layers of materials used for passive Q — switching of

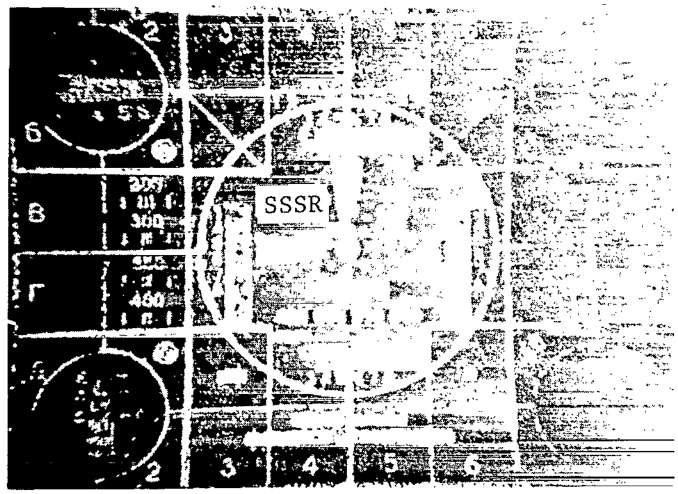


Figure 63. Image of a test TV pattern reconstituted with the help of a hologram recorded on photochromatic organic film.

laser cavities. For example, in [70] holograms were obtained on a layer of cryptocyanine, deposited on a mica substrate (Ruby laser, illumination $5 \cdot 10^7$ watt/cm^2).

To obtain holograms one can also use thermoplastic and photothermoplastic layers. In such layers one takes advantage of the property of certain polymers to deform under heating when an electropotential relief is produced on their surface. Such a relief can be formed, for example, by the cathode ray in a television receiving tube.

Another possibility of obtaining a potential relief is to introduce a photoconducting coloring agent into the thermoplastic or a deposition of a photoconducting layer on it. Holograms on a photothermoplastic were obtained in [71]. Its authors note the high sensitivity of the receiving layer (approximately one order of magnitude higher than in Kodak 649F photographic plates), the high resolution, and a practically complete absence of discrete structures. In contrast with photochromatic materials, only the phase holograms can be obtained on a photothermoplastic or thermoplastic (see p. 82).

Alkali-halide crystals [72] can also be used for recording holograms. When such crystals are irradiated with X-rays or ultraviolet radiation, centers of absorption are formed in them (so-called F centers). Long-wave radiation disturbs these centers and bleaches the crystal. The rate of bleaching increases with the temperature. Therefore, the recording of a three-dimensional interference pattern on crystals is done at an elevated temperature (about 80° C), and the reconstitution of the wavefront occurs at a low temperature on the order of 0° C when the bleaching rate is very small. The resolving ability of /89
such crystal media is on the molecular level: on a single crystal of small size one can record a great number of holograms. In order for them all to be reconstituted independently, it is necessary that, during the recording of each hologram, the reference beam be rotated by a small angle. During the reconstitution the crystal is rotated in the same way.

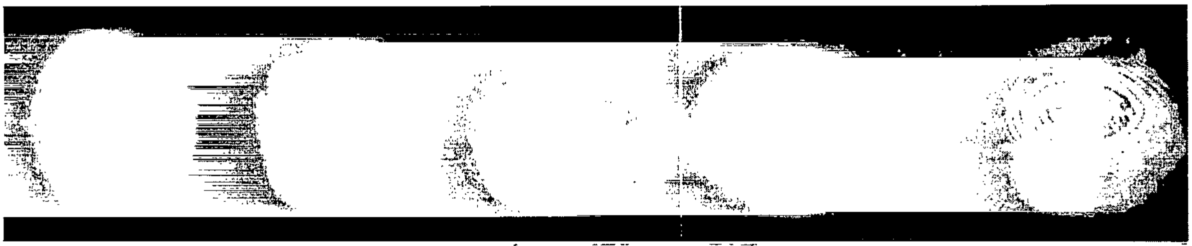
§8. CERTAIN APPLICATIONS OF HOLOGRAPHY

Holographic Motion Pictures and Television

The image observed during a reconstitution of a wavefront is striking in its true-to-life qualities. The parallax, bright flashes from the reflecting surfaces which move along the object with a change in the viewing location, stereoscopicity of the image, the possibility of obtaining multi-color images, all these make the prospect of holographic motion pictures and television very enticing. Present-day technology, however, is making only the very first steps in this direction.

Great but apparently surmountable difficulties stand in the way of holographic movies. The main problem is a creation of large-size holograms through which, as if through a window, the image could be viewed by a large number of people. These holograms must be "live", i.e., they must change in time in accordance with the changes occurring in the object. One of the possible versions is to record many images on a single hologram for different angles of the reference beam [4]. If during the reconstitution the hologram is rotated, the images will be reconstituted sequentially creating the effect of motion. The fundamental possibility of realizing such systems has already been experimentally demonstrated, but one cannot record more than one or two dozen of frames on a single two-dimensional hologram. Much greater possibilities are in this sense presented by three-dimensional media, for example, crystals. However, the dimensions of crystal holograms as yet are not too /90
large.

The future holographic motion pictures will, apparently, be dependent on the progress in a development of media for the recording of dynamic holograms. Such media must be highly sensitive and possess a high resolving power, have small inertia and allow multiple (billions of times!) recording and erasing of holograms. Having this type of recording medium available, one can copy holographic frames on it in sequence (see Figure 64) using for this purpose a powerful impulse laser.



40 120 200 nsec

Figure 64. Five-frame holographic movie film consisting of single-ray (Gabor) holograms of a laser spark.

To obtain holograms and movie holograms of live objects without damaging them irretrievably, the objects are illuminated by a diffusively scattered laser light [73]. Here the illumination of the retina can be lowered to safe levels.

The prospects of the scientific applications of holographic motion pictures are more favorable. At the A. F. Ioffe Physico-Technical Institute of the Academy of Sciences of the USSR an installation was set up for a supersonic movie-holography of plasma [74, 75]. One of the five-frame holographic films of a plasma produced by a laser spark obtained using this equipment is shown in Figure 64 [76]. The movie-holographic installation /91
does not contain any moving parts. Its action is based on using optical delay lines [77] (Figure 65). A light impulse from a ruby laser lasting for 20-30 nanoseconds traverses many times the 12-meter path between mirrors A and B and back, each time forming a hologram of the laser spark. The time interval between the holographic frames is thus about 40 nanoseconds. Of course, by moving the mirrors A and B closer to each other,

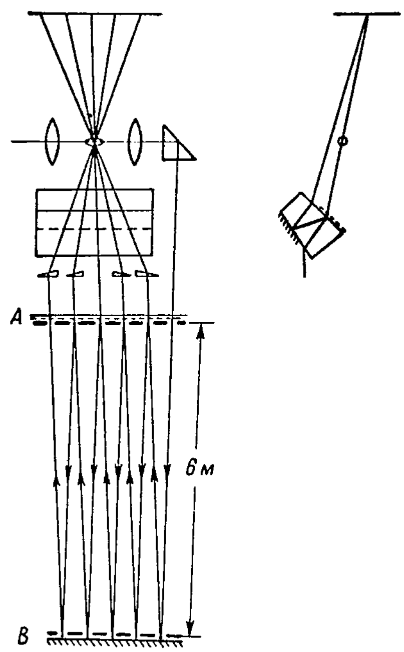


Figure 65. A scheme for obtaining double-ray holographic movies of fast processes with an optical delay line.

one can obtain movie holograms with a higher frequency of frames. Such a system may be used for high-speed recording of other high-speed processes, for example, the processes in which solid bodies are broken by a focused laser beam, exploding wires, etc.

Three-dimensional holographic television is also a problem which in the near future will be the order of the day. In addition to the obvious advantages connected with the three-dimensionality of an image, we must note here reliability, interference-free reception, coding of television messages, possibility of transmitting high-contrast images, etc.

Technology, however, also in this case faces a number of unsolved problems. To transmit a high-quality three-dimensional image one needs a television channel with approximately several thousand times greater trans- /92 mitting ability (the transmission bandwidth) than that used in present television broadcasting [78]. Progress in holographic television should, on one hand, be expected to happen through an increase of the transmission capacity of communications channels, and on the other — through a reduction of the amount of information necessary to construct a hologram.

Wide-band communications channels can, apparently, be set up using laser beams. To reduce the amount of information necessary to construct a hologram, various techniques are possible, both those developed for television and those that are purely holographic. For example, in [79] it is proposed to transmit over a television channel not the entire hologram, but instead its narrow horizontal band. At the output this band is multiplied, and thus a full hologram is created which consists of identical horizontal strips. Of course, during the reconstitution from such a hologram of the wavefront, the parallax will remain only in the horizontal plane. However, it is precisely this parallax which is most important in creating the feeling of depth of a scene since our eyes are in one horizontal plane and are not displaced along the vertical. The same method may be useful in holographic movies. A projection of a slit hologram may be achieved with its simultaneious movement at a constant speed [80].

