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Selected problems in holographic memory design

ANDRZEJ ANDRUCHÓW, ALEKSANDER JASKÓŁKA, EUGENIUSZ JAGOSZEWSKI

Institute of Physics, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50–370 Wrocław, Poland.

The paper concerns the design of a holographic memory system. The results obtained are based on the ray tracing in the optical system proposed. The recommended memory material is $LiNbO_3$ crystal doped with iron. The main task is to obtain maximal packing density using the techniques of both spatial wavelength multiplexing and spatial angular multiplexing.

Keywords: optical system, holographic memory, packing density.

1. Introduction

High capacity, small dimension and low price are the features desired in each holographic memory system being designed. In practice the construction of such a system is difficult, though in the literature numerous attempts have been made at selecting such a system configuration that would allow the information to be quickly read in and read out. Besides the capacity parameter the other two features determine their miscellaneous applications. Our goal is to achieve the maximal capacity of the memory. Owing to a new configuration of a holographic memory system and a slightly modified technique for increasing significantly the volume of the memory medium we obtained some interesting results concerning the capacity as compared to the result reported in [1].

Depending on the configuration of the holographic memory systems different techniques of multiplexing are applied. In applications either a change of angle or a change of wavelength of the reference laser beam are explored enabling a greater number of data to be stored. By dividing the memory medium into particular sectors with the use of the said information storing techniques some further increase of information density in a given volume of the medium is achieved. A more and more intensively developed technique of phase encoding applied simultaneously with angular multiplexing gives the more advantageous possibilities of recording the information, but on the other hand, requires a definite geometry of the holographic memory system, which eliminates the latter from our considerations. In this paper, we present a well developed method of spatial angular multiplexing and spatial multiplexing by wavelength taking advantage of the system proposed in order to achieve high capacity of the holographic memory.

2. Storing of information in common memory medium

2.1. Angular multiplexing

Applying the technique of angular multiplexing a great number of holograms can be mutually superposed in the same volume of the holographic medium [2]. Figure 1 illustrates the concept of this way of recording in the thick medium. The reference beam is deflected by some angle $\Delta\theta_R'$ between the successive object recordings. The reconstruction beam is incident under the same angle as the reference beam, thus selecting the addressed hologram from the assemble of holograms recorded in the medium. The Ewald construction (Fig. 1) was used to plot the spheres being loci of the ends of vectors of the diffraction gratings created during the recording of the object beams. Page composers are, in practice, the objects weakly diffracting the light and the propagation directions of plane waves of the angular pattern of object beam are confined within the core of a relatively small angle of divergence. The vectors of the gratings recorded during one exposure create a circular region on the Ewald sphere. From the picture it follows that if the reference beam is rotated through a certain angle, the same vectors of the signal beam $\mathbf{k}_O$ are recorded in the form of two different gratings of vectors $\mathbf{K}_1$ and $\mathbf{K}_2$ lying on two spheres. Due to this trick the separation of patterns of consecutively recorded holograms is achieved which makes the error free reconstruction possible. Additionally, the angular selectivity of the thick holograms following from the Bragg condition is applied.

