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Microholographic Storing of Information

In this work an analysis of the quantitative relations between the basic magnitudes characteristic for the microholographic information storing has been given and their influence on the image information quality during information processing discussed. Besides, the experimental data illustrating the theoretical conclusions are delivered.

1. Introduction

Classical methods of information storage are based on photographic registration of considerably demagnified two-dimensional images of arbitrary objects. The contemporary technical means enable a demagnification down to the ratio 200:1. This became achievable when the photographic emulsions of resolution as high as several thousands pair lines per milimeter became available and when practically aberration-free optical systems of high quality appeared on the market. This method enables the registration of about 3000 pages on the area 100×150 mm^2 [1]. However, the due technique is complex. Beside the high quality optics a suitable vacuum chamber is required to assure the requested prefect purity of the imaging conditions. Also the printing procedure for microfilms made in this way imposes similar requirements. The process of information recovery is a complex as that of recording.

The holographic method of registration removes all the inconveniences associated with the classical ways of information storage without diminishing the information capacity. However, the problem of coherent noise elimination appears due to coherent light source used. This noise is generated in the information reconstruction step as a result of undesirable diffraction of light on the local extremes of the hologram transmittance produced by interference of the light in the subject beam (intermodulation), another source of noise being connected with the registration in the non-linear part of the light-sensitive material characteristics.

A generalized two-dimensional diffraction grating is produced on the hologram, which is characterized by some spatial carrier frequency, determined by the mean angle between the subject and reference beams and modulated by the frequences defined by the angular dimensions of the object to be holographed. The spatial frequency of the hologram is responsible for the angular propagation of the reconstructed wave, while the contrast of the interference fringes determines the wave amplitude at a given angle.

In the process of holographic recording of information on very small areas the Fourier transforming of the object function is usually performed by applying a suitable system. Holographic recording takes place in the focal plane of this system. As it is well known the zero order diffraction of the light diffracted on the subject structure is responsible for the constant background in the reconstructed image, while the higher diffraction orders determine the definition of all the edges existing in the image or, to say it more generally, the contrast in the image function. Holographic recording in this plane of the separable diffraction orders plays an important part in minimizing the intermodulation coherent noise. Reduction of the holographic recording area in the Fourier plane results in eliminating of the undesired details like scratches and tiny contaminations occuring in the object but simultaneously reduces the definition of the edges in the informational content of the image. Thus a respective optimization of the registration area, which depends additionally on the type of imaging recording device or medium, appears to be unavoidable.

When contrasting the classical way of information collecting with that of microholographic type the following features of the latter should be emphasized:

- insensitivity to dust,
- insensitivity to local emulsion imperfections,
- lack of any optical systems in the information reconstruction process,

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— no necessity of precise recording plate alignment with respect to the optical system,

— simple contactless copying of the microholograms,

— an offered possibility of recording and reconstruction of three-dimensional subjects.

The purpose of this paper is to analyze the quantitative relationships between the basic quantities characterizing the microholographic storing of information and their influence on the information quality in the information processing procedure.

2. Technique of Microhologram Recording and Reconstruction

At present, two methods of microholographic information collecting are in use, which differ from each other by the manner of recording and reconstruction. One of them is presented in Fig. 1 and consists in holographic recording in the spatial

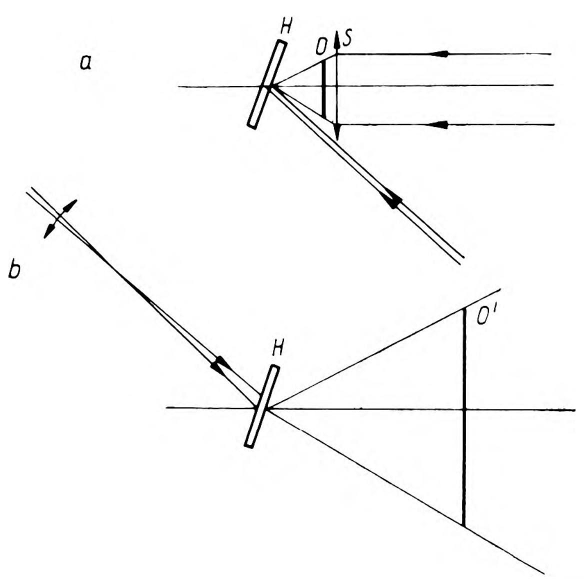


Fig. 1. Holographic recording (a) and reconstruction (b) of the information; H — holographic plate, S — objective, O — object, O' — image of the subject