If one also removes the horizontal parallax by composing a hologram of identical little squares, instead of strips, then it is possible to lower the amount of the information transmitted by approximately three orders of magnitude without an excessive deterioration of the image quality [81]. /93

In holographic television, similarly as it was with holographic movies, one has to solve the problem of recording the dynamic holograms that are formed in an inertia-free way and are at once ready for reconstitution. However, even today holographic television may be useful in solving certain scientific problems, e.g., that of a highly reliable and interference-free, although relatively slow, transmission of information with the possibility of its electric coding, filtration, input in computers, etc. The first attempts in this direction, as imperfect as they are, have already been made (see, for example, Figure 66 [82]).

Much better results have been obtained in transmitting holograms over an inter-city phototelegraphic channel [83] resolving approximately one order of magnitude more elements than a standard television channel. Using the holograms thus received, images have been reconstituted of line, halftone, and three-dimensional objects. As was to be expected, the fact that the holograms transmitted had only two gradations of brightness (black and white)

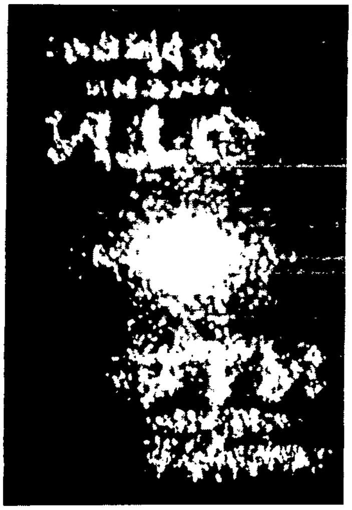


Figure 66. An image reproduced using a hologram transmitted over a television channel.

did not prevent a correct transmission of the tones of an object.

Three-Dimensional Photography

We all know the classic Perrin's experiments in which he determined the vertical distribution of tiny gummigutta balls executing Brownian movement in a liquid. In those experiments Perrin counted the number of moving balls that fell into the visual field of the microscope by focusing it in turn on the emulsion layers lying at different heights. It would be very easy to make such an experiment with the help of holography. During the reconstitution of the wavefront one can also study the emulsion layer by layer, counting the number of the already fixed particles in each layer.

This is approximately how a holographic dysdrometer functions. A dysdrometer is an instrument used in studying moving particles, rain or fog droplets, snow flakes, etc. A hologram is recorded with the help of an impulse laser during an interval on the order of 20 nanoseconds. The three-dimensional distribution of particles was viewed in the reconstitution stage using a helium-neon laser with a continuous emission. Similar equipment is used to record particle tracks in track chambers [84, 85]. The advantages of this method are obvious: the depth of sharply visible space is increased, and, consequently, the efficiency of the camera is enhanced. There is a possibility of separation, and filtration of tracks that have a geometry interesting to the researcher.

Holograms can span very large angles. Figure 67 shows schemes for recording holograms spanning a 360° angle. However, it is possible to obtain

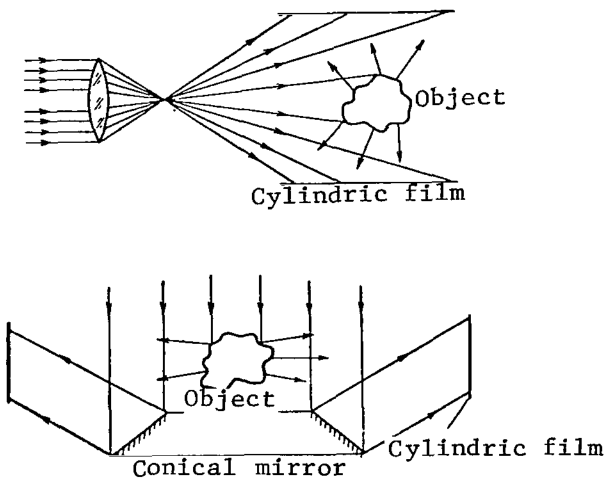


Figure 67. Schemes for recording 360°-angle holograms.

360°-angle holograms using the ordinary (not all-sided) lighting. For this purpose one must make many exposures, each time rotating the object by a small angle, and during each exposure illuminating a narrow vertical strip of the hologram [86].

Three-dimensional properties of the images reconstituted with the help of holograms can be used in advertising, lecture demonstrations, in the construction of artistic panoramas, etc. Finally, color holograms, reconstituted in white light without lasers will perhaps /95 in time replace ordinary photographs.

Phono- and Radiovision

Using holography one can successfully solve the problem of visualizing acoustic waves. The solution of this problem is of great practical importance. The possible applications of sound holography include flaw detection, the obtaining of three-dimensional images of the internal organs of a live organism, the investigation of the relief of the sea bottom, phonolocation (sonar), sound navigation, search for useful minerals, investigation of the internal structure of the Earth's core, etc. The recording of sound holograms is done in such a way that optical reconstitution is possible. For this purpose one can use the following methods.

1. Scanning of sound field. A signal from the sensor (microphone, piezoelement, etc.) modulates the light flux forming an optical hologram.

Various modifications of this scheme are possible. Figure 68 shows one version of the scheme in which a signal of the scanning sensor controls the brightness of an attached point lamp [87]. In other schemes a signal from the sensor is fed to a cathode ray tube. The beam sweeps synchronously with a displacement of the sensor, and the hologram is photographed from the tube screen [88]. The photography is usually done with a strong reduction in size, since the light wavelength is many times shorter than the sound wavelength.

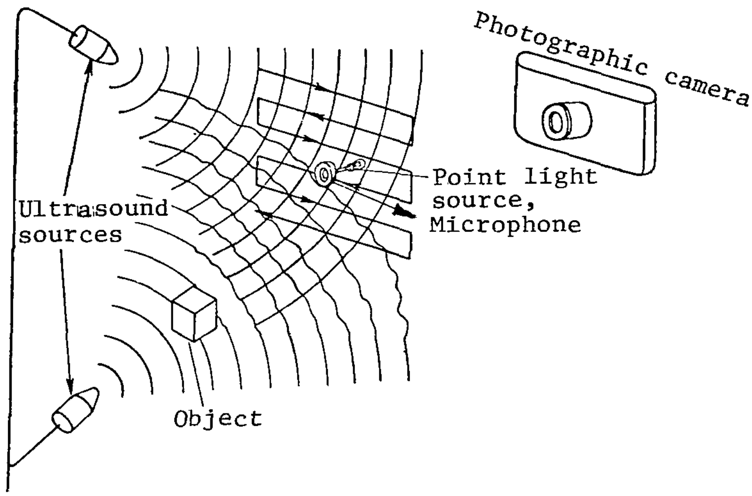


Figure 68. A scheme for obtaining sound holograms with a scanning receiver.

Both single-beam and double-beam versions of sound holography are possible. However, the role of the reference sound beam can be played by an electric signal from a sound generator, added to the sensor signal [88].

2. Photography. The ultrasound field may be recorded directly on a photographic plate using the fact that ultrasounds intensify the chemical reactions occurring when photolayers are developed or fixed. In [89] a photographic plate that was first uniformly illuminated but not developed was placed in a bath containing a weak hyposulfite solution. An ultrasonic field

was produced in it, and a rapid dissolution of silver halides was taking place at the maxima of the sound waves. After 20-30 seconds of sonic exposure the plate was developed in light. A sonic hologram thus obtained was reconstituted using a light beam. In the same way one can expose a photographic plate using ultrasounds in a weak developing solution. The plate should be previously illuminated. The development proceeds much faster at the maxima of the sound waves than at the minima.

3. The deformation of the surface of a liquid under the influence of sound pressure (Figure 69). This method has the advantage that it permits one to achieve an optical reconstitution of the reflection hologram simultaneously with its formation, and thus follow the process in real time [90]. Another version was described in [91]. The surface of a liquid was coated with a thermoplastic film which was deformed by an ultrasonic wave, then it was cooled, and used later as a phase optical hologram. In the recording of ultrasonic holograms, use was also made of a piezoceramic mosaic, its elements being read by a scanning electron beam. /97

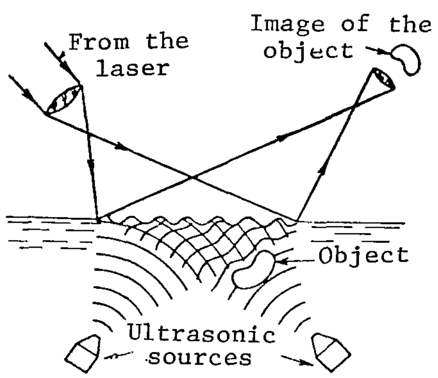


Figure 69. A scheme for obtaining ultrasonic holograms, making use of the surface relief of a liquid.

First successful attempts were made to obtain and optically reconstitute holograms in the centimeter and millimeter portions of the electromagnetic spectrum. These experiments are of great importance for radar. The present radar methods are as a rule incapable of recording the form and size of objects. They only indicate their presence or absence in the visual field of radar antennas. Radioholographic methods make it possible to observe both the form and dimensions of objects which is very important for their recognition. Other applications of microwave holography have also been proposed. They include the study of the surface of the Earth and planets from satellites, optical modeling, and the study of radio antennas.

