

HOLOGRAPHIC MEMORY

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Projection multiplex recording of computer-synthesised one-dimensional Fourier holograms for holographic memory systems: mathematical and experimental modelling

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Abstract. **A multiplex method of recording computer-synthesised one-dimensional Fourier holograms intended for holographic memory devices is proposed. The method potentially allows increasing the recording density in the previously proposed holographic memory system based on the computer synthesis and projection recording of data page holograms.**

Keywords: *holographic memory devices, computer-synthesised hologram, one-dimensional Fourier hologram, multiplex hologram recording, spatio-temporal light modulator.*

1. Introduction

In our previous papers [1, 2] we proposed to use the method of computer synthesis of Fourier holograms for individual pages of binary information with the output of the synthesised hologram to the liquid-crystal spatio-temporal light modulator (LC STLM) followed by its projection onto the holographic carrier with the required scale change. The application of this method allows significant simplification of the optical recording scheme of a holographic memory device.

To increase the information recording density on a holographic carrier the method of multiplex recording is often used. The multiplex hologram is a result of writing several elementary holograms (below referred to as subholograms) with different spatial carrier frequencies on the same area of the holographic carrier. To make separate reading of such subholograms possible, each of them should be produced with a certain change of the recording conditions, e.g., one should vary the angle between the object beam and the reference one (a multiplex hologram with angular selectivity) or the relative position of the plane of object and reference rays and the plane of the holographic carrier (a multiplex hologram with spatial selectivity) [3], which considerably complicates the optical scheme of the device and leads to the growth of its sensitivity to external perturbations.

In the case of recording two-dimensional computer-synthesised Fourier holograms the recording density is limited by the necessity to use sufficient angular separation of the recorded subholograms in order to avoid the overlap of the reconstructed images. In this connection it is interesting to consider the properties of multiplex holograms with one-dimensional Fourier holograms, used as subholograms, since the optical systems having the dual symmetry (anamorphotic optical systems) possess high sensitivity to rotations, which allows one to expect some selectivity advantages both in writing and in reading the data [1–3].

Thus, the method of recording binary data input pages, studied in the present paper, implies the computer-aided synthesis of the appropriate one-dimensional Fourier holograms and their multiplex projection recording on a holographic carrier.

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2. Synthesis of one-dimensional holograms and data reconstruction modelling

In the case under study the synthesis of the one-dimensional Fourier hologram is similar to the synthesis of a common hologram, used in Refs [1, 2] with the only difference that the mathematical analogy with a common spherical Fourier cascade is replaced with the analogy with the known anamorphotic system of the one-dimensional Fourier transform [3]. An equivalent optical scheme of recording of one-dimensional Fourier holograms is presented in Fig. 1. Since the optical scheme includes both spherical and cylindrical lenses, Fig. 1 presents the ray paths in two planes (horizontal and vertical). Each horizontal line of the synthesised hologram is a one-dimensional Fourier hologram, corresponding to one line of the recorded two-dimensional input data page.

In analogy with Ref. [2], consider the case of synthesising a one-dimensional Fourier hologram for an N-line page of binary data. Let $r_i(x) = \sqrt{2\pi}\, C_i \delta(x)$ be the function of the ith point reference source, located in the front focal plane of the Fourier objective (*2*) [plane (*1*)] on the optical axis of the objective (see Fig. 1), where C_i is a dimensionless non-negative factor, and $\delta(x)$ is the Dirac delta-function; $d_i(x-\Delta)$ is the source function of the object beam, corresponding to the ith line of the data page, where Δ is the distance between the line centre and the reference source. To provide the spatial separation of the data page line image from the zero-order image, the value of Δ is chosen to be greater than or equal to half of the recorded line size. As shown in Fig. 1, the transmission function of the $(N-i+1)$th line of the hologram is proportional to the intensity of a superposition of the reference beam, generated by the ith point source , and the object beam, generated by the ith line of the input data page:

$$t_{N-i+1}(x_f) \propto I_i(x_f) = |R_i(x_f) + D_i(x_f)|^2 = D_i^*(x_f) D_i(x_f)$$

$$+ R_i^*(x_f) D_i(x_f) + R_i(x_f) D_i^*(x_f) + R_i^*(x_f) R_i(x_f), \qquad (1)$$

