Quantum Electronics **31** (1) 1 – 15 (2001)

REVIEW

PACS numbers: 95.55.Cs; 42.65.Hw; 42.40.Eq
DOI: 10.1070/QE2001v031n01ABEH001883

Telescopic systems with dynamic nonlinear optical correction for distortions

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Contents

***Abstract*. The review of basic achievements in the field of nonlinear adaptive optics is presented. In particular, schematics and properties of adaptive optical telescopes considered in which the image distortions introduced by defects of the primary mirror and other optical elements are compensated by nonlinear optical methods. The conventional methods of laser optics, such as phase conjugation and dynamic holography, make it possible both to solve the problems of classical (imaging) optics related to the building of telescopes for imaging remote objects with high resolution, which are based on large, light-weight or sectional mirrors, and create the systems that produce laser beams with the high-quality wave front. The basic designs of such telescopes are considered and the possibilities of corrections for distortions in them are analysed and confirmed by experiments.**

Keywords: *telescope, phase conjugation, dynamic holography, distortion correction*

1. Introduction

The obtainment of high-quality, close-to-diffraction-limited images in an optical telescope is one of the classical problems of optics. The main difficulties arising in this field are related to the technology of manufacturing large mirrors and the necessity of maintaining their form under conditions of dynamic mechanical, thermal, and other loads. The direct approach to the solution of this problem based on the manufacturing large high-quality mirrors and their dynamic unloading is exhausted when the diameter of the primary mirror (PM) achieves 2 – 3 m [1, 2]. At the same time, there exist a number of important practical problems, such as the building of space telescopes for extra-atmospheric observational astronomy, the observation of the Earth surface from the outer space, and the generation of directed laser beams, which require diffraction-limited resolution for substantially greater apertures. (It is well known that the resolution of ground classical telescopes is limited by the influence of the atmospheric turbulence. In the case of the best astroclimate, this limitation in the visible range is manifested at the level corresponding to the diameter of the entrance pupil of a few tens of centimetres. Large PMs are required only to collect the light energy from weak sources as much as possible and they should not necessarily have the diffraction quality of the image.)

At present, the image quality in optical telescopes is often improved by the methods of the so-called linear adaptive optics [3]. In the most general form, these methods are based on the implementation, in some or other way, of the following procedure. An optical system forms a distorted image of the observed object – a natural or the so-called artificial beacon, produced due to scattering of laser radiation in atmosphere. In the case when only distortions introduced by the elements of the optical system itself should be corrected, a reference point source can be located inside the system (the so-called proximal beacon). In particular, upon correction for distortions introduced by the telescope PM, such a source can be placed near the centre of the PM curvature.

Distortions of radiation transmitted by the system are analysed using a special auxiliary optical system (interferometer, Hartmann sensor, etc.). Then, the obtained information is digitally processed with a computer and is used for the calculation of the wave-front distortions introduced by the system. Thereafter, the wave-front deformations compensating for the initial wave-front distortions produced by the elements of the system or atmosphere are introduced via the feedback loop with the help of a special controlled optical element (the so-called actuator) incorporated into the optical system being corrected. Such an actuator can represent a controllable flexible mirror (the PM itself or an auxiliary small-aperture mirror), a controllable spatial phase modulator of light, etc.

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Received 24 December 1998; revised version received 25 May 2000
Kvantovaya Elektronika 31 (1) 1 – 15 (2001)
Translated by M N Sapozhnikov

By now considerable advances have been made in the field of conventional adaptive optics [4]. However, its use always involves expensive computer subsystems and time-consuming calculations, which restricts the response time of the system. In addition, the fabrication of a fast, reliable, and reproducible actuator is a challenging technical problem.

It became clear in the mid 1980s that in a number of cases, in particular, upon correction for distortions introduced by defects of the PM and other optical elements of the telescope, the digital methods of linear adaptive optics can be replaced by substantially cheaper and fast methods of analogue nonlinear optical correction based on the use of coherent radiation. These can be the methods of dynamic holography or phase conjugation. In this case, radiation from the artificial remote or proximal beacon 'reads out' the PM distortions and then records a nonlinear-optical corrector. Our review is devoted to advances achieved in this field. The review topic is related in fact to conventional (imaging) optics rather than to laser optics. Nevertheless, all the schemes and methods considered are based on the use of coherent properties of radiation, so that the creation of such systems in inherently related to lasers.

A prototype of dynamic nonlinear optical correction was a technique of static correction. Note at once that we will discuss in our review only the compensation for random and, generally speaking, unknown preliminary phase inhomogeneities with the help of holographic correctors written by the analogue method. We will not consider the correction for regular optical distortions (the so-called Zeidel aberrations such as spherical aberrations, coma, astigmatism, etc.), which can be eliminated in the calculation of auxiliary optical elements, in particular, can be compensated using a holographic optical element (HOE) [5] representing a recorded or synthesised hologram.

The basic concepts of the holographic correction for distortions are contained already in the very first papers on holography. In fact, already Gabor has proposed the correction for aberrations of lenses in an electron microscope as a first application of the holographic method for the wavefront detection invented by him [6].

Among several methods of the holographic correction developed later, such as the method of *conjugated beams* [7, 8], the method of *equal distortions* [9, 10], etc., of special interest for our case is the so-called method of *phase subtraction*, which is also known as the method of *single-pass correction*. Unlike other methods, this method is based not on recording the hologram of an observed object but on recording the hologram of phase distortions of an optical system or an optical medium, which distort the image, and on the use of this hologram as a corrector of these distortions.

The principle of single-pass correction [11, 12] is quite simple. Its application for the correction of distortions of a lens objective is illustrated in Fig. 1. A coherent radiation beam is split into a probe and reference beams. The probe beam propagates along the optical path, whose phase distortions should be corrected, and interferes with the undistorted reference beam in the hologram plane. The recorded hologram is developed and is located at the same place as during recording. Upon illumination of the hologram by the distorted probe beam, the undistorted reference beam is reconstructed, in other words, the phase distortions introduced into the probe beam are subtracted.

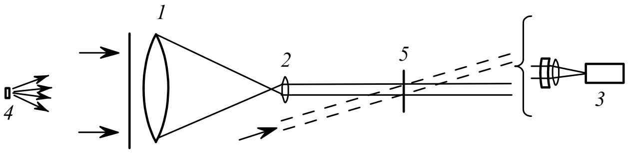

Figure 1. Principal scheme of the single-pass holographic correction for the optical telescope distortions: (*1*) telescope objective being corrected; (*2*) eye-piece; (*3*) image detection system; (*4*) remote observation object; (*5*) hologram recorded as the interference pattern of two coherent light waves from an auxiliary source, one of which has passed through an element whose distortions are being corrected.

Note that the hologram can be reconstructed not only by the probe beam that has been used for its recording but also by oblique beams, including nonmonochromatic beams and beams at the somewhat shifted wavelength. Within some field of view and some spectral range, each such distorted beam reconstructs a virtually plane wave. In other words, the corrected image of a remote object is observed in one of the diffraction orders on the hologram.

This image is decomposed in the spectrum because its different spectral components are diffracted from the hologram at different angles. In Ref. [13], it was suggested to obtain the achromatic corrected image using an auxiliary diffraction grating with the groove density corresponding to the carrier frequency of the correcting hologram. As a result, the corrected image can be observed in a broad spectral range.

However, note here that the use of different wavelengths for the hologram recording and its subsequent correction results in the appearance of residual chromatic aberrations, which cannot be eliminated. This is caused by the incomplete subtraction of the phase distortion of the beam with the wavelength different from that used for the hologram recording upon its diffraction from the hologram. These residual distortions decrease when the observation wavelength approaches the corrector recording wavelength. When the corrector is recorded at the wavelength λ_1 and the object is observed at the wavelength λ_2, the theoretical limit of the ratio of initial wave aberrations W_{in} to residual aberrations W_{res} is $\lambda_1/|\lambda_1 - \lambda_2|$. Nevertheless, despite this effect, the use of the holographic correction allows one to obtain a substantial advantage for operation in a rather broad spectral range as well.

In Ref. [12], the optical inhomogeneities of an optical system were corrected for the first time with the help of a hologram recorded by a plane wave and radiation from a point source located in the object plane. During the reconstruction, the point source was replaced by the observation object, and its corrected image was observed in the first diffraction order behind the hologram. Similar schemes were used later for correction of low-quality objectives of microscopes [14] and the observation of objects through fibre-optic elements [15].

In the case of correction for distortions in large mirror objectives, it is impossible to use this method directly because of the necessity of manufacturing holograms of size that is approximately equal to the size of the objective being corrected and because it is impossible to locate a point source of coherent radiation in the plane of an infinitely remote object.