Methods of recording microwave holograms are similar to methods of recording sonic holograms involving scanning. Thus, for example, in [92] a signal from the sensor was fed onto a screen of a television system whose sweep was synchronized with the movement of the sensor. A hologram was photographed from the screen; the image was reconstituted in laser light. In another paper [93] a scheme for recording a microwave hologram was similar to the scheme in Figure 68. The hologram was recorded on an area of 2 x 2 m (the wavelength was 3 cm). A crystal diode was scanned that controlled /98
the intensity of a point lamp moving along with it. The light from the lamp was projected on a photographic film. The hologram was reduced a 1000 times (down to the size 2 x 2 mm); the image was reconstituted by means of a helium-neon laser (λ 0.63 micron).

Holographic Interferometry(11)

If the hologram is placed in the place where it was exposed, and the object is removed, then as we already know, a light wave is reconstituted which is scattered by the object during the exposure. If the object is not removed, then one can observe two waves: one coming directly from the object and one reconsitituted by the hologram. These waves are coherent and can interfere. If any changes occur in the object, for example deformation, this will have an effect on the form of the image — it will be cut by interference fringes of equal path difference.

Thus, it is possible to make light waves interfere that exist at different times (see, for example, [30,95]). This was

(11) See also [94].

impossible until holography was invented. In an ordinary non-holographic interferometer the object under investigation must have a perfect optical surface in order to be able to produce a beam for comparison with a wavefront of the same form without any difficulty. For example, in the Twyman-Green interferometer (which is a modification of the well-known Michelson's interferometer) in one of the interfering beams one inserts the lens or prism under investigation, and in the other — a reference lens or prism. The interference pattern thus obtained is analyzed for any differences between the part under investigation and the reference part.

Holographic interferometry permits an investigation of objects of irregular form and even objects reflecting by diffusion. Any deviations from the regular surface of an object will not affect the interference pattern, since both interfering waves will be distorted by them to an equal extent, the reason being that the reference light wave is produced by the investi- /99 gated object itself. The interference pattern will be determined only by those geometric or phase changes that occurred in the object.

This method of holographic interferometry is very convenient,since it makes it possible with the help of a single hologram of an object, obtained in its initial (undisturbed) stage, to obtain interferograms of the object in its many states or to follow the dynamics of what happens to it in real time. This method, however, requires an exact repositioning of the hologram in the place at which it was during the exposure. Sometimes for the same purpose the photographic plate is treated in place, for which one needs a special device (see Figure 35).

A much simpler method involves double exposure: on a single photographic plate one records two holograms of an object, finding itself in two different stages. In this case it is only necessary to make sure that the photographic plate will not move during the time interval between the two exposures. This time interval can be made very small, for example in [95] a laser generated a double giant impulse consisting of two peaks spaced by several microseconds, and the holographic interferogram registered those phase changes which occurred in the object during that time.

It will be noted that the requirements on the quality of optical systems which are so strict in ordinary interferometry are usually not essential in holographic interferometry. Both interfering waves are equally distorted by the imperfections of optical parts. This permits interference studies of large objects without great losses on high-quality mirrors, windows, and light-dividing plates.

One of the more important applications of holographic interferometry is the study of the deformation of objects of irregular shape that scatter light diffusively [96, 97]. As already noted, ordinary interference methods are completely powerless. To obtain an interferogram of the type shown in Figure 70 [96, 97] the hologram must be exposed twice — before and after the deformation of the object took place. The holographic interferogram is /101
reconstituted using the usual methods, and to compute deformations from the observed interference fringes one can use methods described in [97].

Holographic interferometry can also be used to study the distribution of stresses in deformed transparent objects. Another of its applications involves the control of dimensions, form, and quality of the treatment of complex parts, for example turbine blades. For this purpose one makes a hologram of a reference part, and leaving it where it was exposed, one replaces the reference part with one which is to be tested. Of course, the interference fringes will also occur when the parts are absolutely identical, but the wavefronts are not exactly in the same position. Therefore, one must reproduce the positions of the tested parts relative to the remaining parts of the holographic system with the greatest possible accuracy.

The holographic method may also turn out to be useful in testing parts of regular form, often very large in size, for example, in testing large astronomical mirrors or objectives [98]. Here there is no necessity to have for comparison the same reference mirror. A spherical reference wave of ideal form can be produced by a point light source.

Holographic interferometry makes it possible to study the topography of objects having a complex form. In [99] two methods have been proposed for this purpose. The first method involves obtaining the interference pattern formed by adding the wave scattered by the object and the same wave rotated by a small angle. For this purpose a hologram is exposed twice, but during one of the exposures the reference light source is displaced. The second method involves an interference comparison between the wave scattered by the object and the same wave but of slightly different scale. To this end the authors of [99] propose to expose the hologram twice, with different wavelengths.

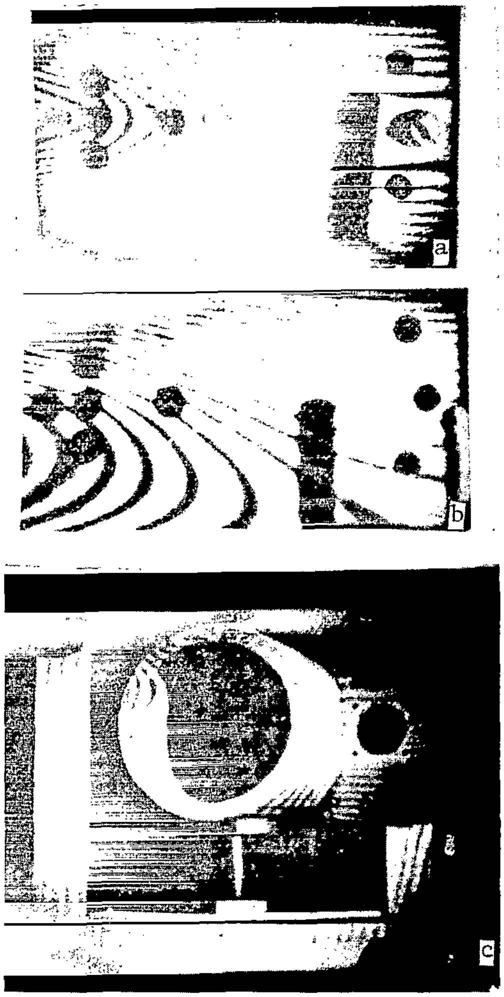


Figure 70. Holographic interferograms of deformed parts (a-c). a,b - the same part attached at different points [97].

To obtain the same result Reference [100] recommends during one of the exposures to change the refractive index of the medium which surrounds the body under investigation (for example, by changing the gas pressure or the composition of the immersion liquid).

Some of the very promising applications of holographic interferometry include the holographic study of vibrations first proposed by Powell and

Stetson [101]. When holograms are obtained according to their method, the vibrating object is exposed with a lag much greater than the period of oscillations. Here the interference structure on the hologram is produced because the object is held at extreme amplitude positions. The light waves scattered by the object in extreme positions, in the reconstitution stage interfere with each other, and as a result the image of an object turns out to be cut by interference fringes of equal amplitudes (Figure 71). From such interferograms one can obtain the spatial distribution of the amplitudes of vibrating objects of complex form. /102

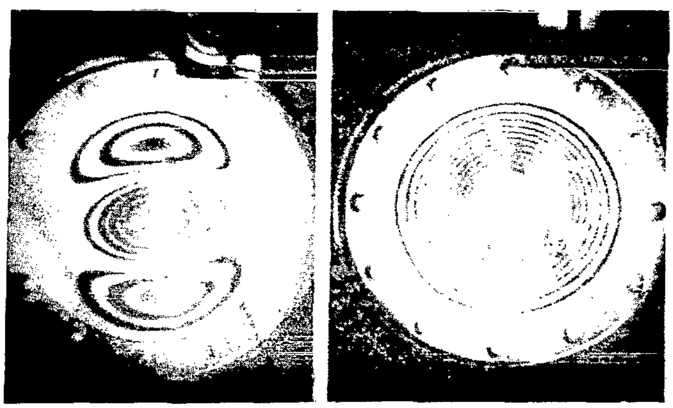


Figure 71. Holographic interferograms of vibrating membranes [101].

The method of Powell and Stetson has, however, the disadvantage that in addition to the useful exposure when the object is at its extreme positions, the hologram is also exposed during its motion. The fraction of this unwanted exposure, producing noise on the hologram, increases with the amplitude of oscillations, the visibility of the interference fringes drops accordingly, and therefore the method turns out to be inapplicable when the amplitude of oscillations exceeds 3-5 λ.

