PACS numbers: 42.65.Hw; 42.40.Eq; 42.70.Df; 42.79.Hp
DOI: 10.1070/QE2007v037n08ABEH013569

Phase conjugation of low-intensity laser radiation in a scheme with a thin dynamic hologram and TV transmission of interferometric information

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***Abstract*. The paper presents the results of a study of the phase conjugation system based on a thin dynamic holographic corrector recorded in an optically addressed liquid-crystal spatial light modulator by using the TV transmission of interferometric information from a CCD array to the photoconductor of the spatial light modulator.**

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

Phase conjugation (PC) methods applied in laser physics are based, as a rule, on the recording volume (thick) dynamic holograms by using various nonlinear-optical effects [1]. This leads to a number of restrictions imposed on the spectrum, coherence, and intensity of laser radiation. As a result, the application of these PC methods in a number of practical problems involving the use of partially coherent and nonmonochromatic low-intensity radiation is problematic.

It has been shown in a number of papers that thin dynamic holographic correctors (HCs) recorded in optically addressed liquid-crystal spatial light modulators (OA LC SLMs) [2] provide the efficient correction of optical distortions in optical elements of observational optical systems [3–6]. Such correctors do not impose strict limitations related to the spectral and angular selectivity of a hologram, duration of optical beams, and the hologram recording and reading times.

The diffraction efficiency of a HC depends on the method of its recording. In the case of the direct HC recording due to interference of a plane (or spherical) reference and signal waves on an OA LC SLM photoconductor layer, a grating with a nearly symmetric groove profile is recorded, as a rule. The theoretical value of the diffraction efficiency of such a HC based on a thin dynamic hologram does not exceed 30 %–40 %. In reality, due to inevitable optical losses in the elements of a modulator, the diffraction efficiency is even lower. This is a disadvantage of the direct HC recording method used in papers [3–6]. This disadvantage can be removed by complicating the HC recording scheme [7, 8] to obtain holographic gratings with asymmetric groove profiles. It is known that the diffraction efficiency of a grating with a saw-tooth groove profile and amplitude 2π is 100 %.

Thin dynamic HCs recorded in OA LC SLMs were used for single-pass correction of optical distortions in elements of observational optical systems. Due to the imperfection of the optical system, the light beam carrying information on the image of a remote object is distorted. The hologram of these distortions is recorded in the HC. As a result, distortions are subtracted after the propagation of the light beam through the HC, and an optical system with the HC gives the undistorted image of an object.

In the present paper, we use HCs recorded in an OA LC SLM for the PC of continuous low-intensity laser radiation. HCs were recorded by using a scheme with the TV transmission of interferometric information from a CCD array on the OA LC SLM, which is a simplified (without the formation of the asymmetric HC groove profile) variant of the scheme proposed in [7].

The essence of the method for HC recording [7] is as follows. The interference pattern of the reference and signal waves is recorded with a CCD array, digitised, and computer-processed by retaining the shape of interference fringes but changing the symmetric profile of the intensity modulation by the asymmetric saw-tooth profile. The interference pattern processed in this way is reproduced on a liquid-crystal display and is optically retranslated on the OA LC SLM. In the latter, the HC with the asymmetric saw-tooth groove profile is recorded.

We have chosen this recording method because it provides not only the high diffraction efficiency but also at the same time solves another important problem of advancement to the near- and mid-IR spectral ranges. At present, the best results for the combination of parameters (spatial resolution, phase modulation depth, response time) are achieved for OA LC SLMs in the visible recording-wavelength range. In the 0.8–1-μm range, the parameters of OA LC SLMs are considerably inferior, while the advancement to a longer-wavelength is problematic. This problem is absent in the HC recording scheme chosen here because the interference pattern is recorded and transferred to an OA LC SLM at different wavelengths not related to each other. The HCs can be used over the entire transparency range of the elements of the OA LC SLM.