frequency plane of the object positioned in the plane of the lens and in reconstructing its image on a screen by using a beam being a mirror reflection of that used for recording [2] while the divergence (convergence) ratio of both beams determines the magnification achieved. An advantage of this way of registering is an offered possibility of information recovery within a broad range of optical magnifications. Its fundamental failure, however, lies in aberrations which appear if the image is reconstructed from the hologram by help of a beam of different divergence (convergence) than that of the recording beam.

Another way of recording and reconstructing the microholograms is shown in Fig. 2 and consists in realizing the holographic registration in the focal

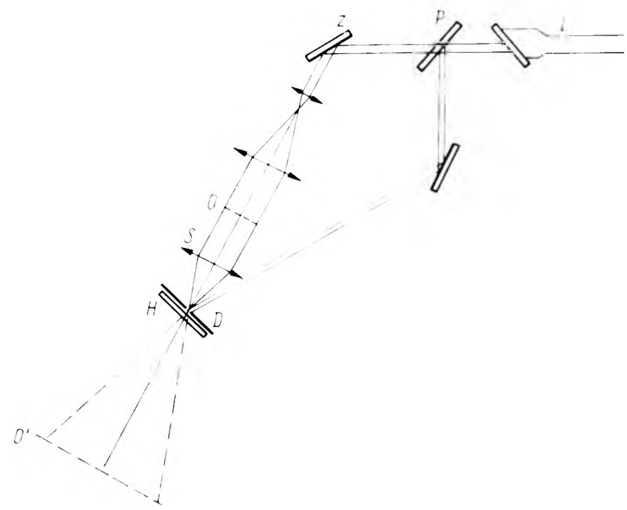


Fig. 2. Scheme of a setup for holographic information storing: L — laser, P — beam splitter, Z — mirror, S — objective, H — holographic plate, D — diaphragm, O — transparency, O' — real image

plane of the optical system which produces a magnified real image. Here, the reconstruction of the magnified image is performed by using a beam identical with the recording one [3]. This technique of microholographic recording of the information proved to exhibit a basic priority over that described earlier and was applied in the experimental work discussed in this paper. Though it is usually required that the high quality optical elements be used in this system (due to great magnification), no necessity occurs of using the optical elements for aberration compensating in the reconstructing setup.

3. General Form of the Image Function

Mathematical analysis of the quantitative relations between the basic magnitudes characteristic for the microholographic recording of information and estimation of their influence on the information quality during the data processing were based on the well-known elementary model of the Fresnel diffraction [4]. According to this model the complex amplitude distribution of the light wave in a plane of interest may be expressed as a convolution of the amplitude A_0 determined in a given plane $z = z_0$ and the normalized Fresnel function Φ, i. e.

$$A(x,y,z) = A_0(x,y,z_0) * \Phi(x,y,z-z_0)$$
$$= A_0(x,y,z_0) * \frac{e^{ik(z-z_0)}}{i\lambda(z-z_0)} \exp\left[ik\frac{x^2+y^2}{2(z-z_0)}\right]$$
$$= \frac{e^{ik(z-z_0)}}{i\lambda(z-z_0)} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} A_0(\xi,\eta,z_0) \times \exp\left[ik\frac{(x-\xi)^2+(y-\eta)^2}{2(z-z_0)}\right] d\xi d\eta, \tag{1}$$

where $k = \frac{2\pi}{\lambda}$ and λ is the wavelength of the light used.