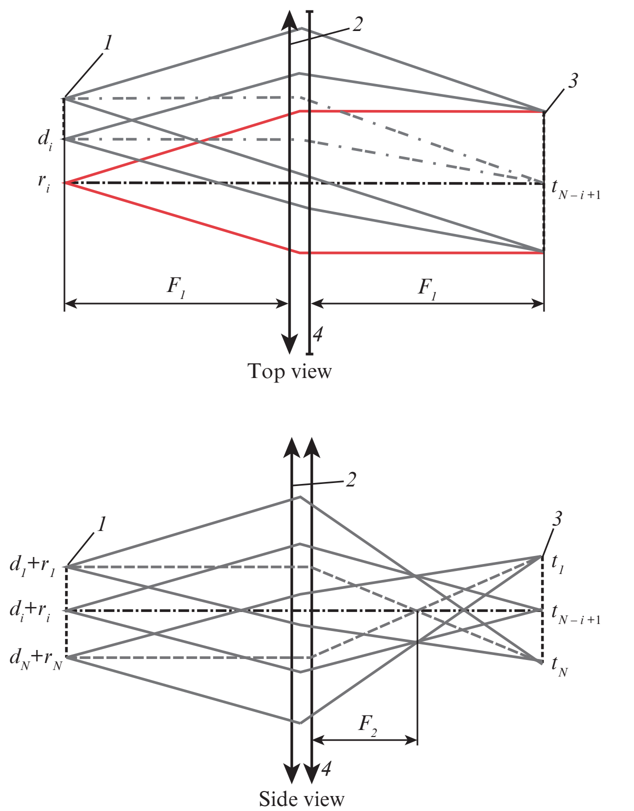

Figure 1. Equivalent optical scheme of the one-dimensional Fourier hologram synthesis: (*1*) object plane (the plane of LC STLM); (*2*) Fourier objective; (*3*) hologram plane; (*4*) cylindrical lens.

where $D_i(x_f)$ is the function of the ith object beam; $R_i(x_f)$ is the function of the ith reference beam; and x_f is the coordinate along the horizontal axis in the hologram plane (*3*).

According to the known property of the spherocylindrical doublet [3], the field amplitudes of the object and reference beam in the plane (*3*) and in the plane (*1*) are related by the one-dimensional Fourier transform. Taking this fact into account, one can rewrite Eqn (1) in the form

$$t_{N-i+1}(x_f) \propto \tilde{F}(d_i^*(x)d_i(x)) + C_i\tilde{F}(d_i(x))\exp(-i\Delta x_f) + C_i\tilde{F}(d_i^*(x))\exp(i\Delta x_f) + C_i^2, \quad (2)$$

where $\tilde{F}(\ldots)$ is the Fourier transform of a function. To calculate the light field amplitude in the image plane, reconstructed from the one-dimensional Fourier hologram, it is necessary to calculate the line-by-line one-dimensional Fourier transform of the hologram amplitude transmission coefficient distribution function. In the reconstructed field an individual region will correspond to each of the terms in the right-hand side of Eqn (2). The autocorrelation region which is twice as large as the recorded data line corresponds to the first term. Two conjugate images of the recorded line, symmetric with respect to the optical axis, correspond to the second and the third term. The bright narrow zero-order image corresponds to the fourth term. Obviously, the autocorrelation component in Eqn (2) can be neglected in the course of the holographic structure synthesis, since its presence may introduce essential distortions into the image reconstructed using the hologram. Thus, the remaining terms in the right-hand side of Eqn (2) yield a real-valued sum. Finally, the equation for synthesising a one-dimensional amplitude Fourier hologram is reduced to the simple form:

$$t_{N-i+1}(x_f) = C_i + \mathrm{Re}[\tilde{F}(d_i(x-\Delta))]. \quad (3)$$

In the process of synthesis the constant C_i is chosen to satisfy the condition $t_i(x_f) \geqslant 0$.

As in Refs [1, 2], during the present study the input data page of the holographic memory was organised according to the International Standard ECMA-377. The computer calculation resulted in the amplitude hologram, presented in the form of a grey-scale raster image. In Fig. 2 an example of a magnified fragment of the calculated Fourier subhologram (scaled 4:1) is shown, and Fig. 3 presents the result of numerical reconstruction of the image from the subhologram. The reconstructed field consists of three spatially separated regions, containing the vertical line of the unit width in the zeroth order and two conjugate images of the recorded data page. The performed mathematical model calculations, analogous to the ones carried out earlier for the computer-synthesised two-dimensional Fourier holograms [1, 2], have shown

