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Wavefront lens corrector for studying flat surfaces

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The method of manufacturing and the results of studies of a lens corrector that converts a spherical diverging front into a plane one and is intended for studying flat surfaces as part of an interferometer with a diffraction comparison wave is described. A feature of the corrector is the use of an aspherical convex surface with a maximum deviation of $\sim 200\,\mu$m from the nearest sphere. The first experimental results are presented, indicating the prospects for using ion-beam processing to improve the quality of the wavefront. After the procedure of ion-beam processing, the aberrations over the entire aperture of the corrector decreased by more than 4 times and amounted to the parameter of the height difference PV $= 207$ nm ($\sim \lambda/3$) and (RMS) $= 19.2$ nm ($\sim \lambda/33$). On an area with a diameter of 80%, the aberrations fell to the nanometer level: PV $= 65$ nm ($\sim \lambda/10$) and RMS $= 8.3$ nm ($\sim \lambda/76$).

Keywords: lens corrector, interferometry, aspherical lens, ion-beam processing.

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Introduction

Interferometry is the main method of measuring the shape and aberrations of optical elements and systems in production sector and laboratories [1]. The point diffraction interferometers (PDI) use light diffraction at low aperture for generation of diverging spherical comparison wave [2,3]. Amplitude-phase characteristics of such wave can be calculated with high precision, thus allowing to ascribe this interferometry method to a class of „first-principles“. However, practically, direct measurements using this method can be performed only for concave spherical, elliptic and toroidal surfaces and for object-glasses. For other types of optical elements and systems the various conversions of the diverging spherical wave are required, for its wavefront to be close to the observed component shape. For instance, for studying the flat surfaces it is required to converse the front to the flat one, while for convex — to the diverging spherical front. This task is solved using an optical element called wavefront corrector [4].

Currently two main approaches are used at correctors formation: diffraction and with use of single lenses and objective-glasses [5–10]. For X-ray optics application, where nanometric and even subnanometric precision of optical surfaces shape is required, the correction of corrector aberrations is required. Diffraction corrector can not be fixed with ionic beams. This means that for studying the ultrahigh-precision optical elements aberrations it is possible to use lens correctors only, for instance [9,10]. However, the above mentioned correctors were used for studying the concave aspherical surfaces with deviations from the nearest sphere of at least $10\,\mu$m, thus allowing to make them using conventional optical machines by means of lapping with the following aberrations correction with ionic beams.

To converse the diverging wavefront into plane or convergent one, the much higher deflection and, as a result, deeper aspheres are required. As calculations showed, such aspheres should have deviations from the nearest spheres of hundreds of μm. Such surfaces can not be made using conventional lapping, so they are manufactured at ultra-precision machines with computer numerical control using small-sized tools.

The purpose of this work is studying the parameters of aspherical lens, made using the mentioned method, and possibility of its use for studying the flat surfaces as a wavefront corrector.

1. Calculation of wavefront corrector

Calculation of wavefront corrector was performed for the first developed PDI intended for operation under industrial conditions [11,12]. Calculation of plane-convex corrector (Fig. 1) was performed in Zemax software. Fixed input data for optimization were: material — fused quartz KU-1; distance between spherical wave source, mounted in corrector focus, and corrector, equal to 178.4 mm; input aperture NA $= 0.26$; thickness of 30 mm and diameter of 105 mm. Fixed geometrical parameters of the corrector were selected based on design features of interferometer, so it can be possible to mount the developed corrector to interferometer instead of previous one without significant adjustment of the instrument, material — due to good homogeneity

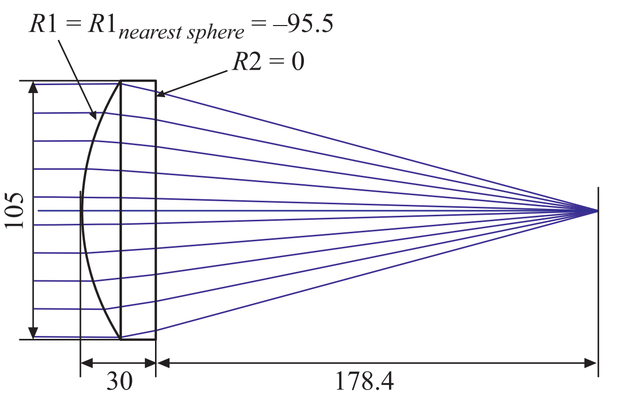

Figure 1. Scheme of corrector for PDI, converting the diverging spherical front of spherical wave source into a plane-parallel wavefront.

