From Lippmann Photography to Selectograms via White Light Holography

Yuri N. Denisyuk

Ioffe Physico-Technical Institute of the Academy of Sciences of Russia, 26, Polytekhnicheskaya Str., 194021 St. Petersburg, Russia

We consider the method of reference-free selectograms that allows obtaining 3-D holographic images of objects illuminated by natural light. The method of reference-free selectograms is based on the phenomenon that is relative to the phenomenon being the base for Lippmann color photography. In this connection, the reference-free selectogram method, the Lippmann color photography method, the method of 3-D reflection holograms, and the local reference beam generated hologram method are analyzed and compared. Like the Lippmann color photograph, the reference-free selectogram represents the recording of a picture of standing waves resulting from the interference of the object wave with its "twin"—the wave that is split off from the object wave with the help of an optical element. The methods differ in the direction of the propagation of the twin wave. In the Lippmann color photograph, this wave is formed by means of a mirror and propagates in the direction opposite to the object wave. For the reference-free selectogram case, the twin wave is formed with the help of a diffraction grating and is directed in the same way with the object wave direction. We show that both in the Lippmann photography and in the reference-free selectogram the main information on the angular distribution of the intensity of the radiation recorded is contained in a thin layer that fits snugly to the surface of the optical element. The thickness of this layer is of the order of several microns. However, the information on the fine details of an object is spread in depth by the order of several millimeters.

Journal of Imaging Science and Technology 41: 205–210 (1997)

Introduction

More than one and a half centuries have passed since the time whenthe development of photography began. Numerous studies were devoted to the invention and development of photography, which is known nowadays down to the slightest detail. One of those minor first-impression details is the history of the discovery and oblivion of one of the methods of color photography, so-called Lippmann interferential color photography.[1,2]

Of course when the events are analyzed from the point of view of the technique, which is used by up-to-date photo-graphy, Lippmann's method is an obvious example of one of the unsuccessful attempts to create color photography. However, when considering the events from the point of view of their contribution to the science of images, then the creation of Lippmann's methods turns out to be the first step in a long chain of discoveries of the material model of a light interference pattern to reproduce the wave fields participating in the formation of this pattern. In particular, on the basis of Lippmann's method, while not being acquainted with the work by D. Gabor, we present a method of reflection three-dimensional holograms.[3,4] Since that time a number of other important imaging properties of an interference pattern of light waves have been discovered. Among them are the ability to reproduce the image of a moving object, including the Doppler shift of the wavelength of radiation reflected by it, the ability to reproduce the wave fields changing arbitrarily in time, and the ability to reproduce the state of the polarization of radiation.[5–7] In the author's opinion, the effect discovered by Lippmann promises many other interesting findings.

The present paper considers a new method of so-called reference-free selectograms, which opens up the possibility of recording a three-dimensional image of objects in natural light without the help of lasers.[8,9] This method is closely related to Lippmann's method of color integral photography.

To reveal the mechanism of this phenomenon, we give some details of Lippmann's method, with special attention being given to those little known details of the method which are similar to some details of the reference-free selectograms. A comparison of the Lippmann method with the method of reflection three-dimensional holograms is given to show the connections of this method with holography.[3,4] It is also shown that the reference-free selectogram allows one to approach the solution of the problem of a so-called "hologram with a local reference beam."[10,11]

Lippmann Interferential Color Photography

The effect of reproducing the spectral composition of the light by a volume photograph of a standing wave pattern was discovered by J. T. Seebek, J. Hershel, and A. Becquerel in the 1840s. In particular, A. Becquerel recorded his photographs on photographic plates whose emulsion layer was deposited on a polished silver plate. To the great surprise of the researchers, their photographs without any dyes reproduced not only the images of the object, but their color, too.

W. Zenker in 1868 and Lord Rayleigh in 1879 advanced a very well founded opinion that the colors of an object were reproduced due to the interference of light in the volume photograph of a standing waves pattern, which originated as a result of the reflection of light from the silver plate. The theory of the effect has been developed by G. Lippmann, who also confirmed the theory by reliable experiments.[1,2]

In the field of experimentation, G. Lippmann developed special high-resolution photographic plates that became the base for the development of holography. Thousands of color photographs were recorded on such plates by Lippmann and other investigators, most of which are now lost.