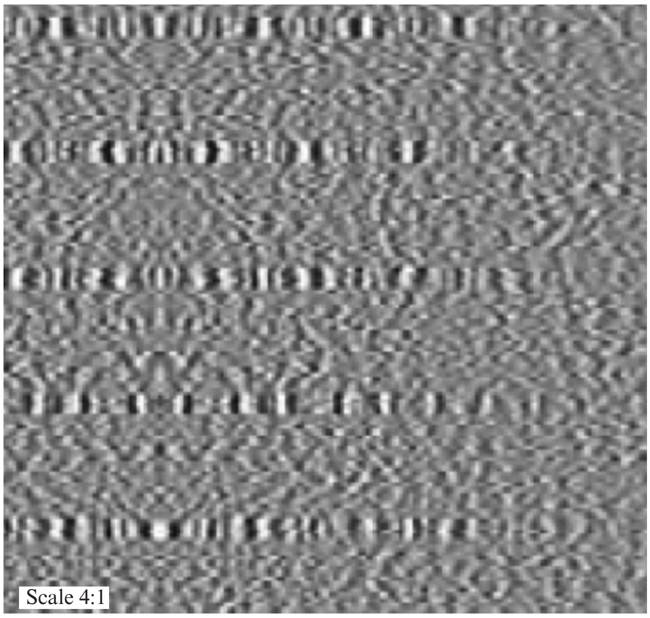

Figure 2. Magnified fragment of the synthesised one-dimensional Fourier subhologram.

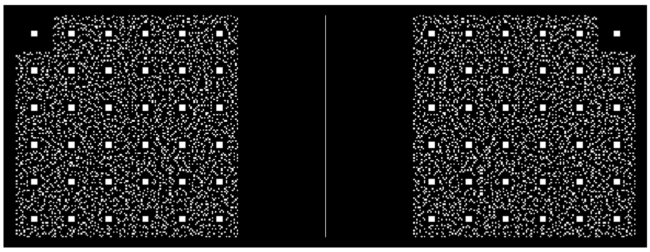

Figure 3. Image, reconstructed from the one-dimensional Fourier subhologram in the course of numerical modelling of the recording and reading processes for the ideal amplitude characteristic of the LC STLM and exposure characteristic of the photographic plate.

the applicability of the computer synthesised one-dimensional Fourier holograms for recording binary data pages.

3. Experimental modelling of data recording and reconstruction

In the experimental studies we used the LC STLM (Holoeye, type LCX-017), to which the computer-synthesised hologram was output. The STLM aperture contains 1024 × 768 pixels (the pixel size 32 × 32 μm). The re-projection of the synthesised subhologram on the high-resolution holography photographic plates was implemented using the optical system, the optical scheme of which is presented in Fig. 4. The calculated one-dimensional Fourier subhologram illuminated by the light beam from a laser (or light-emitting diode) was input to the LC STLM. The optical system formed an image of the Fourier subhologram on the sensitive layer of the photographic plate (type PFG-01) with 10-fold demagnification.

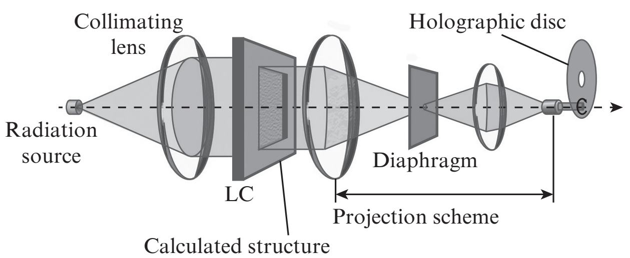

Figure 4. Projection optical scheme for recording computer-synthesised one-dimensional Fourier subholograms.

As a result, the reconstructed image of the input data page was obtained with 10-fold demagnification by the Fourier subhologram (Fig. 5).

The quality of the image reconstructed from a single one-dimensional Fourier hologram of the test object appeared to be unsatisfactory because of strong distortion by discrete-character noises. In the reconstructed image one can also observe the localisation of noise distribution in the information lines of the test object. The brightness of individual elements of the noise component of the reconstructed image is comparable with the brightness of the informative points of the data page, which unavoidably leads to the reading errors.

In the numerical reconstruction of the test input data page image from the synthesised one-dimensional Fourier hologram without grey scale quantisation the signal-to-noise ratio amounted to $\sim 10^{15}$, which is an accuracy limit of the used numerical algorithms. After the quantisation the calculated signal-to-noise ratio fell to 50, and in the experimental studies the signal-to-noise ratio in the reconstructed image amounted to ~ 1. One of the causes of noise appearing in the Fourier subhologram, obtained by means of re-projection onto the sensitive layer of the photographic plate, is the distortion of the synthesised hologram structure both in the course of both its output to the LC STLM and the recording process, caused by the nonlinearity of the recording medium. The experimental studies have shown that the maximal distortions arise due to incorrect reproduction of the shades of grey in the calculated holographic structure in the LC STLM itself due to the nonlinearity of its own amplitude characteristic and, in a less degree, because of the nonlinearity of the exposure characteristic of the photosensitive material.

