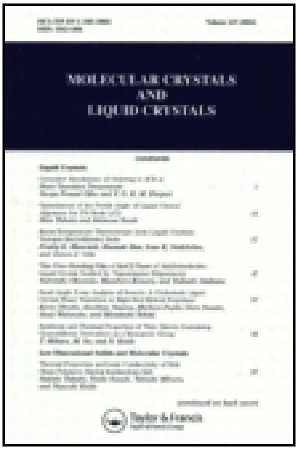

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Large numerical aperture telescope with nonlinear optical correction for distortions, designed for the remote self-luminous object imaging, was realised in experiment and investigated. Dynamic hologram, recorded in optically addressed liquid crystal spatial light modulator, was used as the corrector. Nearly diffraction limited performance of the system was demonstrated.

Keywords: dynamic holography; correction of distortions; telescope; optically addressed liquid crystal spatial light modulator

Just after the very invention of holography, it was proposed [1,2] to apply the holographic methods for the non-distorted imaging through the media with the phase distortions (the so-called one way imaging). Later on the base of these first ideas it was proposed to apply the holographic correction technique to the distortions, imposed by the primary mirror (PM) of the telescope, imaging remote objects [3,4]. In these works the successful holographic correction was realised on the base of the static hologram of the PM distortions, recorded from this PM centre of curvature in the Twyman-Greene interferometer. The hologram was processed and then mounted in the focal unit of the telescope, imaging the remote object. Later similar experiments were carried out in the USA [5-7]. This method, obviously, can be applied only to the static distortions. At the same time, the difficulties due to the necessity to take the hologram out for the processing and then to mount it in the proper position with high accuracy prevented the wide application of the method.

Later the progress in the development of the methods of the dynamic correction for distortions, using the nonlinear-opti al technique of the phase conjugation has resulted in elaboration [8-12] of the so called bypass (nonreciprocal) telescopes, where the effect of phase conjugation compensation was applied to the telescope PM and to other elements. This approach, of course, was applicable only to the systems, working with the coherent radiation, such as laser beam directors or telescopes, imaging the object, illuminated by laser radiation. This technique was realised in several experiments. In particular, in Reference [11] diffraction limited imaging was realised with the use of the bypass telescope with the PM (diameter 300 mm, curvature radius 2400 mm), comprised by six poor quality and non-co-aligned segments. The remote point object was illuminated by the coherent radiation of second harmonics of Nd-laser (λ=0.54 μm). This system has worked practically at the diffraction limit under the severe distortions of the primary mirror (the relative piston shift of the segments was at least 10 μm).

However, the schematics of such systems and the methods of their design are applicable to the task of remote object imaging in incoherent radiation with the use of the dynamic nonlinear-optical correctors, in particular, of the dynamic holographic corrector. The first to our knowledge realisation of the system of such a kind was demonstrated in the work [13]. The dynamic holographic corrector, recorded in the thermal medium by the radiation of the CO_2-laser replaced the phase conjugation mirror. This hologram was used for the correction for the distortions imposed by the PM into the image of the point object, illuminated by the radiation of another CO_2-laser, mutually incoherent with the first one.

Recent years brought fast progress in the technique of the dynamic holographic correction, using various nonlinear optical media. The most spectacular results were demonstrated with the use of the optically addressed liquid crystal spatial light modulators (OA LC SLM). The elements of such a kind [14-17] as well as the volume holograms, recorded in photorefractive crystals [18,19] were successfully applied for the one-way dynamic holographic correction for the severe distortions of the lenses, imaging the complicated test objects in the incoherent radiation. Gruneisen et al. [20] demonstrated the application of the OA LC SLM as the dynamic holographic corrector in the bypass telescope, imaging the monochrome point source of radiation.

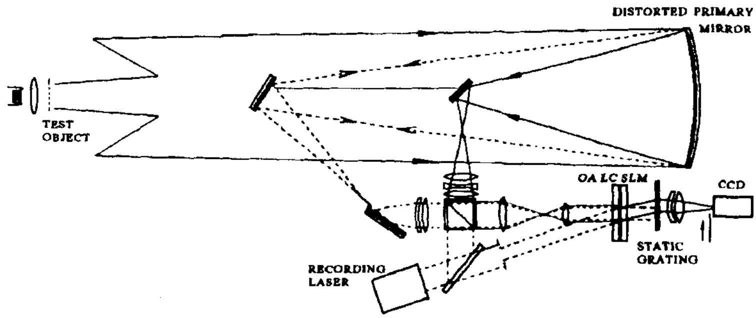

Fig. 1. Scheme of the experiment on the dynamic holographic correction for the PM distortions.