In the field of theory, by applying the Fourier mathematical instrument, G. Lippmann discovered a very essential

Original manuscript received August 11, 1996.

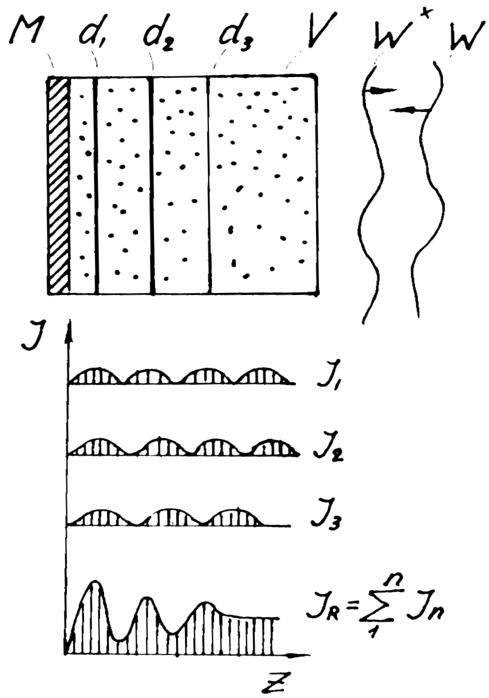

Figure 1. Dependence of the contrast of a standing wave recorded in the Lippmann photography on the depth of recording. *V*, volume light-sensitive layer; *M*, mercury mirror; *W*, wave of the light incident on the layer; *W**, wave of the light reflected by the mirror (the twin of the wave *W*); I_1, I_2, I_3, distributions of the intensity of the standing waves formed by separate monochrome components of incident light; and I_R, distribution of the intensity in a summary standing wave recorded on a photograph.

feature of the effect, which had not been noticed by earlier researchers. It turned out that the Lippmann photograph permitted one to record and reproduce not only the monochrome radiation, but also the radiation characterized by a complicated spectral composition. As a result the Lippmann photograph was able to reproduce the spectrum of the light reflected by natural objects that are illuminated by white light. Thus, the first ring in the long chain of imaging properties of a volume photograph of a pattern of standing waves was discovered.

Consider the mechanism in which the Lippmann photograph records and reproduces the spectral composition of light. Figure 1 presents the scheme for Lippmann photograph recording Wave *W* formed by the lens of a photographic camera is directed onto a transparent light-sensitive layer *V* of a Lippmann photographic plate. This wave is reflected by a mercury mirror *M* whose surface contacts tightly to that of the light-sensitive layer *V*. When reflecting the wave *W*, the mirror *M* generates its twin, i.e., the wave *W** propagating in the opposite direction. When overlapping, these waves form a standing wave that is recorded in the volume of the emulsion layer. The antinode surfaces of this wave are denoted in Fig. 1 as d_1, d_2, and d_3.

In the case when a photograph records the light that is characterized by a complex spectral composition, the resulting standing wave can be represented as a sum of standing waves formed by monochrome components of the incident radiation. In particular, the standing wave formed by a component with a wavelength λ_1 represents a harmonic distribution of intensity I_1, whose spatial period is equal to the half of the wavelength of radiation that has formed the given standing wave. It is of importance that minima of the intensity of all the harmonics are positioned on the surface of the mirror *M*, because the value of the electric field on the metal surface should be equal to zero.

Taking the mentioned rule into account, Fig. 1 shows three harmonics of the intensity that correspond to wavelengths λ_1, λ_2, and λ_3. As can be seen from Fig. 1, near the mirror the maxima and minima of all these harmonics practically coincide. It is easy to understand that in this region the distribution of the intensity of the resulting standing wave I_R will be characterized by clearly manifested maxima and minima. However, when remoting from the surface of the mirror, the picture changes: the maxima of one part of monochrome components coincide with the minima of the other part and the depth of modulation of the resulting standing wave gradually decreases. In practice, in the case of recording natural objects, the depth of the modulation of the pattern of a standing wave, i.e., the region where the basic information on the spectrum of their radiation is contained, is equal to several microns. In order not to lose this information, G. Lippmann had to use a mercury mirror which fitted tightly to the surface of the emulsion layer without making any clearance.