In Fig. 3 a scheme of the optical system is shown, in which the microholographic information storage

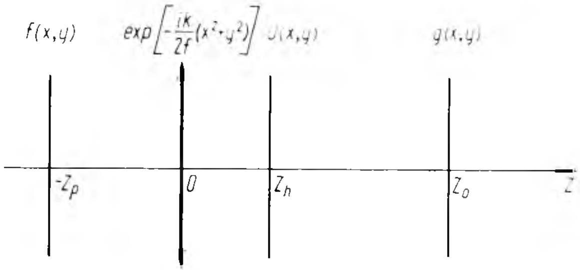


Fig. 3. Diagram of the optical system from Fig. 2

is realized. The coordinate system has been chosen in such a way that the z-axis determines the direction of wave propagation and its intersection point with the lens plane defines the origin of this system. The lens itself is assumed to be infinitesimaly thin so that its functioning may be described by a quadratic phase function $\exp\left(-ik\frac{x^2+y^2}{2f}\right)$, where f denotes the focal length. In the object plane $z = -z_p$ the object to be registered is described by the function $f(x,y)$. The light sensitive material located in the plane of registration ($z = z_h$) is screened by a circular diaphragm of radius R, whose operation is described by the function $U(x,y) = 1$ for $x^2+y^2 \leq R^2$ and $U(x,y) = 0$ for the rest of the x,y-plane. The information reconstructed from the obtained hologram is next read out in the image plane $z = z_0$ on the screen (ground glass). The light amplitude in this plane is of the form

$$g(x,y) = \{[f(x,y) * \Phi(x,y,z_p)]e^{-ik\frac{x^2+y^2}{2f}} * \Phi(x,y,z_h)\}\, U(x,y) * \Phi(x,y,z_0-z_h). \tag{2}$$

After changing suitably the succession of integration and taking account of the formula

$$\frac{1}{f} = \frac{1}{z_p} + \frac{1}{z_0} \tag{3}$$

as well as introducing the magnification factor

$$M = \frac{z_0}{z_p} \tag{4}$$

we obtain the following distribution of the light wave amplitude in the real image reconstructed from the hologram of the circular shape and radius R:

$$g(x,y) = \frac{R}{M\lambda(z_0-z_h)} \exp\left\{ik\left[z_p+z_0+\frac{x^2+y^2}{2(z_0-z_h)}\right]\right\} \times \left\{f\left(-\frac{x}{M},-\frac{y}{M}\right) \times \exp\left[\frac{ik}{2M^2}\cdot\frac{(f-z_h)(x^2+y^2)}{f\cdot z_h+z_p(f-z_h)}\right] * \frac{J_1\left(\frac{kR}{z_0-z_h}\sqrt{x^2+y^2}\right)}{\sqrt{x^2+y^2}}\right\}, \tag{5}$$

where J_1 denotes the Bessel function of the first kind and first order.

In a similar way the amplitude $g(x,y)$ for the image reconstructed from the hologram of rectangular shape with sides $2a$ and $2b$, respectively, may be calculated. In this case

$$g(x,y) = -\frac{1}{\pi^2 M}\exp\left\{ik\left[z_p+z_0+\frac{x^2+y^2}{2(z_0-z_h)}\right]\right\} \times \left\{f\left(-\frac{x}{M},-\frac{y}{M}\right)\exp\left[\frac{ik}{2M^2}\cdot\frac{f-z_h}{fz_h+z_p(f-z_h)}(x^2+y^2)\right] * \frac{\sin\left(\frac{ka}{z_0-z_h}x\right)}{x}\cdot\frac{\sin\left(\frac{kb}{z_0-z_h}y\right)}{y}\right\}. \tag{6}$$