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Received 14 February 2007
Kvantovaya Elektronika **37** (8) 716–719 (2007)
Translated by M.N. Sapozhnikov

Figure 1 shows the scheme of the experimental setup for studying PC. Radiation from laser (*1*) (recording) was split into the reference and signal beams. The signal beam propagated through distorting object (aberrator) (*11*) and interfered with the reference signal in the plane of CCD array (*10*). The interference pattern transformed in a computer and reproduced on liquid-crystal display (*21*) was transferred to the photosensitive layer of OA LC SLM (*17*). The radiation beam from reading-out laser (*2*) was directed on the SLM from the side of the liquid-crystal layer introducing the corresponding phase modulation to its wavefront. We used the reflection OA LC SLM with an internal mirror spatially separating the HC recording and reading channels. A light wave diffracted from the HC into the -1st order had the wavefront conjugated with respect to the distorted signal wave used for recording the HC. Distortions introduced by the aberrator into the wave were subtracted after its propagation through the aberrator and a high-quality beam was formed at the system output.

A commercial Canon LV-S1 multimedia projector was used as liquid-crystal display (*21*). The interference pattern reproduced by a computer was imaged by the projector on scattering white screen (*19*). This image was in turn projected by high-quality reproduction objective (*18*) on the SLM plane.

Unlike traditional PC schemes based on nonlinear-optical effects [1], in the scheme considered here the conjugate wave is not automatically reproduced upon diffraction of the reading wave from a hologram. To obtain PC, it is necessary to obtain in the OA LC SLM plane the transverse spatial conjugation of the distorted wavefront of the probe wave and the image of the interference pattern used for HC recording. To compensate for 'smooth' distortions (of the type introduced by a lens), the conjugation accuracy should be relatively small (200 – 300 μm). To compensate for random small-scale phase distortions, the conjugation accuracy should be higher. For the aberrator used in our experiments, this accuracy was about 30 μm. The combining was performed in our experiments by selecting the scale and position of the image of the interference pattern on the photosensitive layer of the SLM with the help of internal electronic control units of a multimedia projector, which were also used to correct the projective distortions of the image.

We used various optical elements as aberrators: optical wedges deflecting the beam from its initial direction by the angle up to 3×10^{-3} rad; a spherical lens increasing the beam divergence up to $\sim 4 \times 10^{-3}$ rad ($\sim$27 diffraction angles); a cylindrical lens increasing the beam divergence up to $\sim 6.7 \times 10^{-3}$ rad ($\sim$45 diffraction angles); a glass plate etched in hydrofluoric acid increasing the wave beam divergence by a factor of 50 compared to the diffraction-limited divergence. Figures 2 – 4 present the interference patterns of the light beam in the absence of an aberrator

