My Way in Holography

Yu. N. Denisyuk

ABSTRACT

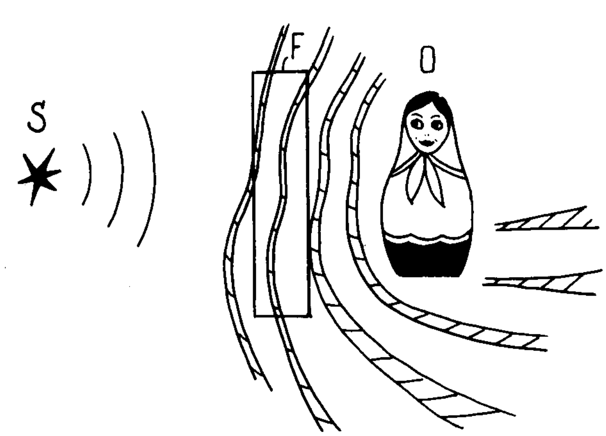
The author reviews the development of 3D holograms recorded in 3D light-sensitive media, while emphasizing his contributions to this field and relating personal moments that accompanied his investigations. He reviews some representations of the mode of action of a 3D hologram and introduces the notion of 'the general phenomenon of holography', which unites various types of holograms. Special attention is given to the Soviet system of organizing research in the field of holography. Some details and perspectives concerning holography applications in imaging techniques and in optical computing are also discussed.

DREAMS

As early as my school years, it was already my dream to work in the field of the fundamentals of physics, i.e. quantum mechanics and the theory of relativity, which was attracting many young people at that time. However, the reality turned out to be quite different from my plans. After graduating from the Institute of Fine Mechanics and Optics (Leningrad) in 1954 and starting work at the Vavilov State Optical Institute (Leningrad), I found myself occupied with very dull work relating to the development of conventional optical devices consisting of lenses and prisms.

At that time, I was very fond of reading science-fiction stories. Among them, I came across the story "Star Ships" by the well-known Soviet writer Yu. Efremov. One of the episodes from this story greatly impressed me. In this episode, contemporary archaeologists, while excavating a site where reasonable creatures from a foreign planet had been hunting for dinosaurs millions of years ago, accidentally found a strange plate. "A thrill pierced the hearts of both professors when the dust had been removed from the surface of the plate. From a deep, absolutely transparent layer, a strange face was looking at them. The face was enlarged by some unknown optical method to its natural size and was three dimensional in its shape. The most striking feature of this face was its unbelievable animation, especially in its eyes."

Fig. 1. Diagram of a spatial standing wave arising around an object O onto which the radiation of the source S is falling. The process of recording a hologram with the help of the reference wave propagating in the direction opposite to the object wave implies that the photoplate F is placed between the source of radiation and the object O, i.e. in the region where the structure of the standing wave is highly compressed. Under these conditions, the structure of the hologram becomes volumetric.



PLANS AND IDEAS

A bold idea occurred to me: why not try to create such photos by means of modern optics? Or, to be more precise, why not try to create photos that reproduce the full illusion of the reality of the scene that has been registered on them?

The first steps in solving this problem were rather simple. It was obvious that it would be possible to completely fool the human visual system and to create the illusion of the appearance of a real object if one succeeded in reproducing the wave field of the light scattered by this object. It was also clear that the problem of wave-field reproduction could be solved if one found a method of registering and reproducing the phase distribution of this field.

Dennis Gabor's work, in which he suggested the principles of holography [1], was unknown to me, and in 1958 I began to work on solving this problem on my own. While following approximately the same route as Gabor, I came up with the idea of revealing the phases of a complicated object wave through interference with a simple reference wave. Proceeding from the Huygens principle, like Gabor, I assumed that the recording and reproduction of a wave field must be accomplished at the surface. Here I encountered the main difficulty in realizing my idea.

Indeed, while Gabor recorded a hologram on a photoplate positioned behind the object, i.e. where the object and reference waves propagate approximately in the same direction, I intended to direct the reference wave in the opposite direction from the object wave. As shown in Fig. 1, this means that the photoplate **F** should be placed between the radiation source **S** and the object **O**. The interference picture (standing wave) of the object and reference waves has a very fine structure in this region. Indeed, the distance

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Received 17 January 1991.