To eliminate the influence of this effect, [102-104] and others have proposed a strobe-holographic method of investigating vibrations. A hologram is exposed only at those times when the vibrating body is in either of its /103
extreme positions (Figure 72). This improved the visibility of the interference fringes, and thus the limiting amplitude of vibrations for which it is possible to apply the method became greater (Figure 73). The stroboscopic method permits an observation of interference fringes of various amplitudes in real time [102, 103]. A hologram of a stationay object is developed in

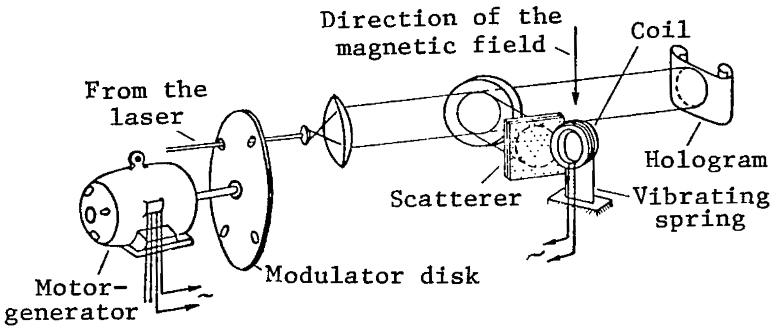


Figure 72. A scheme of the strobe-holographic investigation of vibrations.

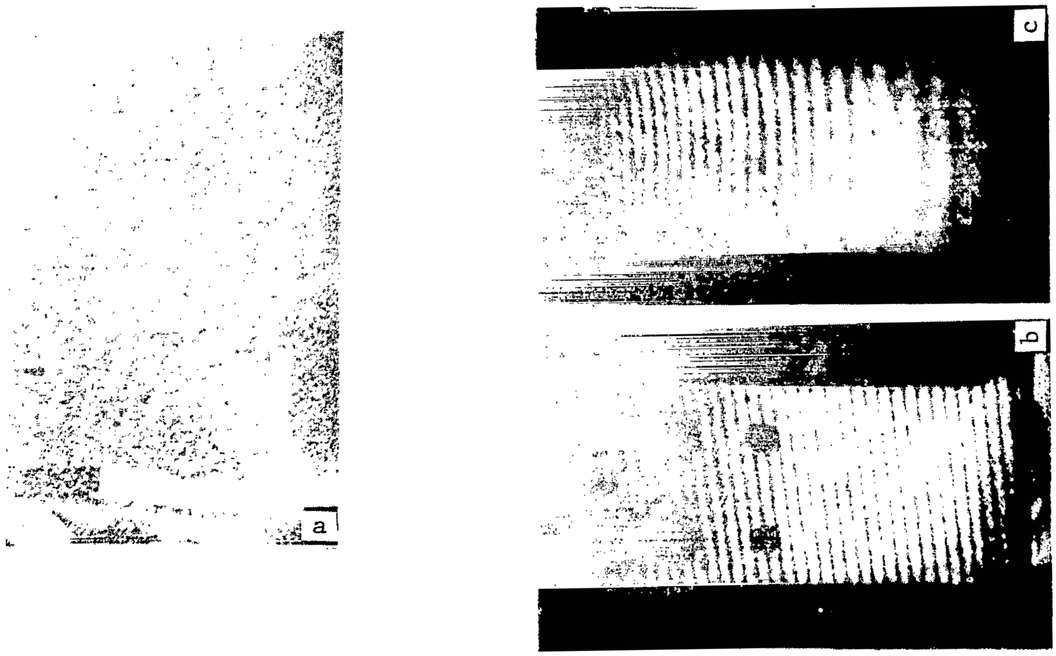


Figure 73. Strobe-holographic interferograms of a vibrating plate obtained using the set-up in Figure 72.

a - with a disk; b - without a disk; c - reconstituted in real time place, and then it is used to view the vibrating object in stroboscopic light (one flash per period of oscillations).

The holographic methods make it possible to study vibrations of parts and instruments — for example, acoustic transducers, ultrasonic sources, vibrating stands — and to study surface waves. Methods were proposed of discovering internal defects of parts from the distribution of the minima and maxima on its surfaces.

Many new possibilities are presented by holographic interferometry for studying impulse and stationary phase inhomogeneities — gas flows, flames, explosions, shock waves [30, 95], plasma [14]. The basic possibility is the fact that we can now obtain interferograms of phase inhomogeneities contained in vessels with optically imperfect walls. Figure 74 shows holographic interferograms, obtained using the method of double exposure, of stationary gas flows in the bulb of an electric incandescent lamp and in the flame of a candle. Figures 75 and 76 show interferograms of the plasma of a standard impulse krypton lamp IFK-2000 [105], laser spark [75], krypton lamp of super-high pressure [14], and the shock wave from a bullet.

In some of these cases, the volume investigated was separated from the external medium by optically inhomogeneous walls. Ordinary interferometric methods do not permit this type of investigation — the volume under study must be closed off by plane-parallel (at least up to $\lambda/2$) windows.

Holographic methods make it possible to obtain interference holograms that span a large solid angle. During reconstitution of such holograms at various angles, it is possible to obtain information about the spatial distribution of phase inhomogeneities that lack an axis of symmetry. When interference holograms of phase inhomogeneities are obtained, the interpre- /104
tation of the results is made slightly easier if — during one of the exposures — one changes the angle of incidence of the object beam on the hologram. This is done by inserting a thin glass wedge [75] into the beam, which results

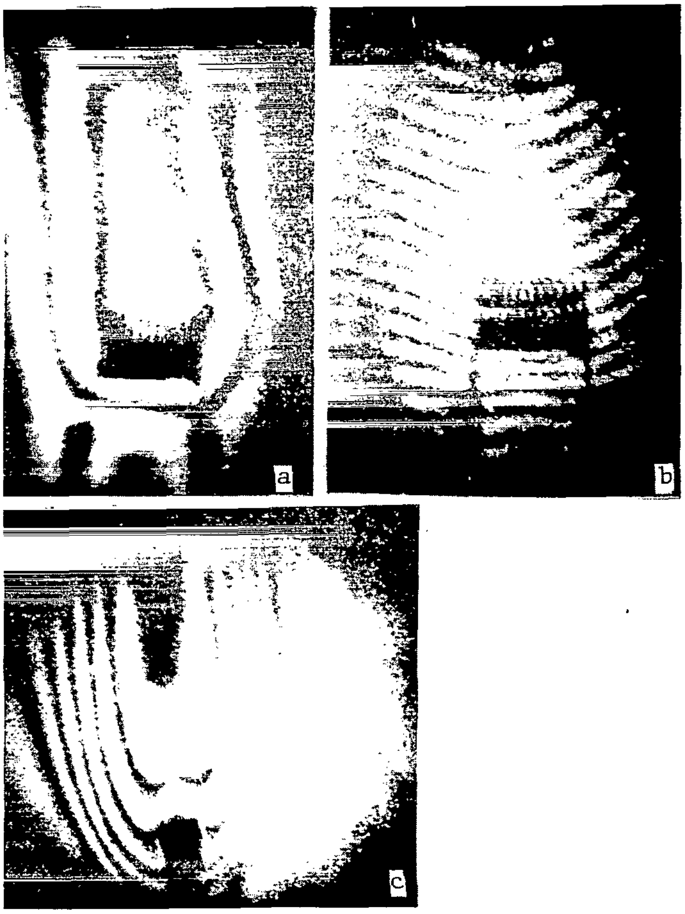


Figure 74. Holographic interferograms obtained using the double-exposure method.

a - gas flows in the bulb of a movie lamp (without the wedge); b - the same but with the wedge; c - candle flame

in the appearance of interference fringes parallel to the edge of the wedge (in the absence of perturbations from the investigated phase inhomogeneity). The form of the fringes produced as a result of the combined action of both the wedge and the inhomogeneity is shown in Figures 74, b, 75, a and b. The same results can be obtained by rotating the wedge by a small angle about the optical axis during one of the exposures, or by changing the gas pressure in a hollow wedge.

Methods of holographic interferometry also permit one "to erase" holographic images. For this purpose, it is enough during one of the two exposures to introduce a half-wave path difference into the object or reference beam. The reconstituted waves will be in opposite phase and will cancel each other [106]. This method may turn out to be useful in those cases when it is necessary only to record changes that occur in the object. During the reconstitution of the image of such a differential hologram, those parts of the object that have not undergone any changes will not be visible.

