Quantum Electronics **43** (1) 87 – 89 (2013)

HOLOGRAPHIC MEMORY

PACS numbers: 42.40.Ht; 42.40.Jv; 42.40.Eq
DOI: 10.1070/QE2013v043n01ABEH014927

Method of computer generation and projection recording of microholograms for holographic memory systems: mathematical modelling and experimental implementation

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Abstract. **A method of computer generation and projection recording of microholograms for holographic memory systems is presented; the results of mathematical modelling and experimental implementation of the method are demonstrated.**

Keywords: *holographic memory, computer-generated hologram, spatio-temporal light modulator.*

The development of methods for compact and long-term data storage is one of the most important problems of modern information technologies. The use of holographic methods in solving the problems of long-term data storage potentially allows achievement of high information capacity and writing/reading rate and also offers a number of other known advantages. At present a large number of publications devoted to this field is known; a considerable part of the newest research has applied character; there are also data about a number of attempts of commercialisation of the holographic memory systems [1 – 10]. In this paper we present a method of producing microholograms, in which the computer calculation of holograms is combined with their projection recording on photosensitive media.

As a rule, in the systems of holographic memory the 'classical' approach is used, which consists of fixing the pattern produced by interference of coherent reference and object waves. As an alternative of the interference hologram recording, we propose to use the computer generation of holograms. In this case a hologram with the response, corresponding to the required data page, is numerically calculated (generated). The generated hologram is presented in the form of a digital image, which is directly projected onto the holographic carrier by means of a spatial light modulator (SLM). After the exposure a diffraction pattern with desired characteristics is formed in the carrier, providing the reconstruction of the initial data page image. The advantage of such approach is that no interference holographic schemes are needed, which essentially simplifies the system as a whole.

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Received 22 June 2012; revision received 16 November 2012
Kvantovaya Elektronika **43** (1) 87 – 89 (2013)
Translated by V.L. Derbov

In the holographic memory systems the object of recording is a 2D array of binary elements – the binary data page with special reference points, playing a technical role in the process of reading. At present the organisation of data in holographic memory pages is regulated by the international standard ECMA-377 [11]. A specific feature of such an object is that each pixel carries definite information, so that the requirements to the possibilities of correct sorting and localisation of 'black' and 'white' elements in the reconstructed image are rather severe.

An example of a data page with 6×6 information blocks is presented in Fig. 1. Below the pages of this size are considered in this study. The computer generation of Fourier holograms was implemented in a standard way; the calculations were performed using the known methods of zero-order sup-

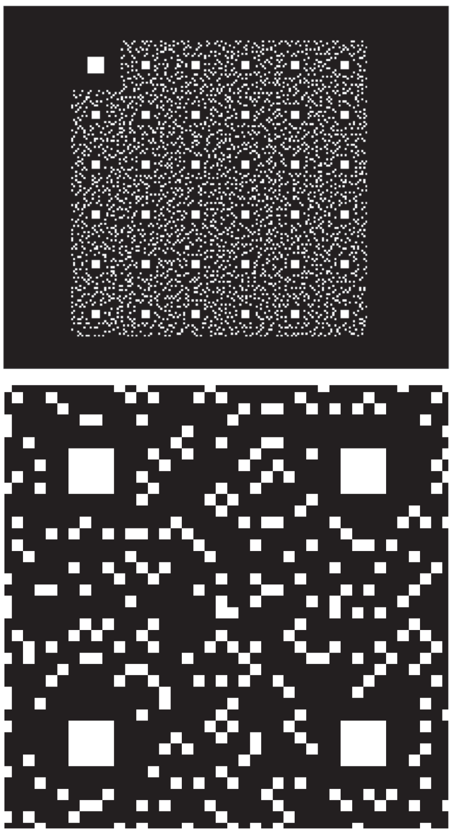

Figure 1. Binary data page (upper pane – the complete page view with 6×6 information blocks, lower panel – a magnified fragment).