The reconstruction of the Lippmann photograph is performed by using a point source of white light. Due to the fact that three-dimensional gratings possess a so-called spectral selectivity, each monochrome standing wave selects from the white source spectrum and reflects only that very monochrome component whose wavelength coincides with that of the radiation that had formed the given monochrome standing wave at the stage of recording. When summing up, the reflected monochrome components reproduce the spectral composition of the radiation recorded on the photograph.

It is well known that three-dimensional gratings are characterized not only by the spectral selectivity, but also by the angular selectivity. The Lippmann photograph case, in which a grating is recorded by beams propagating in opposing directions, is characterized by a high value of spectral selectivity. However, the angular selectivity does not become zero and therefore the Lippmann photograph admits the reconstruction only by the radiation that propagates in the directions close to normal to the photographic plate.

When considering the recording scheme of the Lippmann photograph, a question arises as to what properties such as a photograph will have in case a standing wave is formed by directing the twin of the object wave not in the direction opposite to the initial object wave, but at a small angle to it. In the section devoted to the so-called reference-free selectogram, it is shown that the volume photograph of such a standing wave has the property of reproducing the spatial structure of the wave field of light, i.e., three-dimensional images.

3-D Reflection Hologram

The next step in the study of imaging properties of a volume picture of standing waves is a so-called reflection hologram with recording in a 3-D media.[3,4] While trying to solve the problem of the creation of a photograph that reproduces the three-dimensional images of objects, we came to the conclusion of the possibility of recording a complex object wave by means of its mixing with a simple spherical wave, i.e., the conclusion of holography that was proposed by D. Gabor in 1948.[12] Like D. Gabor, proceeding from the Huygens principle, there was the assumption that the interference pattern of an object and reference waves

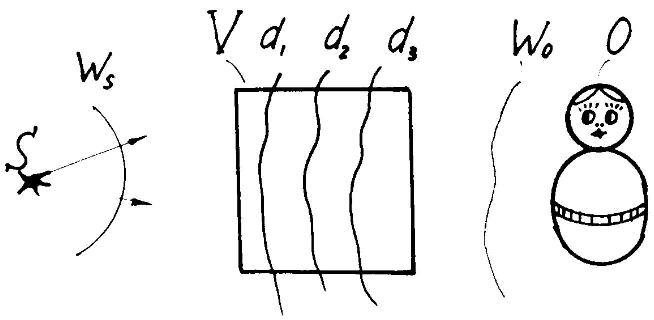

Figure 2. Scheme for the recording and reconstructing of a 3-D reflection hologram. O, object; V, volume light-sensitive layer; S, monochrome source of light; and d_1, d_2, and d_3, antinode surfaces of the standing wave resulted from the interference of the incident wave W_S and wave W_O of the light reflected by the object O. The reconstruction is carried out by a source of white light.

should be recorded on the surface. However, in the case when the waves propagated in opposite directions, it turned out to be practically impossible to perform such a recording. Indeed, when meeting with a reference wave W_2, the wave W_0 scattered by object O forms a standing wave that is characterized by antinode surfaces d_1, d_2, d_3... (see Fig. 2) In the visual frequency spectrum, the distance between the antinode surfaces is approximately equal to 0.25 μm. To record a flat cross-section of such a structure, it is necessary to have a photographic plate with a thickness of an emulsion layer of the order of 0.1 μm, while the thickness of the emulsion layer of real photographic plates is equal to 5 to 10 μm.

The way out of this deadlock was shown by the work by G. Lippmann. A natural idea arose that perhaps there is no sense to insist on the surface recording. If the system of flat antinode surfaces in the Lippmann photograph contains an exact information on the spectral composition of radiation, then perhaps the system of complicated curved surfaces of the antinodes of a hologram could also contain information on the spatial distribution of phases of a light wave. Several variants of the theory and experiment had confirmed the validity of this suggestion. The imaging properties of a thin hologram are but only a part of the imaging properties that are inherent to a volume photograph of a standing wave. Such a photograph permits reproducing both the spectrum and the form of the wavefront of the radiation scattered by all object.