The authors of Refs [16, 17] have overcome this restriction. Aberrations introduced by a deformed large mirror

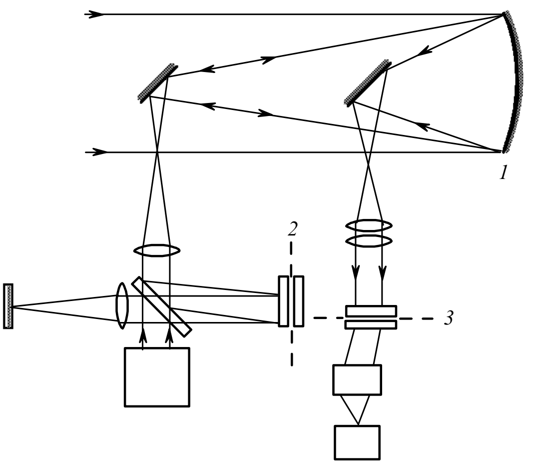

Figure 2. Scheme for recording and using a static holographic corrector of the PM distortions in a telescope. The hologram of distortions of PM *1* read out from its centre of curvature is recorded by coherent radiation in the image plane *2* of the PM pupil. After the development and processing, the corrector hologram is placed at the focal point of the telescope in the image plane *3* of the PM pupil.

objective were eliminated with the help of the hologram of the focused image of this objective, which was detected using an auxiliary interferometer (Fig. 2) in which a point source of coherent radiation was located near the centre of curvature of the objective.

After recording and developing, the hologram was placed at the focal point of a telescope in the image plane of the deformed mirror produced by the telescope ocular. In this case, the scale of the PM image obtained with the help of the ocular or the auxiliary interferometer should be the same. The object image was observed in the first diffraction order on the hologram.

The holographic correction of telescopic systems with the diameter of a mirror objective of 150 mm and the relative apertures $D:F = 1:5.7$ and $1:2.3$ was experimentally simulated in Refs [16, 17]. In Ref. [17], the correction for the hologram chromatism was performed by using an auxiliary diffraction grating. The experiments showed that the wave aberrations of the image caused by the PM deformation reduced by a factor of 70 when the object was observed at the corrector recording wavelength (0.63 μm) and by a factor of 5.5 when observing at the wavelength 0.53 μm. When the object was observed in a broad spectral range from 0.52 to 0.68 μm, which included the recording wavelength of the holographic corrector, the three-fold improvement of the image quality was achieved compared to the image obtained using an uncorrected telescope.

The ideas discussed in Refs [16, 17] were later confirmed in Refs [18–24]. In Refs [18, 19], aberrations of a mirror objective of diameter 500 mm with a synthesised aperture (the mirror consisted of 18 elements arranged in a ring) were corrected. When the object was observed at the corrector recording wavelength, the wave aberrations caused by the deformation of a PM of diameter 450 mm decreased by a factor of 1000, from 100λ to 0.1λ.

Nevertheless, the methods of static holographic correction for random defects of the PM have not found a practical application because it is impossible to monitor dynamic deformations and, in addition, the alignment of the hologram-corrector involves difficulties. The results of the studies described above found applications in the technique of holographic correction of regular distortions (aberrations) of optical systems [5]. As for the correction for random dynamic distortions, the new development of the described systems was stimulated in the 1980s by the results of phase-conjugation compensation.

2. Schematics of telescopes with the phase-conjugation (PC) compensation

Since the end of 1970s, the study and application of phase conjugation of coherent radiation in laser technique has received much attention. It is known that upon nonlinear optical interaction of radiation with matter, in particular, upon scattering of light from a dynamic hologram or stimulated scattering of light, a light wave can be generated with the wave front conjugated to the wave front of the incident wave, i.e., having the same shape but propagating in the opposite direction. This effect, the principles of fabricating phase-conjugate (PC) mirrors and their parameters such as reflectivity, the phase-conjugation fidelity, etc. have been considered in monographs [25, 26] and many reviews.

At present, the phase conjugation is mainly applied for compensation for phase distortions introduced by laser amplifiers [25, 26]. The compensation is based on the property of propagation reciprocity of light beams: when the conjugated wave propagates again through the same distorting optical medium, the phase distortions, which have been accumulated before, are compensated. For example, to correct a laser amplifier, a light beam with the high-quality wave front is fed to its input. The phase distortions caused by the amplifier defects, its thermal deformations, and other inhomogeneities are accumulated during amplification.

Then, the phase conjugation is performed, resulting in the change in the sign of accumulated wave-front distortions. After repeated passage in the opposite direction along the same optical path, the distortions are compensated, and the system produces a high-quality amplified output laser beam. If necessary, the absolute divergence of this beam can be reduced with the help of an output telescope. However, unlike the elements of a laser amplifier, the requirements to the quality of elements of this telescope remain high because they are not subjected to the phase-conjugation compensation.

Distortions introduced by the system that forms a laser beam or by another optical system can be also compensated owing to their reciprocity. In [27, 28], it was suggested to use phase conjugation for the self-guidance of high-power laser radiation to a small object. The object was illuminated by low-power radiation, and the radiation scattered by the object was collected with a low-quality objective. After amplification and phase conjugation, all the amplified radiation was collected on the object. A similar system can be also used for the high-quality imaging of an object at the scale 1:1 (Fig. 3), for example, in microphotolithography.

It is quite obvious that distortions can be also compensated in the case of nonreciprocal propagation of the beams, when the radiation propagates after phase conjugation along another optical path, which introduces, nevertheless, the same or almost the same distortions. For example, it was proposed in Ref. [29] to use two identical amplification cascades that introduce almost the same distortions. The radiation propagating to the PC mirror was amplified in one

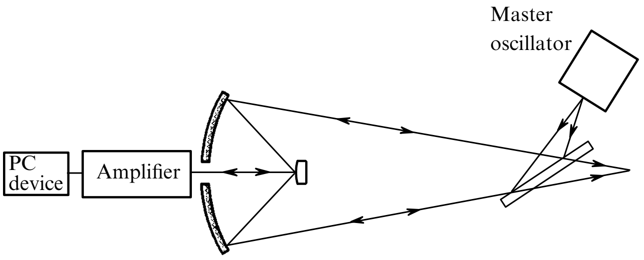

Figure 3. Simple scheme of the PC compensation for distortions in optical systems.

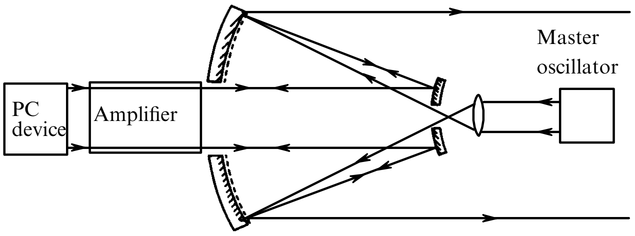

Figure 4. System for generating a directed laser beam with the dynamic compensation for distortions of the telescope PM based on the use of a diffraction structure on the PM surface [30, 31].

of the cascades and was directed, after phase conjugation, with a beamsplitter to the second module, the distortions introduced by both modules being mutually compensated.

The same approach can be applied to optical elements. In particular, it is clear intuitively that upon the transformation of light beams by a mirror or a lens, the defects of the optical element will be manifested in a similar way in the wave fronts of light beams having a different curvature. Therefore, if one 'reads out' distortions introduced by a mirror or a lens with the help of a laser beam with a given wave-front curvature, performs the wave-front phase conjugation, and then, using an auxiliary optical system, changes the wave-front curvature and repeatedly 'reads out' the distortions, the effect of distortions can be in principle compensated in some degree or another.

In the early 1980s, two schemes have been independently proposed in USSR and USA, which realise this idea in a different way. The most elegant is the scheme suggested in Refs [30, 31] (Fig. 4), where a PM is used which has a concentric diffraction structure deposited on it (HOE). This system operates in the regime of formation of a directed laser beam as follows. A point source of coherent light is formed at the telescope entrance with the help of an auxiliary optical system. The HOE acts at the laser radiation wavelength like a concave mirror with the curvature different from that of the substrate mirror. The HOE forms the real image of the point source in the PM focus. Then, the radiation is directed, using the auxiliary optical system, to the PC mirror channel, which can contain, in particular, a laser amplifier.* After the PC procedure, the radiation passes again through the amplifier (with compensation for the distortions introduced by the amplifier), returns to the PM, and reflects this time from it to the zero diffraction order. Thus, the system as a whole constructs the image of the initial point source at infinity. Using this system, one can construct the image of a remote object in the reverse beams (using, of course, illumination by coherent radiation).

If the PM surface is deformed, the distortions introduced by deformations into the wave fronts of light beams diffracted into the zero order and other orders are approximately the same, so that the effect of these distortions is compensated in the reverse beams. This is confirmed by the results of theoretical and experimental papers [31–33], which will be discussed below. Note that in such a system, the distortions introduced by all elements of the optical channel, except the system of formation of the point radiation source, are compensated. The system is compact because its physical length is approximately equal to the PM focal distance, i.e., it virtually coincides with the physical length of a classical telescope.