These applications make use of the real images produced by holograms. When a powerful laser illuminates a hologram, one can create complicated

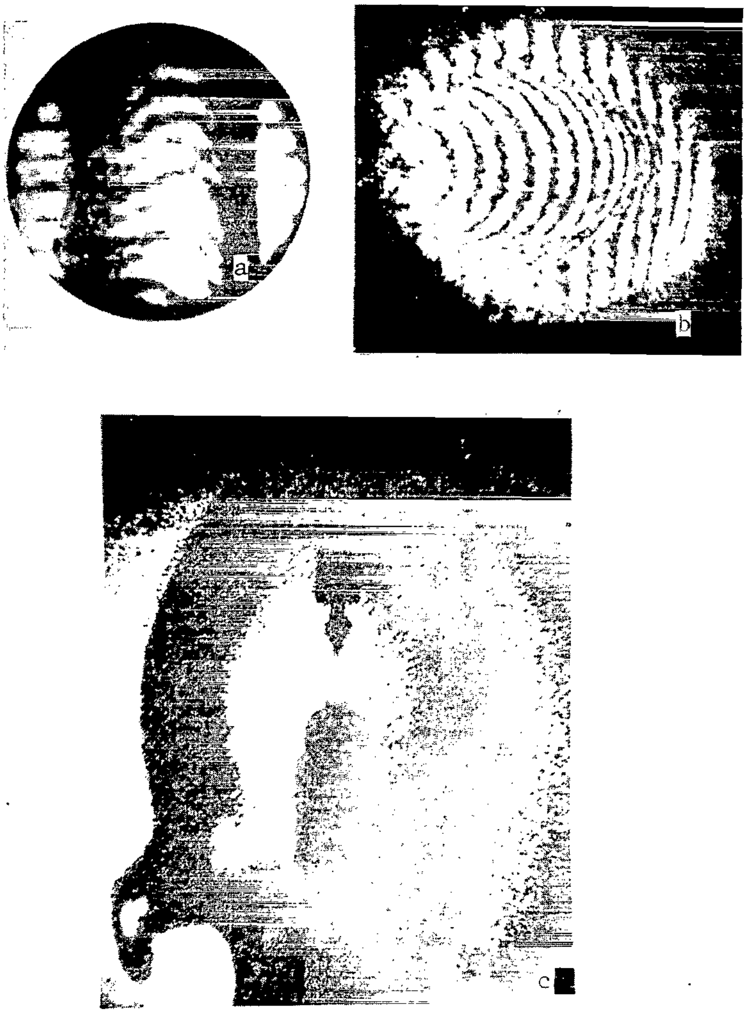


Figure 75. Interference-holographic investigation of a plasma.

a - impulse lamp IFK-2000; b - laser spark; c - krypton lamp of super-high pressure.

patterns on the surface thus treated. In particular, holograms have already been used for contactless deposition of microcircuits. The resolution thus achieved is higher than when using objectives, and the service period of a hologram is longer than that of contact /109 photostencils It is also important that the image is not affected by dust particles that have fallen on the hologram, cracks, and other defects. At the same time, for contact and projection methods this leads to a defect.

The disadvantage of holographic methods is the fact the laser light is utilized only to a limited extent. A good deal of the emitted energy goes into the formation of a virtual image and the zero-order beam. The efficiency of phase or reflection holograms is considerably higher. A reflection hologram is, apparently, most conveniently placed in a laser resonator [107] (Figure 77). In this case, the zero-order beam is completely used to maintain the laser emission.

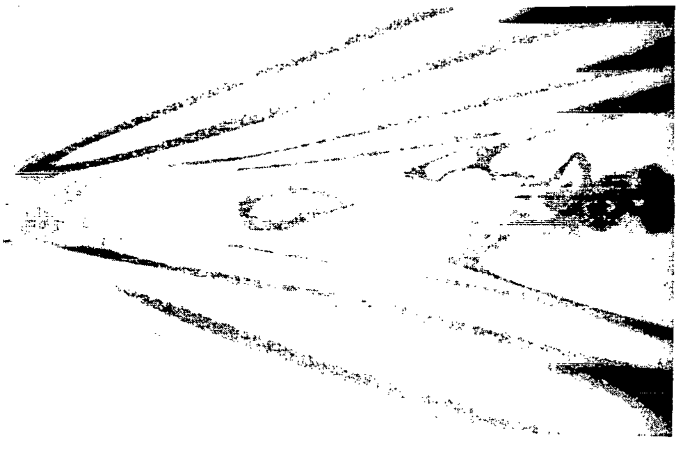


Figure 76. A holographic interferogram of a shock wave from a bullet [95].

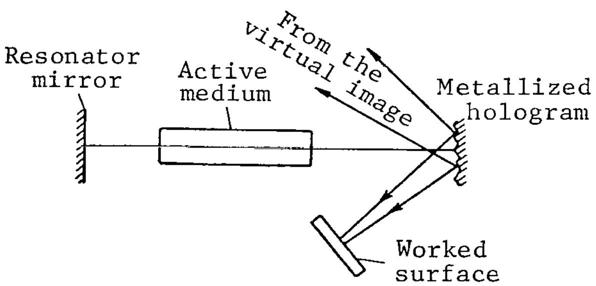


Figure 77. A reflection hologram as a mirror of a laser resonator.

Applications of Holography in Optical Technology

A hologram is an optical equivalent of an object, since it reconstitutes an exact copy of the light wave coming from the object. Along with this wave, the hologram reconstitutes an associated wave forming the real image of the object. The front of the associated wave has a reverse relief, and the phase of each point of the wavefront is shifted by π relative to the direct reconstituted wave (the wave forming the virtual image). This is used to look through light-scattering obstacles (see, for example, [108]). When the real image of the obstacle coincides with the obstacle itself, reconstitution of the initial form of the light wave occurs, and thus an undistorted image of the object is obtained. One of the possible schemes for accomplishing this is shown in Figure 78. The first stage is to obtain a hologram of the scatterer which is focused on the hologram. The second

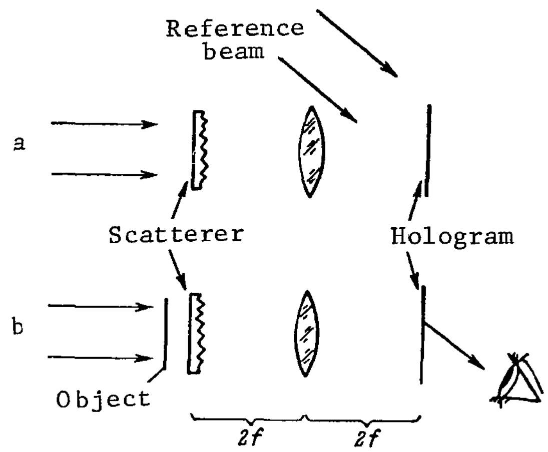


Figure 78. Scheme for observing an object through a scattering medium.

a - formation of the hologram of the scatterer; b - viewing of the object.

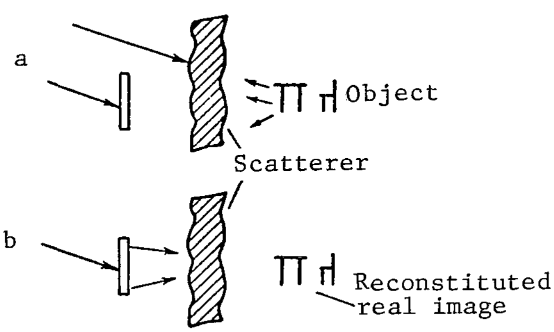


Figure 79. Scheme for the holographic compensation of the distortion of a wave.

a - formation of the hologram of the object and the inhomogeneities; b - compensation of inhomogeneities.

stage involves visual reconstitution through this hologram of an undistorted image of a transparency located behind the scatterer [109].

The second scheme for looking through a scattering medium is shown in Figure 79 [107].

A similar possibility offered by the associated wave is to eliminate the aberration of optical systems (see, for example [110]). For this purpose, one records a hologram of a plane wave, distorted by aberrations, and then uses the reconstituted associated wave to cancel aberrations.

Focusing properties of zone plates have been known for a long time, but their application was limited by the difficulty of preparation. Holographic zone plates, i.e., holograms of a point source, are simple to make and will find applications in optics. Zone plates may be used as focusing elements, thus replacing lenses. For example, a hologram of several point objects may serve as a multiplying objective [111]. As compared with ordinary /110 screens, such a hologram has the advantage that it forms all images without a parallax, from the same viewing position. The aperture of each zone plate making up this type of hologram is determined by the full size of the entire hologram. One must, however, not forget about the strong chromatism of zone gratings; they can only be used in monochromatic light.

In certain applications of zone gratings, it is their strong chromatism that is utilized. One such application involves the compensation of the chromatic aberration of a lens system, and is based on the fact that chromatic aberrations of a lens and a zone grating are opposite in sign. Another application of the chromatism of holograms involves preparation of diffraction /111 gratings [7]. As we have seen, the efficiency of holograms, particularly of phase and reflection types, may be very high. Therefore, it seems that holographically made gratings will with time replace gratings cut by a machine. When a holographic grating is made, it can be given any focusing properties — for example, one can obtain plane holograms that are similar in their effect to a bent grating, but devoid of astigmatism which characterizes the latter.

Reflection gratings with a sinusoidal line profile do not produce fringes of orders higher than the first. This property will turn out to be very valuable for use in the vacuum ultraviolet portion of the spectrum, where there are no methods of separating superimposed spectral orders. The efficiency of holographic diffraction gratings may reach 90% [112].

Pattern Recognition

In various branches of science and engineering, one often has to separate a given signal from a set of signals, that differ from it to a greater or smaller extent. This type of problem is solved, for example, by a radio /112 operator who separates the radiation from one definite radio station from the radiation of thousands of stations; by a spectrum analyst who picks out the lines corresponding to a given element from a complex pattern of the spectral lines of the specimen analyzed; by a bibliographer that finds in the immense ocean of books and articles those that are of interest to the reader; or by a criminologist comparing fingerprints left at the scene of the crime with those in a file.