Portions of this article were previously published in Yu. N. Denisyuk, "Certain Features of the Development of Display Holography in the USSR", *International Symposium on Display Holography, Proceedings of SPIE* **1600** (1991) pp. 1600–1621 [32].

Translated by Lydia M. Alexandrova.

Pergamon Press Ltd. Printed in Great Britain.
0024-094X/92 $5.00+0.00

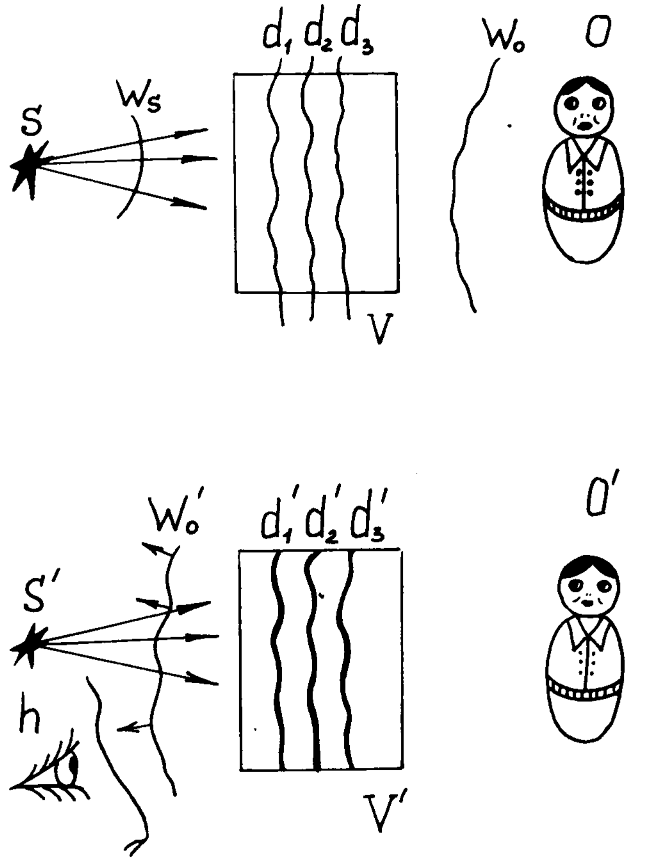

Fig. 2. Diagram of the recording (top) and reconstruction (bottom) of a 3D hologram.

between the antinode surfaces of the standing wave is equal to the half-length of the light wave, or to 0.25 μ in the visible spectrum. To record a plane section of such a structure it is necessary to have a photographic plate with the thickness of the emulsion layer being equal to 0.10 μ, while the layer thickness of real photoplates is equal to 5–10 μ. I considered this difficulty insurmountable, and I was close to stopping my work in this direction.

The way out of this deadlock was provided by the work of G. Lippmann, who had demonstrated at the end of the nineteenth century that a photograph of a volume picture of a plane standing wave had the property to reproduce the spectral composition of the light recorded on it [2]. The following suggestions then occurred to me: Perhaps there is no reason to insist on the surface recording. Perhaps the complicated curves of the antinode surfaces of the standing wave recorded in the volume contain information not only on the spectral composition but also on the phase of the wave fields. Several variants of the theory and experiment confirmed the validity of this suggestion [3–6]. Indeed, it was found that a volume photographic model of a standing-wave pattern actually possesses the most wonderful reflecting properties. It is capable of reproducing the precise values of the phase, amplitude and spectral composition of the object wave. At that time, since I was not aware of Gabor's method and the term 'hologram' introduced by him, I gave my own term 'wave photograph' to this model. In my first papers I used this term as a generalization of the notion 'hologram' onto the third dimension [7].

The Scheme of Recording and Reconstructing a 3D Hologram

If anyone were to ask me for the briefest description of my ideas that I would like to leave to my descendants, I would find it very easy to answer. Of course, the picture of the scheme of the recording and reconstruction of a three-dimensional (3D) hologram would be comprehensible to any reasonable creature.