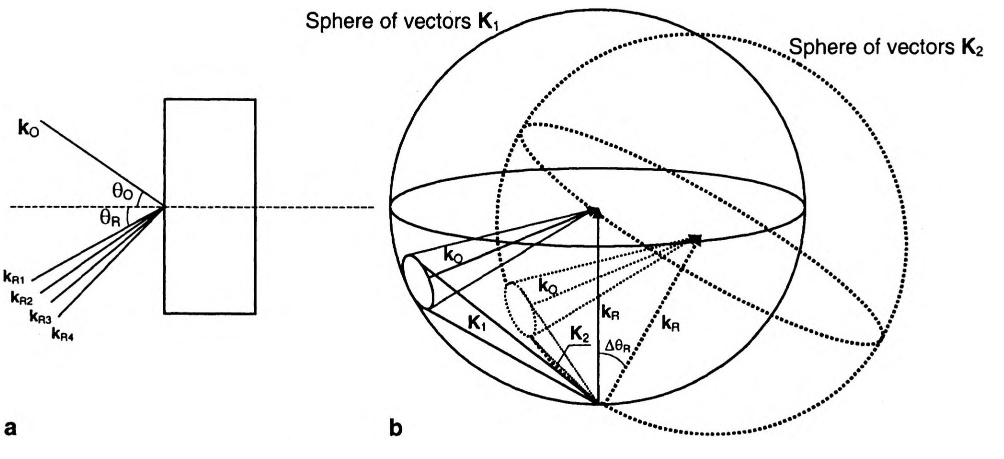

Fig. 1. Principle of hologram recording in the angular multiplexing; **a** – recording geometry, **b** – Evald sphere construction.

This is based on the fact that the reconstruction of hologram recorded in a volume medium with the help of the beam deflected by some angle with respect to the reference beam used for recording causes a significant decrease in the diffraction efficiency of the image created. If the deflection angle of the reference beam occurring between the consecutive exposures has a strictly determined value, the "neighbouring" holograms are not practically reconstructed when reading out the selected hologram using the beam satisfying the Bragg condition. Both these properties of the thick recording media enable an easy separation of pattern of the consecutive holograms as well as the angular selectivity allowing the optical noise generated by interhologram crosstalk to be minimized. The analysis of the angular selectivity can be performed based on the Kogelnik theory [3] according to which the diffraction efficiency of the transmission holograms is defined by

$$\eta = \nu^2 \frac{\sin^2(\nu^2 + \xi^2)^{1/2}}{\nu^2 + \xi^2} \tag{1}$$

while that of the reflection hologram is described by

$$\eta = \frac{\nu^2 \sinh^2(\nu^2 - \xi^2)^{1/2}}{\nu^2 \sinh^2(\nu^2 - \xi^2)^{1/2} + \nu^2 - \xi^2}. \tag{2}$$

The parameters ν and ξ, for an arbitrary angle of declination of the vector **K** with respect to the axis are described by the formulae:

$$\nu = \frac{\pi n_1 L}{\lambda \sqrt{\cos\theta_R' \cos\theta_O'}}, \qquad \xi = \frac{\Delta\theta_R' K L \sin(\theta_O' - \theta_R')}{2\cos\theta_O'} \tag{3}$$

where θ_R', θ_O' – angles of incidence of respective reference and object waves inside the medium, λ – light wavelength used during the recording, n_1 – amplitude of the modulation of the refraction index, K – modulus of the grating vector, L – the thickness of the medium. In practice, $\nu \ll 1$ which makes Eqs. (1) and (2) simplify to the form

$$\eta = \nu^2 \operatorname{sinc}^2 \frac{\xi}{\pi}. \tag{4}$$

The angular deflection of the reference beam $\Delta\theta_R'$, for which the diffraction efficiency of the "neighbouring" hologram drops to zero, is determined by the first zero place of the sinc function in Eq. (4), which is shown in Fig. 2. Just after rotation of the beam by an angle $\Delta\theta_R'$ the next hologram is recorded. The appropriately modified equation for the angular deviation of the reference beam takes the form

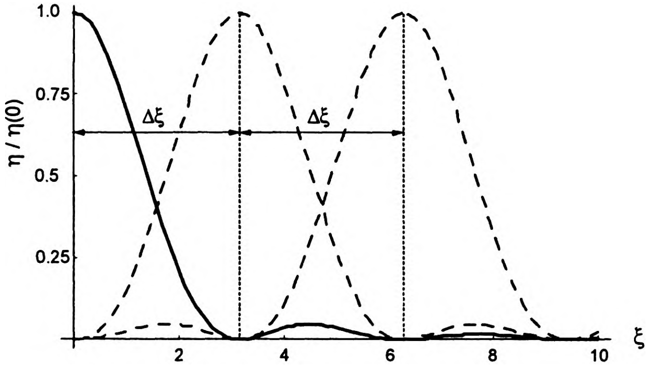

Fig. 2. Plot of the hologram recording of the neighbouring gratings ($\nu \ll 1$, $\Delta\xi \approx \Pi$).