If the surface of the holographic record is unlimited ($R\to\infty$ or $a, b\to\infty$) then exploiting the well-known relations

$$\lim_{\sigma\to\infty}\frac{\sigma J_1(\sigma r)}{2\pi r} = \delta(r)$$

and

$$\lim_{a\to\infty}\frac{\sin(ax)}{\pi x} = \delta(x),$$

where δ denotes the Dirac delta function, we end up with the formulas (5) and (6) in the form

$$g(x,y) = \frac{1}{M} f\left(-\frac{x}{M}, -\frac{y}{M}\right) \exp\left\{ik\left[z_p + z_0 + \frac{x^2+y^2}{2(z_0 - f)}\right]\right\}. \quad (7)$$

The appearance of the factor $1/M$ in this formula indicates that the light intensity in the image is inversely proportional to the squared magnification

$$|g(x,y)|^2 = \frac{\left|f\left(-\frac{x}{M}, -\frac{y}{M}\right)\right|^2}{M^2}. \quad (8)$$

The phase factor in the expression (7) determines the character of the image light wave propagation. This is a divergent spherical wave emerging from the focus of the optical system. The form of the argument of the object function indicates that the image is reversed and magnified.

If the holographic registration will be carried out in the Fourier plane ($z_h = f$) the image function for the circular aperture will be given by the expression

$$g(x,y) = -\frac{R}{\lambda f M^2}\exp\left\{ik\left[z_p + z_0 + \frac{x^2+y^2}{2(z_0-f)}\right]\right\} \left[f\left(-\frac{x}{M}, -\frac{y}{M}\right) * \frac{J_1\left(\frac{kR}{Mf}\sqrt{x^2+y^2}\right)}{\sqrt{x^2+y^2}}\right]. \quad (9)$$

From the formula (9) the invariance of the image function with respect to R and f may be concluded, if $R/f = \text{const}$. This indicates that theoretically it is possible to diminish the region of holographic registration without any influence on the reconstructed image quality if only reducing by the same factor the focal length of the optical system, realizing the Fourier transformation. Evidently, the above conclusion is justified for arbitrary shape of the microhologram surface. However, the reduction of the focal length of the optical system involves usually higher requirements on the aberration correction.

4. The Case of the One-Dimensional Zero-One Type Object Function

In most cases informations to be stored are given in the form of a text, a table, a graph etc. Thus, they are the object functions of the zero-one type. For the one-dimensional case the image function reconstructed from a linear hologram of length $2a$ takes the following form:

$$g(x) = f\left(-\frac{x}{M}\right)\exp\left[\frac{ik}{2M^2}\frac{f - z_h}{f z_h + z_p(f - z_h)}x^2\right] * \frac{\sin\left(\frac{ka}{z_0 - z_h}x\right)}{x} \quad (10)$$

with the accuracy of a constant factor. If the zero-one function of the form:

$$f(x) = \begin{cases} 1 \text{ for } x \in \langle -x_0, x_0\rangle \\ 0 \text{ for } x \notin \langle -x_0, x_0\rangle \end{cases} \quad (11)$$

is recorded on a hologram in the Fourier plane ($z_h = f$) then the image function is described by the following integral:

$$g(x) = \int_{\frac{x}{M} - x_0}^{\frac{x}{M} + x_0} \frac{\sin\left(\frac{ka}{f}\xi\right)}{\xi}\, d\xi. \quad (12)$$

Graphs of the functions (11) and (12) are presented in Fig. 4. Their comparison gives an insight in the qualitative character of the information deformation, which occurs in the process of its microholographic recording and reconstruction.

The quantitative measure of the deformation may be defined as the quotient of the spatial frequency ν_0 of the object function and the oscillation frequency ν of the function (12):

$$\frac{\nu_0}{\nu} = \frac{f\lambda}{2x_0 a}, \quad \nu_0 = \frac{1}{2Mx_0}, \quad \nu = \frac{a}{Mf\lambda};$$