The system described above has some disadvantages, which are typical for HOE systems [5]. First, these are unavoidable losses upon diffraction and specular reflection from the PM and, second, strong chromatism of the HOE, which hinders the use of the system at several wavelengths. However, the main obstacle, which does not allow one to implement this approach in real telescopes so far, is the limitations of modern technologies for manufacturing large HOEs. At present, neither of these technologies (direct holographic recording, photolithography, diamond turning) make it possible to deposit diffraction structures of the required type on the surface of substrates several tens of centimetres in diameter, to say nothing of required several metres.

The use of a segmented mirror also does not solve the problem, because in this case only distortions caused by defects of the reflecting surface of the mirror are compensated, however, the individual segments of the diffraction structure should be joined into a single spatial system, the errors of joining not being compensated at all. The attempt to realise such an approach was made in Ref. [32]. As expected, it was shown that the joining is possible, however, it requires the use of approximately the same methods of linear adaptive optics (and, therefore, the same efforts and time) as a simple phasing of the PM segments.

The authors of Ref. [33] proposed to solve the problem of building a large PM with the HOE on its surface by recording the dynamic HOE in a special nonlinear-optical layer on the PM surface by radiation from an auxiliary laser. This layer can be, for example, a semiconductor layer. The short-wavelength laser radiation can produce the relief of charge carriers in the layer, which modulates the reflection coefficient of the layer for the longer-wavelength radiation. This method opens up the possibility for building such systems with the segmented PM. However, this approach is also far from practical applications because of the technological problems involved in manufacturing homogeneous layers, the necessity of using a sufficiently powerful additional laser, and the low diffraction efficiency of the dynamic HOE.

Thus, despite the elegance of the PM–HOE scheme, at present the dynamic compensation can be mainly obtained using an alternative scheme, which lacks the elegance and compactness of the schemes described above and employs a usual PM. The compensation in the PM–HOE system is achieved because the wave-front defects obtained earlier (with the opposite sign, i.e., as if 'turned inside out') are

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*Note that the physical essence of a PC device is not important for this system and other systems considered below. This device is assumed to provide an ideally exact conjugation of the wave fronts and thus is considered simply as an optical element among others (mirrors, lenses, etc.)

returned in conjugated beams to the PM defects that have generated them. In this case, the radiation propagates reciprocally from the PM to the PC mirror and in an opposite direction. The nonreciprocity is achieved because the PM itself represents a beamsplitter. A similar effect can be obtained by using a scheme in which the radiation propagates along different paths from the PM to the PC mirror and back, while the wave-front defects are returned to the places where they emerged with the help of an auxiliary projection optical system.

Fig. 5 shows the principal scheme of the system of this kind, which is called a nonreciprocal telescope or a bypass telescope [34–37]. This system contains an objective to be corrected, a PC mirror with a beamsplitter at its input, and two auxiliary projection systems, which represent, in a simplest case, two projection objectives. Both these objectives image the pupil of an objective being corrected at the same scale in planes *3* and *4*, which are located at the same distance from the PC mirror.

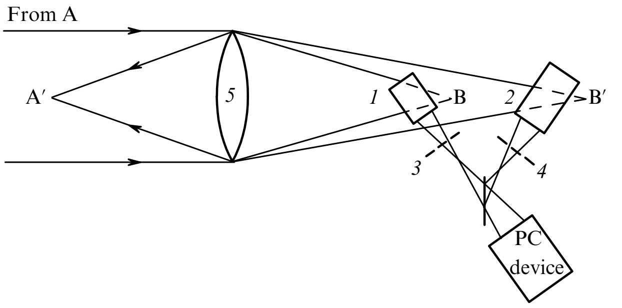

Figure 5. Dynamic compensation for distortions in the bypass scheme [34–37]. Auxiliary optical systems *1* and *2* image the pupil of the objective *5* being corrected in planes *3* and *4*, which are optically conjugated with respect to a PC mirror.

The system images a remote point source A of coherent radiation in the following way. The objective being corrected forms the distorted image of point A in a plane passing through point B perpendicular to the optical axis of the system. The radiation is intercepted by the first auxiliary objective and is directed to the PC device. After the PC device, a beamsplitter directs the radiation along another path through another auxiliary objective. In this case, the distorted image of the initial point object is reconstructed in the plane of point B′, while the image of the pupil of the compensated objective formed by the first auxiliary objective in the plane *3* is reconstructed in plane *4*. The plane *4* coincides with the plane where the same image is formed by the second auxiliary objective. The image of the pupil of the compensated objective is reconstructed at the 1:1 scale in the pupil plane in reverse beams after their passage through the second auxiliary objective (the so-called self-projection condition [34, 36, 37]). In other words, as in the PM–HOE scheme, the wave-front distortions return (again, being 'turned inside out') to the defects of the compensated objective, which have produced these distortions. After the second passage through this objective, the distortions became compensated, and the corrected image of the initial point source is reconstructed in the plane of point A′.

The reconstruction of the image of the objective or PM pupil on itself can be performed by using auxiliary objectives both with the positive and negative optical power. Objectives with the positive optical power are convenient for imaging remote objects using additional laser illumination. To generate a directed high-power laser beam, a scheme with negative auxiliary objectives, which has no internal focusing points, is more convenient. In this case, the 'self-projection' is achieved by bringing imaginary images of the PM pupil into coincidence.

Auxiliary optical systems can be more complex than a simple projection objective. For example, in [38, 39], the scheme of a laser collimator was proposed in which all the elements of a nonreciprocal telescope were located on the same axis. In this scheme, a semitransparent mirror deposited on the convex surface of the last lens of the first auxiliary projection system plays the role of a beamsplitter and the only element of the second auxiliary projection system. Such an axially symmetric system is more compact and convenient for the adjustment compared to the systems in which a plane mirror is used as a beamsplitter. At the same time, a plane beamsplitter can represent a polarising mirror, and phase conjugation can be accompanied by rotation of a polarisation plane. This allows one to eliminate the light-energy losses in the system, which are unavoidable when common interference or diffraction beamsplitters are used.

Note that, compared to the PM–HOE system, the bypass system has, along with somewhat inferior compensation abilities (see below) and the twice length (which is no longer determined by the focal distance of the PM but by its radius of curvature), another principal drawback. Whereas in the PM–HOE system, the distortions of all its optical elements are corrected, except the system of formation of the point source of coherent radiation, this is not the case for the bypass system where the high requirements are imposed on both auxiliary optical systems, while the correction is performed only for the PM and elements located between a beam-splitter and the PC mirror. At the same time, it is well known that high-power radiation can cause the deformation of optical elements. This means that the bypass system is inferior to the PM–HOE system with respect to the formation of high-average power directed laser beams.

This problem has been solved in a hybrid system, which combines both methods of the distortion correction [40]. One can build a telescope in which distortions introduced by the PM defects are corrected using the bypass principle, while the distortions introduced by the only thermally loaded element of a small diameter are corrected based on the PM–HOE principle. Fig. 6 shows the principle scheme of such a hybrid telescope, which is called a TENOCOM (telescope with nonlinear-optical compensation).

This scheme uses a convex mirror with a HOE deposited on its surface, which is equivalent to a concave mirror at the laser wavelength. A comparatively lower-power source of coherent radiation is located at the system entrance. The concave mirror, a lens, a small convex mirror, and the HOE form the first auxiliary optical system, which gives the imaginary image of the PM pupil in the same plane (and at the same scale) as the convex mirror–HOE substrate system. The radiation diffracted from the HOE is directed to the PC mirror channel, which also contains a compensated power amplifier. If the diffraction efficiency of the HOE is low, the larger fraction of the amplified PC radiation undergoes specular reflection from the HOE mirror substrate, is reflected again from the PM, and escapes to the focusing point.

One can easily see that phase conjugation used in such a system results in the compensation for distortions intro-

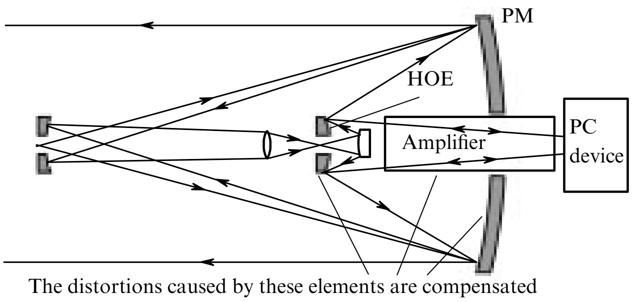

Figure 6. Scheme of a TENOCOM telescope with the PC compensation for distortions introduced by all elements of the input channel.

duced by all elements of the power amplifier channel, the PM defects (due to the reconstruction of its image on the PM itself in reverse beams, as in any other bypass system), and by deformations of the only element of the second auxiliary projection system – a convex mirror with the HOE deposited on its surface, which represents the only thermally loaded element of a small diameter provided the diffraction efficiency of the HOE has been properly chosen.