In the experiments the exposure time was chosen to ensure the subhologram recording in the linear region of the exposure characteristics of the PFG-01 photographic plates, which was provided by the known data about them. In the course of experiments the amplitude characteristic of the LC STLM was investigated. The shades of grey from 0 to 255 were sequentially output to the LC STLM and the transmission was measured using the optical radiation power meter. The measured relative amplitude characteristic of the LC modulator is shown in Fig. 6; the maximal relative intensity of the radiation transmitted through the LC transparent was taken for 256, and the minimal one for zero. From the presented plot it follows that the linear region of the hologram amounts to ~ 110 shades of grey only.

With the obtained amplitude characteristic of the LC STLM taken into account, the Fourier hologram with linearized level quantisation was synthesised. Figure 7 presents the image of a fragment of the input data page, reconstructed

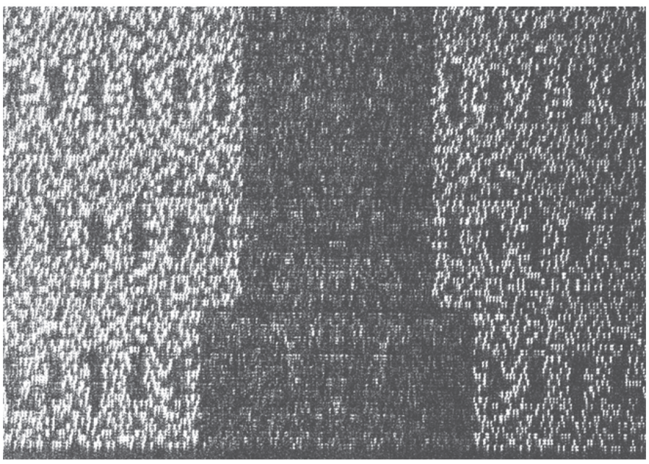

Figure 5. Image of a fragment of the input data page, experimentally reconstructed from the one-dimensional Fourier subhologram, with the +1st (left-hand data page) +2nd (right-hand data page) diffraction orders shown.

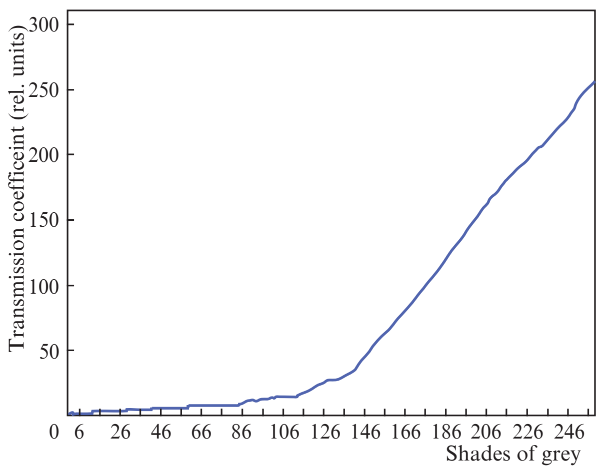

Figure 6. Relative amplitude characteristic of the transmission coefficient of the LC STLM (Sony LCX-017).

from the obtained single Fourier subhologram. The comparison of the fragments of the data page lines, reconstructed from the really obtained Fourier subhologram (Fig. 7) with those reconstructed as a result of numerical mathematical modelling (Fig. 3) shows that for the Fourier subholograms, really obtained in the experiments, the zeroth order is broadened due to the diffraction limitations of the reconstructing optical system, and the noises, localised near the zeroth order, are the result of residual distortions of the holographic structure due to the partial pre-compensation of the nonlinearity of the amplitude characteristic of the LC STLM, as well as insignificant nonlinearity of the exposure characteristic of the sensitive material of the photographic plates for the quantisation with 256 levels of brightness.

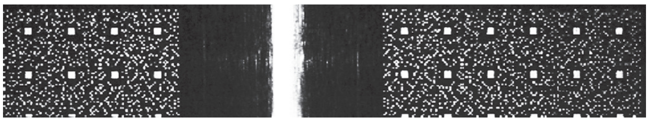

Figure 7. Image of the input data page fragment, reconstructed from the synthesised one-dimensional Fourier subhologram, allowing for the introduction of pre-distortion, partially compensating the nonlinearity of the LC STLM amplitude characteristic.