On this base there developed a simple method (see Fig. 2). Object O is illuminated through a transparent emulsion layer V by the radiation W_3 of a monochrome source S. The standing wave resulted from the interference of an object and reference waves are recorded in the volume of a light-sensitive layer. The reconstruction is performed by means of a point source of white light. Like the Lippmann photograph, the hologram selects from a continuous spectrum of the reconstructing source and reflects only its spectral components that were present in the spectrum of the radiation scattered by the object. The antinode surfaces of the volume hologram are curved in such a manner that would provide the transformation of a simple spherical reference wave into a complex object one. The final result of all these complicated processes is the reconstruction of the three-dimensional color image of an object. The fact that a 3-D hologram allows reconstruction by means of a source of natural light essentially facilitated its application in imaging techniques. Nowadays such holograms can often be seen both in museums and exhibitions as well as private houses.

Local Reference Beam Generated Hologram

An essential fact and inherent drawback of any hologram, including a three-dimensional one, is that highly monochrome laser radiation is necessary for its recording.

This condition essentially limits the field of application of the given method, because in this case it is impossible to record the object and scenes illuminated by natural light. An attempt to overcome this obstacle was made as far as at the dawn of the "second birth" of holography by B. T. Cathey in 1965, who suggested a method of a local reference beam generated hologram.[10,11] The main point of the method is that a reference beam is formed from the radiation of the object. Because in such a situation the reference wave will be always coherent to the object one, the requirements as to the coherence of the recording light are not so severe compared to when a conventional hologram is recorded.

However, an attempt to solve the problem of recording a local reference beam generated hologram when not going beyond the frames of a conventional hologram was unsuccessful, because there appeared serious obstacles. Indeed, due to the main principle of a hologram, it is necessary to have a point reference source for its recording. The attempts to form such source by decreasing the image of an object by using optical methods leads to essential losses of light. Moreover, a natural extended object cannot in principle be transformed into a point at the expense of its scale change. To realize the low requirements as to the coherence of the recording light is a very difficult problem. Indeed, though the object and reference waves are mutually coherent in this case, the depth of the interference pattern is very small if the object is illuminated by natural white light. The researchers of the given method have noted that to compensate the small extension of an interference pattern, it is necessary to develop a method that would permit the splitting off of a reference wave from one object immediately at the surface of the light-sensitive layer of a photographic plate. However, such a method has not been found.

The both previously mentioned problems, i.e., the possibility of recording the hologram when using an extended reference source and forming the reference wave from one object immediately at the surface of the light-sensitive layer can be solved with the help of the so-called reference-free selectogram that will be considered next. The "payment" for the solution of these problems is the necessity to perform the recording in a thick-layered light-sensitive medium.

Scheme of the Reference-Free Selectogram

As was mentioned earlier, the necessity to use a point-like reference source when recording a hologram is one of the most essential obstacles to its application in 3-D imaging of the objects and scenes illuminated by natural light. Trying to solve this problem and the problem of the creation of holograms that would permit, like a conventional photograph, the reconstruction of 3-D images illuminated by an extended luminous source of light, we have proposed a method of so-called selectograms.[13] According to this method, a 3-D image of an object is formed from the light of an extended luminous background thanks to the angular selectivity property of the gratings of a deep 3-D hologram. The experiments on the selectogram recording were carried out with the help of the technique of pseudodeep holograms. This technique allows one to imitate the

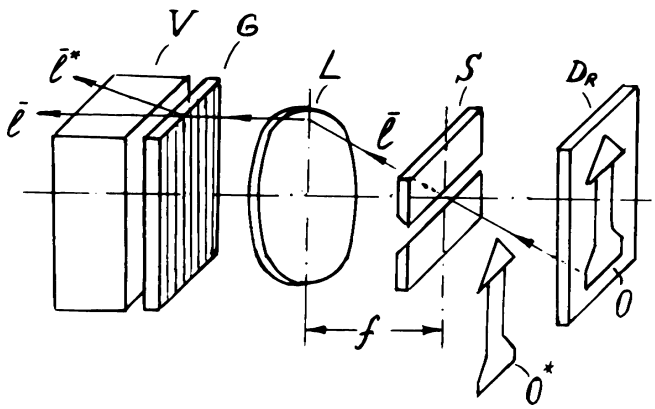

Figure 3. Scheme for the recording of the reference-free selectogram. The rays of the object *O* are filtered by slit *S* in such a way that after passing the lens *L* only the rays that propagate in the horizontal plane remain. The diffraction grating *G* splits from the object wave $\vec{l}$ its twin $\vec{l}^{\,*}$. The result of the interference of the waves $\vec{l}$ and $\vec{l}^{\,*}$ is recorded in a volume emulsion layer *V*. The reconstruction is performed by means of a uniformly illuminated diffusor D_R, the grating *G*, and object *O* being removed.

