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Asymmetrisation of the profile of a thin dynamic holographic grating in a TV-locked optical feedback loop*

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***Abstract*. A system for recording a dynamic holographic grating in an optically addressed liquid-crystal spatial light modulator is studied. The system provides the asymmetrisation of the grating profile by using a TV-locked optical feedback loop (nonlinear or adaptive interferometer).**

Keywords: *liquid crystal, spatial light modulator, dynamic holography, distortion correction, phase conjugation.*

The dynamic holographic correction of distortions in optical and laser systems (see, for example, [1]) is one of the efficient methods of modern adaptive optics. The operation principle of such systems is as follows. A probe laser beam is transmitted through a distorting optical system. The distortions introduced by this system should be corrected. Then a distorted (signal) beam interferes with the undistorted reference beam and writes a hologram (static or dynamic), which is used as a corrector of distortions introduced by the given system. The correction procedure implements the hologram reconstruction by radiation distorted by the system. For example, when the system images some object, the image of each of these object points corresponds to a light wave distorted by the system. During diffraction of each of these waves from the hologram corrector to the -1st order, distortions are subtracted and a set of undistorted light waves corresponding to the undistorted image of the object is reconstructed. Experimental studies have shown that thin (plane) dynamic holograms are optimal for correction problems. These holograms are not subjected to limitations imposed by the angular and spectral selectivity and, therefore, can be used to correct images in a certain field of view and a certain spectral region around the wavelength of radiation used for recording the hologram corrector (see details in review [1]).

The use of the so-called optically addressed liquid-crystal spatial light modulators (OA LC SLMs) [2] proved to be most convenient for recording such thin dynamic holograms. These modulators are sandwich-like devices containing, in particular, an LC layer and a photoconductor (PC) layer to which a voltage is applied. The conductivity of the PC layer increases under the action of radiation, which leads to the increase in the voltage applied to the LC layer, resulting in a change in the birefringence of the thin LC layer. The use of such elements allows, in particular, the recording of efficient thin dynamic (rewritable in real time with a maximum rewriting rate of 10 – 1000 Hz) holographic gratings.

However, it is known that when a thin holographic grating is written by the conventional 'direct' method as the interference pattern of two laser beams, its diffraction efficiency in the $+1$st and -1st diffraction orders cannot exceed 33 % for the sinusoidal grating profile or 40 % for the rectangular grating profile (meander), which leads to high energy losses in the optical system with such a hologram used as a corrector.

This problem is solved by using asymmetric holographic grating profiles in manufacturing various static holographic and diffraction optical elements, which are also known as kinoforms (see, for example, monograph [3]). In particular, when a phase transmission grating with the right triangle profile and the phase modulation depth of 2π is used, its diffraction efficiency to the $+1$st or -1st diffraction orders can achieve 100 %. In this case, if the general structure of the interference pattern (hologram), i.e. the local period and direction of fringes, remains invariable, then the field structure reconstructed by such an asymmetric-profile hologram upon diffraction to the $+1$st or -1st orders remains in the first approximation the same as upon diffraction from the initial hologram.

This procedure can be also used for recording dynamic gratings, in particular, with a period variable over the hologram area, i.e. thin phase holograms. Such asymmetrisation was performed in experiments [4, 5] by using the digital transformation of the interference pattern recorded with a CCD camera. Note, however, that because digital processing involves a great amount of calculations, thereby reducing the rewriting ability of the system, it is not applied in practice so far.

An alternative analogue method for asymmetrisation of the interference pattern profile was proposed and theoret-

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ically studied in [6]. The method is based on recording a dynamic hologram with the help of the so-called nonlinear or adaptive interferometer, which is also known as a negative optical feedback system. Such interferometers were used in a number of papers (see, for example, [7, 8]) for recording dynamic phase correctors and, as a rule, they use an OA LC SLM with an internal mirror located between LC and PC layers. The mirror is used to separate recording and reading channels and, in particular, to realise a scheme in which the phase shift in the LC layer is controlled by the interference pattern from two light waves illuminating the PC layer, one of the waves being previously transmitted through the LC layer of the same modulator. It was shown in [7, 8] and other papers that in this case the phase shift profile is formed in the LC layer, which is additional to the path difference of the wavefronts involved in the control of the modulator and can serve, in particular, as a corrector of wavefront distortions for one of the beams.