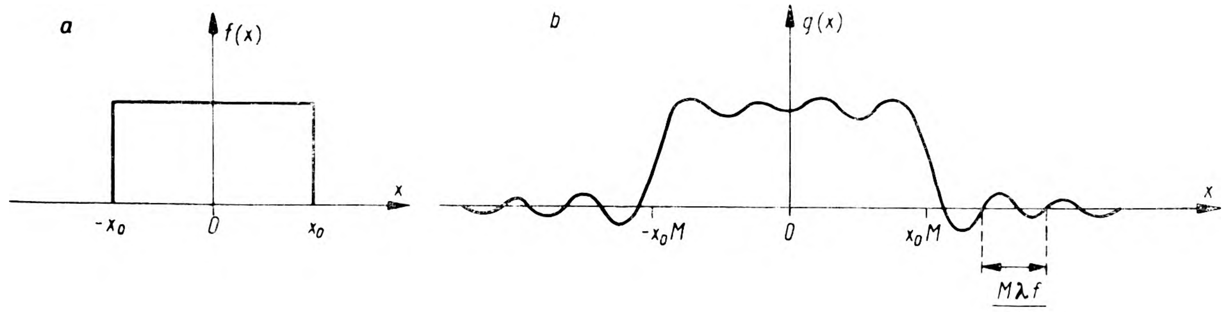


Fig. 4. Graphs of the object function (a) and the image function (b)

5. An Influence of the Light Sensitive Material Characteristics on the Quality of the Holographic Imaging

There appears a necessity of taking into account the effect of the photographic material characteristics on the exposure conditions in the process of microholographic information storing. Highly non-uniform light intensity distribution in the spectrum plane causes an overexposure in the optical axis region and an underexposure in the region of higher diffraction orders, especially, if conventional light sensitive materials are used. Lack of higher diffraction orders worsens the definition of edges, while absence of the zero-order diffraction in the recorded spectrum reduces the constant component in the image density. Both the effects reduce the information content in the image. For this reason the exposure is made in a plane slightly shifted with respect to the Fourier plane. This assures a more uniform light intensity distribution on the emulsion but simultaneously causes an undesirable increase of the coherent noise due to the appearing intermodulation.

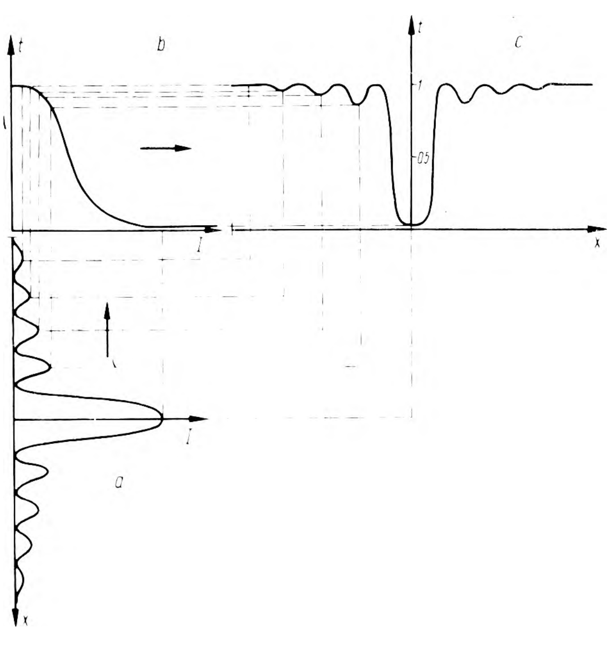


Fig. 5. Influence of the photographic emulsion non-linearity (b) on the Fourier spectrum deformation of the zero-one type function in the process of recording; (a) – a spectrum created by the optical system, (c) – spectrum recorded on the emulsion

Fig. 5 shows the Fourier spectrum deformation of a rectangular object function caused by the non-linear characteristics of the light sensitive material.