As mentioned above, unlike the schemes with reciprocally propagating beams, in the nonreciprocal case, the distortions introduced during forward and reverse propagation of the beams are approximately the same, but not identical, resulting in a certain residual incomplete compensation. The compensating abilities of bypass systems were analysed in Refs [36, 37], and the features of the aberration calculation of such telescopes demonstrated by this analysis were considered in Ref. [41]. The main results of this analysis are as follows.

First of all, one can rigorously prove mathematically [36, 37] that distortions introduced by the objective defects are completely compensated in the systems of this type in the paraxial approximation based on the approximation of a sphere by a parabola.

Outside the paraxial region, all the types of telescopes under study have inherent residual distortions, which cannot be eliminated in principle. Their origin is obvious. It is known that upon reflection of a plane wave from an uneven mirror surface, the surface roughness $\varphi(x,y)$ is reproduced in the wave front of the reflected wave as $2\varphi(x,y)\cos\alpha$, where α is the angle of incidence of light on the mirror. In the bypass system, operating in the regime of the remote object imaging, a radiation beam first is incident on the PM from infinity and then – from its centre of curvature. In the regime of the formation of laser beams, the beams propagate in the opposite direction. Correspondingly, in any case, upon two reflections of the beam from the PM, the defects of the PM surface are reproduced in the wave front differently.

For this reason, the wave-front distortions are not completely compensated and only substantially decrease. This decrease (the coefficient or degree of compensation ξ) is inversely proportional to the square of the angle of radiation incidence on the mirror. For the ratio of the PM diameter to its radius of curvature equal to 1:6 – 1:8, which is typical for telescopes, this decrease at the mirror edge amounts to a few thousands times [36, 37, 41], while for wide-aperture systems, in which this ratio is 1:3 – 1:4, the decrease amounts to a few hundred times [41].

The incomplete compensation in the PM–HOE system is described by the relations that are similar to those in the case of the bypass system and has the same order. However, there exists yet another factor in the bypass system that further impairs the accuracy of the distortion compensation. Whereas in the PM – HOE system the wave-front distortions of the PC radiation beam are automatically fall on the PM defects that produce them, such a coincidence in the bypass system is provided by auxiliary projection systems. The aberrations of these auxiliary systems and defects of their manufacturing and alignment prevent the ideal fulfilment of the 'self-projection' condition. As a result, the same ray is reflected from the PM before and after phase conjugation at two close but different points. This additionally reduces the compensation abilities of the system (5 – 10 times, as follows from the calculation and simulation of real systems), and the dependence of ξ on the transverse scale of the PM defects appears: small-scale distortions are compensated worse than the large-scale ones [36, 37, 41].

Nevertheless, despite all the facts considered above, numerical and experimental simulations of telescopes with the PC compensation showed that the maximum tolerable deviations of the real PM surface from the calculated ones are restricted in most cases not by the parameter ξ but by purely technical reasons, such as the radiation vignetting by the te-lescope elements, the restricted field of view of the PC device or the preceding optical channel, etc.

All the above considerations about compensation abilities are valid not only for the image of a point located on the system axis but also for off-axis points. If the angular field of view of the system is much smaller than its aperture angle (which is typical for optical telescopes) and if the PM 'self-projection' condition is satisfied for an off-axis beam, the compensation abilities of the system for this off-axis beam will be the same as those for the axial beam. Therefore, the field of view of the telescope with the PC compensation is determined by the same factors as in a usual telescope, i.e., by the possibility of eliminating field aberrations.

The features of the aberration calculation (aberration optimisation) of bypass telescopes were considered in detail in paper [41]. The calculation was performed for a certain specified shape of the PM, neglecting its defects. The system is optimised not only to construct the high-quality image of the object plane within the specified field of view but also to obtain the condition of the PM 'self-projection'. Such aberration optimisation can be performed with the help of available computer programs providing simulation of holographic optical elements (a PC device can be also considered as a hologram).

During the aberration optimisation of such telescopes, some of their features should be taken into account. In usual optical telescopes, a proper choice of the shape of the PM aspherical surface is very important. The combination of this shape with that of the secondary mirror allows one to efficiently correct both spherical and field aberrations. Unfortunately, this cannot be done in bypass telescopes. As shown in Refs [36, 37], such systems possess a specific spherical aberration, which depends on the geometry of the system as a whole rather than on the exact shape of the aspherical PM. Its origin is quite obvious.

Let us assume that we use a spherical mirror as the PM. In this case, the mirror will image a point to itself at the centre of the PM curvature without any aberrations. When the same mirror images the focal point at infinity, a spherical aberration appears which is caused by the difference of a sphere from a parabola. If, on the contrary, a parabolic PM is used in the system, it will image the focal point at infinity without any aberrations, whereas the same spherical aberration will appear upon imaging the centre of the PM curvature. One can easily verify that in both cases, as well as for the hyperbolic or elliptic PM, the main component of the spherical aberration will be invariable for the system as a whole. Therefore, in most cases it is expedient to employ spherical mirrors in bypass telescopes.

To correct the spherical aberration in such systems, this aberration should be taken into account in the development of the secondary (eye-piece) optics. This is quite possible, although restricts the telescope magnification. The calculations [41] showed that the spherical aberration can be corrected in telescopes with the magnification (i.e., the ratio of the light diameters of the PM and ocular) of $10^{\times}$ and higher, which corresponds to standard parameters of optical telescopes.

During the last decade, several bypass telescopes have been developed, optimised, and simulated. Some of them were used in experiments (see below), whose results confirmed theoretical estimates and numerical simulations.

In Ref. [41], a TENOCOM telescope, which has the greatest numerical aperture among the developed nonreciprocal systems, was simulated in detail. The telescope had the PM of diameter 1 m and the length of 3 m, which was determined by the radius of the PM curvature (i.e., the numerical aperture of the PM was $D : F = 1 : 1.5$). The telescope was intended for operating in a space lidar for global CO_2 laser-based monitoring. The results of the numerical simulation of this telescope showed that the degree of compensation for the local error was $10-20$ times. As in the systems with a lower numerical aperture, the degree of compensation for global distortions of the astigmatism type or deviations in the PM curvature is even higher. In particular, such a telescope yields almost diffraction quality of the generated beam at rather large toric distortion (astigmatism) of the PM surface $\delta R_x = -\delta R_y$ equal to $10^{-3}R$.

3. Experimental studies of telescopic systems with the PC correction for distortions

Experimental studies of telescopic systems with the PC correction for distortions have been initiated in the mid 1980s, although the first papers in this field were published much later [36, 37, 42, 43]. The first experiments with nonreciprocal optical systems were performed using lens objectives with a comparatively low numerical aperture [43]. The first and second auxiliary optical systems in these experiments shared one element (usually a lens). Such a correction scheme cannot have in principle a high aperture ratio for a large diameter of the primary element and a small aperture of auxiliary optical elements. Nevertheless, experiments with systems of this type allowed one to verify the correctness of some concepts of compensation for distortions in nonreciprocal systems. In the first experiments [36, 37, 43], distortions were simulated by inhomogeneous phase plates of different types and simplest lined transparent objects were used.

The authors of Ref. [43] studied a system for forming high-quality radiation beams ($\lambda = 1.06$ µm) focused at the finite distance (50 m) using a spherical PM of diameter 500 mm with the aperture ratio of 1:11. The system generated high-power output single pulses with the energy up to 10 J and used PC upon SBS in various media. To avoid the strong mutual screening of auxiliary elements, the experiment was performed using the off-axis geometry. The divergence of the output radiation was close to the diffraction one.

After the formulation and substantiation of basic principles of the construction of nonreciprocal optical systems with independent auxiliary systems (see section 2), which make it possible in principle to build compact telescopic systems with compensation for distortions, experimental studies of these systems were started [36, 37, 42, 44].

In the experiment [36], distortions of a lens objective of diameter 300 mm and focal distance 2000 mm were corrected. This objective had strong distortions, which caused blurring of the uncorrected image of a point object to several tens of diffraction angles. Complex transparent objects representing groups consisting of several tens of test patterns were imaged in pulsed experiments ($\lambda = 0.53$ µm). To provide high-quality PC for highly divergent radiation, in these experiments the Brillouin-enhanced four-wave miximg (BEFWM) was used [45]. The possibility of obtaining corrected images of complex objects in the field of view of the order of $1000\theta_d$, where $\theta_d = 2.44\lambda/D$, was demonstrated.

The theoretical studies of limiting possibilities of the compensation for distortions of different type, in particular, piston distortions, as well as direct numerical simulation have shown that it is possible to obtain substantial compensation coefficients even in mirror telescopic systems with the high numerical aperture. The authors of [42, 44] (Fig. 7) studied the imaging quality of the system consisting of the segmented PM of diameter 30 cm and focal distance 1.2 m. The images of nine (3×3) point sources of coherent radiation were studied, which were simulated by a lens raster *4* through which a plane wave of the 0.54-µm second harmonic from a single pulse Nd:YAP laser propagated. The test object being imaged was located at a distance of 16.5 m from the telescope PM being compensated and occupied all the calculated field of view with the angular width 2′.