characteristics of a deep recording when using conventional thin-layered light-sensitive materials.[14,15]

Further study of this method led us to the conclusion that it is possible to form an extended reference source directly from the object wave by splitting this wave into two parts with the help of a diffraction grating, which fits snugly to the surface of a light-sensitive layer.[8,9,16] The method has been referred to as a "reference-free selectogram." In the experiments, the selectograms were recorded both in a real thick-layered light-sensitive material and by using the pseudodeep hologram technique.[9,17]

Consider the mode of action of a reference-free selectogram by comparing the details of the method with the corresponding details of Lippmann color photography. The scheme for recording and reconstructing a reference-free selectogram is presented in Fig. 3. The rays $\vec{l}$ of the light scattered by the object *O* are filtered by slit *S* and then are collimated by lens *L*. As a result, only the rays propagating in the horizontal plane are selected from the radiation scattered by the object and are recorded on the selectogram. The diffraction grating *G* splits a part of the rays of the object wave $\vec{l}$, thus forming its twin $\vec{l}\,^*$. It should be noted here that unlike the case of the Lippmann color photography in which the twin wave *W** propagates in the direction opposite to the object wave *W* (see Fig. 1), in the case of the reference-free selectogram the wave $\vec{l}\,^*$ propagates in the same with the object wave $\vec{l}$ direction (see Fig. 3). As a result of this difference, the interference patterns in these two cases will differ as well. Indeed, while in the case of the Lippmann color photograph the antinode surfaces of a standing wave are parallel to the surface of the photographic layer, in the case of the reference-free selectogram they are close to being perpendicular to this surface.

The reconstruction of the reference-free selectogram is performed with the light scattered by the uniformly illuminated diffusor *D* that is positioned in the place where the object *O* was placed at the recording. The grating *G* and object *O* are removed at the stage of the reconstruction. We show that the selectogram transforms the rays of the diffusor D_R in such a way that they form the image of the object *O** (see also Refs. 13 through 16).

We represent the standing wave that is formed in the volume of the light-sensitive material as a sum of simple 3-D gratings formed as a result of the interference of the rays that differ in their direction of propagation (see Fig. 4). Rays $\vec{l}_1$ and $\vec{l}_1^{\,*}$ correspond to the radiation of the same point of the object and its twin image formed by the diffraction grating *G*. As a result of the interference of these rays a three-dimensional grating originates, the antinode surfaces g_1 being denoted as continuous lines in the figure. Correspondingly, the rays $\vec{l}_2$ and $\vec{l}_2^{\,*}$ that belong to another point of the object from a three-dimensional grating whose antinode surfaces g_2 are denoted by a dashed line. In the case where the object is illuminated by natural light, there will be no cross-interference patterns because the radiation emitted by different points of the object is noncoherent.

At the stage of the reconstruction, the selectogram is illuminated by a bundle of beams of rays that propagate along the directions of the rays of the object wave (rays $\vec{l}_1, \vec{l}_2 \ldots$). Due to the fact that the 3-D gratings have the property of angular selectivity, the grating g_1 selects from the whole variety of incident rays $\vec{l}_1, \vec{l}_2 \ldots$ its "own" ray $\vec{l}_1$ and transforms it into the ray $\vec{l}_1^{\,*}$. Other rays recorded on the selectogram are reconstructed in a similar way. The reconstruction of all the rays means the reconstruction of the three-dimensional image of the object formed by t.hem.