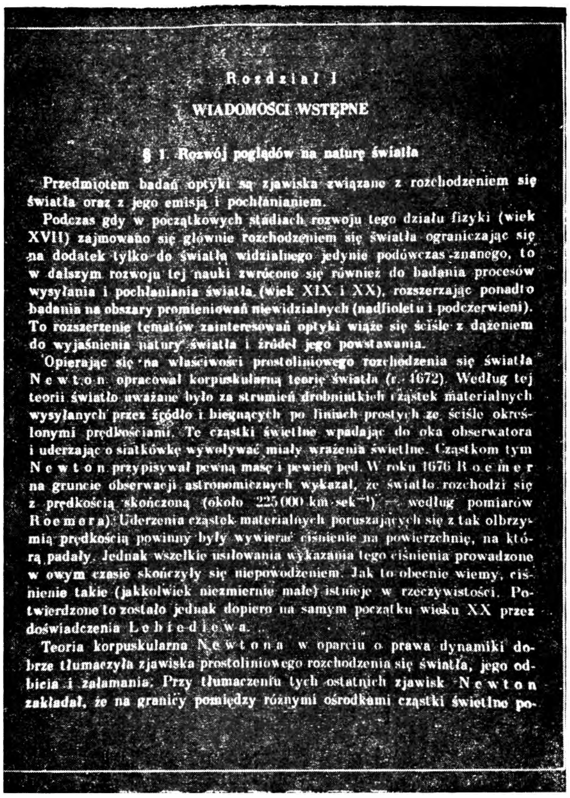
6. Discussion of the Experimental Results

The scheme of the setup used for experimental examination of the microholographic information recording is presented in Fig. 2. The source of coherent light was a single-mode He–Ne laser (λ = 632.8 nm). The subject, having the form of a negative transparency of a printed page* of sizes 15 × 12 mm was illuminated immediately by a plane wave. The objective of a 50 mm-focal length was positioned in such a way with respect to the transparency that it produces a demagnified real image in the optically conjugate plane. A circular diaphragm of 1.5 mm-diameter was introduced into the focal plane with a Kodak 649 F holographic plate located immediately behind it. As a reference beam an unformed laser beam was used. The holograms were reconstructed with the help of the same setup by using the reference beam. The image was recorded on a holographic plate placed in the image plane.

The choice of the transparency type (positive or negative) was considered from two view points: limited region of the straight-liness of the light-sensitive material characteristics and the quantity of the light intensity in the information content (characters) of the reconstructed image. The area of the characters occupies about 10% of the whole text area. Hence the value of the light intensity in the negative transparency Fourier spectrum is by one order of magnitude less than that appearing for a corresponding positive transparency. Consequently, a considerable reduction of the non-linearity effect of the holographic material appears when recording a spectrum of a negative in comparison to that occuring for a positive. On the other hand for the negative the total energy of the light beam diffracted on the hologram in the reconstruction step and producing a real image is distributed only across the area of the letters which rises the contrast in the holographically reconstructed image by one order of magnitude as compared with that for the positive.

In Fig. 6 an image of a transparency is shown, which is produced directly by the optical system situated along the subject beam trace with a diaphragm in the focal plane. The high quality of this image indicates only a slight influence of the hologram area reduction realized in the experiment on the information for the setup parameters specified

*) A page from the Textbook by Stefan Pieńkowski „Experimental Physics-Optics" (in Polish).


Rozdział I

WIADOMOŚCI WSTĘPNE

§ 1. Rozwój poglądów na naturę światła

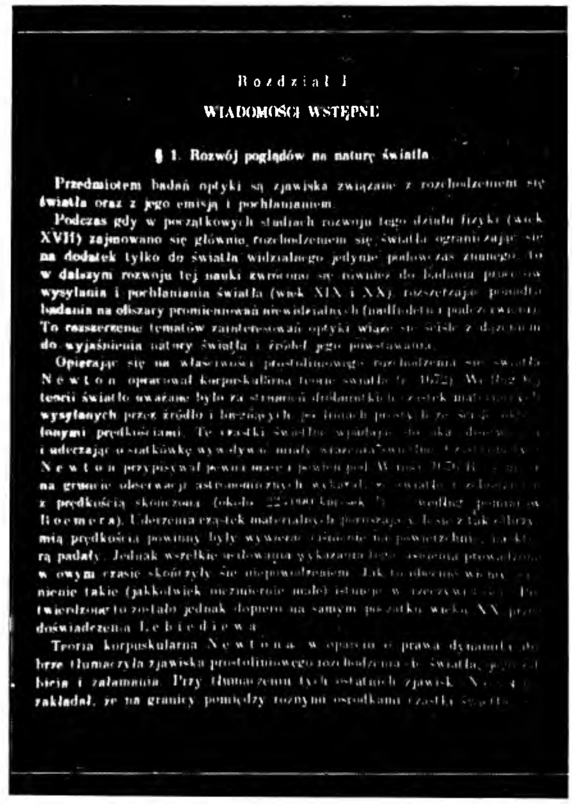
Przedmiotem badań optyki są zjawiska związane z rozchodzeniem się światła oraz z jego emisją i pochłanianiem.