Figure 2 (top) shows the scheme of the recording of a 3D hologram. The light from a monochromatic source **S** falls on an arbitrary object **O**. While scattered by the object (wave $\mathbf{W_o}$), it interferes with the incident light (wave $\mathbf{W_s}$) and so-called standing waves arise as a result of that interference. The antinode surfaces of the standing wave (places where the intensity of light is maximum) are designated $\mathbf{d_1}$, $\mathbf{d_2}$, $\mathbf{d_3}$. A certain volume **V** filled with a transparent light-sensitive material is inserted in the standing-wave field. After exposure and subsequent chemical processing, a material model of the standing wave is formed inside the volume, with each antinode surface registered by the hologram being transformed into a peculiar curved mirror.

Figure 2 (bottom) presents the process of reconstructing a 3D hologram. The spherical wave $\mathbf{W_s}$ of a conventional white-light source falls onto the hologram **V**. When reflected by each of the aforementioned mirrors, it is transformed into the object wave $\mathbf{W_o}'$. As to the set of subsequent mirror surfaces as a whole, its role is to reproduce the spectral composition of light registered on the hologram. This means that the 3D hologram selects out of the continuous spectrum and reflects backwards only those monochrome components that were recorded on it.

As a result of all these processes, the observer **h**, who perceives waves of the light reconstructed by the hologram, sees the unique colour 3D image of the object, which is impossible to distinguish from the real object. Unlike the Gabor hologram, there are no distortions and no false image in this case; nor are there any limitations to the size of the object.

Is a 3D Hologram a Method or a Phenomenon?

Once the magical properties of a 3D hologram were revealed, the following questions arose: What is the main result achieved? Is a 3D hologram a new method of imaging or a new phenomenon of nature, i.e. a new scientific truth? In spite of the fact that my primary aim was to create a new imaging technique, it was clear to me that a new, interesting physical phenomenon was of prime importance in this case. The difference between the terms 'method' and 'phenomenon' is far from formal. While a method gives only the possibilities that are provided by its inventor, a phenomenon exists according to its own laws and sometimes may be considerably more vast than one would have initially thought.

Having decided that I was dealing with a phenomenon, I gave it a rather complicated title: "The phenomenon of the reflection of optical properties of an object in the wave field of light scattered by it" [8]. The idea underlying this title can be summarized as follows. We have a right to compare only those things that are similar and that really exist. A material object and its material hologram both really exist. The hologram, after being placed side by side with the object, becomes its optical equivalent (in respect to the radiation by which it has been recorded). These two objects are related by the same wave field; hence, the optical properties of the object are reflected in some way in the light-wave field. To some extent, this process is similar to the one depicted in the scene from Dante's *Inferno* in which a man and a serpent, while looking at each other, are transformed: the man into a serpent and the serpent into a man.

When summarizing the information on the hologram that was known to me by that time, I presented the general phenomenon of holography in the following way (Fig. 3) [9]. The most complete information on the wave field of the object is contained in an infinite 3D picture of the standing wave surrounding the object **O**. All the known types of holograms can be considered fragments of this picture. The property of these fragments to reconstruct wave fields is degraded according to the decrease in the fragment size. In particular, the limited volume **V** of the initial picture preserves the property to reconstruct the phase, amplitude and spectral composition of the object wave; however, in this case, the accuracy of the reconstruction is limited. A plane section δ of the initial picture does not have the property to reproduce the spectral composition. Its ability to reproduce phases of the wave field is also limited, which results in the appearance of a conjugate image $\mathbf{O}^*$. A further decrease in the hologram size, up to the fragment $\Delta\delta$, increases the blur of the points in the reconstructed image of the object.

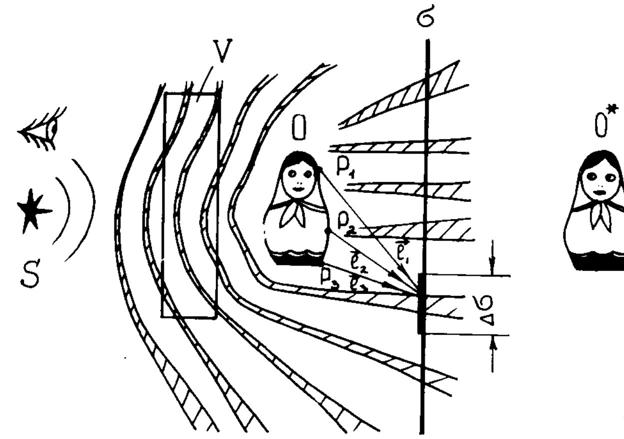

Fig. 3. Diagram of the general phenomenon of holography.