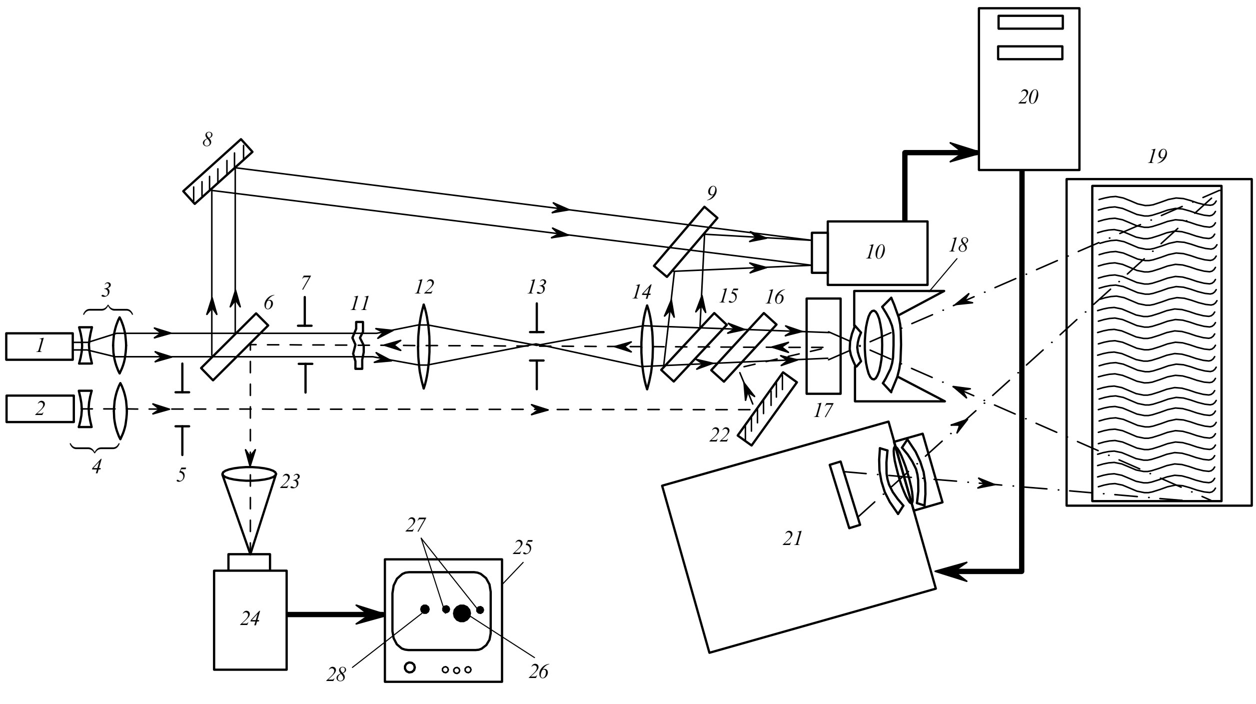

Figure 1. Scheme of the experimental setup: (*1*) He – Ne laser for HC recording; (*2*) He – Ne laser for HC reconstruction; (*3*, *4*) laser-beam expanding telescopes; (*5*, *7*, *13*) apertures; (*6*, *9*, *15*, *16*) plane – parallel beamsplitters; (*8*, *22*) mirrors; (*10*, *24*) CCD arrays; (*11*) aberrator; (*12*, *14*) lenses of a telescope transferring the aberrator-plane image to the HC plane and a plane conjugate to the CCD-array plane for recording an interference pattern; (*17*) OA LC SLM for HC recording; (*18*) objective imaging screen (*19*) onto the OA LC SLM; (*20*) computer; (*21*) multimedia projector; (*23*) lens; (*25*) monitor for observing signals from CCD-array (*24*); (*26*) image of the beam reflected from the OA LC SLM to the zero diffraction order; (*27*) images of the beams produced due to Fresnel reflections from the modulator; (*28*) image of the beam reflected to the -1st diffraction order; the beam path is shown by lines with arrows; the solid lines are radiation beams from a He – Ne laser used for recording the aberrator interferogram on the CCD array; the dot-and-dash lines are nonmonochromatic radiation beams from the multimedia projector used to reconstruct the interference pattern in the OA LC SLM plane; the dashed lines are radiation beams from a He – Ne laser used for the reconstruction of a dynamic hologram [phase conjugated with respect to the beam from laser (*1*)] and for the visualisation of the correction of aberrator distortions on monitor (*25*).

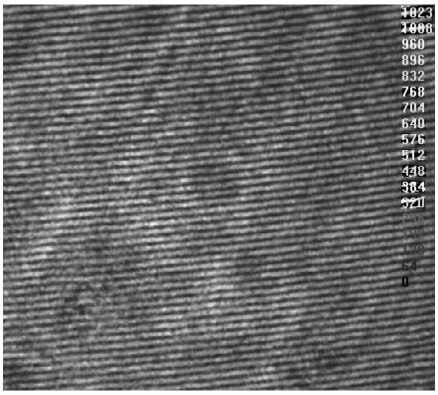

Figure 2. The HC structure in the absence of an aberrator.

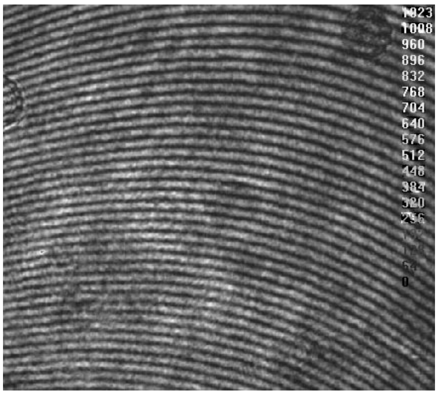

Figure 3. The HC structure with a spherical lens aberrator.

