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HOLOGRAPHIC RECORDING DEVICE BASED ON LCoS SPATIAL LIGHT MODULATOR

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A PC-controlled holographic recording device has been developed in which a LC-R- 2500 Spatial Light Modulator (SLM) based on reflective Liquid Crystal on Silicone (LCoS) display was used. The device allows the amplitude and phase modulation of coherent light wave fronts. In the optical scheme, a DPSS (Diode Pumped Solid State) laser with nanosecond pulse duration and wavelength 532 nm was applied. The holographic recording was made and tested in the amplitude and phase wave front modulation modes on a chalcogenide semiconductor photoresist $As_{40}S_{15}S_{45}$. The experimental results are presented.

Key words: *holographic recording, spatial light modulator, digital holography.*

1. INTRODUCTION

With the development of spatial light modulators and computer technologies, the digital holographic recording has received wide recognition. Nowadays, digital holograms are used for identification of industrial products and documents, protection of documents and goods against counterfeiting as well as for packing and decorating purposes. With the appearance of Liquid Crystal on Silicon (LCoS) modulators of new generation, an interest has grown as to their use in optical schemes for recording computer-generated holograms (CGH) and diffractive optically variable image devices (DOVID).

An LCoS chip has a parallel-aligned nematic liquid crystal (LC) layer to modulate light: it changes the phase and polarization state of the reflected light. The modulation parameters depend on the alignment of such an LC and the polarization of incident light. The LC alignment is controlled pixel-by-pixel, using the CMOS backplane and DVI signal via a PC. The electro-optical effects in LC displays make them suitable for amplitude and phase modulation of coherent wave fronts, therefore such a display can be used as programmable diffractive element.

At the current state of technological development, LCoS optical modulators have characteristics that outperform those of modulators created by the LCD (Liquid Crystal Display) and DLP (Digital Light Processing) technologies. From the viewpoint of their practical application, LCoS devices have the best of such important parameters as small pixels (down to 8 μm), a great number of pixels (1920x1080 resolution), the high fill factor (up to 95%) and frame rate (up to

180 Hz), high reflectivity (better than 70%), weakly coupled amplitude or phase modulation, high contrast, and the depth of phase modulation above 2π in the visible range. These improved parameters of recent LCoS displays make them appropriate for high-quality digital holography [1–4] as well as for many other coherent optical applications [5–8].

2. EXPERIMENTAL

Figure 1 shows the picture and general scheme of the experimental setup for holographic recording using an LC-R 2500 LCoS modulator [9]. In the setup, radiation of laser *1*, with the help of aligned mirror *2*, is delivered to optical filter *4*.

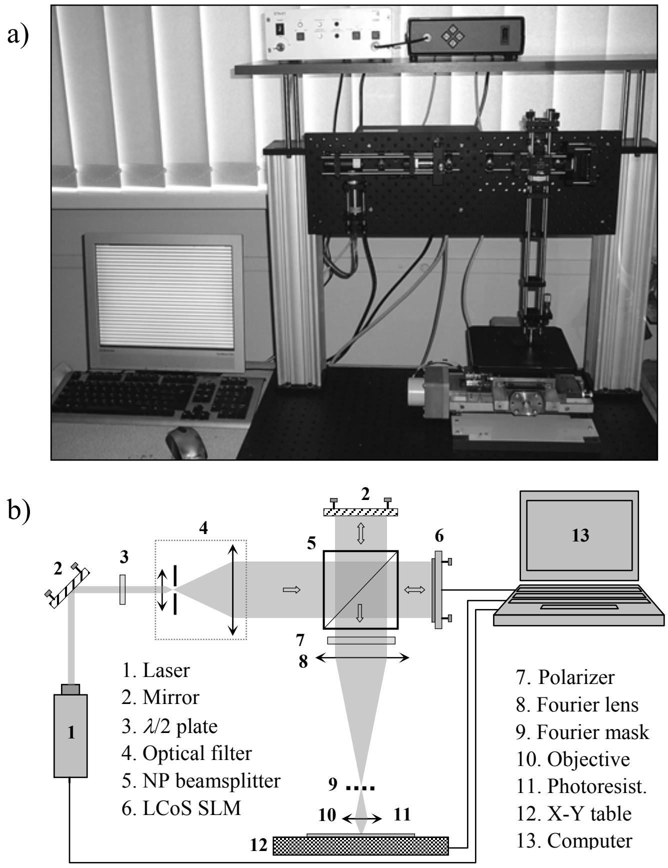

Fig. 1. Photo (*a*) and schematic diagram (*b*) of the experimental setup.