MODE OF ACTION OF A 3D HOLOGRAM

As a rule, a physical phenomenon can be considered from different points of view. In physics, the coincidence of the results of different versions of a theory is one of the ways to prove its validity. In addition, each version of a theory usually reveals its individuality in reflecting the most obvious and simple aspect of some part of the process. I have proven the existence of the given phenomenon by using four different variants of the theory of holography; these are the wave, beam, operator and Fourier variants [10]. The main disadvantage of these variants is that they use the Born approximation, and thus, they are able to present quantitative results only when the diffraction efficiency of a hologram is small enough. However, this approximation predicts the most important properties of a 3D hologram rather well.

INITIAL EXPERIMENTS

The first question that arose while I was preparing the experiment seemed quite simple: What light-sensitive material should be chosen for the recording of a 3D standing wave? Although plenty of time has passed since then, this question remains the primary one. Light-sensitive materials have changed each other: I have to work with silver-halide plates, photopolymers, mixtures of gases and liquid crystals; nevertheless, their role in holography has remained decisive.

My first encounter with light-sensitive materials disappointed me. Having repeated the procedure for the fabrication of super-resolving plates proposed by G. Lippmann [11] and, after him, by E. Valenta [12] and by H. E. Ives [13], I came to the depressing conclusion that the sensitivity of such photoplates is negligibly low. It seems to me that the photochemists of the beginning of this century possessed a 'know how' that they did not publish in their papers.

Luckily for me, I was well acquainted with a specialist in the photochemistry of silver-halide photoplates, the late R. R. Protas. She recalled that someone had discovered that a bath of a solution of triethylnolamine could double or triple the sensitivity of ready-made photographic plates. The results from applying this process to Lippmann photoplates was impressive, as the sensitivity increased 10^3 times and became sufficient for the experiment to be carried out. In spite of that, I tried to improve these photoplates even more: in total, I carried out 200 syntheses of emulsions, varying the concentration of silver, the spectrum region of sensibilization, the sizes of the grains of silver halide and the thickness of the emulsion layer [14].

I began experimenting with the recording of 3D holograms in 1958. Since the laser had not yet been invented, I chose a high-pressure mercury-vapour lamp as the light source. The light of this lamp was collimated, and from it the spectral component of the wavelength $\lambda = 5460$ Å was selected through the use of a filter. The longitudinal coherence of this light was equal to several tenths of a millimeter, which was why the depth of the object relief needed to be limited to the minimum. This requirement essentially limited the choice of objects. As a result, I chose convex mirrors with a large curvature radius (from 2×10^3 to 3×10^2 mm). The first experiments on recording such objects were carried out at the end of 1958 and demonstrated that the 3D holograms that are obtained are indeed the optical equivalents of convex mirrors. For the first time, I could relax: my theoretical speculations had a practical base.

To this day, I still regret that I did not think of choosing a metal-coin relief as an object. If I had, I would have immediately reached my initial goal, i.e. to prove the possibility of using holography to develop an imaging technique that could create an illusion of the real existence of the objects depicted. My mistake proves once more the truth that, in holography, the choice of the object essentially determines the success of both the scientific and the artistic investigations.

Disappointments and Struggle

The first stroke of fate was my becoming acquainted with Gabor's work [15]. By an amazing coincidence, on the very day I had planned to consider a scheme that resembled Gabor's, I found lying on my table a collection of reports that a colleague had brought from a conference he had attended in Stockholm. While looking through it, I suddenly came across an article by H. M. A. El-Sum, whose ideas struck me as suspiciously familiar.