This paper is devoted to the studies of the non-monochrome complicated test-object imaging with the use of the bypass telescope with the large numerical aperture and dynamic holographic correction for its PM distortions, using the OA LC SLM as the medium for the dynamic hologram recording. The above mentioned bypass telescope [11] (PM diameter 300 mm, curvature radius 2400 mm, focal length 1200 mm) served as the prototype for this telescope design (general composition and secondary lenses were the same as in the experiment with the phase conjugation compensation). Reference [21] gives the details of the system optical design and the results of its performance numerical simulation. According to the results of Ref. [21], in the case of the bypass schematic application for the imaging in the comparatively wide spectral range, the requirements to the PM quality are more rigid than in the case of monochrome radiation. Therefore, in this case the poor quality solid mirror with the same geometry parameters replaced the segmented PM of Ref. [11]. The experiments with the poor quality PM were accompanied by the control experiments with the high-quality PM.

Optical scheme of the experimental setup is shown in the Fig. 1. Imaged test object was mounted at the distance of 16500 mm from the elescope PM. The radiation from the test object is collected by the PM nearby its focal plane. The three component lens of special design [11,21] (clear aperture 30 mm) images the object to the infinity. In the assumption of the non-distorted PM this image quality is to be practically diffraction limited. Beam splitting cube sends the beam to the corrector unit (special relay telescope reduces this beam diameter twice down to 15 mm so as to obtain the optimal radiation energy at the element and to fill within the experimental facility dimensions; the overall clear aperture of the OA LC SLM available in this experiment was 30 mm) and to the registering system (lens and CCD-camera or photographic camera). The system design made it possible to record both the zero and first diffraction (at the dynamic hologram) orders without system re-adjustment. The zero diffraction order was used while system adjusting and provided the control for the images, recorded without application of the correction technique (see further).

In the mode of correction for distortions the system action consists of two stages. On the first stage the distortions of PM are read out by the pulsed radiation (second harmonics of single mode Q-switched Nd-laser, λ=0.54µm). This radiation records the hologram of these distortions. After some delay, when the pulsed radiation is absent, the test-object is imaged with the correction.

The hologram of PM distortions is recorded in the following way. Laser radiation enters the system as a plain wave through the beam splitting cube. Two component lens of special design [11,21] (clear aperture 30 mm) focuses it in the PM centre of curvature. The radiation, reflected by the PM, goes back through the lens. The beam, whose wavefront bears the information on the PM distortions, is sent by the beam splitting cube to the relay telescope and to the corrector unit.

The dynamic hologram was recorded as the interference pattern of the distorted beam with the plain reference wave. The angle between two beams was equal 3°, so the spatial carrier frequency of the dynamic grating was equal to 95 mm^{-1}. Special shutter protected image registration system from the laser radiation. The performance and parameters of the dynamic holographic corrector were rather similar to that described in the Ref. [16,17].

On the image reconstruction stage the radiation from the test object reaches the dynamic hologram, which corrects in the first order of diffraction for the distortions imposed by the PM. Static diffraction grating [4,6,16,17] with the same spatial frequency of 95 mm^{-1} works in the minus first order of diffraction and thus compensates for the dynamic grating chromatism. Now the registering system entrance is open and the reconstructed image can be recorded (while recording the corrected image in the diffraction order, the non-corrected image, going in the zero order of diffraction was shut off). In the reported cycle of studies we have realised only imaging in the single flash mode, but, in principle, in the future such a system can be used in pulse repetitive mode action.