In the scheme for recording a dynamic hologram proposed in [6], one of the writing beams (either the undistorted reference beam or the signal beam carrying information), before its interference with another beam, is also transmitted through the LC layer of the modulator used for recording the dynamic hologram. The theoretical study and numerical simulation of this scheme performed in [6] confirmed that in this case the phase profile of the interference pattern of writing waves (and hence, of the dynamic hologram) transforms to the saw-tooth profile for the time corresponding to the two – four rewriting times of the modulation picture, while the diffraction efficiency to the +1st or −1st orders achieves 100 %.

Unfortunately, the realisation of this scheme in practice proves to be rather difficult. One of the problems is purely technical and is related to the necessity of accurate spatial combining (at the 1 : 1 scale) the phase relief produced on the ‘front’ side of the modulator in the LC layer with the wavefront of the light beam modulated in the modulator, which is directed on the PC layer on the ‘rear’ side of the modulator. In [7] and other papers, this was performed by using a complicated and inflexible imaging optical system. When a dynamic hologram is recorded [6] rather than a phase corrector [7], the requirements to the accuracy of imaging and optical resolution of this system considerably increase, which makes its construction even more complicated.

The second problem is of the fundamental type. The recording of a holographic grating in the OA LC SLM in the optical feedback loop in scheme [6] is the essentially dynamic process. During the establishment time of the asymmetric profile, the nonmonotonic change in the phase profile depth in time can be observed in certain modulator regions. Note that such phase gratings are recorded with the ‘grey’ phase-modulation depth scale by using, as a rule [1, 2, 4, 5], modulators based on the so-called S-effect (variant of the known Freedericksz effect) in a nematic LC. The Freedericksz effect consists in the orientation of LC molecules along an electric filed. When the electric field is switched off or reduced, the relaxation of molecules occurs as in the case of thermal decay. Thus, the types of orientation and relaxation processes in this case are substantially different and they are described by different temporal laws. When the control electric field is changed nonmonotonically, this can lead to hysteresis effects and blurring of a holographic grating being recorded.

In this paper, we studied the scheme for recording a holographic corrector in an optical feedback loop which is locked by the TV-computer method [4, 5, 8, 9]. This data transfer method considerably simplifies the optical scheme, while the frame rewriting of the interference pattern eliminates the influence of hysteresis phenomena.

The iteration process of the establishment of the grating profile was numerically simulated in [10]. The modulator was simulated as a light-controlled phase grating with the phase shift distribution $\varphi(x, y)$ dependent on the control radiation intensity $I(x, y)$ and described by the expression

$$\varphi(x, y) = k_i I(x, y), \qquad (1)$$

where k_i is a proportionality coefficient.

The interference of two light waves occurs on a photosensitive element (CCD array) of the system. The first wave is a plane wave, while the second one carries information on the current phase profile of the LC layer of the modulator, which is also plane at the initial moment (in the first iteration). The interference pattern recorded in the CCD array is reproduced without distortions on the photosensitive layer of the OA LC SLM, thereby locking the optical feedback loop. It is assumed that the loop is locked strictly linearly, i.e. neither the CCD camera nor the digital data transfer channel nor the device reproducing the interference pattern introduce distortions into the intensity distribution due to their nonlinearity, noise or the saturation of their parameters.

The result of this interference can be written in the form

$$I(x) = I_{rr}[1 + p\sin(kx + \varphi(x, y))], \qquad (2)$$

where k is the wave number and I_{rr} and p are transfer coefficients.

The obtained intensity distribution determines the phase profile of the modulator in the next iteration. The simulation showed that such an iteration process quite rapidly (for 3 – 4 rewriting events) converges to a substantially asymmetric profile, which is close to the required saw-tooth profile (Fig. 1). Figure 1 shows that the position of the minima of the saw-tooth profile coincides with that of the minima of the initial interference pattern. This means that the transverse structure of the hologram, i.e. the local period and direction of fringes, remains invariable and, therefore, such a hologram can be used, for example, to correct images.

We also calculated the diffraction efficiency of a diffraction phase grating with a profile presented in Fig. 1d. The calculation was performed by numerical integration with the help of the Helmholtz – Kirchhoff formula, in which the radiation intensity at point P is calculated as the result of interference of secondary spherical waves:

$$I(\mathrm{P}) = \frac{\mathrm{i}}{2\lambda}\int\int u(x, y)\frac{\exp(-\mathrm{i}kr)}{r}(1 + \cos\theta)\mathrm{d}S, \qquad (3)$$

where λ is the wavelength; $u(x, y)$ is the radiation intensity on the modulator surface; r is the distance to the point at which the intensity is calculated; θ is the wave propagation direction; and $\mathrm{d}S$ is a surface element of the source of secondary waves (radiation wavefront).