Note that the previously considered process may be carried out in one plane only, because in general a 3-D grating has the property to select from the diffuse background and to transform a whole family of rays that are lying on the surface of a certain cone. This is because the rays scattered by the object are filtered by the horizontal slit *S*, which selects only those rays that lie in the horizontal plane. The 3-D images reconstructed by rainbow holograms show that such an operation does not effect considerably the visual perception of a 3-D image.[18]

Structure of the Reference-Free Selectogram

It is easy to see that the process of reconstruction of the reference-free selectogram is exactly similar to that of reconstruction of a Lippmann color photograph if we replace the notion "distribution of intensity with respect to wavelengths" by "distribution of intensity of rays with respect to the angle of their propagation." Indeed, while being characterized by a high value of spectral selectivity, Lippmann color photograph gratings select from a continuous spectrum and reflect the spectral components of the radiation recorded on the photograph. The gratings recorded on a reference-free selectogram have a high value of angular selectivity and therefore they select from an extended diffuse background and reconstruct the directions of the rays scattered by the object recorded on the selectogram.

The similarity between the Lippmann photograph and reference-free selectogram also extends to the dependence of the contrast of an interference pattern of the radiation recorded on the selectogram on the depth of the recording. Figure 4 explains the process that causes this dependence.

At the surface of the selectogram, the modulation of the wave field of light is completely determined by the grating *G*. As a result, all of the 3-D gratings originating in the selectogram volume coincide with the same grating on the selectogram surface. In other words, the grating *G* is the start for all the gratings recorded in the selectogram. In Fig. 4 this fact is taken into account by making all of the antinode surfaces of the gratings g_1 and g_2 proceed from the same points at the surface of the selectogram.

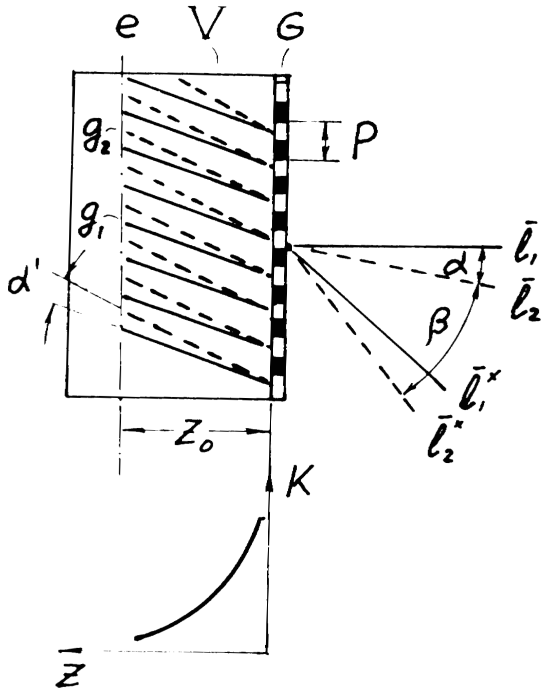

Figure 4. The structure of the standing wave recorded in a volume of a reference-free selectogram. V, volume light-sensitive layer; G, diffraction grating; $\vec{l}_1, \vec{l}_2$, the rays of the object wave; $\vec{l}_1^*, \vec{l}_2^*$, the rays that are split from the object wave by the diffraction grating G; g_1, g_2, antinode surfaces of the standing waves formed by the rays $\vec{l}_1$ and $\vec{l}_2$ of the radiation scattered by the object; and K, the dependence curve of the contrast of the summary standing wave on the depth of the recording z.

This situation is absolutely similar to the Lippmann photograph case for which the intensity of all the gratings originating in a volume becomes equal to zero at the mercury mirror surface, i.e., the mirror surface serves as a start for all the gratings recorded in the volume of the photograph.

The fact that all selectogram gratings coincide on its surface means that, similar to the Lippmann photograph case, the contrast of the interference pattern is maximum on this surface. As the distance from the selectogram surface increases, the contrast of the interference pattern decreases, because the maxima of the intensity of one of the gratings starts to coincide with the minima of the other gratings. In particular, in the place e the maxima of the grating g_2 coincides with the minima of the grating g_1. In general, the dependence of the contrast of the interference pattern K on the distance to the mirror surface is similar to that given in the lower part of Fig. 4.