The λ/2 plate (position *3* in the figure) placed in front of the optical filter makes it possible to vary the angle of the laser beam polarization relative to the optical axis of modulator *6*. The widened and spatially filtered laser beam with a flat wave front falls on non-polarizing beam splitter *5* (with the coefficient of amplitude division 50/50). The first portion of the split beam is incident on the optical modulator LC-R 2500, and, after reflecting from its surface, undergoes a local change of phase and polarization plane in accordance with the image on the computer monitor. After reflection of the beam from mirror *2*, its second portion is used as a reference beam in the interference mode for transition from the phase- to the amplitude-modulation of the wave front in optical recording.

The modulation modes (amplitude and phase) are determined by the configuration of the optical scheme (Fig. 2*a,b*) as well as by the position of polarizer *7* and the angle between the laser radiation polarization plane and the modulator optical axis. Lens *8* (with a large focal length f = 450 mm) forms in its focal plane a Fourier's spatial spectrum of the laser radiation diffraction on the amplitude-phase image, which is transferred from the PC to the modulator. Mask *9* is situated in the focal plane of lens *8* and is meant for modifying the Fourier spectra. A zero maximum of radiation diffraction on the modulator and all other maximums higher than the first one are blocked by means of the mask. The inverse Fourier transformation is performed by micro-objective lens (50x, n.a. = 0.5, f = 3.6 mm) 10 onto the surface of a plate with photoresist *11*. A compact diode-pumped SHG ns laser (STA-01SH model, λ = 532 nm, P = 50 mW) modulated electronically through TTL signals was used in the optical scheme [10]. In order to form sequential light pulses with a given energy, the mode of laser *1* operation is used when optical radiation is generated by external synchronizing pulses. A laser pulse with duration ~1 ns and energy ~1.5 μJ corresponds to one external TTL synchronizing pulse. The optical exposure is obtained by a series of electric synchronizing pulses on the carrier frequency of 30 kHz. The pulses are formed by the developed electronic unit operated through the USB interface by the program of computer *13*. Modulator *6* is connected to the computer video card as a second monitor through the DVI interface. The display content is transferred to the modulator with the discretion of 8 bit (one colour channel) in the CLONE driver mode of the video card. As a result, an amplitude-phase modulation of the reflected wave takes place corresponding to the initial pattern.

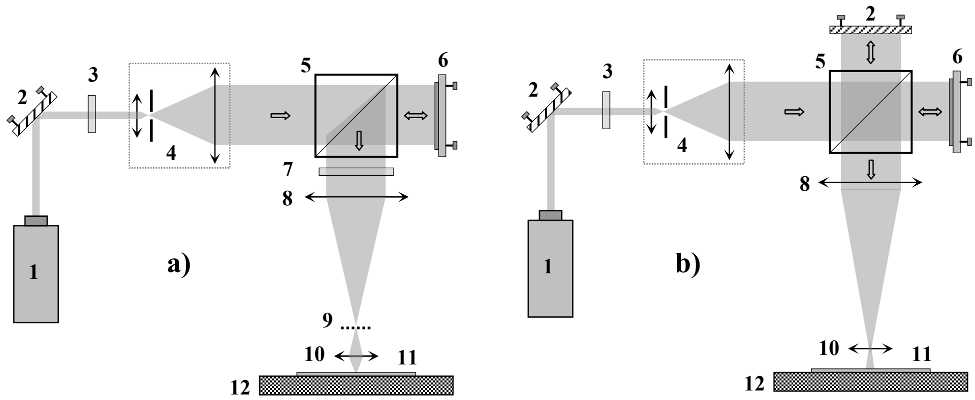

Fig. 2. Optical schemes corresponding to different modes of operation:
a) modulation of wave front amplitude and phase; b) amplitude modulation by the phase contrast method.