There is an optimal method of solving such problems. Let us consider this problem first, having in mind the kind of problems that a radio operator or a spectrum analyst has to deal with. What these problems have in common is the fact that electromagnetic emissions from various radio stations, just like the optical emission of various elements, differ in their frequency spectrum. In each radio receiver there is an element, called a frequency filter, that passes only the radiation of certain frequencies.

In spectral analysis, these filters are also sometimes used, but since it is difficult to make their band sufficiently narrow, the filtration is often done in the following way. First the radiation under investigation is decomposed into a spectrum, i.e., the light waves of different frequencies are bent at different angles, and consequently, they strike different points of the focal plane. This operation is usually accomplished with the help of a spectrograph with a prism or a diffraction grating. Then the spectrum thus obtained is compared with the spectra of known elements, and the coinciding spectral lines are identified. To make this process automatic in the focal plane of the spectrograph, one can place exit slits at those places where the lines of different elements are located, and observe the signals from the photomultipliers positioned behind these slits.

This method has the disadvantage that not all the lines of each element are separated out, but merely one. This means that the probability of cross disturbances is high: a line belonging to another element may fall into the region of the spectrum cut by the slit, and thus the signal registered by the photomultiplier will be spurious.

A better method of filtration has also been proposed. In the focal /113
plane of the spectrograph, we place a positive of the spectrum of the desired

element, obtained using the same spectrograph [113]. Behind the plate, we place a light collector and a photomultiplier whose signal will now be determined by the degree of correlation between the entire analyzed spectrum (and not just one line) and the spectrum of a given element. This system represents an ideally matched filter. The effect of disturbances and accidental concidence of lines on the signal will in this case be minimal.

We have described this process in such great detail, because the filtration of images using holograms is done in a very similar way, with the only exception that the image is decomposed into a spectrum of spatial frequencies (not time frequencies), where the decomposition (and filtration) are done simultaneously in two coordinates.

It must be noted that the foundations of the ideas presented below were laid by the German optician Ernst Abbe about a hundred years ago. The ideas were further developed in [114-117].

Each two-dimensional image can be decomposed into a two-dimensional spectrum of spatial frequencies. This operation corresponds to a representation of an image in the form of a set of sinusoidal diffraction gratings of various periods and orientations (see, for example, [9]). Similarly, in radio engineering or spectroscopy, when a signal is decomposed into a spectrum, it is represented in the form of a set of sinusoidal oscillations of various frequencies.

The decomposition of an image of a transparency into a spectrum of /114
spatial frequencies is usually done with the help of a lens (left portion of Figure 80). Each of the sinusoidal gratings into which one can decompose an image acts independently. A grating of large spatial frequency deflects the light of the first few orders by large angles. These rays are focused with a lens L_1 into a point distant from the center of the plane 2. Gratings with a smaller period give rise in the plane 2 to luminous points less distant

from the center. Examples of spectra obtained using this method are given in Figure 81. We shall not dwell on the mathematical side of the question; we only note that an operation performed on an image in this scheme is called a Fourier transformation.

We shall indicate the important properties of the set-up in Figure 80. When a transparency is rotated about the optical axis, its spectrum will also rotate. The spectrum also changes with a change of the scale /115 of the transparency: it is widened when the scale is smaller, and made more narrow when the scale is larger. Translational motion of a transparency in plane 1 does not have any effect on the spectrum. Zero order fringes will produce at the center of the plane 2 a bright point corresponding to the constant term in the expansion of an image in a Fourier series.

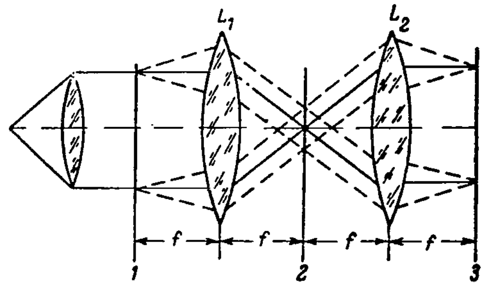


Figure 80. Formation of a matched filter and a filtration of images.

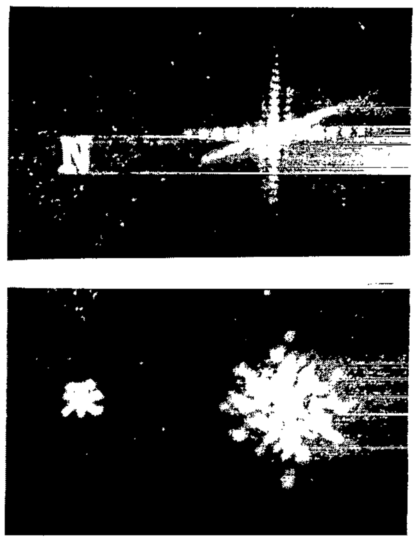


Figure 81. Spatial spectra of letters [118] . On the left - a letter; on the right — its spectrum.

Now let us consider Figure 80, also including its right-hand side. It is not hard to see that the confocal lenses L_1 and L_2 form in the plane 3 an inverted image of the transparency. Placing in the plane 2 various filters or masks, we can pass those of other parts of the spatial spectrum of the object, and thus form an image. This method is used, for example, to correct an image by weakening or, conversely, by revealing high and low spatial frequencies [114]. One can isolate from the entire image only certain definite details — for example, only letters N from a page of text. For this purpose, one must place in plane 1 (Figure 80) a transparency of the page of the text to be analyzed; in plane 2, we shall see its image. If now in plane 2 we place a filter of the spatial frequencies of the letter N (Figure 81), then all details, except for this letter, will disappear from the image of the page.

This method of spatial filtration of an image has a basic disadvantage: the filter does not contain all the information about the object according to which the latter is constructed, and the phase information is lost during recording. Therefore, a light signal at the output from the system contains parasitic components which are superimposed on the images being analyzed, and make the interpretation of the results more difficult.

In the holographic method for obtaining a matched spatial filter [117], the phase information about the object is preserved, and the noise is sharply reduced. A scheme for obtaining a holographic matched filter of spatial frequencies is represented in the left-hand part of Figure 82. In plane 2, as previously, a Fourier image of a transparency placed in plane 1 is formed, but as a result of interference with coherent noise produced by the wedge, in plane 2 a holographic diffraction grating, called a Fourier transform hologram is formed. Now it is not neccessary to make a positive /116
copy of the hologram filter. We know that will not change any properties of the hologram.

When an object is placed in plane 1, and a holographic filter of any part of the object is placed in plane 2, we shall see, as before, an image in the middle of plane 3 due to the zero-order beam. The filter will not distort it in practice; it will just weaken it slightly. In the images of the first few orders, we shall see bright recognition points whose coordinates correspond to the distribution over the object of those details which went into the formation of the holographic filter.

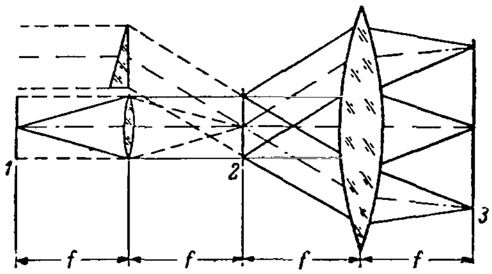


Figure 82. Obtaining a holographic filter and pattern recognition.

The above method of pattern recognition increases in reliability with the complexity of the object to be recognized. Satisfactory results were, for example, obtained in the recognition of fingerprints [119]. Even if only a small part of the fingerprints was preserved, the recognition point was still sufficiently bright. The device whose scheme is shown in Figure 82 was used as a basis for automatic readers that are already operational. It has been possible to isolate objects of certain form or direction on aerial photographs. Instruments have been developed for processing geophysical data, etc.

The filtering properties of a hologram will be easy to understand if one recalls the reciprocity relation between the reference and object waves that was already mentioned before. If a hologram is obtained by exposing a plate with light from the objects A and B, and then illuminated by the wave from A, we shall see a reconstituted wave from B. Conversely, if the same hologram is illuminated by light from B, the wave scattered by A will be reconstituted. If A is a point source, then its image will be produced by a hologram only /117
when the illuminating object is B. A hologram thus performs the operation of recognizing its "own" object [120]. This principle can be used to reconstruct an entire image from its parts.

We have already mentioned that any part of an object can be used as a reference light source with respect to the remaining parts of the object (and to the reference source, if it was there during the formation of the hologram). Therefore, when a hologram is illuminated by a portion of the object, "phantom" images of all its lacking parts are reconstituted (see, for example, [121, 122]).

The size of this brochure did not allow us to discuss here many other, no less important applications of holography — for example, in microscopy (including electron microscopy), spectroscopy, in recording and storage of information.