We estimate the depth of the interference pattern recorded on the selectogram, i.e., the distance z_0 within which the contrast of the interference pattern is not close to zero (see Fig. 4). As a criterion we use the distance at which the contrast of the sum of the gratings g_1 and g_2 formed by the rays $\vec{l}_1, \vec{l}_1^*$ and $\vec{l}_2, \vec{l}_2^*$ become equal to zero. Here we suppose that the rays $\vec{l}_1$ and $\vec{l}_2$ correspond to two opposite edges of the object recorded on the selectogram. As it follows from Fig. 4, the angle α' between two antinode surfaces of the gratings g_1 and g_2 may be taken equal to the angle α between the rays $\vec{l}_1$ and $\vec{l}_2$ in the paraxial rays approximation. In the same approximation the spatial period P of the grating G and the angle β by which it deflects the incident radiation are related in the following way:

$$P \approx \frac{\lambda}{\beta}. \quad (1)$$

The distance z_0 at which the minima of the grating g_1 coincide with the maxima of the grating g_2 is found from the relation

$$z_0 \alpha' \approx \frac{P}{2}. \quad (2)$$

By substituting the value P from Eq. 1 into 2 and setting α' ≈ α, we have:

$$z_0 \frac{\lambda}{2\alpha\beta}. \quad (3)$$

If we take λ = 0.5 μm, the angular size of the object α = 5 deg, and the angle of the deflection of the rays by the grating β = 10 deg, we have

$$z_0 = 12.5\ \mu m. \quad (4)$$

Thus the main contribution into the diffraction efficiency of the selectogram is introduced by a thin layer fitting snugly to the diffraction grating, similar to the Lippmann photograph case when its diffraction efficiency is determined by a thin layer adjacent to the surface of a mercury mirror.

As it follows from the prior consideration, it is very important to provide a close fitting between the light-sensitive layer and diffraction grating when a reference-free selectogram is recorded in natural light. G. Lippmann had solved such a problem by using a mercury mirror. In the reference-free selectogram, it is possible to move the plane of the zero phases into the depth of the layer by using an interferometer composed of diffraction gratings.[17]

Note that it does not follow from relation 3 that the thickness of the photographic layer on which a reference-free selectogram is recorded should be limited by the value z_0 determined as it was considered before. In fact, this layer contains only the information on large-scale details of the objects. The major part of the intensity of the light reconstructed by the selectogram corresponds to these details. The information on the fine details of the object structure extends to a much greater depth. We determine this depth z_0' by taking the angular resolution of the selectogram equal to Δα = 3.6' = 0.001. In this case we suppose that the angle between the rays $\vec{l}_1$ and $\vec{l}_2$ in Fig. 4 is equal to the angular size of the detail of the object that is to be resolved in the object image reconstructed by the selectogram. By substituting the value Δα = 0.001 instead of α in Eq. 3, we find that z_0' = 1.25 mm. Thus to provide the given resolution of the selectogram, it is necessary to record it in a photographic material whose thickness is about 1 mm.

The clearance between the diffraction grating and the selectogram surface badly influences the reconstructed image. As it is seen from Fig. 4, the part of the interference pattern characterized by the greatest contrast will not be recorded on the selectogram. The consequence of this loss is the fact that the lowest spatial frequencies that characterize large-scale details of the object are absent in the image reconstructed by the selectogram. The total brightness of the reconstructed image decreases considerably, the brightness of fine details of the object structure decreasing also, though to a lesser degree.

The experiment on recording the reference-free selectograms of objects illuminated with an incoherent light was carried out by means of the technique of pseudodeep holograms.[16] Here a special interferometer is used that shifted the plane of the zero phase difference from the diffraction grating plane to a certain plane in space. The selectogram is recorded along the line of the intersection of this plane with a surface of an inclined photographic plate. As a result, the reconstructed image also has a form of thin strips reproducing one of the cross-sections of the object with a horizontal plane.

Conclusion

Thus we have shown that the reference-free selectogram and the Lippmann color photograph represent two related methods in which the two sides of the same phenomenon are presented. In one of these cases the three-dimensional gratings have a high spectral selectivity, which allows recording and reproducing the spectral composition of the recorded light. In another case, the 3-D gratings have a high value of angular selectivity which permits recording and reconstructing the angular distribution of the intensity of the radiation scattered by the object, i.e., reproducing its image. Both the Lippmann color photograph and reference-free selectogram require the pattern of standing waves to be recorded in a thick-layered light-sensitive material. It is important for both cases that the light-sensitive material fits snugly to the surface of the optical element, which splits the object wave into two components.