In the experiments with optical recordings, As–S–Se chalcogenide thin films (~3 μm) were taken as inorganic photoresist. Amorphous As–S–Se films have been recently used as a promising material for holography in the visible spectrum (λ ≤ 650 nm) with a high resolution (>5000 lines/mm) and the light sensitivity in the range 0.5–20 J/cm^2. The phenomenon of the formation of a surface relief is based on the difference in dissolution rate of the exposed and unexposed areas of a chalcogenide film in alkali developers [11–13].

The general principle of forming a large size hologram is shown in Fig. 3. The recording is performed sequentially by micron-sized (160×120 μm in our case) areas (Fig. 3*a*). Positioning the plate with photoresist is performed by X–Y motorized table 12.

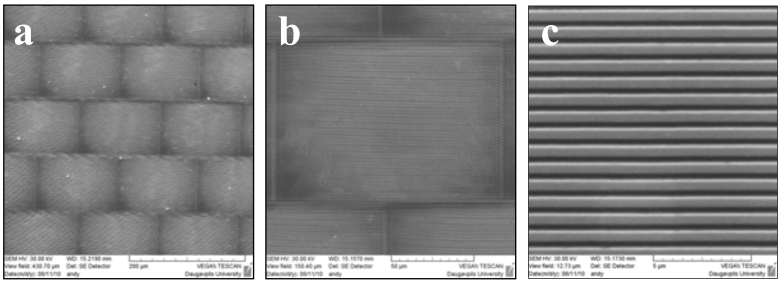

Fig. 3. SEM images of image-matrix hologram at different magnification:
a) Image-matrix structure of hologram; b) image of one frame;
c) diffraction grating in the frame.

The table is operated through the USB interface by an applied computer programme. The sections tightly fill the entire area of the hologram, and a human eye does not perceive a discrete structure of the hologram consisting of micron-sized sections. Optical recording of the interference pattern is performed on each individual area of the hologram. The pattern is set by the amplitude-phase image on the modulator and corresponds to the graphic figure on the computer monitor.

In order to lessen the perceived discreteness of the hologram structure, the neighbouring rows of its micro-images are shifted relative to each other by the half-frame length. Each separate image from a matrix structure contains a computer-generated hologram (CGH); in a simple case, this may be a set of gratings with a pitch and orientation adjusted to the requirements (Fig. 3*c*).

3. RESULTS AND DISCUSSION

After the reflection from LCoS modulator, the flat wave undergoes a local change of the phase and polarization plane. The size of the minimum area of the wave front undergoing change is determined by the size of the modulator pixel (~19 μm in our case). The degree of parameter change in the reflected wave depends on the angle between the optical axis of modulator and the polarization direction of a laser beam, as well as on the level of electrical signals on the modulator pixels. Two possible extreme cases are as follows. In the first one, the modulator changes only the phase of the reflected wave, leaving polarization and amplitude unchanged. This is a phase modulation mode. In the second case, the modulator changes the direction of polarization plane, with small changes of phase in all sections of the wave front. The wave becomes modulated in amplitude after going through the polarizer.

The optical scheme of a holographic recording device shown in Fig. 2*a* is intended for functioning in the amplitude and phase modulation modes of the laser radiation wave front. In the amplitude modulation mode, polarization of the incident laser radiation coincides with the optical axis of modulator; the orientation angle of polarizer relative to the SLM optical axis is $\alpha = 90^o$. After reflection from the SLM surface, at the local area of the wave front the polarization plane is rotated proportionally to the signal on a cell of the modulator. The turn angle is determined by the grey level of the point on the monitor, which corresponds to the modulator pixel (19×19 μm in size). While going through polarizer *7*, the wave front undergoes amplitude modulation. After the direct and inverse Fourier transformations (performed by lens 8 and objective 10) the wave front is projected on the photoresist surface with ~120-fold minimization to form a frame. In turn, to form an image in the frame, the full Fourier spectrum is used; in this case the mask is absent. The amplitude modulation mode allows for recording holograms with a given profile of diffraction grating (rectangular, triangular, sinusoidal, etc.) and frequency in the range 0–800 mm^{-1}. The maximum frequency can be determined by the formula:

$$F_{max} = n.a./\lambda \, , \qquad (1)$$

where *n.a.* is the numerical aperture of objective,

λ is the laser wavelength.

