## Development of projection-type optical scheme for computer-generated Fourier hologram recorder

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Received November 27, 2016; accepted December 28, 2016; posted online February 10, 2017

Projection-type recorders of computer-generated Fourier holograms have potential due to the decreased precision requirements of the optical scheme compared to most known holographic data recorders based on two-beam schemes. In the case of optical memory system development, the reduction factor of the projection scheme requires the application of properly developed optical components. The present report is dedicated to the development of special objectives for the projection scheme of computer-generated Fourier holograms.

OCIS codes: 090.0090, 110.0110, 210.0210. doi: 10.3788/COL201715.040903.

Computer-generated Fourier holograms (CGFHs) are prospective candidates for applications in such areas as holographic memory systems, optical correlators, and augmented reality systems. The advantage of CGFH is the simplicity of its numeric synthesis, as only several operations of fast Fourier transformations (FFTs) are required. Also, CGFH can be displayed by spatial light modulators (SLMs) and recorded onto a photosensitive carrier using a simple projection scheme with significantly lower precision requirements than those for classic two-beam Fourierhologram recording schemes<sup>[1]</sup>. In the case of memory system development, the last advantage can significantly decrease the cost of bit recording, which is the cornerstone problem of most known holographic data recorders.

However, the application of proper optical elements in projection scheme design is very important, especially in the case of the significant reduction of the CGFH aperture during the recording process, as it is required for memory systems. In this report, we review two schemes of projection-type data recorders. The first one uses standard optical objectives, while the second one is based on specially developed objectives. Both schemes are compared by means of analysis of numeric estimations of transfer function and analysis of object images reconstructed by the experimentally recorded holograms.

Figure <u>1</u> illustrates the principal optical scheme of the CGFH data recorder that was used in the research. This scheme is based on the application of a liquid-crystal-onsilicon (LCoS) SLM; see position 5 in Fig. <u>1</u>. Since this type of SLM is a reflection type, beam splitter 6 with polarized coating of its surfaces [Figs. <u>1(a)</u> and <u>1(b)</u>] must be used. A laser or light emitting diode (LED) can be used as light source 1. Objectives 2 and 4 and pinhole diaphragm 3 form a beam collimating system, which is used to adjust the beam's spatial characteristics to match the SLM aperture. Fourier-transform objective (FTO) 7, backward FTO (BFTO) 9, and diaphragm 8 compose an optical 4-f telescopic system that translates the SLM aperture onto the photosensitive carrier (position 10) and provides the spatial frequency filtering. The reduction factor of the projection optical module is determined by the focal lengths of its objectives as the ratio k = F1/F2. Element 11 is the X/ Y shifter of the holographic carrier mounted to provide CGFH recording onto the full surface of the holographic disk.

An LCoS SLM Holoeye Pluto with a resolution of  $1920 \times 1080$  pixels, screen sizes of  $15.36 \text{ mm} \times 8.64 \text{ mm}$ , and a pixel pitch of 8 µm was used in the experimental prototype of the projection-type holographic data recorder. In our experiments, we used an LED source with an illumination central wavelength of 521 nm and a spectral width of 20 nm.

The optical projection scheme based on the standard objectives of the CGFH recorder was composed by two standard objectives: "Era-7" with the focal length  $f_1 = 150$  mm as the FTO and "Jupiter-3" with the focal length  $f_2 = 51.54$  mm as the BFTO. The reduction factor of the system is ~0.33×.



Fig. 1. Principal optical scheme of CGFH projection data recorder based on reflection type LCoS SLM: 1—LED; 2 objective; 3—diaphragm; 4—objective; 5—LcoS SLM; 6—beam splitter; 7—FTO; 8—diaphragm; 9—BFTO; 10—photosensitive plate; and 11—XY-shifter and rotator mechanics.



Fig. 2. MTF of optical scheme based on standard optics.

The size of the LCoS in the recording medium is 7.68 mm  $\times$  4.32 mm, and the size of holographic structure is 8  $\mu m$  (2 LCoS pixels).

The geometric size of the axial spot in the image plane is equal to 2.102  $\mu$ m, and the edge of the field  $-8.614 \mu$ m. The quality of the optical scheme for the recording of the CGFH was analyzed using the Zemax modeling tool, and the calculated modulation transfer function (MTF) is shown in Fig. <u>2</u>.