When I looked at the references, I found Gabor's initial paper; I was shocked. Of course, Gabor's work differed a great deal from mine, and the recording scheme was less complete. However, the formulation of the idea presented in the abstract left no doubt that the author had deeply understood the part played by the reference wave when recording a phase of the radiation. As a result, I had to make a few changes to my almost-finished article and to include a reference not only to Lippmann's work but also to Gabor's.

I cannot say that it was pleasant for me to discover that Gabor's work had been done before mine. Nevertheless, the fact that I was not alone in my thoughts was pleasant. Less pleasant were the events that followed my attempts to publish my results. I suddenly discovered that I, a young researcher, had many powerful enemies, including an academician, a corresponding member of the Academy of Sciences and several doctors of science. Fortunately, I also had my supporters. Academician V. P. Linnik helped me most of all by recommending that my article be published in the journal *Reports of the USSR Academy of Sciences* [16], which was of decisive importance for me. Publication of other articles [17] that had been sent at the same time as the first one was considerably delayed. When the last article was published in 1965, the editorial staff deliberately changed the date of its arrival.

My position improved when holography became famous as a result of the publication of E. N. Leith and J. Upatnieks's paper on the recording of a 3D image of a chessboard [18]. The subsequent scientific boom in the field of holography favoured my being awarded the Lenin Prize, the USSR supreme scientific award, in 1970.

Also in 1970, I was elected a Corresponding Member of the USSR Academy of Sciences. The positive references to my work that were made to M. V. Keldysh, president of the academy, during his visit to the United States, greatly contributed to my successful election.

My struggles with conservative colleagues and my subsequent triumph had a bad influence on my investigations in the field of holography. During these long years, I was bombarded by journalists and numerous beginners who wished to become involved with holography. These were not my best years.

Some Peculiarities of Scientific Research in the USSR

The story about the further development of holography in the USSR would not be comprehensible unless I explained the principles of organizing scientific research in this country. Unlike many other countries, the Soviet Union still has an Academy of Sciences—a special state institution designed to be in charge of scientific investigations. Within the Academy of Sciences, there is a vast system of special research institutes, each of which, as a rule, deals with various problems. In addition, the academy has a system of scientific councils, with each council uniting scientists from different institutes who are dealing with the same problem.

In general, the effectiveness of the Academy of Sciences is far from perfect; however, in my opinion, this is not due to the principles at its base. The USSR Academy of Sciences presents certain possibilities to those who indeed want and are able to develop science.

The Scientific Council on the Problem of Holography is responsible for all investigations in the field of holography. This institution has no financial support. Its task is to organize conferences and seminars and to set up meetings to discuss perspectives in the development of this or that problem. As a rule, those present at these council meetings were holographers, specialists in the field of information processing, and chemists working both in the system of the Academy of Sciences and in industry. The routine of our meetings was like this. We would enthusiastically discuss, for example, the desired properties of photoplates designed for image holography, or we would consider a new phenomenon of energy transfer by a dynamic hologram and the measures that should be taken to provide its development. Afterward, we would realize that we had no financial or administrative resources for the immediate realization of our ideas—and we would depart greatly disappointed.

Nowadays, it has become evident that our meetings and talks were not in vain. As a result of our having discussed the requirements for light-sensitive media, photochemists have taken an interest in this problem and have organized the manufacturing of photoplates appropriate for holography. The discussion of new phenomena considerably stimulated scientists' interest to work in new scientific fields. So-called 'dynamic holography' and 'polarization holography' have been developed in this way.

Image Holography and Other Applications

Being able to demonstrate image holograms makes things much easier for a holographer, even if dealing with the development of optical instruments. My laboratory had to exhibit image holograms when looking for financial support, too. At first, we tried to demonstrate holograms recorded by the Leith and Upatnieks method. However, it soon became clear that this was troublesome and expensive. Each hologram required its own laser, and these lasers needed to be delivered to the exhibitions and serviced during the entire time of operation.

Experiments on the recording of reflection 3D image holograms were also carried out in our laboratory; however, due to a lack of imagination, coins, medals and other objects of small depth were recorded on these holograms. The first large-scale reflection 3D hologram with an image of a marble statuette was obtained by G. A. Sobolev in 1967 at the Cinema-Photo-Institute (Moscow). After this, intensive studies were initiated on the development of Lippmann photoplates, which were necessary for the registration of these holograms.