$$\Delta\theta_R' = \frac{\lambda}{nL}\frac{\cos\theta_O'}{\left|\sin(\theta_R' - \theta_O')\right|} \tag{5}$$

where θ_O' – angle of incidence of the object wave inside the medium, n – average refractive index of the medium matter, L – the thickness of the medium.

For the transmission holograms $0 < |\theta_R'| < \pi/2$, while for reflection holograms $\pi/2 < |\theta_R'| < \pi$. It is assumed that the incidence angle for the signal beam is contained within the interval $0 < |\theta_O'| < \pi/2$ and it should be remembered that in the case of holographic memory the object wave is an assembly of plane waves propagating under different angles θ_R'. For this reason each of them is characterised by its own value of $\Delta\theta_R'$. The above considerations may refer to the central wave in this assembly. For the remaining plane waves carrying information about the object these relations will be fulfilled approximately, being the more accurate the less the divergence of the object wave.

The number of holograms N_0 which can be recorded with this method is determined by the number of directions of propagation of the reference beam contained between the limiting angles θ_1 and θ_2 when taking account of the angular distance between the neighbouring directions which satisfy Eq. (3). Generally, in all systems of angular multiplexing both extreme reference beams are located on one side of the object beam and thus $0 < (\theta_O' + \theta_1) < (\theta_O' + \theta_2) < \pi$ or $-\pi < (\theta_O' + \theta_1) < (\theta_O' + \theta_2) < 0$. In order to determine N_0 Eq. (5) is reduced to the form

$$\left|\sin(\theta_R' + \theta_O')\right|\Delta\theta_R' = \frac{\lambda}{nL}\cos\theta_O'. \tag{6}$$

If we add $N_0 - 1$ to such equations (one for each value θ_R') and approximate the left hand side of the sum by an integral we get

$$\int_{\theta_1}^{\theta_2} \left|\sin(\theta_R' + \theta_O')\right| \mathrm{d}\theta_R' = \frac{\lambda(N_\theta - 1)}{nL} \cos\theta_O'. \tag{7}$$

Hence the number of angular multiplexed holograms is given by the formula

$$N_\theta = 1 + \frac{nL}{\lambda} \frac{\left|\cos(\theta_O' + \theta_1) - \cos(\theta_O' + \theta_2)\right|}{\cos\theta_O'}. \tag{8}$$

The architecture of the holographic memory assumes very often perpendicular incidence.of the object beam. Then, $\theta_O' = 0$ and

$$N_\theta = 1 + \frac{nL}{\lambda} \left|\cos\theta_1 - \cos\theta_2\right| \tag{9}$$

where $0 < \theta_1 < \theta_2 < \pi/2$. The number N_0 can be increased by applying the reflection holograms with the help of beams propagating from the opposite sides of the recording material. Under these circumstances N_0 can be increased by the factor of 4, however, the application of such a method in practice makes the architectures of both the recording and reading systems of holographic memory much more complex.

The deviation of the reference beams during the recording is due to light deflectors. The acoustooptic and electrooptic deflectors assure very quick access (of the order of 10 μs) to the hologram of arbitrary address. There are also some mechanical solutions which consist in deflecting the beams by rotating small mirrors, however, at the expense of a longer access time sometimes amounting to milliseconds.