The maximum frequency of the LCoS image is

$$\nu_{x \max} = \frac{1}{2 \times 0.008} = 62.5 \text{ mm}^{-1}.$$
 (1)

The MTF for this frequency is about 0.3, so the optical system with standard components meets the criterion of quality (the MTF for the maximum frequency should be more than 0.3).

The optical scheme discussed above is capable of recording CGFH, but increasing the recording density with an acceptable MTF requires the design of a special optical system. Moreover, the use of lenses 4 and 7 (see Fig. <u>1</u>) causes the overall scheme to be big.

The main criteria of the new objective design are a high spatial resolution, a light source with a wide spectrum that can be used in the scheme, compactness, and a high reduction factor. For the maximum spatial frequency of  $62 \text{ mm}^{-1}$  of the interference pattern structure displayed on the LCoS Pluto SLM, and a light source with a wavelength of 521 nm and a spectral range of  $\pm 10$  nm for the projection system for the recording CGFH with a reduction factor of  $0.2 \times$  was developed. Figure 3 presents the developed optical scheme. The scheme consists of a group of 4 lenses that is used instead of a light source collimator lens 4 and FTO objective 7 (see Fig. 1). Lenses 6 and 8 are added to compensate for the distortions caused by chromatic and spherical aberrations. A group of 9 lenses forms the BFTO of the scheme. The parameters of the FTO are as follows:  $f' = 100.195 \text{ mm}, s_F = -32.24 \text{ mm}, \text{ and}$ 



Fig. 3. Optical scheme of designed objective: 1—LED; 2 objective; 3—LCoS; 4—lenses of FTO; 5—beam splitter; 6 correcting lens; 7—diaphragm; 8—correcting lenses; 9—lenses of BFTO; and 10—recording medium.

 $s_{F'}=52.2$  mm. Those of the BFTO are: f'=20.65 mm,  $s_F=-3.34$  mm, and  $s_{F'}=28.87$  mm.

The modeling of the proposed scheme using Zemax software showed that the MTF for the maximum frequency of the reduced LCoS image (312.5 mm<sup>-1</sup>) is about 0.31, so the designed optical system meets the quality criterion of CGFH recording (Fig. <u>4</u>).

The developed optical system [see Fig. <u>5(a)</u>] for CGFH recording was tested in a recording device experimental prototype [see Fig. <u>5(b)</u>]. First, we recorded amplitude gratings with spatial frequencies of 312.5, 164.25, and 82.125 mm<sup>-1</sup> and measured their contrast [see Fig. <u>6(a)</u>]. During the experiments PFG emulsion was used as the photosensitive media carrier. The development of the photographic plate was performed with the developer SM6. The contrast for the grating with the maximum frequency was about 0.3, so the experimental results match the theoretical MTF.

Also, the recording of the synthesized CGFH structures was performed [see Fig. <u>6(b)</u>]. The recorded holograms were recovered with the classic system of optical Fourier cascade<sup>[2]</sup>. An example of a data page restored as a hologram and post-processed digitally on a PC is shown in Fig. <u>7</u>.

The data page is a massive work of coded 7-bit numbers in return-to-zero mode aligned horizontally (see Fig.  $\underline{7}$ ). The highlighted regions show the reference points; the



Fig. 4. MTF of designed optical scheme.



Fig. 5. Optical system with LCoS and recording device.



Fig. 6. Photo of recorded (a) grating with spatial frequency  $312.5 \text{ mm}^{-1}$  and (b) recorded hologram.

information points are between the reference points. The numbers are coded with standard binary coding: (1) is a bright dot, and (0) is a dark dot.

Post-processing of the detected image is made to equalize the brightness of the photo and prepare it for decoding.

The estimated value of the signal-to-noise ratio was about 6.4; this allowed us to decode the digital information from the data pages without errors and losses.



Fig. 7. Recovered information from hologram.

Two recording systems for CGFHs are described: with standard components, and with specially designed components. The optical system quality is analyzed. The main criterion is the MTF for the maximum spatial frequency of the recorded hologram (>0.3)<sup>[3]</sup>. The specially developed objective is designed using the criteria of compactness, high spatial resolution, allowing for  $0.2 \times$  reduction, and suitable for applications with wide spectral ranges of the LED used as the light source.

The experimental modeling proves the possibility of recording and recovering CGFH with a low bit error rate and with a resolution of 2 million holographic dots per  $5 \text{ mm}^2$ .

The study was performed as a part of the state assignments of the Ministry of Education and Science of the Russian Federation, No. 3.9.2014.

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