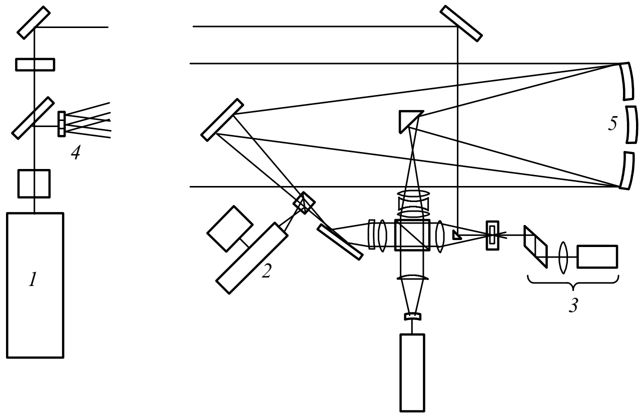

Figure 7. Scheme of the experimental setup [42, 44]: (*1*) illumination laser (second harmonic of a single-pulse Nd:YAP laser); (*2*) system for detecting the corrected image; (*3*) PC subsystem (BEFWM mirror); (*4*) lens raster; (*5*) segmented PM being corrected.

Special achromatic two- and three-lens objectives were used in the system. The system as a whole was achromatic in the spectral range 530 ± 30 nm and operated in a pulsed regime with the low pulse repetition rate. The PC of weak radiation coming from the object was performed, as in the experiment with a lens objective described above [36], using the BEFWM.

Fig. 8 shows the image of one of the nine point objects, which was located at the centre of the field of view of the system. The image was obtained when the system operated in the regime of compensation for the PM distortions (Fig. 8a). For comparison, the image of the point object obtained without compensation for the PM distortions is shown at the same scale in Fig. 8b. Because the quality of all mirror segments was far from the diffraction one, the image obtained without compensation represented a speckled spot with the angular dimension of $\sim (10-20)\theta_{\mathrm{d}}$. Under such conditions, the system operating in the compensation regime produced the image of almost diffraction quality with the divergence of $\sim (4-6)\times 10^{-6}$ rad. The high quality of the image was retained at the angular maladjustment of the mirror as a whole and its individual segments with respect to the system axis by $\sim 30\theta_{\mathrm{d}}$ and the error of the piston shift of the segments relative to each other by ~ 10 μm.

The authors of Ref. [35] performed in USA investigated by the method of interferometry the quality of correction for small distortions of a low aperture ratio ($D:F = 1:4.2$) spherical mirror 150 mm in diameter, which was used as a PM in the nonreciprocal telescopic system with two independent single-lens auxiliary optical systems. The system generated a plane wave using a 1 W, 514-nm cw argon laser. The PC was performed in a photorefractive $BaTiO_3$ crystal. The parameters of auxiliary elements of the system were chosen so that to achieve the PM self-projection required for the distortion compensation.

Because of the low aperture ratio of the system, it was possible to simulate the PM distortions with the help of an optically inhomogeneous thin glass plate placed close to the mirror. In the experiment, the quality of the output radiation of the telescope without correction and with correction for the distortions introduced by the glass plate was compared. The maximum deviation of the wave front without correction was 1.3λ at the root-mean-square deviation equal to $\lambda/3$. In the case of correction, the root-mean-square deviation of the wave front was $\lambda/17$.

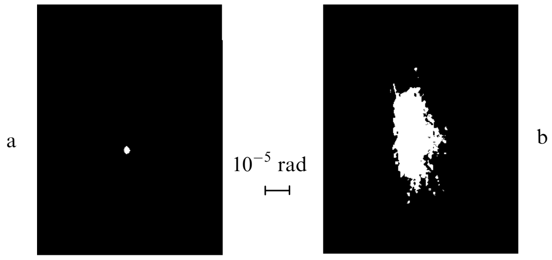

Figure 8. Images of a point source obtained in experiments [42, 44] using a system with the distortion compensation (a) and a common telescope (radiation of an aligning laser) (b) for the same PM.

This experiment has demonstrated by the example of a telescope with a small aperture ratio that it is possible to achieve high-quality output optical radiation using small distortions of the PM. This approach can be obviously used for manufacturing optical collimators with the high aperture ratio [39, 46].

The TENOCOM system was first experimentally studied using a repetitively pulsed TEA CO_2 laser with a comparatively low average power of ~ 20 W and a pulse repetition rate of ~ 10 Hz [40, 47–50]. The scheme of the experiment is shown in Fig. 9. The segmented spherical

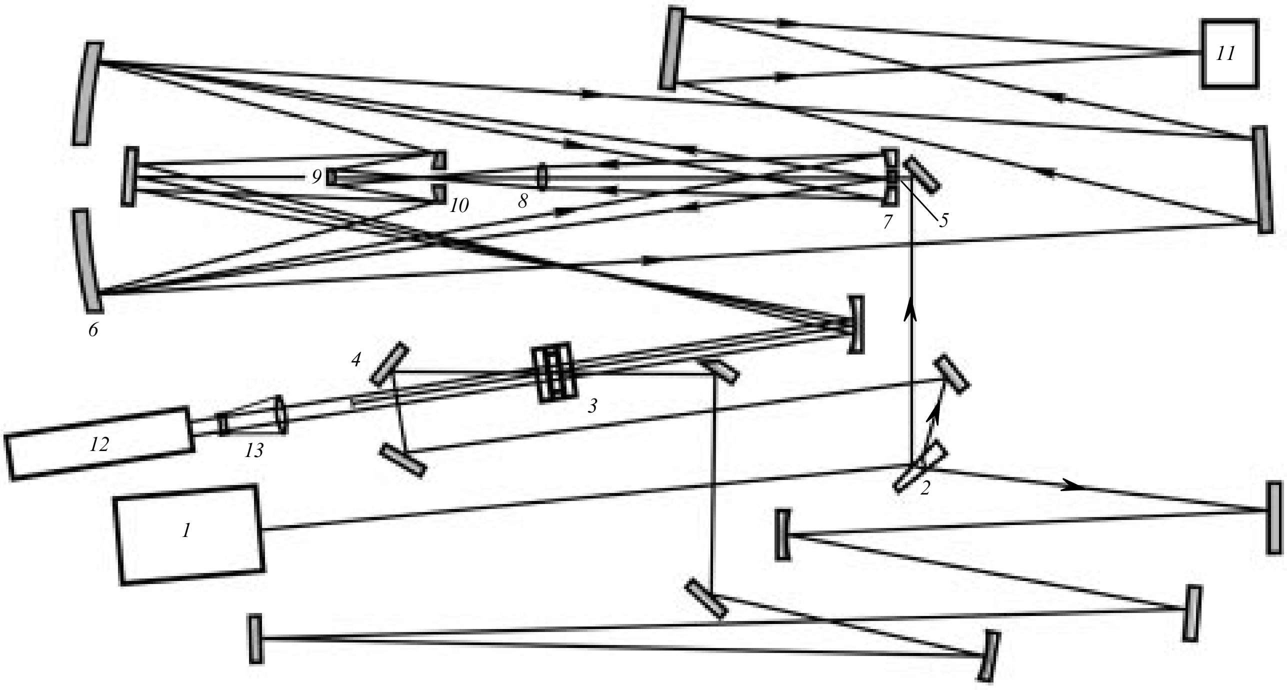

Figure 9. Scheme of the experimental setup [40, 47–50]: (*1*) pulsed TEA CO_2 laser; (*2*) ZnSe beamsplitter wedge forming a signal wave and two pump waves of a four-wave PC mirror (a cell with the SF_6 gas flow); (*3*) PC mirror; (*4*) lens for the formation of an auxiliary alignment beam; (*5*) KCl negative lens; (*6*) PM being compensated ($D = 400$ mm, $F = 2000$ mm, 6 segments); (*7*) concave mirror; (*8*) KCl lens; (*9*) convex mirror; (*10*) compensated convex counter-reflector with a concentric diffraction structure (the diffraction efficiency is 8 %); (*11*) detection system (photographic camera with the spark illumination or calorimeter); (*12*) alignment He-Ne laser; (*13*) collimator.

PM of diameter 400 mm and focal distance 2000 mm had six subapertures. The diffraction structure was fabricated on the surface of the secondary mirror of diameter 60 mm by the method of photolithography and had the maximum density of lines at the mirror edge equal to 18 lines/mm. The PC was performed using the degenerate four-wave mixing in an absorbing medium (the SF_6 gas [51]).

Fig. 10 shows the fraction of the radiation energy propagating within the solid angle as a function of this angle (expressed in units of $\theta_d = 2.44\lambda/D$, where D is the diameter of the corresponding beam) for the initial diaphragmed laser beam, after phase conjugation of the beam with the help of a PC mirror, which was used on the main experiment, and at the output of the beam-generating telescopic system.