Podczas gdy w początkowych stadiach rozwoju tego działu fizyki (wiek XVII) zajmowano się głównie rozchodzeniem się światła ograniczając się na dodatek tylko do światła widzialnego jedynie podówczas znanego, to w dalszym rozwoju tej nauki zwrócono się również do badania procesów wysyłania i pochłaniania światła (wiek XIX i XX), rozszerzając ponadto badania na obszary promieniowań niewidzialnych (nadfioletu i podczerwieni). To rozszerzenie tematów zainteresowań optyki wiąże się ściśle z dążeniem do wyjaśnienia natury światła i źródeł jego powstawania.

Opierając się na właściwości prostoliniowego rozchodzenia się światła Newton opracował korpuskularną teorię światła (r. 1672). Według tej teorii światło uważane było za strumień drobniutkich cząstek materialnych wysyłanych przez źródło i biegnących po liniach prostych ze ściśle określonymi prędkościami. Te cząstki świetlne wpadając do oka obserwatora i uderzając o siatkówkę wywoływać miały wrażenia świetlne. Cząstkom tym Newton przypisywał pewną masę i pewien pęd. W roku 1676 Roemer na gruncie obserwacji astronomicznych wykazał, że światło rozchodzi się z prędkością skończoną (około 225 000 km·sek^{-1}) — według pomiarów Roemera). Uderzenia cząstek materialnych poruszających się z tak olbrzymią prędkością powinny były wywierać ciśnienie na powierzchnię, na którą padały. Jednak wszelkie usiłowania wykazania tego ciśnienia prowadzone w owym czasie skończyły się niepowodzeniem. Jak to obecnie wiemy, ciśnienie takie (jakkolwiek niezmiernie małe) istnieje w rzeczywistości. Potwierdzone to zostało jednak dopiero na samym początku wieku XX przez doświadczenia Lebiediewa.

Teoria korpuskularna Newtona w oparciu o prawa dynamiki dobrze tłumaczyła zjawiska prostoliniowego rozchodzenia się światła, jego odbicia i załamania. Przy tłumaczeniu tych ostatnich zjawisk Newton zakładał, że na granicy pomiędzy różnymi ośrodkami cząstki świetlne po-

Fig. 6. Image of a transparency produced directly by the optical system with a diaphragm in the focal length