2.2. Multiplexing based on change of wavelength

This technique is an alternative for recording many holograms in the common volume of the memory medium. In this case, the angles of incidence of the reference and object beams remain stable, while the recording wavelength changeds between the successive exposures by $\Delta\lambda$ part of the wave used in recording. The principle of recording is shown in Fig. 3. Usually both beams enter the medium from the opposite sides under the angles close to 0°. This allows the greatest number of independent holograms to be recorded. The Ewald spheres corresponding to consecutive recordings made using the increasing wavelength have smaller and smaller curvature radii and lie completely inside the initial sphere. Owing to this the separation of the assembly of gratings is achieved (similar to the case of angular multiplexing), which are records of the object beams. For this reasons each of them can be reconstructed without any disturbance. The wavelength is changed by using a tunable laser. It is requested that the laser be capable of choosing suitable frequency, which can be done by applying a resonator of tuning device in the form of acoustooptic filters and the etalons used by us. It should

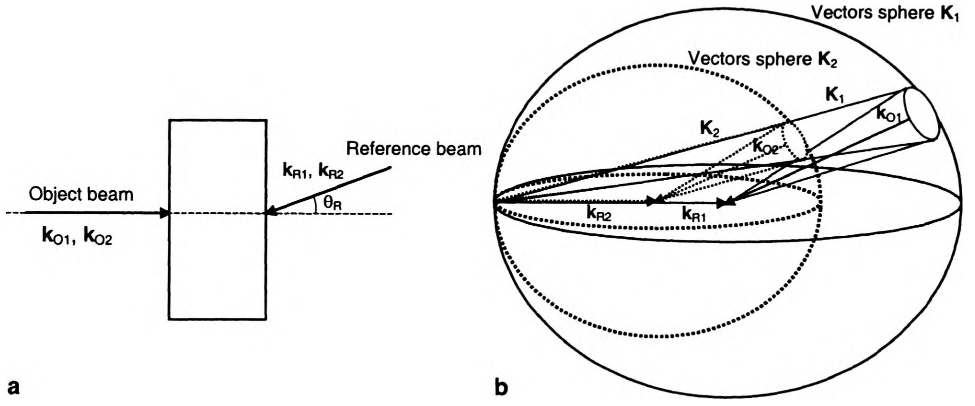

Fig. 3. Principle of hologram recording in the wavelength multiplexing technique; **a** – recording geometry, **b** – Evald sphere construction.

be remembered, however, that a proper configuration of the computer programme steering the emitted laser light is needed.

The difference in wavelength used to recording the neighbouring holograms is due to the chromatic selectivity of the thick holograms. If the wavelength of beam reconstruction is the same as that of beam recording, then the Bragg condition is fulfilled [4] and the hologram is reconstructed with the maximal diffraction efficiency under the given condition. In the case of its change some phase mismatch occurs resulting in a decrease of the diffraction efficiency η. In order to minimise the crosstalk, change of the wavelength between the recordings of consecutive holograms should be such that the efficiency of the previous hologram reconstruction $\eta = 0$. Similarly to the case of angular multiplexing, the change $\Delta\lambda$ can be calculated from the first zero place of Eq. (6), while the parameter ξ is determined as follows:

$$\xi = \frac{\Delta\lambda K^2 L \sin(\theta_O' - \theta_R')}{2\cos\theta_O'}. \tag{10}$$

Assuming $\cos\theta_O' = 1$ we get

$$\Delta\lambda = \frac{\lambda^2}{nL(1+\cos\theta_R')} \quad \text{or} \quad \frac{\Delta\lambda}{\lambda^2} = \frac{1}{nL(1+\cos\theta_R')} \tag{11}$$

If the waves of wavelength belonging to the interval from λ_1 to λ_2 ($\lambda_1 < \lambda_2$) are used for multiplexing the number of recorded holograms N_λ will be greater by 1 than the number of the subintervals $\Delta\lambda$ contained in the said interval and fulfilling the condition (10). Adding $N_\lambda - 1$ such equations and approximating the left hand side of the sum by a respective integral we set

$$\int_{\lambda_1}^{\lambda_2} \frac{\Delta\lambda}{\lambda^2} = \frac{N_\lambda - 1}{nL(1 + \cos\theta_R')}. \tag{12}$$

After solving (12) we get the number of multiplexed holograms

$$N_\lambda = 1 + nL(1 + \cos\theta_{R2}')\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right). \tag{13}$$

In order to determine the number of sectors in the memory medium we must perform the following analysis.