Then the experiments with multiplex recording of one-dimensional Fourier subholograms in the same region of the photosensitive material were performed. In the course of multiplexing, the recording of each subsequent subhologram was performed with the photographic plate (hologram carrier) rotated through a definite angle around the axis, coinciding with the axis of the projecting beam. The instrumentation presently available for the authors provides the possibility of multiplex recording of up to 20 subholograms in one region of the hologram carrier, which is due to the high resolution of the photosensitive material, the PFG-01 photographic plates, used for such recording.

The optical scheme of separate page-wise reading of the multiplexed Fourier subholograms is presented in Fig. 8. It consists of a collimator [microscope objective (*2*), pin-hole diaphragm (*3*), objective (*4*) and diaphragm (*5*)], providing the illumination of the aperture of the multiple subhologram and the anamorphotic projection optical system, placed after the photographic plate (*6*). The anamorphotic optical system consists of a spherical Fourier objective (*7*) and a cylindrical lens (*8*). The images of the fragments of the input data pages, reconstructed from the Fourier subholograms were fixed using a matrix photodetector (*9*), placed in the back focal plane of the anamorphotic optical system. In the case of the reading light beams direction mismatch with respect to the cylindrical lens plane, the latter introduces essential distortions into the structure of the reconstructed image.

Figure 9 presents the result of reconstructing the images of the fragments of input data pages from three Fourier subholograms, multiplex-written with the carrier rotation step of 20°. The comparison with the result of a single hologram reconstruction, shown in Fig. 10, clearly reveals the blurring of the reconstructed multiplexed holograms along the vertical coordinate. Since the image planes of the three holograms coincide with each other, these noises are the blurred image, reconstructed by the adjacent subholograms. In the process of recording the reconstructed image with the matrix photodetector, in some regions the recognition errors were observed due to the overlap of the first orders of diffraction by the adjacent holograms. The second diffraction orders were spatially separated and did not fit into the registration plane of the camera, and therefore, they did not affect the quality of the reconstructed image.

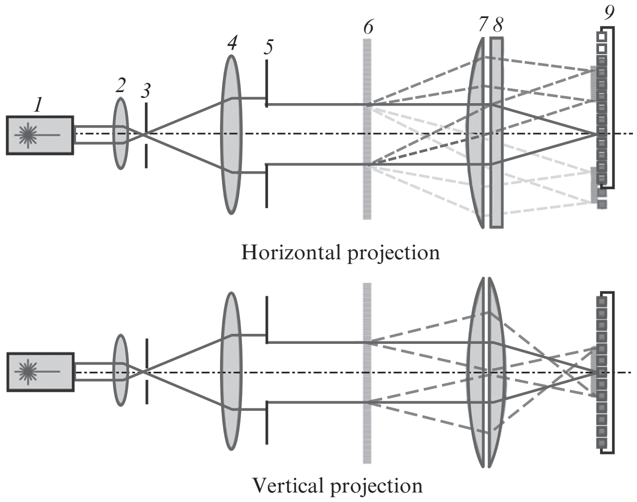

Figure 8. Optical scheme for page-by-page reading of one-dimensional computer-synthesised Fourier subholograms: (*1*) laser; (*2*) microscope objective; (*3*) pinhole diaphragm; (*4*) objective; (*5*) diaphragm; (*6*) photosensitive information carrier; (*7*) Fourier objective; (*8*) cylindrical lens; (*9*) matrix photodetector.

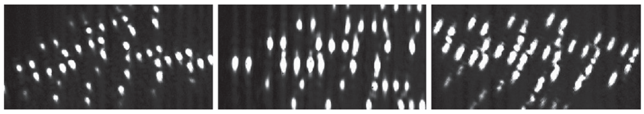

Figure 9. Test object image of the input data page fragment, reconstructed sequentially from three multiplex-recorded synthesised one-dimensional Fourier subholograms (identical fragments of the data page are presented for clarity).

Figure 10. Image of the test object in the form of the input data page fragment, reconstructed from a single one-dimensional Fourier subhologram.

It is also worth noting that the experiments have shown the reasonability of using line-by-line reading of the input data pages, recorded in the Fourier subholograms, using the projection method, since in this case one can expect increased reading rate and improved signal-to-noise ratio at the expense of the increased brightness of the read image. In more detail this issue will be discussed in the next paper, since it requires additional studies.

4. Conclusions

We have considered the possibility of increasing the data recording density in the holographic memory system using the computer synthesis and projection multiplex recording of computer-synthesised one-dimensional Fourier subholograms. The advantages of such system are determined by the fact that the one-dimensional holograms possess high selectivity to the change of the direction of the reading laser beam with respect to the hologram. The presented results demonstrate the possibility of increasing the information recording density in the form of input data pages, proportional to the number of Fourier subholograms, recorded in a single multiplex hologram.

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