The method of reference-free selectograms opens up a new basic possibility of recording three-dimensional holographic images of objects illuminated by natural light. The main difficulty in realizing this method is related to a small depth of the interference pattern and hence to the necessity to use a light-sensitive material with high modulation properties. Besides that, it is necessary to improve the methods ensuring the close contact of the region of an interference pattern existence with the light-sensitive layer. Strange as it is, but the width of the spectral range of the radiation being recorded does not influence the structure of the reference-free selectogram. As it was shown in Ref. 15, if one records the selectogram with the help of the diffraction grating, which splits the radiation of an object into two symmetric orders, the structure of the selectogram does not depend on the wavelength, but depends on the angular distribution of the intensity of the light only.

Acknowledgments. Financial support for this work was provided by the Russian Foundation for Fundamental Research (grant 95-02-03887-a) and the George Soros International Science Foundation (grants NU-4000 and NU-4300) is gratefully acknowledged.

References

1. G. Lippmann, “La photographic des couleurs,” *Comptes Rendus a Academie des Sciences*, **112**, 274 (1891).
2. G. Lippmann, “Sur la théorie de la photographic des couleurs simples et composes,” *J. Phys.*, 3e série, **3**, 97–107 (1894).
3. Yu. N. Denisyuk, “On the reflection of optical properties of an object in the wave field of the light scattered by it,” Doklady Akademii nauk SSSR (Reports of the USSR Academy of Sciences), **144**(6), 1275–1278 (1962).
4. Yu. N. Denisyuk, “On the reflection of optical properties of an object in the wave field of the light scattered by it,” *Optika I Spektroskopija* (*Op. Spectros.*), **15**, 523–532 (1963).
5. Yu. N. Denisyuk, “Some peculiarities of wave front conjugation by means of a Doppler 3-D dynamic hologram,” *Zhurnal Tekhnicheskoi Fiziki* (*J. Tech. Phys.*) **52**(7), 1338–1345 (1982).
6. P. Saari and R. Kaarli, “Picosecond time- and space domain holography by photochemical hole burning,” *JOSA* **3**(4), 527–533 (1986).
7. Sh. D. Kakichashvili, “Method of polarization recording of a hologram,” *Kvantovaja elektronika* (*Quantum Electron.*), **1**(6), 1435–1441 (1974).
8. Yu. N. Denisyuk, “Recording and reconstruction of three-dimensional images by means of a reference-free selectogram,” *Pis’ma v Zhurnal Tekhnicheskoi Fiziki* (*Lett. J. Tech. Phys.*), **21**(2), 51–57 (1995).
9. Yu. N. Denisyuk and N. A. Savostyanenko, “Three-dimensional imaging by means of a reference-free selectogram recorded in a thick-layered light-sensitive material,” *Opt. Eng.* **35**(2), 554-569 (1996).
10. W. T. Cathey, “Local reference beam generation for holography,” US patent 3415587 (1968).
11. H. J. Caulfield, J. I. Harris, and J. B. Cobb, “Local reference bean generation in holography,” *Proc. IEEE* **55**, 1758 (1967).
12. D. Gabor, “Microscopy by reconstructed wave fronts,” *Proc. Roy. Soc.* (London) **A197**, 454 (1949).
13. Yu. N. Denisyuk, “Recording and reconstruction of 3-D images by means of a selectogram,” *Pis’ma v Sh. T. F.* **18**(2), 15–21 (1992).
14. Yu. N. Denisyuk and N. M. Ganzherli, “On the possibility of the recording and reconstruction of three-dimensional images when using an extended reference source and pseudodeep hologram,” *Opt. Eng.* **32**(5), 958–962 (1993).
15. Yu. N. Denisyuk and N. M. Ganzherli, “Three-dimensional imaging of objects focused on a selectogram surface,” *Opt. Eng.* **33**(10), 3307–3314 (1994).
16. Yu. N. Denisyuk, “Window effect of 3-D imaging by means of a selectogram (reference-free selectogram)” *Practical Holography IX,* S. A. Benton, Ed., *Proc. SPIE* **2406**, 65–73 (1995).
17. N. M. Ganzherli, “Formation of three-dimensional images when using selectogram and diffraction grating,” *Practical Holography IX*, S. A. Benton, Ed., *Proc. SPIE* **2406**, 357–367 (1995).
18. S. A. Benton, “Hologram reconstruction with incoherent extended sources,” *JOSA* **50**(10), 1545A (1969).