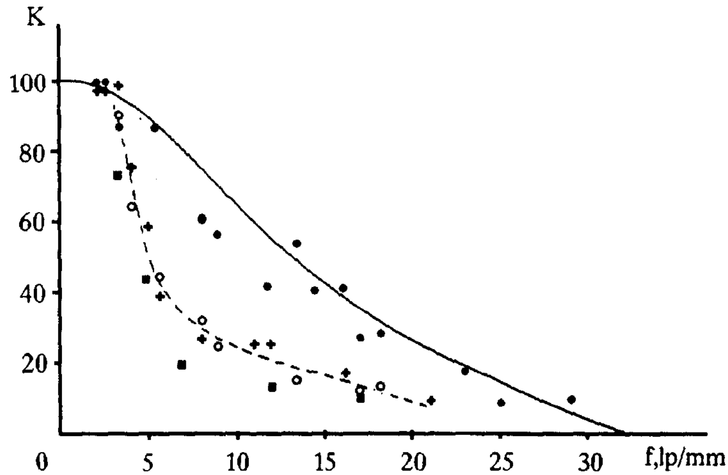

Fig.2. Dependence of image contrast vs. spatial frequency of the pattern

In the experiment we have registered the images of the standard test-object. These images were processed, providing thus the information on the dependence of the image contrast K $=\{I_{max} - I_{min}\}/\{I_{max} + I_{min}\}$ (here I_{max} and I_{min} correspond to the maximal and minimal exposition in the image) vs. the spatial frequency of the imaged object. The transverse size of the test-object was 9 mm, fitting to the design aberration-free field of system vision (~ 2 minutes in the angular measure). This test object was illuminated either by a halogen lamp (power ~ 50 W) or by a photographic flash lamp. Colour filters with the transmission maximum in green band were mounted between the lamp and test-object so as to provide necessary spectral content of imaging radiation. Images of test-object, recorded under various conditions of the experiment were subject of frequency vs. contrast analysis. The measured dependence of the image contrast vs. spatial frequency of strokes (the so-called frequency/contrast characteristic) is shown in Fig.2.

The evaluation of the system with the correction performance was preceded by the evaluations of ideal system performance. On the very first stage of the experiment the high-quality s herical mirror was mounted in the telescope. The image of the test-object was first recorded in the zero diffraction order, i.e. without use of corrector. The corresponding results are shown in Fig.2 as solid dots. The solid line corresponds to the theory limit of the same characteristics, calculated for the case of the rectangular test object and for the ideal PM quality [22]. One can see that the optical performance of the very telescope was practically diffraction limited.

On the next stage we have evaluated the performance of the system with the "correction" (i.e. with the record of the corrector and image reconstruction in the first order of diffraction) for the case of ideal PM. The corresponding values of the frequency/contrast characteristics are shown in the Fig.2 as the hollow circles. One can see that in this case the system performance is somewhat worse than in the first case. Possible reasons are the large number of auxiliary elements in the beamlet of corrector and the non-ideal quality of the corrector unit. Obviously, these results, indicated in Fig.2 also by the dotted line, are to be treated as the best possible parameters, available in the case of realisation of the system with the correction for the real distortions.

On the next stage of experiment the ideal PM was replaced by the poor quality PM, realised as the thin (15-mm thickness) and slightly flexible mirror. This mirror was intentionally distorted by means of longitudinal stress. In Fig.3 is shown the interferogram of the poor quality PM, mounted in the telescope. This interferogram was recorded in the plane of the holographic corrector; the proper spatial frequency of the interference fringes was realised by choosing the proper angle between the probe and reference beams. One can see that the global deformation of the PM surface with respect to the spherical shape equals some 5-8 fringes.

Fig.4 shows the severely distorted image of the test object, recorded in the zero diffraction order (i.e., without correction for distortions) in the system with such a distorted PM and the corrected image, recorded for the same distortions of PM with the use of the colour filter (bandwidth 50 nm, centred at the recording wavelength of 540 nm). In Fig.2 crosses show the corresponding values of frequency/contrast characteristics. One can see that this system performance was identical to that using the ideal quality PM, i.e. the distortions were completely eliminated.

At the shifted wavelength one has to observe the deterioration [17,18,22] of the correction fitness. In experiment we have used the colour filter, whose band centre was shifted in 25 nm with respect to recording wavelength (bandwidth 75 nm). The corresponding values of frequency/contrast characteristics are shown in the Fig.2 by squares.