One type of Lippmann photoplate, the LOI-2, was developed at the S. I. Vavilov Optical Institute by R. R. Protas, who continued earlier investigations on

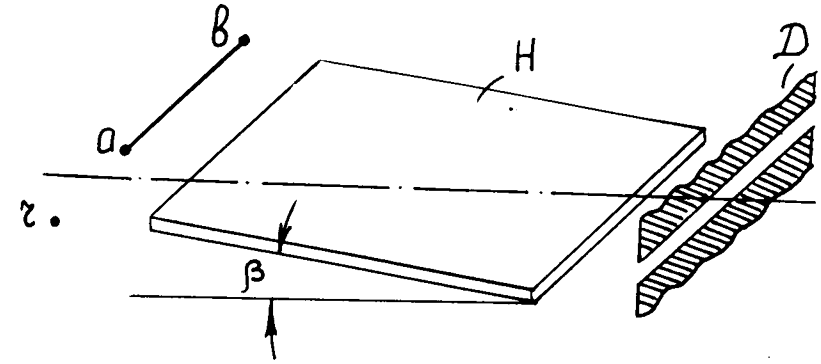

Fig. 4. Diagram of the recording and reconstruction of a pseudodeep inclined hologram. H represents a 2D thin hologram; β, the angle of the hologram inclination to the optical axis of the system; ab, a line object; τ, a reference source; D, a slit that selects the beams lying in the object plane out of the set of beams of the reconstructed light.

the development of photoplates suitable for recording 3D holograms. The sensitivity of these photoplates is equal to 0.5×10^{-3} J/cm^2 and the diffraction efficiency reaches the value 50%. Another type of Lippmann photoplate, the PE-2, was developed in Moscow by N. I. Kirillov working together with the holographer G. A. Sobolev [19]. The sensitivity of these photoplates is 10 times greater than that of the LOI-2 at the same, or even higher, value of the diffraction efficiency. As a rule, holographers prefer to use the PE-2 photoplates, though their parameters are less stable than those of the LOI-2 photoplates.

By using the photoplates developed in the described way, a few groups of holographers in Leningrad, Moscow, Kiev and Tbilisi have produced striking large-scale reflection holograms, which are widely displayed at various exhibitions. For many years, these holograms have retained the leadership in their field.

By 1968, our laboratory had begun to develop a technique for recording volume holographic portraits of people [20]. At initial stages of the study, the registration was accomplished by using a ruby laser. However, inconveniences associated with needing to touch up the client's lips with a blue lipstick (which was unavoidable when recording in red light), together with the difficulties of producing high-quality ruby crystals, made us turn to taking portraits in the green light of the neodymium laser, a frequency-doubled laser (λ = 5300 Å).

Here, the initial hologram is recorded using the Leith-Upatnieks scheme; afterwards, it is copied in off-axis beams so that the final portrait can be reconstructed using a conventional source of white light [21]. Many high-quality portraits were obtained in this way. Unfortunately, these portraits somewhat lack that peculiar animation that was specific to the portrait described by the science-fiction writer Yu. Efremov. The experiments carried out in the last few years showed that the transfer to taking colour portraits could considerably improve the impression produced by these phantom images of people.

In addition to studying the general properties of 3D holograms and working on the development of 3D image holograms, my colleagues and I have carried out a number of investigations of another sort. Among them, it is worth mentioning the development of a method for obtaining a holographic portrait of the function of the spatial coherence of light. Such a portrait visualizes a 4D function by using two spatial coordinates of the reconstructed image and two spatial coordinates of a point on the hologram through which the observation is made [22].

A similar approach has been used for registering the picture of the temporal coherence of light. Here the hologram reconstructs the picture of the wave train of the radiation emitted by the laser. When changing the point of the hologram through which the observation is made, the reconstructed image of the wave train is shifted along the trajectory and reproduces the picture of the flight of this wave train across the space [23,24].

Among other investigations, I could mention the development of a method for recording holograms of noncoherent objects by strobing the travelling picture of interference [25,26]. Such methods can be used to obtain images of distant celestial bodies.