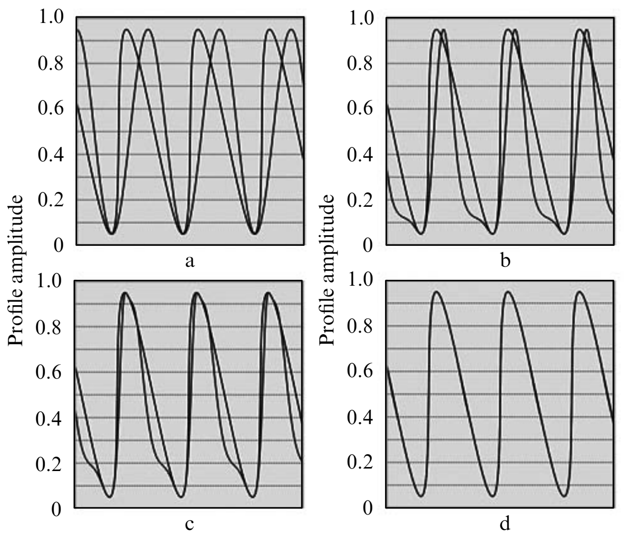

Figure 1. Results of the numerical simulation of the establishment of the saw-tooth profile of phase modulation. The corrector profile at the different stages of the formation process is compared with the limiting profile. Iteration numbers: 1 (a), 2 (b), 4 (c) and 30 (d). Figures 1a–c also show the profile presented in Fig. 1d.

The radiation intensity on the modulator surface can be considered constant, but the phase shift should be taken into account. The integral can be reduced to a one-dimensional integral in the case of the symmetric phase profile. The calculation method is based on the integration of secondary waves from the modulator surface to each direction taking the phase shift into account:

$$D(\varphi) \sim \int_0^{2\pi} \left[\int_{-L}^{L} \sin(t + kr + I(l)\mathrm{d}l \right]^2 \mathrm{d}t. \quad (4)$$

Here, $D(\varphi)$ is the relative intensity of a signal diffracted at an angle φ; the internal integral describes the interference of all secondary waves emitted in the same direction; t is the initial phase of the diffracted wave; l is the distance to a plane perpendicular to the propagation direction of the required diffraction order (which can be estimated as $l\sin\phi$); and $I(l)$ is the phase profile of the modulator. The external integral sums the squares of the amplitude of the resulted wave for each initial phase from 0 to 2π, which corresponds in fact to the wave intensity.

The number of periods of the phase grating was set equal to 20 (the integral cannot be reduced to one period), and the number of integration points was 1300. The results of numerical integration in model calculations, performed by using the program developed for phase profiles for which the exact analytic solution (sinusoid, rectangular meander, ideal saw-tooth distribution) exists, showed that the accuracy of such estimates is rather high and the discrepancy between the theory and numerical calculation does not exceed 0.3 %. The diffraction efficiency to the –1st order calculated for the curve in Fig. 1d was 67 % for the phase modulation depth 2π (from the minimum to maximum value) and 85 % for the phase modulation depth 1.6π, which was optimal for the given profile.

The considerations presented above were verified in the model experiment. Figure 2 shows the scheme of the experimental setup. The radiation beam of a 633-nm He–Ne laser (*1*) was expanded in collimator (*2*) and directed into a Michelson interferometer formed by 50 %

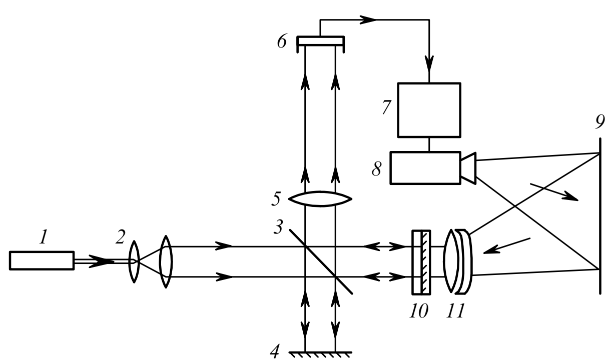

Figure 2. Scheme of the experimental setup (the direction of beams is shown by arrows): (*1*) He–Ne laser; (*2*) collimator; (*3*) beamsplitter; (*4*) mirror; (*5*) lens; (*6*) CCD camera; (*7*) personal computer; (*8*) multimedia projector; (*9*) scattering screen; (*10*) OA LC SLM with an internal mirror; (*11*) matching objective.

beamsplitter (*3*), plane mirror (*4*) and internal OA LC PLM mirror (*10*). The parameters of this modulator (see details in [11]) provide the optically controlled modulation of the optical thickness of the LC layer within 3π (1.5λ) at the He–Ne laser wavelength with a resolution of no less than 15–20 mm^{-1}.