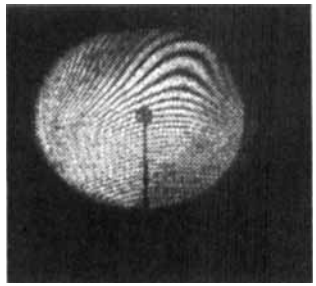

Fig.3. Interferogram of the deformed mirror, recorded at λ=0.54 μm

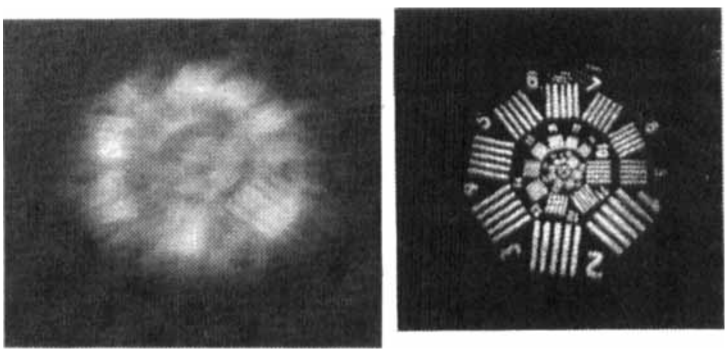

Fig.4.Test-object, imaged by conventional kind telescope (without correction) with the distorted PM (left) and with correction (right).

One can see some deterioration of the system performance. However, it can be explained not only by the effect of non-fitting to the distortions while hologram reconstruction at the shifted wavelength, but also by the incomplete achromatisation of the auxiliary optics, used in this experiment.

We have shown experimentally that one can use the bypass telescopes with the dynamic holographic correction for the PM distortions in the mode of complicated object imaging in the sufficiently wide spectral band. The quality of the corrected image is rather high.

References

[1] J. Upatnieks, A. VanderLugt, E. Leith, *Appl.Opt.*, **5**, 589, (1966).
[2] H. Kogelnik, K.S. Pennington, *JOSA*, **58**, 273, (1968).
[3] Yu.N. Denisyuk. S.I. Soskin, *Opt. Spektrosc.* **31**, 992 (1971).

[4] Yu.N. Denisyuk. S.I. Soskin, *Opt. Spektrosc.* **33** 994 (1972).
[5] J. Munch, R. Wuerker, *Appl. Opt.*, **28,** 1312 (1989).
[6] J. Munch, R. Wuerker, L. Heflinger. *Appl. Opt.*, **29,** 2440 (1990).
[7] G. Andersen, J. Munch, P. Veitch, *Appl. Opt.*, **36,** n.7, p.1427 (1997).
[8] O.V. Kulagin, A.A. Leshchev, G.A. Pasmanik, V.G. Sidorovich. Patent USSR 1729221, priority May, 21, 1985, published in «Bulleten izobreteniyi i otkritiyi SSSR», 15, 1992.
[9] J. Menders, R. Aprahamian, J. Godden. Proc. of SPIE, **1044** (1989).
[10] A.A. Leshchev, G.A. Pasmanik, V.G. Sidorovich, M.V. Vasil'ev, V.Yu. Venediktov. *Izv. Acad. Nauk SSSR. Ser.Fiz.*, **55,** 260 (1991).
[11] A.A. Leshchev, P.M. Semenov, V.G. Sidorovich et al. *Kvantovaya electronika,* **18,** 1405 (1991).
[12] A.A. Leshchev, V.G. Sidorovich, M.V. Vasil'ev, V.Yu. Venediktov, G.A. Pasmanik, *Int. J. of Nonl. Opt. Phys.*, **3**, 89 (1994).
[13] A.A. Ageichik, S.A. Dimakov, O.G. Kotayev et al. *Proc. of SPIE,* **2771,** 156 (1996).
[14] M.A. Kramer, C.J. Wetterer, T. Martinez, *Appl. Opt.*, **30,** 3319 (1991).
[15] S. Fukushima, T. Kurokawa, M. Ohno, *Appl. Phys. Lett.*, **58,** 787 (1991).
[16] V.A. Berenberg, M.V. Vasil'ev, V.Yu. Venediktov, A.A. Leshchev, L.N. Soms. *J. Opt. Technol,* **64,** 863 (1997).
[17] V.A. Berenberg, A.A. Leshchev, M.V. Vasil'ev, V.Yu. Venediktov. *Proc. of SPIE,* **3353,** paper145.
[18] J.D. Downie. *Appl. Opt.*, **33,** 4353 (1994).
[19] S.A. Dimakov, S.I. Kliment'ev, N.A. Sventiskaya, V.E. Sherstobitov. *Opt. Spektrosc.*, **80,** 628 (1996).
[20] M.T. Gruneisen, K.W. Peters, J.M. Wilkes, *Proc. of SPIE,* **3143,** p. 171–181, (1997).
[21] N.A. Bezina, A.A. Leshchev, M.V. Vasil'ev, V.Yu. Venediktov. *Proc. of SPIE,* **3353,** paper 95.
[22] M. Born, M. Wolf, Principles of Optics, Pergamon press, New York, 1964.