In 1988 I changed workplaces and now work at the A. F. Ioffe Physical-Technical Institute of the Academy of Sciences of the USSR. At this Institute, investigations in solid-state physics, the physics of semiconductors and microelectronics are carried out. This change of workplace coincided with a growth of general interest in applying optics to computing. As a result of these events, I became interested in studying the possibilities of applying holography to optical computing.

The most general approach to this problem involves the idea that the intellect is not a storehouse of truths but a universal system of connections and comparisons of different objects and events. From this point of view, wires along which electrical signals propagate are, strange as it may seem, one of the main intellectual devices of the electronic computer.

Holography suggests another type of interconnection. In this case, signals are transferred by propagating the superimposed waves in space, the connection between these waves being accomplished with the help of gratings that are also superimposed. A deep hologram is the most perfect element for connecting different waves, because the 3D gratings that compose it unambiguously connect definite pairs of waves and do not respond to any other waves. However, the application of such holograms encounters great difficulties due to the necessity to produce light-sensitive materials of great thickness (of the order of several millimeters or more).

To avoid the problems associated with the recording of extremely deep holograms, we have proposed a method of so-called pseudodeep holograms, according to which the holograms are recorded in a conventional thin-layered light-sensitive material while the 3D effects are achieved by limiting the recording to one-dimensional pages of information [27,28].

The scheme for recording pseudodeep holograms is shown in Fig. 4. A light-sensitive layer **H**, on which a fan of beams propagating from a line object **ab** is recorded, is placed at a small angle β relative to the plane of the propagation of these beams. A slit **D** is situated behind the hologram. During reconstruction, this slit selects the beams that are lying in the object plane and removes all the others. As a whole, it is a specific combination of an optical device and a hologram.

Using this method, we have made a number of operations that are characteristic of a deep 3D hologram; in particular, we have accomplished associative reconstruction, whereby a part of the object reconstructed the whole image recorded on the hologram [29]. We have also made multiple recording holograms onto one and the same photomaterial region [30] and conducted experiments involving the reconstruction of an object wave to a point-reference source [31]. In the future, we expect to be able to apply the method of the pseudodeep hologram not only to information processing but also to the recording and projecting of volume images in cinema and television.

CONCLUSION

In general, the number of points of view regarding one and the same subject is equal to the number of people living on the planet. To my mind, holography is first of all an important physical phenomenon that has already manifested and proven its obvious inclination and ability to exactly reproduce various wave fields. Since every material particle of our world is accompanied by a wave, one may suppose that holographic phenomena underlie the very base of the structure of the world.

The perspectives of the technical applications of holography are determined mainly by success in the development of different light-sensitive media. In particular, the possibilities of applying holography to computing techniques in such fields as the creation of associative memory devices and quick-switching interconnections depend on the possibilities of developing highly sensitive reversible light-sensitive media capable of operating at a rate near 10^{-12} sec. The achievements of modern physics in such areas as quantum holes, supergratings and spectral-selective media provide hope for quick progress in the development of such light-sensitive media.

The immediate future of reflection 3D holograms should bring a considerable increase in the sensitivity and effectiveness of Lippmann photoplates and photopolymer systems. This will open up the way to the development of very large-scale colour holograms, which will decorate the interiors of buildings and will be widely used as copies of museum exhibits.

The development of holographic cinematography and television remains a major problem for holography, one that will be solved through the wide application of computers and optoelectronics. The principles of contemporary holography and quantum electronics permit the possibility of creating unusual photographs capable of reconstructing 'alive' moving volume images that will reproduce brief scenes of real life according to a program coded in the molecular structure of a light-sensitive medium.

Acknowledgments

The author wishes to express his gratitude to R. R. Protas for timely assistance in researching Lippmann photographic plates, to N. M. Gopstein for consulting on the Maxwell theory, to A. E. Elkin, V. P. Linnik, L. A. Artsimovich and M. V. Keldysh for their timely appreciation of my first works on holography, and to V. Rongonen for assisting with experiments on Lippmann emulsions. Special thanks to my colleague Lydia M. Alexandrova, who has translated all my papers into English.

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