To determine the characteristics of amplitude and phase modulation when optimizing the process of holographic recording, the computer program *PhasCam* [9] was used. A diagram reflecting the dependence of relative radiation intensity on the grey level in the original computer image in the process of amplitude modulation is presented in Fig. 4*a*, whereas in Fig. 4*b* a case of optical recording is shown where concentric circles are recorded on the photoresist $As_{40}S_{15}Se_{45}$ in the amplitude modulation mode after which the etching is performed to obtain the microrelief.

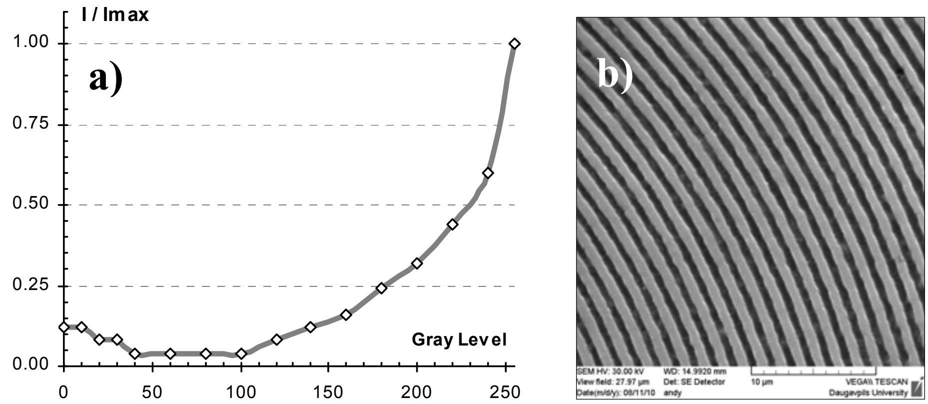

Fig. 4. a) Beam intensity changes in the amplitude modulation mode
(λ=532 nm, beam polarization $\alpha = 0^0$, polarizer $\beta = 90^0$);
b) axicon grating recorded in the amplitude modulation mode (SEM photo).

In the phase modulation mode (see also Fig. 2*a*), the polarization plane of the incident wave is at angle $\alpha = 25^o$ with the optical axis of the modulator and the polarizer is orientated at the angle $\beta = 145^o$. In this mode, the polarization of wave front reflected from the modulator undergoes slight changes in the direction. After the polarizer, the intensity changes are maximum 20%. The phase changes in the range from 0 to 2π are proportional to the level of the incoming signal (Fig. 5*b*).

On the modulator, a phase hologram (~60%) is created with diffraction efficiency $DE = (I_{+1}+I_{-1})/I_0$. A diffraction spectrum appears in the focal plane of lens 8 and correspond to the phase image on the modulator (Fourier spectrum) (Fig. 3*a*). Intensity peaks of the spectrum that are the farthest from the centre correspond to the higher orders of diffraction. Mask *9* blocks the zero diffraction order and the orders higher than the first one. After the inverse Fourier transformation, a hologram with a doubled frequency of diffraction grating is created with the help of objective *10* by interference of the I_{+1} and I_{-1} orders of the wave diffracted on the modulator. This means that the image on the photoresist surface for periodic structures is formed only due to the interference of the second harmonics of spatial spectra. For example, if we send on the modulator the image corresponding to N black-and-white stripes, on the photoresist surface we will get a sinusoidal intensity distribution consisting of 2N peaks.

The phase modulation mode with Fourier's filtration is promising for the use in applied holography since it offers the opportunity to obtain diffraction gratings with a frequency in the 500–1500 mm^{-1} range. The maximum frequency is in this case $F_{max} = 2\ n.a./\lambda$.