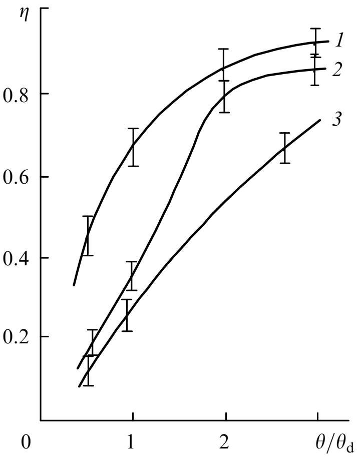

Figure 10. Dependences of the fraction η of radiation energy propagating within the solid angle θ on θ for the initial laser beam diaphragmed to 0.3 in diameter before (*1*) and after (*2*) PC, and for the output signal beam (*3*).

The divergence of the beam at the input of the telescopic system was close to the diffraction one (for the beam vignetting coefficient equal to 0.3, the maximum fraction of radiation propagating within the angle θ_d, was 65 %). Some increase in the laser-beam divergence after PC was explained by the nonideal quality of pump beams of the four-wave PC mirror. The comparison of curves 2 and 3 shows (Fig. 10) that the angular energy distribution at the central kernel of the beam generated by the telescopic system does not virtually differ from its maximum value that can be achieved for the given vignetting of the beam and the PC quality. The increase in the fraction of radiation energy in the wings was explained by the diffraction of the light beam from optical and construction elements of the telescopic system.

The quality of the generated beam did not deteriorate at the relative piston displacements of segments up to 150λ (i.e., up to 1.5 mm) and at the relative tilts of segments through angles up to $25\lambda/D$. The angle $25\lambda/D$ was determined by vignetting of the light beam by the auxiliary optical elements.

Later, this telescope was studied using repetitively pulsed CO_2 laser, which had the pulse repetition rate up to 100 Hz, and the PC system in the active medium of a CO_2 laser [52]. Fig. 11 shows the directivity diagram for radiation reflected from the PM obtained without compensation for the PM alignment and with compensation for errors in the tilts of the PM subapertures. Fig. 12a presents the results of the system operation at frequency 50 Hz when the angular vibration of the PM was added at frequency 12 Hz. Fig. 12b shows the dynamics of the radiation pattern for the uncompensated PM. The results of these experiments demonstrate the system operation stability to the PM perturbations. The effect of distortions introduced by the secondary mirror defects on the system operation was not studied in papers [40, 47 – 50, 52].

Figure 11. Image in the far-field radiation zone formed only by the PM of the TENOCOM system without compensation for the mutual tilt of subapertures (a) and by the entire TENOCOM system with the same PM (b); presented are three images detected with different attenuation.

Figure 12. Image in the far-field radiation zone formed by a repetitively pulsed laser using the entire TENOCOM system (a) and only the PM subjected to periodic vibrations without compensation for its distortions (b).

Alongside the studies of nonreciprocal systems, telescopic systems with diffraction structures on the PM have been also experimentally investigated. In experiments [31] with a TEA CO_2 laser, the PM of diameter $D = 150$ mm and the radius of curvature equal to 3 m was used. The diffraction structure was deposited on this mirror by the method of photolithography. The PC of radiation was performed by the same method as in the case of nonreciprocal optical systems, i.e., using the degenerate four-wave mixing in the SF_6 gas [51]. It was shown that this scheme generates a virtually diffraction-limited light beam with the stable radiation pattern upon rotation of the PM through angles up to ~ 2 mrad, the range of tilt angles being limited only by the radiation vignetting in the PM hole. The displacement of the initial point source within the field of view of the system resulted in the tilt of the generated beam without violation of the compensation.

In paper [32], experiments were performed in a similar geometry but using a 1.06-μm Nd : YAG laser. The diffraction structure was deposited by the holographic method to the PM with the same parameters as in [31]. In these experiments, the stable directivity diagram of output radiation of the diffraction quality was observed for the PM tilts through angles up to 0.15 mrad. Similar results were obtained for a segmented PM having four subapertures with the transverse size equal to 40 mm. These experiments also showed that to achieve the diffraction-limited divergence of the output radiation using the sectional aperture, a very precise alignment of the transverse position of the

PM subapertures is required. In addition, these experiments demonstrated for the first time the operation of a telescopic system in combination with a pulse energy amplifier located in the compensated channel of the telescopic system.

As was mentioned in section 2, the possible solution of the problem of building of large mirrors with the HOE on their surface is to use a dynamic hologram instead of a stationary diffraction structure 'imprinted' to the PM. The dynamic hologram is recorded on the mirror surface using an auxiliary laser and can be restored as required (depending on the rate of appearance of the segmented mirror distortions). This method was first proposed and experimentally simulated in Ref. [33].

In Ref. [33], the dynamic hologram was recorded by two waves from an auxiliary laser in a germanium layer deposited on a copper mirror. Free carriers were generated in the semiconductor layer by radiation from a 1.06-μm Nd^{3+} : YAG laser. As a result, a dynamic hologram with the relaxation time about of 100 ns was produced on the mirror surface.

The optical scheme of the experiment is shown in Fig. 13. The radiation from a TEA CO_2 laser generated a probe wave and two conjugated waves for pumping a PC cell containing the $^{34}SF_6$ gas [51]. The probe pulses with 0.8 J energy and a duration of ~ 1 μs were incident on a two-segment plane mirror. A 5.8-lines/mm dynamic grating was recorded by 0.5-μs pulses from a Nd^{3+} : YAG laser, which provided the energy density of 50 mJ cm^{-2} in each of the recording beams. Under these conditions, the diffraction efficiency of the grating for a probe wave was about 1 %. The diffracted probe wave, which contained information on the distortions of the segmented mirror, was incident on the PC cell. The PC radiation propagated in the opposite direction. The radiation with the corrected wave front underwent specular reflection from the segmented mirror and was incident on the detection system. This experiment has demonstrated the possibility to correct the influence of mutual tilts of the mirror segments by angles ±4.5 mrad and the piston displacement up to 2 mm.

4. Telescopic systems with dynamic holographic correction for the PM distortions

With the advent of telescopes with the PC correction and the development of the laser technique, it has become possible to return to the use of holographic correction of distortions in observational telescopes operating with usual (incoherent) optical radiation, but now by using the methods of dynamic holography. New reversible media have been developed for dynamic holography, such as optically addressable liquid-crystal spatial light modulators (OA LC SLMs), photorefractive crystals, etc., which allowed one to reduce the time interval between the hologram recording and reconstruction, thereby providing the correction in the dynamic regime.

Studies of the imaging with the dynamic holographic correction for optical distortions can be divided into two groups. The first group includes the papers in which the use of a variety of nonlinear media as dynamic correctors is demonstrated and their temporal and spatial characteristics are studied. Almost in all these papers, the schemes of a single-passage correction were used, in which a point source of the signal wave involved in the recording of the corrector was located in the object plane. The second group of papers is devoted to the study of the system for correction of mirror objectives of telescopic systems with a point source located near the centre of curvature of the surface being corrected.

Consider first the papers belonging to the first group. All the holographic correctors can be divided into plane and volume dynamic holograms. The advantages of volume holograms (photorefractive crystals, thermal gratings, etc.) are the high diffraction efficiency, which can be theoretically close to 100 % for phase holograms. The single-pass correction with the use of volume holograms has been experimentally studied in various nonlinear media, in particular, photorefractive crystals [53 – 55], bacteriorhodopsin films [56, 57], and a fluorescein-doped boric glass (FBAG) [58 – 60]. However, the spectral and angular selectivity of such correctors substantially restricts the field of view of the system and the width of the operating spectral range.

At the same time, correctors, in which plane holograms are formed, do not have spectral and angular limitations at a lower diffraction efficiency. It is these correctors that appear the most promising for the holographic correction in a broad spectral range. Among such media, OA LC SLMs have no rivals [61, 62]. The layers of a polycrystalline or amorphous photoconductor and a liquid crystal is such a modulator are located between transparent electrodes to which a voltage is applied. Upon illumination of the photoconductor by light, its conduction (the total resistance) changes in the illuminated region, resulting in the redis-

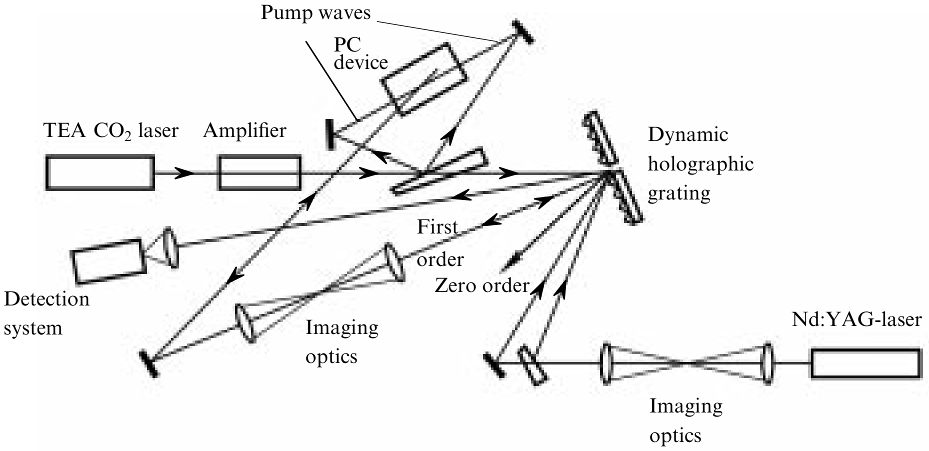

Figure 13. Principal scheme of the experiment [33].

tribution of the applied voltage between the layers of the photoconductor and the liquid crystal. This leads to the reorientation of liquid-crystal molecules, modulation of the refractive index and, hence, to the phase modulation of the reading radiation in accordance with the distribution of the photoconductor illumination.