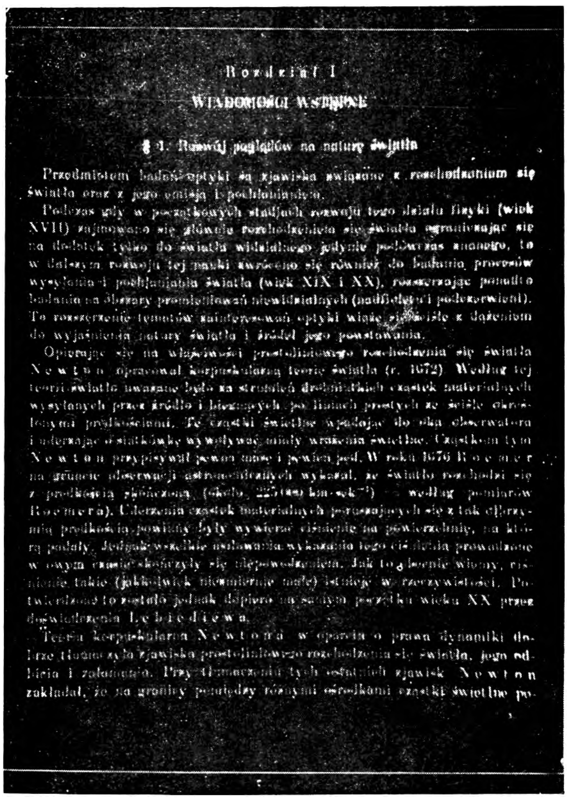

Rozdział I

WIADOMOŚCI WSTĘPNE

§ 1. Rozwój poglądów na naturę światła

Przedmiotem badań optyki są zjawiska związane z rozchodzeniem się

Fig. 8. Image of a transparency reconstructed from a hologram made in the plane displaced with respect to the Fourier plane


Rozdział I

WIADOMOŚCI WSTĘPNE

§ 1. Rozwój poglądów na naturę światła

Fig. 7. Image of a transparency reconstructed from the hologram made exactly in the Fourier plane

above. Qualitative deformation of the character shape is visible only in the region of the tiny and dense text and remains in accordance with the mathematical description presented in the paragraphs 3 and 4.

Fig. 7 shows an image of a transparency reconstructed from a hologram produced exactly in the Fourier plane. The visible deformation of the text proves a strong influence of the light-sensitive material non-linearity on the quality of the holographic imaging.

The picture shown in Fig. 8 was obtained by reconstruction of a hologram made in the plane shifted 3mm with respect to the Fourier plane. Much better quality of this image as compared to that of the image shown in Fig. 7 results from spreading the extremal amplitudes of the single diffraction orders in the quasi-Fourier plane. A slight increase of the coherent noise is connected with the subject beam intermodulation in the plane of holographic recording.

7. Conclusions

Though the theoretical model used in mathematical description of the microholographic information storing was considerably simplified the experimental results were in good accordance with the conclusions following from the theoretical analysis.

In summing the results of this work the following conclusions concerning the microholographic data storage optimization should be formulated:

— information content density on a hologram depends on the focal length of the optical system,

— quantitative measure of the optical information deformation determined by the expression (13) depends on: geometrical size of the characters on the transparency, focal length of the optical system, size of the hologram and the wavelength of light used,

— holographic registration should not be performed exactly in the Fourier plane because of the restricted linearity range of the light-sensitive material,

— record of information should be made by using a negative transparency (rather than a positive one) in order to restrict the influence of the nonlinearity of the recording material and to achieve both good contrast and brightness of the image reconstructed holographically,

— transparency should not exhibit any light diffusing properties (diffusion in emulsion and in the substrate), which would increase the undesired coherent noice.

Accumulation microholographique des informations

On a donné l'analyse des relations des grandeurs fondamentales caractéristiques pour le problème de l'accumulation microholographique des informations. On a discuté, également, l'influence de cettes grandeurs sur la qualité de l'information dans le processus de sa transformation. En outre, on a présenté le matériel empirique illustrant les conclusions théoriques.

Микроголографический СБОР информации

Произведен анализ количественных зависимостей между основными величинами, характерными для микроголографического сбора информации, и обсуждено влияние их на качество информации в процессе ее обработки. Кроме того, представлен опытный материал, которым иллюстрируются теоретические выводы.

References

[1] Tauber A. S., Myers W. C., Proc. Ann. Meet. Nat. Microfilm Assoc. **11**, 256 (1962).

[2] McMahon D. H., Appl. Opt. **11**, 798 (1972).

[3] Friesem A. A., Tompkins E. N., Hoffman G. E., *15 th Annual Technical Symposium*, Proceedings, September 1970, Anaheim, California, p. 67.

[4] Born M., Wolf E., Principles of Optics, Pergamon Press 1964.

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