2.3. Spatial multiplexing

An increment of the holographic memory capacity above the 10 Gb level (up to 100 Gb and more) requires application of the spatial multiplexing technique. The latter consists in dividing the recording medium into many hologram units. Each location separated in this way contains holograms multiplexed in its volume either by changing the incidence angle or by changing the wavelength of the reference beam.

During the recording of the data both the reference beam and the object beam must be deflected in such a way as to localise them exactly in the chosen places. In the case of joined application of angular and spatial multiplexing one deflector directs the beams to the corresponding unit of the medium while the other serves to select the unit recording holograms. The maximal number of separate units (sectors) into which the memory medium can by divided is [1]

$$N_s = \frac{A}{q} = \frac{A}{a_h a_v} \tag{14}$$

where: A – crystal surfaces, a_v, a_h – lengths of the sides of the element rectangle. The surface of the element q is determined by the geometry of the hologram recording. It must be large enough to make both beams interfere mutually within the whole common space inside the medium where they meet. This condition assures that the beams should not overlap the region of neighbouring units and diffuse the holograms recorded there. Such a situation for the spatial multiplexing joined with the angular one is shown in Fig. 4 [1]. It has been assumed that the object beam falls normally on the medium. In most cases in the holographic memories either a conventional image of a data page or its Fourier transform are recorded.

The most advantageous solution is such a positioning of the medium that the image plane or Fourier plane lie in its centre. There, the length of the side a_h defined by the value of defocusing of the recorded optical filed on the border surface of the medium is shorter. The length of the side a_h affects the width and the incidence angle of the

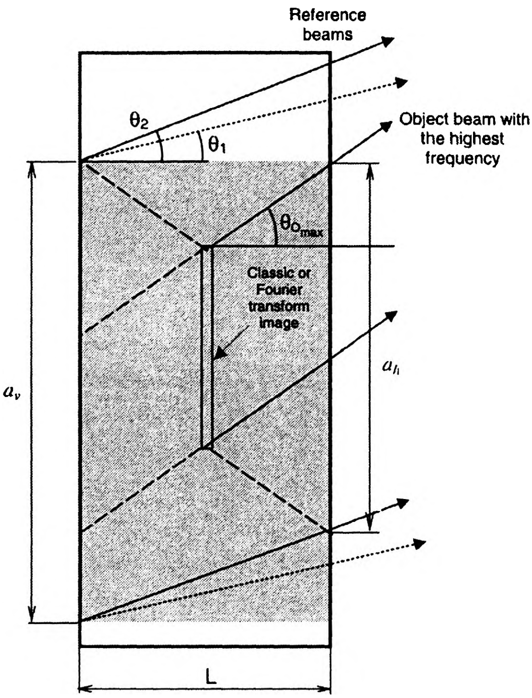

Fig. 4. Recording geometry of the joint angular and spatial multiplexing; required minimal region of interference of both beams is marked by grey colour.

reference beams which must be chosen in such a way that the whole volume of hologram occupied by the object beam is illuminated. The interference of the beams of geometry thus chosen assures lossless holographic recording of the information earned by the object wave. The range of the defocused image on the surfaces can be calculated by analysing the trace of the rays corresponding to the greatest spatial frequency $\xi_{\max} = 1/h' = 1/\beta h$ (h is a linear dimension of the pixel on the data page, β is the magnification introduced by the system). This frequency corresponds to the plane wave propagating inside the medium at the angle $\theta'_{O_{\max}} = \arcsin(\lambda/nh\beta)$. Hence, we have