For the liquid-crystal layer of thickness a few micrometres and the angle between the recording beams $\sim 10^{-2}$ rad, a phase structure is formed in the modulator, which has properties of a plane hologram with the theoretical limit of the diffraction efficiency equal to 34 % for a sinusoidal grating and about 40 % for a grating with the rectangular profile of grooves. The experimental diffraction efficiencies achieved upon pulsed feeding of the modulator [63] are close to these values [64].

The authors of papers [65, 66] studied the parameters of the OA LC SLM operating in the pulsed recording regime in the scheme of single-pass correction of optical distortions. The scheme of the experiment is shown in Fig. 14. The hologram of distortions of the objective of a lens telescope imaging a standard dashed test pattern illuminated by an incandescent lamp was recorded in the OA LC SLM by pulsed radiation of the second harmonic of a Nd : YAP laser. Etched glass plates placed in front of the objective simulated its distortions. The use of an auxiliary diffraction grating to compensate for the chromatism of the holographic corrector recorded in the OA LC SLM made it possible to obtain the corrected image of the test object in the entire visible range. Fig. 15 shows the distorted and corrected images of the test object. The correction quality was analysed by the contrast of images of lines of the test pattern. Fig. 16 shows the measured frequency-contrast characteristics of the optical system. One can see from Figs 15 and 16 that the image quality in the green spectral region with the width 50 nm is close to the diffraction one.

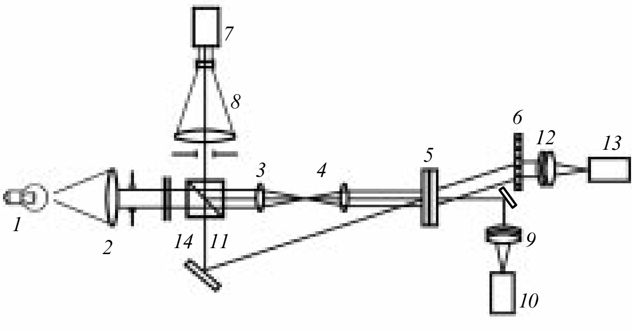

Figure 14. Scheme of the experimental setup [65, 66]: (*1*) test object; (*2*) objective; (*3*) objective of the compensation telescope; (*4*) eye-piece; (*5*) corrector hologram; (*6*) diffraction grating; (*7*) laser for recording of the corrector hologram; (*8*) expansion telescope; (*9, 10*) elements of the detection system of the uncorrected image; (*11*) beamsplitter cube; (*12, 13*) elements of the detection system of the corrected image; (*14*) light filters.

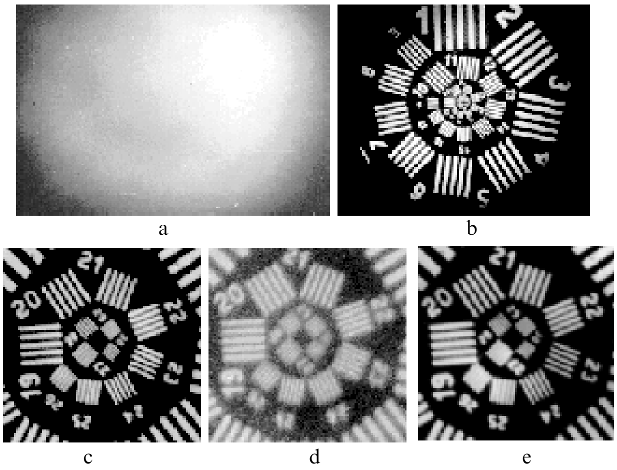

Figure 15. Image of the test object [65, 66] in the uncorrected telescope obtained by placing a glass plate etched in hydrofluoric acid in front of the objective (the beam divergence is 6×10^{-3} rad) (a); corrected image (b); central zones of the corrected image detected in the spectral ranges 0.53 ± 0.04 (c) and 0.63 ± 0.04 μm (d, the image quality is somewhat worse because of the shift of the frequency interval relative to the recording wavelength of the corrector), and within the entire visible spectral range (e).

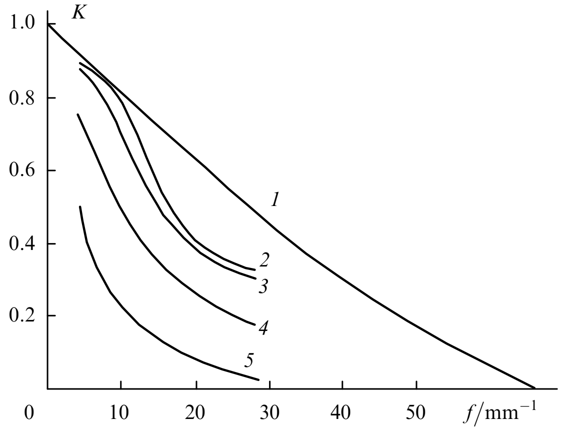

Figure 16. Frequency-contrast characteristics of the system in the absence of distortions of the lens objective (*1, 2*) and in the presence of its small-scale distortions (*3–5*): (*1*) characteristic of an ideal system; (*2*) characteristic of the optical system used in the experiment; (*3*) correction for the objective distortions in the green spectral region; (*4*) correction within the entire visible region; (*5*) correction in the red spectral region.

The authors of paper [67] have demonstrated the use of the OA LC SLM with the separating mirror layer (i.e., with the optical separation of channels of the hologram recording and reading) in the scheme of single-pass holographic correction for optical distortions. A hologram was recorded and read out at wavelengths of 543 and 633 nm, respectively. In the experiment, both static and dynamic distortions caused by the turbulence of heated ambient air were compensated. The characteristic response time of the OA LC SLM in this experiment was 5 ms. Compensation for distortions of a turbulent layer with the help of the OA LC SLM with a ferroelectric liquid crystal was later demonstrated in similar experiments [68]. The characteristic frequency of variation of optical inhomogeneities was 10 kHz.

Advances in the development of the technique of holographic single-pass correction made it possible to implement in experiments the scheme with an internal reference source (proximal beacon).

In schemes of static holographic correction (see Introduction), a hologram was recorded in an auxiliary interferometer. After the appropriate processing, the corrector was located in another plane – the image plane of the objective pupil produced by the telescope eye-piece. The use of additional relay elements in the scheme made possible the spatial combination of the hologram recording and reconstruction planes. The principle schemes of telescopic systems with the dynamic holographic correction for distortions and schemes of systems with the PC correction proved to be quite similar. Therefore, the basic conclusions about the compensation properties of telescopic systems with the PC correction remain also valid for telescopic systems with the holographic correction. This question was discussed in more detail in Refs [69, 70].

The only substantial difference between these two systems is caused by spectral distortions. As mentioned above, the holographic correction allows one to image objects not only at the recording wavelength of the distortion hologram but also at other wavelengths lying in some spectral range. In this case, due to the distortions of the wave front, which was reconstructed by radiation at the wavelength different from the recording wavelength, the degree of compensation for distortions of the telescope objective will decrease with distance from the recording wavelength. The possibility of correction in such telescopes was discussed in papers [69, 70]. Thus, upon recording the corrector at the wavelength $\lambda_1 = 530$ nm and reconstruction of the image at the wavelength λ_2 separated from λ_1 by the distance $\Delta\lambda = 25$ nm, distortions can be decreased no more than by a factor of $\lambda_1/\Delta\lambda \approx 20$.

The dynamic holographic correction for distortions has been performed in a few papers. In the first experiments, monochromatically imaged model objects and bulk holographic media have been used.