pression and addition of a random phase mask [12, 13]. The latter method was optimised with the distribution of 'white' and 'black' elements of the recorded objects taken into account. The result of computer calculation, the amplitude hologram, is presented in the form of a grey-scale raster image. Figure 2 shows the example of a fragment of the calculated Fourier hologram, and in Fig. 3 the distribution of the light field numerically reconstructed from this hologram is presented. The reconstructed field consists of three spatially separated areas, containing a delta function in the zero order and two conjugate images of the recorded object in the ± 1 diffraction orders. Model calculations for Fourier holograms have shown their applicability for recording pages of binary data. The calculated holograms provided the ratio of intensities of zero and first diffraction orders at the level of 10^4 without the use of random phase masks and 10^3 with the phase masks. Since the real spatial light modulators and holographic carriers possess a limited dynamic range of modulation, we carried out the modelling of limitation of the dynamic range of modulation of the generated Fourier hologram, which has shown that it is necessary to use not less than 6–8 levels of transmission. It was found that the best quality of the reconstructed object is achieved with addition of random phase masks.

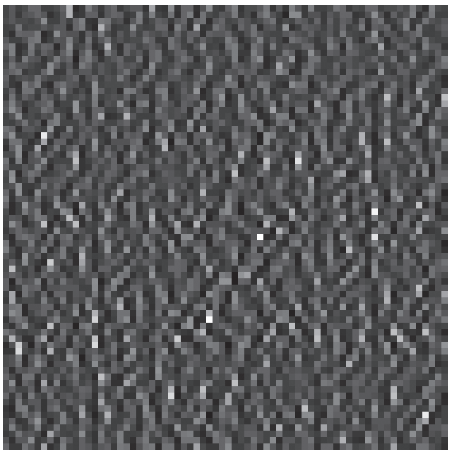

Figure 2. A magnified fragment of the generated Fourier hologram.

The experiments on implementing the generated Fourier holograms and using them for data page reconstruction were carried out. To input the projected image we used the liquid-crystal SLM Holoeye LC-R1080, operating in the transmitted intensity modulation regime (the modulator pixel size 32 μm, the modulator dimension 1024×768 pixels). The projection was implemented onto high-resolution photographic plates PFG-01 and PFG-03 with the photographic emulsion on the base of silver halogenides as a photosensitive layer. The acutance is 3000 lines mm^{-1} for the PFG-01 emulsion and 10000 lines mm^{-1} for the PFG-03 emulsion. This is far beyond the values, required for recording the projected images of the calculated holograms in emulsions.

Two methods of projection recording were studied making use of a coherent radiation source (laser) and an incoherent source (light-emitting diode). The comparative analysis of the images, reconstructed from the holograms, obtained with coherent and incoherent projection, has shown that there is no essential difference in the image quality. Under the incoherent projection we observed some higher spatial noise; however, this did not affect the result of reading, provided that the employed facilities of sorting 'black' and 'white' elements are similar.

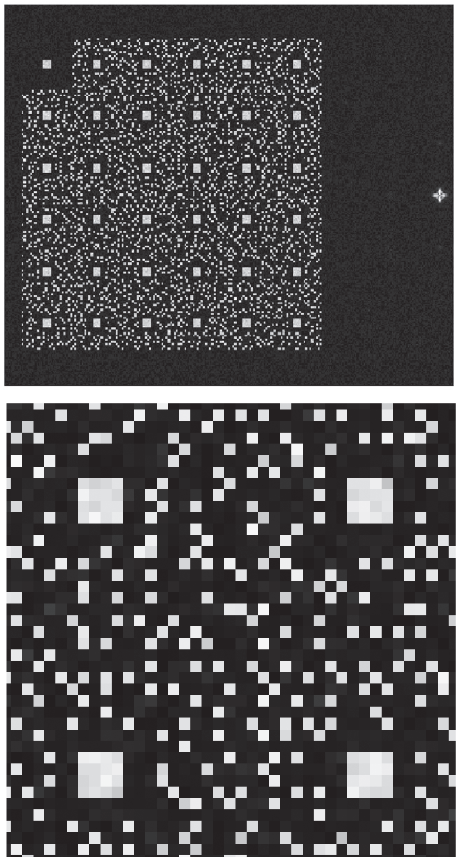

Figure 3. The result of numerical reconstruction of the hologram response. Upper panel – the view of zero and first diffraction orders, lower panel – a magnified fragment of the first diffraction order.