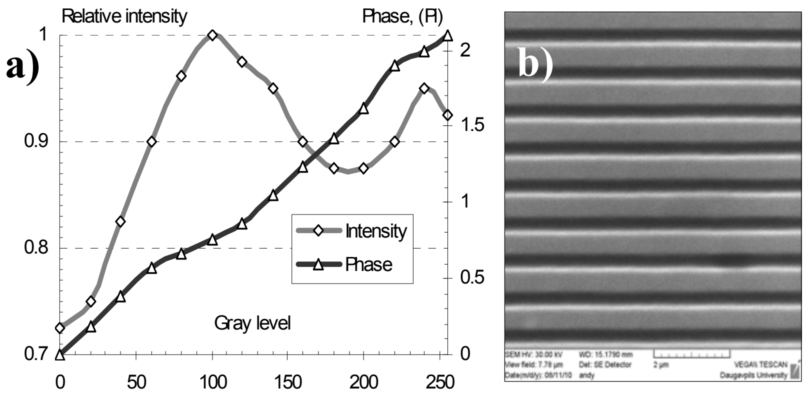

Fig. 5. a) Changes of beam intensity and phase in the phase modulation mode (λ = 532 nm , beam polarization $\alpha = 25^0$, polarizer $\beta = 145^0$);
b) diffraction grating recorded in the phase modulation mode (SEM photo).

The minimum frequency is determined by the size of the central diaphragm (L ~ 1 mm) in mask *9*, which blocks the zero order of diffraction and is calculated by the formula:

$$F_{min} = L/(\lambda f),$$

where λ is a laser wavelength,
f is the focal length of the objective, and
L is the size of the central diaphragm.

Disadvantages of this mode are considerable energy losses during Fourier's filtration and limitations in recording gratings with profiles other than the sinusoidal one.

In the technique for phase visualisation known as the common path interference method [14] (shown above in Fig. 2*b*) the signal and reference beams travel along the same optical axis and interfere at the output of optical system. In this case, the LCoS modulator works only in the phase modulation mode. The reference wave front allows visualization of the phase information in the original wave front. The technique is also known as the phase contrast method.

From the viewpoint of Fourier's optics, a reference beam in the focal plane of lens 8 changes the amplitude and phase of the zero-order component in Fourier's spectra of the wave diffracted from the object, and the SLM image after the reverse Fourier transformation on the photoresist surface by objective *10* has an amplitude component that changes proportionally to the initial phase.

Another way of realizing the phase contrast technique makes it possible to visualize the phase perturbations using Fourier's plane phase shifting filter *9* as shown in Fig. 2*a*. In this case, an efficient filter might have ~ 100% transmission and π/2 phase shift in the central region. However, making such a filter under laboratory conditions is a technologically involved task.

The SEM images in Fig. 6 show the relief-phase diffraction gratings recorded using the optical scheme presented in Fig. 2*b*. For example, in order to record diffraction gratings with the periods of 2 μm and 5 μm (Fig. 6*a*,*b*), a picture of grey and white stripes with the periods of 12 and 30 pixels should be displayed on the computer monitor.

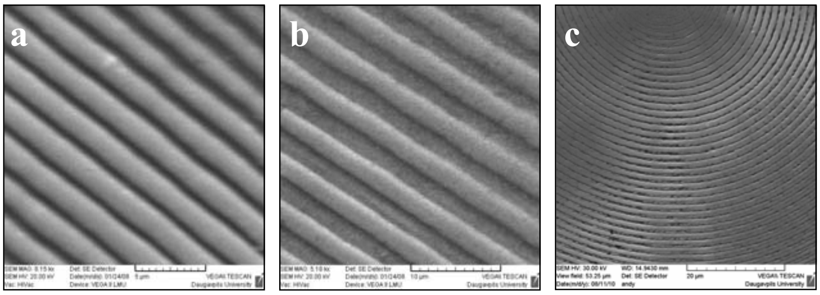

Fig. 6. SEM photos of the diffraction grating recorded by the phase contrast method: a) grating period 2 μm; b) grating period 5 μm; c) axicon grating with period 1.5 μm.