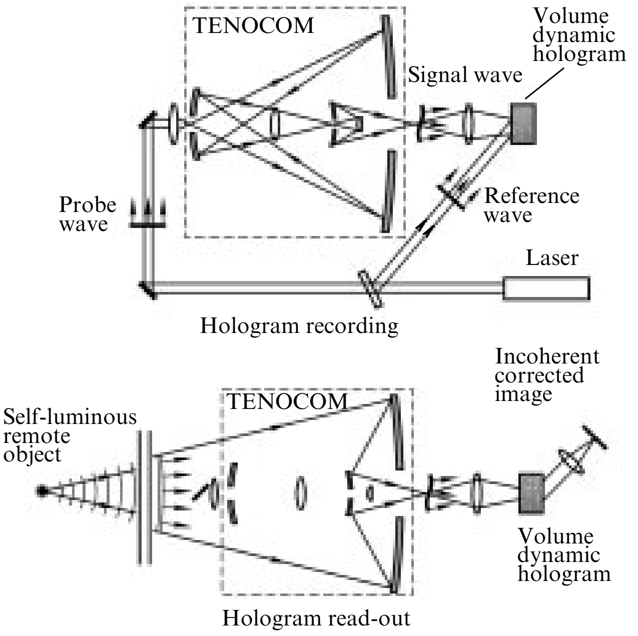

Figure 17. Principal scheme of the experiment [52].

It seems that the dynamic holographic correction has been first performed in paper [52]. In this experiment, a modified telescope with the diffraction structure on the secondary mirror was used, which was employed earlier in experiments with the TENOCOM system [40, 47–50] (see above) containing a six-segment PM of diameter 400 mm and focal distance 2000 mm. As a corrector, a volume thermal grating was used, which was recorded in SF_6 at a wavelength of 10.6 μm (Fig. 17). The telescope imaged a point source illuminated by radiation from an auxiliary incoherent source. The compensating ability of the system was demonstrated by tilting individual segments of the PM with respect to the telescope axis in the radial direction by angles ~ 0.12 mrad. As a result, the uncorrected image of the point source consisted of six spots (radiation transmitted by the hologram in the zero diffraction order), whereas the corrected image of the point source of quality close to the diffraction one was observed in the first diffraction order.

In experiments [70, 71], photorefractive two crystals $Sr_{0.6}Ba_{0.4}Nb_2O_6$ (SBN) and $Bi_{12}SiO_{20}$ (BSO) have been used as bulk transmitting holographic correctors. In the experiment with a mirror objective of diameter 25 mm, upon recording a hologram by a 514-nm argon laser, a point source was imaged at several wavelengths with the total width of the spectrum equal to 40 nm. The hologram chromatism was compensated with the help of a reflection diffraction grating.

In the experiment with the segmented objective of diameter 150 mm, a point source illuminated by radiation from a He–Ne laser (633 nm) was imaged. The difference $\Delta\lambda$ between the wavelengths of the hologram recording and reconstruction was 120 nm. A standard lined test pattern illuminated by radiation from an incandescent lamp was imaged with the help of a one-piece mirror objective of diameter 150 mm. Its distortions were simulated with an inhomogeneous glass plate placed close to the objective. A system of filters separated the visible range of width 350 nm from the emission spectrum of the lamp. The corrected image of the test object prove to be limited and coloured because of the selectivity of the volume hologram. Different angles of incidence of radiation on the hologram corresponded to different points of the object. The diffraction efficiency for each angle of incidence was maximal for a certain spectral component satisfying the Bragg condition.

The use of OA LC SLMs as dynamic holographic correctors in telescopes with an internal reference source was studied in papers [72–75]. In [74], a 150-mm membrane mirror with the aperture ratio of 1 : 6 was corrected. The correction quality was estimated by from image of a point source located at infinity at the hologram-recording wavelength (radiation of a 543-nm He–Ne laser). As a holographic corrector, a modulator with a separating mirror layer and a ferroelectric liquid crystal was used, which operated at frequency 300 Hz. For the initial distortions of the objective of the order of $\sim 200\lambda$, the size of the corrected image of the point source exceeded by a factor of 1.6 the size of a diffraction-limited spot.

In papers [72, 73], a telescopic system with the high numerical aperture was studied, which imaged a dashed test pattern in the spectral range of width 50 nm with a centre coinciding with the wavelength of the hologram recording (540 nm). In these studies, a modified telescope was used [42, 44], which was initially intended for the imaging of coherently illuminated remote objects with the PC compensation. In [69], the required modifications of the telescope construction were analysed and the modified scheme was numerically simulated.

The principal scheme of the experiment [72, 73] is shown in Fig. 18. The corrector chromatism was compensated with the help of a transmission diffraction grating with the spatial frequency ~ 100 lines/mm, which corresponded to the carrier frequency of the holographic corrector. A thin mirror 300 mm in diameter and the aperture ratio of 1 : 4 was used as the telescope objective. The deviations of the mirror surface shape from a sphere were ~ 2 μm. Fig. 19 shows the images of a lined test pattern without and with correction. Fig. 20 presents the frequency-contrast characteristics of the system. In paper [75], published simultaneously with [73], a 750-mm mirror objective was corrected using a similar scheme.

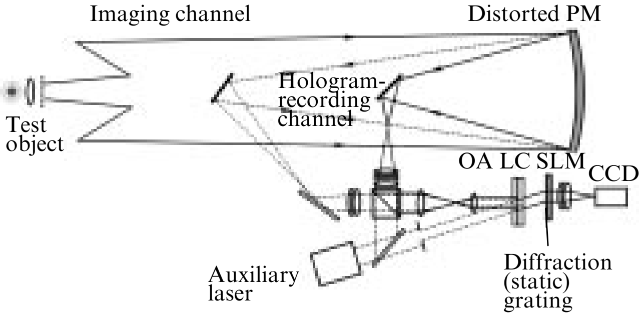

Figure 18. Principal scheme of the telescopic system with holographic correction for distortions [72, 73].

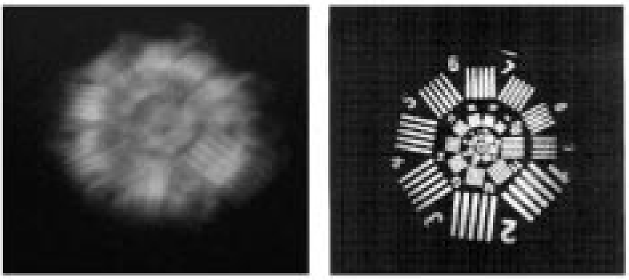
a b

Figure 19. Image of the lined test pattern without (a) and with (b) correction [72, 73].

In conclusion of this section, note that, although the experimental studies of systems with the holographic correction for distortions have been performed only for the observation of remote objects, a similar approach can be also applied to the systems generating highly directional radiation, in particular, to large collimators [38, 39, 46], as well as for the correction for distortions in laser systems operating at several wavelengths.

Note also that the methods of dynamic analogue nonlinear-optical correction for distortions are not restricted to the dynamic holography only. There exists an alternative technique based on the use of an optically addressable phase modulator in the negative optical feedback loop [76, 77]. Its advantages are the absence of energy losses and a broader (compared to holographic correctors) spectral range of radiation being corrected. The drawbacks of this technique are related first of all to the parameters of phase modulators [61, 62], namely, to their slow response and the inadequate degree of modulation. Recently [78], it was shown that the combination of a scheme with the negative feedback and dynamic holography in one system is promising. However, these studies are only at the initial stage.

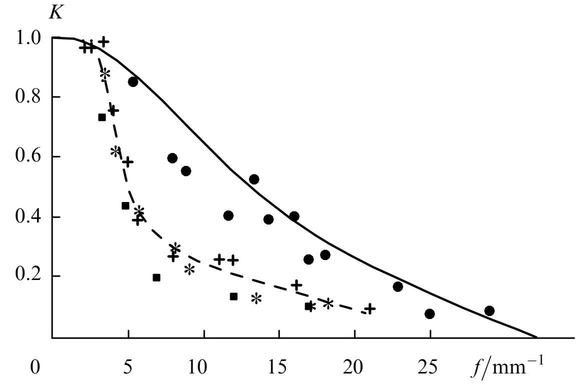

Figure 20. Frequency-contrast characteristics of the telescopic system [72, 73]: The input channel of a system with the high-quality PM (●); an ideal system (solid line); a system with the high-quality PM with compensation for distortions (∗); a system with the deformed PM (+); and a system with the spectral shift of the object illumination (■).

5. Conclusions

The theoretical and experimental studies showed that the telescopic systems with correction for random distortions of the PM and optical channels based on the methods of nonlinear optics and dynamic holography represent a new promising class of adaptive optical systems. By now the telescopes have been built with the diameter of the PM aperture up to ~ 500 mm, however, it is quite obvious that many useful properties of such systems can be scaled. Thus, for example, the maximum degree of compensation for distortions is independent of the diameter of the telescope PM, so that using telescope mirrors of a large diameter achieving several metres, one can substantially lower the price of the system.

Capable of strong compensating optical distortions tens and even hundreds times, such systems can be efficiently used for solving practical problems of two types:

– the generation of high-quality, wide-aperture laser beams, and

– imaging of remote objects.

The problems of the first type are related both to energy or information transfer over large distances (up to the interplanetary distances [79]) and the development of wide-aperture metrological optics intended for certifying large optical elements and measuring inhomogeneities of media in large volumes. The problems of the second type are related to the building of the systems for observation of the Earth surface with high resolution and the development of the communication systems for space crafts and the next generation space telescopes [80].

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