$$a_h = M + L\tan\theta'_{O_{\max}} = N_p\beta h + \frac{L}{\sqrt{\left(\frac{nh\beta}{\lambda}\right)^2 - 1}}, \tag{15}$$

$$a_v = a_h + L\tan\theta_2 = N_p\beta h + \frac{L}{\sqrt{\left(\frac{nh\beta}{\lambda}\right)^2 - 1}} + L\tan\theta_2 \tag{16}$$

where: M – size of the page composer image, N_p – number of pixels along the row or column of the page composer, L – the thickness of the medium. Finally, the maximal number of the separated units is defined by the equation

$$N_{s\theta K} = \frac{A}{\left(N_p\beta h + \dfrac{L}{\sqrt{\left(\dfrac{nh\beta}{\lambda}\right)^2 - 1}}\right)\left(N_p\beta h + \dfrac{L}{\sqrt{\left(\dfrac{nh\beta}{\lambda}\right)^2 - 1}} + L\tan\theta_2\right)}. \tag{17}$$

The pacing density G_K in bits/cm^2 can be obtained on the basis of the relation

$$G_K = N_{s\theta K}\frac{N_p^2 N_0}{A}.$$

The geometry of the recording within a simple location in the case of multiplexing with the aid of wavelength changing is shown in Fig. 5 [1]. Now, both the beams fall perpendicularly to the medium surface from the opposite sides of the latter.

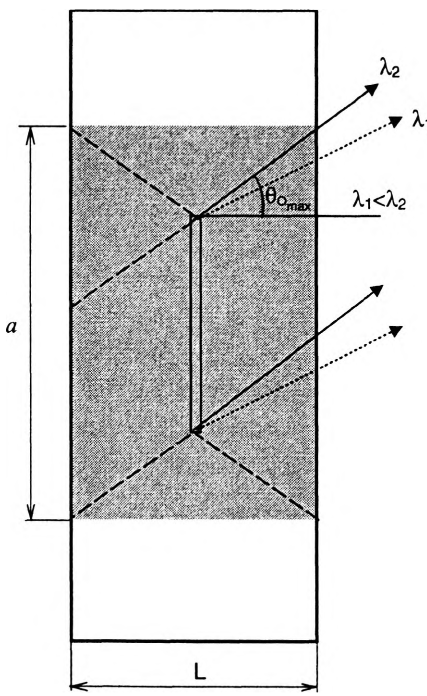

Fig. 5. Recording geometry of the combination of the spatial and wavelength multiplexing.

The linear sizes of the unit are the same in both directions $a_h = a_v = a$, while its area is $q = a^2$. For this reason the area to be separated for recording within the whole assemble of holograms is now determined only by the defocusing of the data page image at the bolder surfaces. It is the greatest for the longest wavelength λ_2 of the light used for recording. For a hologram of conventional image the following expression is obtained

$$a = M + L\tan\theta'_{O_{\max}} = N_p\beta h + \frac{L}{\sqrt{\left(\frac{nh\beta}{\lambda_2}\right)^2 - 1}} \tag{18}$$

while the number of units is

$$N_{s\lambda K} = \frac{A}{a^2} = \frac{A}{\left(N_p\beta h + \frac{L}{\sqrt{\left(\frac{nh\beta}{\lambda_2}\right)^2 - 1}}\right)^2}. \tag{19}$$

The density of recording G_λ in bits/cm^2 can be obtained on the basis of the relation

$$G_\lambda = N_{s\lambda K}\frac{N_p^2 N_\lambda}{A},$$

from which the memory capacity of the holographic system is calculated in the case of application of the spatial multiplexing technique with the help of the wavelength.

3. Holographic memory system

In the holographic memory system a dye laser has been applied together with the wavelength multiplexing technique with a possibility of wavelength retuning within the interval 500–540 nm. The selection of the light wavelength is done by two etalons located inside the laser resonator [5]. Obviously, the computer programme controlling the positioning (declination angle) of the etalons depending on the generated light wavelength realises the corresponding supply of the voltage. Figure 6 illustrates the trace of the light rays emitted by the laser of 7 W power in the proposed system of holographic memory.