A considerable disadvantage of the proposed recording method is the curvature of the modulator surface that introduces a phase error into the original image which is difficult to compensate. In our experiments, only recording of simple objects (such as binary diffraction gratings) has been performed satisfactorily. The best results were obtained under the condition of a considerably smaller grating period as compared with the linear sizes of the modulator surface with a phase error of π radian.

4. CONCLUSIONS

The designed and constructed experimental setup for recording dot-matrix holograms based of a nanosecond pulse laser and the LCoS LC-R 2500 amplitude-phase modulator made it possible to obtain characteristics of the device performance in the amplitude and phase modulation modes. The holographic gratings have been successfully recorded in the modes of wave front amplitude modulation, wave front phase modulation with filtration of the Fourier spectrum and using the phase contrast method. We have recorded holograms on chalcogenide $As_{40}S_{15}S_{45}$ films with the grating frequency range from 200 to 1000 mm^{-1} and the diffraction efficiency up to 30%. The optical setup is being optimised for recording of the relief-phase protective holograms suitable for their duplication by standard modern technologies.

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REFERENCES

1. Lee, C.-K., Wu, J.W.-J., Yeh, S.-L., & Tu, C.-W. (2000). Optical configuration and color-representation range of a variable pitch dot matrix holographic printer. *Appl. Optics, 39* (1), 40.
2. Yaotang, L., Tianji, W., Shining, Y., & Shichao, Z. (1998). Theoretical and experimental study of dot matrix hologram. *Proc. SPIE, 3569*, 121
3. Bulanov, A., Gerbreders, V., & Paschkevich, V. (2007). Dot-matrix holographic recording in amorphous chalcogenide films. *Proc. SPIE, 6596*, 124
4. Pizzanelly, D. (2004). The development of direct-write digital holography. *Technical review* (Holographer.org.).
5. Kohler, C., & Schwab, X.. (2006). Optimally turned spatial light modulators for digital holography. *Appl. Optics,.45* (5), 960–967.
6. Inoue, T., Tanaka, H., & Fukuchi, N. (2007). LcoS spatial light modulator controlled by 12-bit signals for optical phase-only modulation, *Proc. SPIE, 6487.*
7. Sutkowski, S., & Kujawinska, M. (2000). Application of liquid crystal (LC) devices for optoelectronic reconstruction of digitally stored holograms. *Opt. Laser Eng., 33*, 191–201
8. Sarma, R. (1999). Liquid Crystal Display. CRC Press LLC.
9. www.holoeye.com
10. www.standa.lt/products/catalog/lasers
11. Teteris, J. (2002). Holographic recording in amorphous chalcogenide semiconductor thin films. *JOAM, 4* (3), 687.
12. Teteris, J., & Reinfelde, M. (2003). Application of amorphous chalcogenide semiconductor thin films in optical recording technologies. *JOAM, 5* (5), 1355.
13. Mednikarov, B., & Sahatchieva, M. (2005). Photolithographic structuring with evaporated inorganic photoresist. *JOAM, 7* (3), 1415.
14. Goodman, J.W. (1996). *Introduction to Fourier Optics*. McGraw-Hill.

UZ LCoS TELPISKO GAISMAS MODULATORU BALSTĪTA HOLOGRĀFISKĀ IERAKSTA IERĪCE

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K o p s a v i l k u m s

Mēs esam izstrādājuši datorvadāmu hologrāfiskā ieraksta iekārtu, kurā tiek izmantots LC-R 2500 telpisks gaismas modulators (SLM), kas izveidots uz atstarojošā LCoS (*Liquid Crystal on Silicone* – šķidrie kristāli uz silīcija pamatnes) displeja bāzes. Ar šo ierīci var tikt modulēta koherenta starojuma viļņa frontes amplitūda un fāze. Optiskajā shēmā tika lietots DPSS (Diode Pumped Solid State) lāzers ar nanosekunžu impulsa ilgumu un viļņa garumu 532 nm. Hologrāfiskais ieraksts tika veikts un pārbaudīts viļņa frontes amplitūdas un fāzes modulācijas režīmā uz halkogenīdu $As_{40}S_{15}S_{45}$ pusvadītāju fotorezista. Eksperimenta rezultāti ir tikuši prezentēti.

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