§9. WHAT TO READ ON HOLOGRAPHY

Unfortunately, thus far, there has not yet been written a thorough book on holography which would give a readable and well thought out theory of the method, and would describe in detail the experimental achievements and prospects of its application. The book by G. Stroke [11] that was translated into the Russian language, apparently does not meet any of these requirements, and may create in a reader who is not acquainted with the original literature an incorrect notion of both the state of holography and the history of its development. The book by Stroke contains complete translations of the first two holographic articles by D. Gabor and a survey by I. P. Nalimov on the applications of holography with a detailed list of literature (up to the first third of 1967).

We should also note the surveys by L. M. Soroko [123] and I. P. Nalimov [124] that appeared a year earlier. The latter describes in detail the research done by E. Leith and J. Upatnieks [4, 5].

A great deal of holographic literature was surveyed in [125]. A list of literature up to the middle of 1968 is given in [126]. Surveys of articles on holography are being constantly published by Referativny Zhurnal "Fizika" in the section "Geometrical Physics". A full list of the published papers and notes on holography by January of 1969 contained more than 1,000 entries. The /118
list of literature included in the present brochure contains articles and books that are most easily accessible, mainly published in Russian or available in Russian translation.

It often happens that the same proposal was made simultaneously and independently in several laboratories. This was the case, for example, with holographic interferometry, stroboscopic studies of vibrations, etc. The fact that only one of such papers is mentioned here is in no way an attempt at belittling the importance of others, and is only due to the impossibility of giving a fairly complete list of the literature here.

REFERENCES

1. Gabor, D. Nature, Vol. 161, 1948, p. 777.

2. —. Proc. Roy. Soc., London, Vol. A197, 1949, p. 454; translation, see p. 218 [11].

3. —. Proc. Phys. Soc., Vol. B64, 1951, p. 449; translation, see p. 270 [11].

4. Leith, E. and J. Upatnieks. JOSA, Vol. 53, 1963, p. 1377.

   —. JOSA, Vol. 54, 1964, p. 1295.

5. —. JOSA, Vol. 51, 1961, p. 1469.

   —. JOSA, Vol. 52, 1962, p. 1123.

6. Denisyuk, Yu. N. Doklady Akademii Nauk SSSR (DAN), Vol. 144, 1962, p. 1275.

7. —. Optika i spektr, Vol. 15, 1963, p. 522.

8. —. Optika i spektr, Vol. 18, 1965, p. 275.

9. Landsberg, G. S. Optika (Optics). Gostekhizdat, Moscow, 1957.

10. Konstantinov, B. P., A. N. Zaydel', V. B. Konstantinov and Yu. I. Ostrovskiy. Zhurnal Tekhnicheskoy Fiziki (ZhTF), Vol. 36, 1966, p. 1718.

11. Stroke, G. Introduction to Coherent Optics and Holography. "Mir" Press, Moscow, 1967.

12. Winthrop, I. and C. Worthington. Phys. Lett., Vol. 15, 1965, p. 124.

13. Meier, R. W. JOSA, Vol. 56, 1966, p. 219.

14. Zaudel', A. N., G. V. Ostrovskaya and Yu. I. Ostrovskiy. ZhTF, Vol. 38, 1968, p. 1405.

15. Vandewarker, R. and K. Snow. Appl. Phys. Lett., Vol. 10, 1967, p. 35.

16. Stetson, K. A. Appl. Phys. Lett., Vol. 11, 1967, p. 225.

17. Turukhano, B. G. and N. Turukhano. Optika i spektr, Vol. 25, 1968, p. 309.

18. Montgomery, W. D. Appl. Opt., Vol. 7, 1968, p. 83.

19. Bragg, W. L. Nature, Vol. 149, 1942, p. 470.

20. Aristov, V. V., V. L. Broude, L. V. Koval'skiy, V. K. Polyanskiy, V. B. Timofeyev and V. Sh. Shekhtman. DAN SSSR, Vol. 177, 1967, p. 65.

21. Katalog tsvetnogo stekla (Catalogue of Colored Glass). Compiled by T. I. Veynberg. Mashinostroyeniye, Moscow, 1967.

22. Hamasaki, J. Appl. Opt., Vol. 7, 1968, p. 1613.

23. Neumann, D. and H. Rose. Appl. Opt., Vol. 6, 1967, p. 1097.

24. Bolstad, J. O. Appl. Opt., Vol. 6, 1967, p. 170.

25. Casler, D. H. and H. D. Pruett. Appl. Opt., Vol. 10, 1967, p. 341.

26. Mikaelyan, A. L., M. L. Ter-Mikayelyan and Yu. G. Turkov. Opticheskiye generatory na tverdom tele (Solid State Lasers). Izdatel'stvo "Soviet Radio", Moscow. 1967.

27. Melroy, D. O. Appl. Opt., Vol. 6, 1967, p. 2005.

28. Born, M. and E. Wolf. Principles of Optics, London, 1965, p. 69.

29. Watts, J. K. Appl. Opt., Vol. 7, 1968, p. 1621.

30. Brooks, R. E., R. Heflinger and J. Q. Wuerker. IEEE, J. Quant. Electr. Vol. QE-2, 1966, p. 275.

—. Zarubezhnaya Radioelektronika, No. 4, 1967, p. 135.

31. Gerke, R. R., Yu. N. Denisyuk and V. I. Lokshin. OMP, No. 7, 1968, p. 22.

32. Davis, L. W. Appl. Phys. Lett., Vol. 10, 1967, p. 301.

33. Blombergen, N. Nelineynaya optika (Nonlinear Optics). "Mir" Press, Moscow, 1966.

34. Brooks, R., R. Heflinger and J. Wuerker. Appl. Phys. Lett., Vol. 12, 1968, p. 302.

35. Zaydel', A. N., I. I. Komissarova, G. V. Ostrovskaya and L. L. Shapiro. FTI Preprint (Preprint of Physicotechnical Institute), im. A. F. Ioffe, No. 182, 1969.

36. Gusev, O. B. and V. B. Konstantinov. ZhTF, Vol. 39, 1969, p. 354.

37. Worthington, C. JOSA, Vol. 56, 1966, p. 1397

38. Leith, E. and J. Upatnieks. JOSA, Vol. 57, 1967, p. 975.

39. Lohmann, A. JOSA, Vol. 55, 1965, p. 1555.

40. Stroke, G. and R. Restrick. Appl. Phys. Lett., Vol. 7, 1965, p. 229.

41. Froehly, C. and J. Pasteur. Rev. optique, Vol. 46, 1967, p. 241.

42. Rukman, G. I. and Yu. I. Filenko. Pis'ma Zhurnal Eksperimental'noy i Teoreticheskoy Fiziki (ZhETF), Vol. 8, 1968, p. 538.

43. Collier, R. and K. Pennington. Appl. Opt., Vol. 6, 1967, p. 1091.

44. Friesem, A. and R. Fedorowicz. Appl. Opt., Vol. 6, 1967, p. 529.

45. Lin, L. and C. Lo Bianco. Appl. Opt., Vol. 6, 1967, p. 1255.

46. Paques, H. Proc. IEEE, Vol. 54, 1966, p. 1195.

47. Ramberg, E. G. RCA Rev., Vol. 27, 1966, p. 467.

48. Lin, L. Appl. Opt., Vol. 6, 1967, p. 2004.

49. Brumm, D. Appl. Opt., Vol. 5, 1966, p. 1946.

50. —. Appl. Opt., Vol. 6, 1967, p. 588.

51. Mikaelyan, A. L. Golografiya (Holography). Izdatel'stvo "Znaniye", Moscow, 1968.

52. Stroke, G., A. Funkhouser, C. Leonard, G. Indebetouw and R. Zech. JOSA Vol. 57, 1967, p. 120.

53. Brooks, R. Appl. Opt., Vol. 6, 1967, p. 1418.

54. Coltman, J. JOSA, Vol. 44, 1954, p. 468.

55. Royer, H. Compt. Rend., Vol. 261, 1965, p. 5024.

56. Zaydel', A. N., V. B. Konstantinov and Yu. I. Ostrovskiy. Zhurnal nauchnoy i prikladnoy fotografii i kinematografii, Vol. 11, 1966, p. 381.

57. Ostrovskiy, Yu. I. Author's certificate No. 199659, 1966. Byulletin' Izobr, No. 15, 1967.

58. Ostrovskiy, Yu. I. Author's certificate No. 212751, 1967. Byulletin' Izobr. No. 9, 1968.

—. Author's certificate No. 207018, 1967. Byulletin' Izobr. No. 1, 1968.

59. Protas, I. R. and V. N. Sintsov. Vliyaniye svoystv fotograficheskogo materiala na kachestvo izobrazheniya, vosstanovlennogo iz gologrammy. Lektsiya. Materialy shkoly po golografii (Influence of the Properties of Photographic Material on the Quality of an Image Reproduced from a hologram. Lecture. Material from the holography school). Moscow, 1969.