A widened and split laser beam after having passed through two systems of suitable acoustooptic deflectors trawels in one arm through a page composer to the recording crystal and in the other one plays the part of a reference beam which interferes with the object wave in this crystal. The frequency generators of deflectors are positioned on the opposite sides in such a way that the frequency is the same for each deflector of the system and the deviation angle of the light beam in the deflector is equal to half

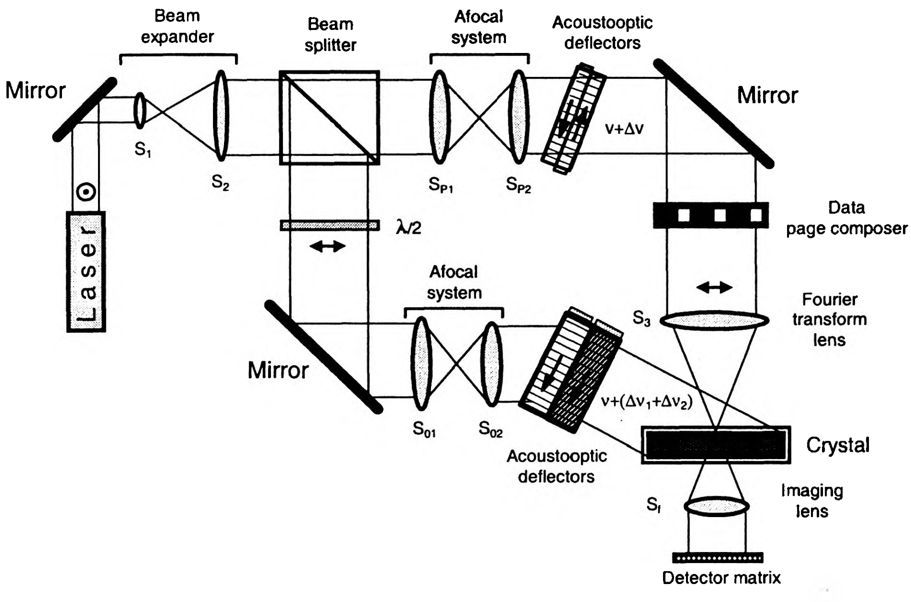

Fig. 6. Ray-tracing in the system of holographic memory.

value of the frequency delivered to the system of deflectors located in the arm of the reference beam.

The introduction of information is done with the help of the data page composer. We have applied a liquid crystal composer made up of 4-pentyl-4'-butyloxyphenyldioxane 2, 6 [6] of sizes 2.3×2.3 cm^2 and thickness 0.2 cm. It is composed of 1024×1024 cells, hence the spacing between them is about 0.002 cm. The signals (in the form of corresponding data) are introduced to the page composer in the form of voltage distribution which depends on the transmitted image and suffers from continuous changes. Behind the data page composer there is a Fourier objective

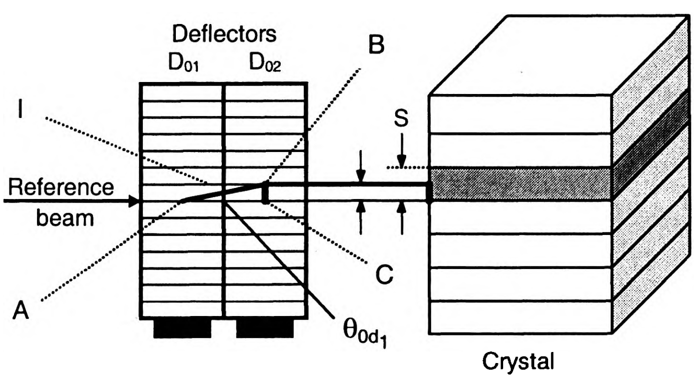

Fig. 7. Addressing of the laser light beam to the particular crystal sectors.