The results of experimental implementation of Fourier holograms with limitations of dynamic range of transmission confirmed the results of numerical modelling, demonstrating the necessity of using not less than 6–8 grades of hologram transmission, which is not a severe requirement for the presently available spatial light modulators.

The image, reconstructed from the hologram, obtained using the scheme of incoherent projection on the photosensitive medium with twentyfold demagnification of the liquid crystal modulator aperture is shown in Fig. 4. It is seen that, in spite of appreciable distortion of the shape of reference points and information bits, the contrast and geometry of the reconstructed image of the data page provide the correspondence between the read result and the recorded page.

Thus, we presented the method of computer generation and projection recording of microholograms for holographic memory systems. The relevant results of mathematical modelling and experimental implementation of the method are presented. In our opinion, provided that all other conditions are equal, the use of the method allows cardinal reduction of requirements to optical and optoelectronic units of holographic memory systems at the expense of replacing the interference hologram recording with projection recording of numerically generated holograms. The rate of hologram calculation using the up-to-date computer facilities can be very

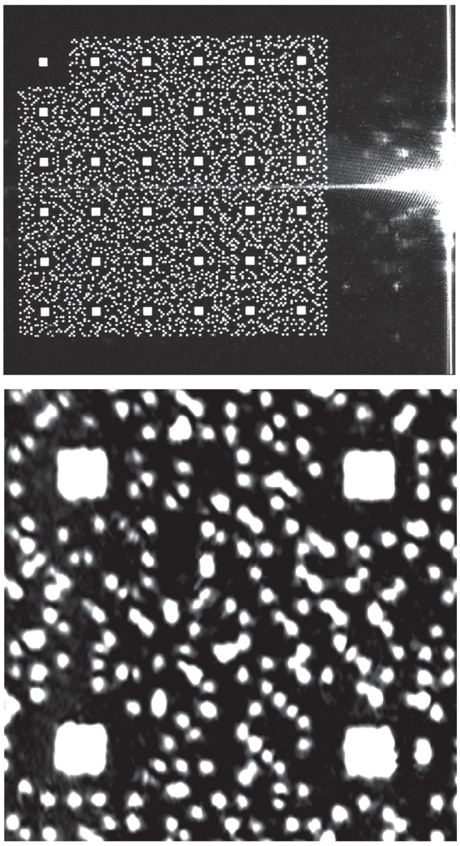

Figure 4. The result of experimental reconstruction of the hologram response. Upper panel – the view of zero and first diffraction orders, lower panel – a magnified fragment of the first diffraction order.

high and reach thousands of pages per second, as shown by the most restrained estimates.

The performed estimations of information capacity of Fourier holograms, taking into account the specific features of their calculation and of presenting the data pages (size of reference points, spatial filling factor of elements, etc.), demonstrated that with the available spatial modulator of light with the dimensions 1024×768 pixels the maximal possible amount of written/read information amounts to $\sim$50 Kbytes (whereas the dimensions of modern advanced commercially available modulators can provide an output of up to 200 Kbytes of information). Obviously, alongside with the resolution of the hologram carrier and the parameters of optical systems, the dimension of the used spatial light modulator is also a crucial factor that limits the performance characteristics of data recording by means of the presented method. Since the size of holograms, projected onto the photosensitive medium, may approach a few square millimetres, the photosensitive materials have an essential reserve in resolution, which, probably, allows multiplex recording of holograms; however, this issue requires separate discussions.

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