60. Schultze, D. Laser Focus, Vol. 4, No. 11, 1968, p. 23.

61. Cathey, W. T. JOSA, Vol. 55, 1965, p. 457.

62. Russo, V. and S. Sottini. Appl. Opt., Vol. 7, 1968, p. 202.

63. Rigler, A. K. JOSA, Vol. 55, 1965, p. 1693.

64. Sheridan, N. K. Appl. Phys. Lett., Vol. 12, 1968, p. 316.

65. Armistead, W. and S. Stookey. Science, Vol. 144, 1964, p. 150.

66. Savost'yanova, M. V. OMP, No. 5, 1966, p. 31.

—. OMP, No. 4, 1966, p. 9.

67. Kirk, J. Appl. Opt., Vol. 5, 1966, p. 1684.

68. Powell, R. and J. Hemnye. JOSA, Vol. 56, 1966, p. 23.

69. Mikaelyan, A. L., V. N. Bobrinev and V. V. Shatun. DAN SSSR, Vol. 181, No. 5, 1968.

70. Gerritsen, H. J. Appl. Phys. Lett., Vol. 10, 1967, p. 239.

71. Urbach, J. C. and R. W. Meier. Appl. Opt., Vol. 5, 1966, p. 666.

72. Bosomworth, D. R. and H. J. Gerritsen. Appl. Opt., Vol. 7, 1968, p. 95.

73. Laser Focus, Vol. 4, Apr. 1968, p. 43.

74. Zaydel', A. N., G. V. Ostrovskaya, Yu. I. Ostrovskiy and T. Ya. Chelidze. ZhTF, Vol. 36, 1966, p. 2208.

75. Kakos, A., G. V. Ostrovskaya, Yu. I. Ostrovskiy and A. N. Zaydel'. Phys. Lett., Vol. 23, 1966, p. 81.

76. Komissarova, I. I., G. V. Ostrovskaya and L. L. Shapiro. ZhTF, Vol. 38, 1968, p. 1369.

77. Ostrovskiy, Yu. I. Author's certificate No. 179188, 1963. Byulletin' Izobr. No. 4, 1966.

—. Optika i spektr, Vol. 21, 1966, p. 620.

78. Leith, E., J. Upatnieks, A. Kozma and N. Massey. J. Soc. Motion Picture and Telev. Engrs., Vol. 75, 1966, p. 323.

—. Russian translation: Zarubezhnaya radioelektronika, No. 1, 1967, p. 142.

79. De Bitetto, D. J. Appl. Phys. Lett., Vol. 12, 1968, p. 176.

80. —. Appl. Phys. Lett., Vol. 12, 1968, p. 295.

81. Lin, L. H. Appl. Opt., Vol. 7, 1968, p. 545.

82. Gurevich, S. B., G. A. Gavrilov, A. B. Konstantinov, V. B. Konstantinov, Yu. I. Ostrovskiy and D. F. Chernykh. ZhTF, Vol. 38, 1968, p. 513.

83. Konstantinov, B. P., S. B. Gurevich, G. A. Gavrilov, A. A. Kolesnikov, V. B. Konstantinov, A. B. Konstantinov, A. A. Rizkin and D. F. Chernykh. ZhTF, Vol. 39, 1969, p. 347.

84. Komar, A. P., M. B. Stabnikov and B. G. Turukhano. Doklad na ob"yedinennom seminare po metodike puzyr'kovykh kamer fizikov OIYaI i TsERNa. Materialy seminara (Report to the Combined Seminar on Methodology of Bubble Chambers by Physicists of the Joint Institute of Nuclear Research and European Center of Nuclear Research. Seminar Materials). Dubna, 1965, p. 7.

85. Welford, W. T. Appl. Opt., Vol. 5, 1966, p. 872.

86. King, M. C. Appl. Opt., Vol. 7, 1968, p. 1641.

87. Yoshinao, Aoki. Appl. Opt., Vol. 7, 1968, p. 1402.

88. Metherall, A. F. and S. Spinak. Appl. Phys. Lett., Vol. 13, 1968, p. 22.

Metherall, A. F. and H. M. A. El Sum. Appl. Phys. Lett., Vol. 11, 1967, p. 20.

89. Greguss, P. Forschungsfilm, Vol. 5, 1965, p. 330.

90. Mueller, R. and N. Sheridan. Appl. Phys. Lett., Vol. 9, 1966, p. 328.

91. Young, J. and J. Wolf. Appl. Phys. Lett., Vol. 11, 1967, p. 294.

92. Dooley, R. Proc. IEEE, Vol. 53, 1965, p. 1733.

93. Yoshinao, Aoki. Appl. Opt., Vol. 6, 1967, p. 1943.

94. Ostrovskiy, Yu. I. Gologra ficheskaya interferometriya. Lektsiya. Materialy shkoly po golografii (Holographic Interferometry. Lecture. Materials from the holography school). Moscow, 1969.

95. Heflinger, L., R. Wuerker and R. Brooks. J. Appl. Phys., Vol. 37, 1966, p. 642.

96. Haines, K. and B. Hildebrand. Appl. Opt., Vol. 5, 1966, p. 595.

97. Aleksandrov, Ye. B. and A. M. Bonch-Bruyevich. ZhTF, Vol. 37, 1967, p. 360.

98. Hilderbrand, B. P., K. A. Haines and R. Larkin. Appl. Opt., Vol. 6, 1967, p. 1268.

99. Hilderbrand, B. P. and K. A. Haines. JOSA, Vol. 57, 1967, p. 155.

100. Shiotake, N., T. Tsuruta, Y. Iton, J. Tsujichi, N. Takeya and K. Matsuda. Japan J. Appl. Phys., Vol. 7, 1968, p. 904.

101. Powell, R. L. and K. A. Stetson. JOSA, Vol. 55, 1965, p. 1593.

102. Archbold, G. E. and A. E. Ennos. Nature, Vol. 217, 1968, p. 942.

103. Zaydel', A. N., L. G. Malkhasyan, G. V. Markova and Yu. I. Ostrovskiy. Preprint FTI im. A.F. IOffe, No. 94, 1968.

—. ZhTF, Vol. 38, 1968, p. 1824.

104. Shajenko, P. and C. Johnson. Appl Phys. Lett., Vol. 13, 1968, p. 44.

105. Ashcheulov, Yu. V., A. D. Dynmikov, Yu. I. Ostrovsky and A. N. Zaidel. Phys. Lett., Vol. 25A, 1967, p. 61.

106. Gabor, D., G. Stroke, R. Restrick, A. Funkhouser and D. Brumm. Phys. Lett., Vol. 18, 1965, p. 116.

107. Halimov, I. P. Primeneniye golografii (Application of Holography). Review in [11].

108. Kogelnik, H. Bell System Techn. J., Vol. 44, 1965, p. 2451.

109. Kogelnik, H. and K. Pennington. JOSA, Vol. 58, 1968, p. 273.

110. Upatnieks, J., A. V. Lugt and E. Leith. Appl. Opt., Vol. 5, 1966, p. 589.

111. Groh, G. Appl. Opt., Vol. 7, 1968, p. 1642.

112. Shankoff, T. A. and R. K. Curran. Appl. Phys. Lett., Vol. 13, 1968, p. 239.

113. Kustanovich, I. M. Materialy X Vsesoyuznogo soveshchaniya po spektroskopii, (Materials from Tenth All-Union Conference on Spectroscopy). Vol. II, 1958, p. 452.

114. Mareshal', A. and M. Franson. Struktura opticheskogo izobrazheniya (Structure of an Optical Image). "Mir" Press, Moscow, 1964.

115. O'Neill, E. Introduction to Statistical Optics. "Mir" Press, Moscow, 1966.

116. Cutrona, L., E. Leith, C. Palermo, L. Porcello. IRE Trans., Vol. IT-6, 1960, p. 386.

—. Russian translation: Zarubezhnaya radioelektronika, No. 10, 1962, p. 3.

117. Van der Lugt, A. V. IEEE Trans., IT-10, 1964, p. 139.

118. Pernick, B., C. Bartolotta and D. Yustein. Appl. Opt., Vol. 6, 1967, p. 1421.

119. Horvath, V., J. Holeman and C. Lemmond. Laser Focus, Vol. 3, 1967, p. 18.

120. Gabor, D. Nature, Vol. 208, 1965, p. 422.

121. Collier, R. and K. Pennington. Appl. Phys. Lett., Vol. 8, 1966, p. 41.

122. Rosen, L. and W. Clark. Appl. Phys. Lett., Vol. 10, 1967, p. 140.

123. Soroko, L. M. Uspekhi Fizicheskikh Nauk, Vol. 90, 1966, p. 1.

124. Nalimov, I. P. Zarubezhnaya radioelektronika, No. 2, 1966, p. 3.

125. Chambers, R. and J. Courtney-Pratt. J. Soc. Motion Picture and Telev. Engrs., Vol. 75, 1966, pp. 373, 759.

—. J. Soc. Motion Picutre and Telev. Engrs., Vol. 76, 1967, p. 392.

126. Bibliograficheskiy ukazatel' po golografii (Bibliographical Index to Holography). OIYaI (Joint Institute for Nuclear Research), Dubna, 1968.

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