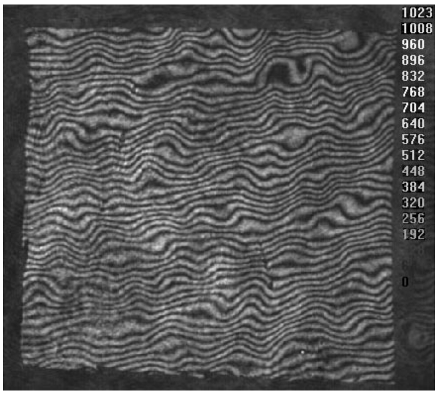

Figure 4. The HC structure with an etched glass plate.

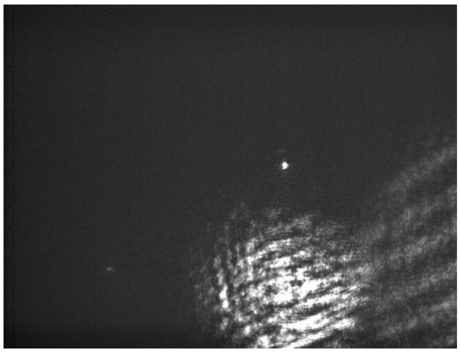

Figure 5. Far-field zones of the distorted and corrected beams with a spherical lens aberrator.

Figure 6. Far-field zones of the distorted and corrected beams with a cylindrical lens aberrator.

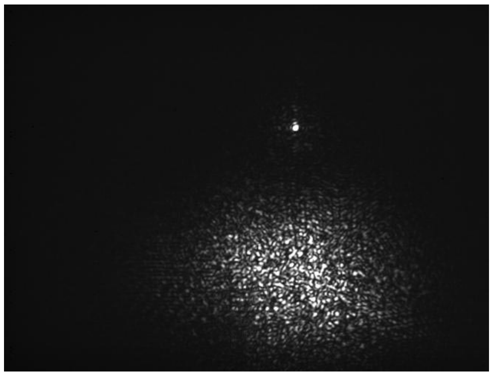

Figure 7. Far-field zones of the distorted and corrected beams with an etched glass plate aberrator.

and of beams transmitted through lenses and the etched glass plate. The transverse size of these interference patterns on CCD array (*10*) and in SLM plane (*17*) was 4 mm.

The angular divergence of the signal beam considerably increased when lenses or the etched glass plate were used as aberrators. The presence of the PC compensation of aberrator distortions was determined by analysing the far-field images of the corrected beam formed by lens (*23*) in the plane of auxiliary CCD array (*24*). Simultaneously, the far-field image of the distorted beam was observed on the same CCD array by using the Fresnel flash of the reading beam from the OA LC SLM surface. Figures 5–7 demonstrate such images. A bright spot at the centre of photographs corresponds to the PC beam with compensated distortions with nearly diffraction-limited divergence.

We observed in our experiments the correction of images in the dynamic regime. Thus, when a wedge was introduced into the scheme [element (*11*) in Fig. 1], the far-field image of a light beam on the monitor display 'jumped' to the position corresponding to its deviation by the wedge. After the end of the HC rerecording for tenths of a second, the far-field image returned to its initial position. When lens aberrators were moved with velocities not exceeding 0.2–

0.3 mm s^{-1}, the continuous motion of the distorted beam and an immobile bright point corresponding to the PC wave were observed on the display. The PC wave disappeared with increasing the displacement velocity of lenses.

Thus, we have confirmed experimentally that the scheme for recording a dynamic HC by using the TV transmission of the interferometric hologram can be used for the PC of radiation from a low-power cw laser. Note that interferometric information can be recorded in a CCD array and the PC wave can be produced by using mutually incoherent lasers. The spectral range of lasers and the photosensitivity of the PC scheme are determined completely by the corresponding parameters of a CCD array used in experiments.

Acknowledgements. The authors thank N.A. Feoktistov for his participation in the manufacturing of the OA LC SLM used in experiments. This work was partially supported by the ISTC (Project Nos 2113 and 2101r).

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