Light beams reflected by mirror (*4*) and internal modulator mirror (*10*) were combined at a small angle and interfered on the CCD array (with a 8-mm aperture) of camera (*6*). The planes of mirrors (*3*) and (*10*) were imaged on CCD array (*6*) by means of lens (*5*). The period of the interference pattern was varied in different experiments from 0.5 to 2 mm, i.e. 4–16 periods of the interference pattern were fitted in the CCD array aperture.

The real-time signal of the CCD camera was fed to the input of personal computer (*7*) and then to Cannon LV-S1 commercial multimedia projector (*8*). The computer-reproduced image of the interference pattern was projected on scattering white screen (*9*). This image was projected in turn by high-quality reproduction objective (*11*) on the SLM plane.

As mentioned above, to realise the analogue asymmetrisation procedure, it is necessary to provide with a high accuracy the coincidence (at the 1 : 1 scale) of the interference pattern image and phase modulation in the LC layer of the SLM that produced the interference pattern. This was achieved in our experiments, as in experiment [9], with the help of internal electronic adjustments of the multimedia projector, which allowed us to select the scale and position of the interference pattern image on the photosensitive layer of the SLM and correct the projective distortions of the image.

Our experiments showed that after 4–5 iterations in this system, i.e. within the change of 4–5 frames after the switching on of the modulator power supply, the interference pattern of two beams acquired a distinct asymmetry. Figure 3 demonstrates the sections of interference patterns for different spatial frequencies.

One can see that these interferograms are not free from the spatial noise. The main sources of this noise are the speckle noise and parasitic interference in numerous SLM layers. In the case of computer holography, the pixel nature of a CCD camera also contributes to the noise. However, Fig. 3 shows that the depth of the noise component is approximately an order of magnitude smaller than the

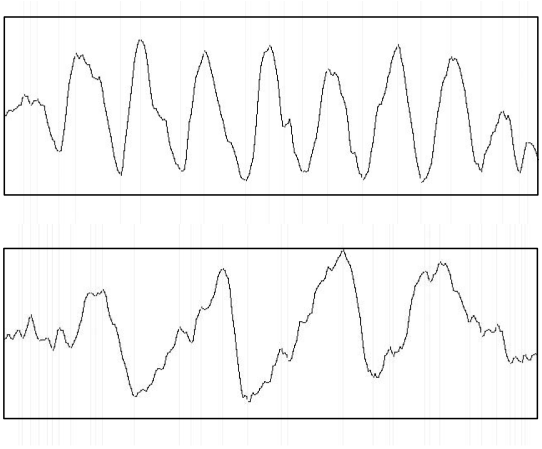

Figure 3. Sections of interference patterns after establishment of the asymmetric profile, obtained in experiments for different spatial frequencies of the interference pattern.

grating depth. Taking into account that the optimal depth of the phase modulation for an asymmetric grating is approximately equal to one radiation wavelength, the intensity of scattering from such a noise grating cannot exceed a few percent. This noise can be also filtered, if necessary, with the help of a spatial filter (a pinhole in the focal plane of the objective imaging the interferogram), but filtration was not performed in this model experiment.

According to the calculation performed by expressions (3) and (4), the diffraction efficiency in the first order for such structures was from 65 % to 75 % for different realisations, the optimal depth of phase modulation varying from 1.6π to 2π. This is close to the diffraction efficiency of dynamic holograms with asymmetric line profiles recorded by the digital method [4, 5].

We have obtained the following results:

(i) The scheme for recording a holographic corrector in a TV-locked optical feedback loop has been simulated numerically and experimentally;

(ii) it has been shown that the use of such data transfer considerably simplifies the optical scheme, while the frame rewriting of the interference pattern excludes the influence of hysteresis effects;

(iii) the establishment dynamics of the asymmetric profile of a holographic grating has been studied and the diffraction efficiency in the first order has been found to achieve 70 % – 75 %;

(iv) these results open up the way to the development of efficient thin dynamic holographic gratings that can be used for the holographic correction of distortions, in diffraction couplers, etc.

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