Table. Obtained results.

Type of multiplexing	Wavelength λ [nm]	Angle [deg]	Linear size of pixel [μm]	Number of holograms N
Angular	500	10–20	2.09	2978
Wavelength	500–540	—	2.09	9778

which performs the Fourier transformation of the amplitude transmittance in the image from the page composer to the recording medium. The applied photorefractive crystal is $LiNbO_3$ doped with iron of refractive index $n = 2.2$. Figure 7 illustrates the addressing of the laser light beam directed suitably by the system of deflectors into the crystal memory. Consider the above crystal $LiNbO_3$ in the form of a cube of 1.5 cm edge divided into 7 sectors in the case of angular multiplexing, and into 12 sectors for wavelength multiplexing. The grey layer in Fig. 7 denotes the separated sector to which the holograms are addressed.

After having addressed the information to the selected sector the other deflector of the system angular multiplexes the reference beam by an angle changing within the borders from 10° to 20° which results in alteration of the acoustic frequency of the deflector from 973 MHz to 2.0656 GHz, respectively. In the case of wavelength multiplexing the wavelength is changed by changing the angle of etalon position in the laser resonator while the frequency of the acoustic wave of the second deflector remains constant. The reference plane wave introduced at a fixed angle to the crystal sector interferes with the object wave creating a hologram of a definite data page composer in the form of respectively modulated refractive index of the crystal. The read-out of the information recorded in the crystal is done with the help of the reconstructing wave (equivalent to the reference wave) which after passing through the photorefractive material and being transformed by the consective Fourier lens creates the image of the page composer on the matrix of semiconductor photodetectors connected mutually in the system xy [7]–[10].

In the mean time the signal in the form of voltage variation at the output of the detector amplifier is suitably interpreted by the computer steering unit. The Table presents values of the particular parameters attained in the system using the technique of angular multiplexing with the help of light wavelength variation.

4. Summary

In the present paper, a holographic memory system employing the technique of both angular and wavelength multiplexing is proposed. The storage of information in the form of holographic memory is done in a three-dimensional photorefractive $LiNbO_3$ medium doped with iron. From our study, it follows that the wavelength multiplexing technique is more advantageous since the density of recording is distinctly higher than

Table. Continued.

Thickness of the crystal [mm]	Packing density [bits/μm^2]	Surfaces [mm^2]
15	90	225
15	670	225

that of the angular multiplexing method. Also important here is the access time (time of reading in) as well as the aberrations of the focusing beams during the recording, which should be analysed in more detail. A change of system configurations, in particular, that aiming at diminishing its sizes can have essential influence on evaluation of these parameters.

References

[1] Yu H., Li S., Psaltis D., Appl. Opt. **33** (1994), 3764.
[2] Mok H.F., Opt. Lett. **18** (1993), 915.
[3] Kogelnik H., The Bell Sys.Techn. Jeur. **48** (1969), 2009.
[4] Jagoszewski E., *Optical Holography*, PWN 1986 (in Polish).
[5] Demtroder W., *Laser Spectroscopy*, PWN 1993 (in Polish).
[6] Żmija J., Zieliński J., Parka J., Nowinowski-Kuszelnicki E., *The Liquid Crystal Display*, PWN 1993 (in Polish).
[7] Hill B., *Computer Holographic Memory*, WNT 1981 (in Polish).
[8] Ashley J., Bernal M.P., Burr G.W., Coufal H., Guenther H., Hoffnagle I.A., Jefferson C.M., Marcus B., Macfarlane R.M., Shelby R.M., Sincerbox G.T., IBM J. Res. Develop. **44** (2000), 341.
[9] Jaskółka A., Andruchów A., *The designing of the computer holographic memory*, MSc Thesis, Wrocław University of Technology, Wrocław 2002 (in Polish).
[10] Vander Lugt A., Appl. Opt. **12** (1973), 1675.

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