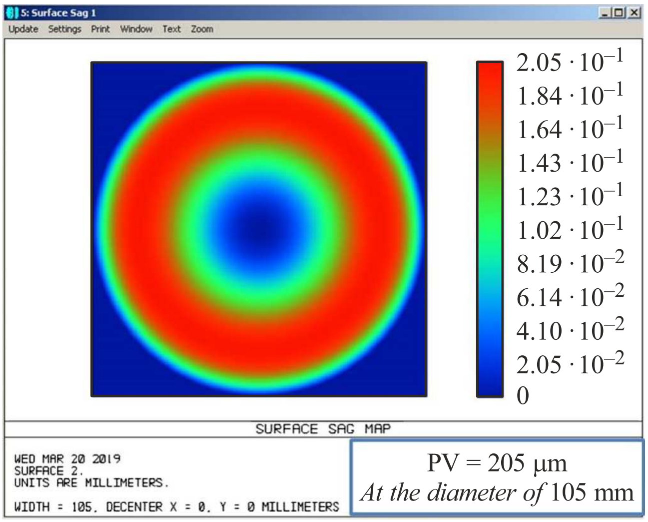

Figure 2. Map for asphierization of corrector convex surface.

of quartz KU-1, allowing to perform ion-beam etching to deep depths without development of surface roughness.

After optimization the curve radius of the corrector convex surface (nearest sphere radius) was found, equal to -95.5 mm, as well as coefficients at polynomials, describing deviation $h(r)$ of aspherical surface from the nearest sphere:

$$h(r) = 2.6125 \cdot 10^{-4} \cdot r^2 - 7.320 \cdot 10^{-8} \cdot r^4 - 5.302 \cdot 10^{-12} \cdot r^6 - 9.011 \cdot 10^{-16} \cdot r^8, \quad (1)$$

where $r = 0{-}52.5$ mm — radius of examined point on convex surface.

Aspherical shape of the corrector convex surface (Fig. 2) is axially-symmetrical and removes spherical aberration. Maximum vertical drop was PV = 205 μm.

2. Technique and experimental results

2.1. Manufacturing and studying the wavefront corrector aberrations

Aspherical lens-corrector manufacturing was performed at the line of aspherical grinding and aspherical polishing machines of well-known manufacturers: Schneider, Optotech and SatisLOH. Control of asphere shape was performed both during manufacturing (profile meter) and during final delivery of a component (interferometer). Both devices had feedback with the machines for making corrections in components processing program after intermediate measures. In this study the profile meter Talysurf 1240 made by TAYLOR HOBSON (UK) and interferometer ZYGO were used. As per manufactureres data the technology provides the following precision of aspheric surfaces manufacturing: PV $= 0.5\,\lambda$ and root-mean-square deviation (RMS) $= 0.07\,\lambda$, where λ is interferometer operating wavelength.

Studying the wavefront aberrations was performed using PDI based on single-mode optical fiber with subwave output aperture at horizontal interferometer stand described in [13]. Picture of the stand with designations of the main elements of the measuring scheme is presented in Fig. 3. Spherical diverging wave comes out of interferometer *1* and falls onto the wavefront corrector *2*, at output of which the plane front is formed. This front falls on flat reference mirror *3* and after reflection goes back to interferometer through the closest path. In this experiment the pre-measured flat reference with RMS $\sim \lambda/100$ was used. Reference error during measurement was not considered. Measurements accuracy improvement technique, described in [10], was also not used, since the corrector errors were significantly bigger than $\lambda/100$.

Fig. 4 shows the measured interferogram and reconstructed map of wavefront deviations from the required. Corrector aberrations measured at 100% area were RMS = 79.7 nm ($\sim \lambda/8$), vertical drop PV = 849 nm ($\sim 1.3\,\lambda$). At 80% diameter aperture the aberrations were: RMS = 37.9 nm ($\sim \lambda/17$), vertical drop PV = 304 nm ($\sim \lambda/2$).

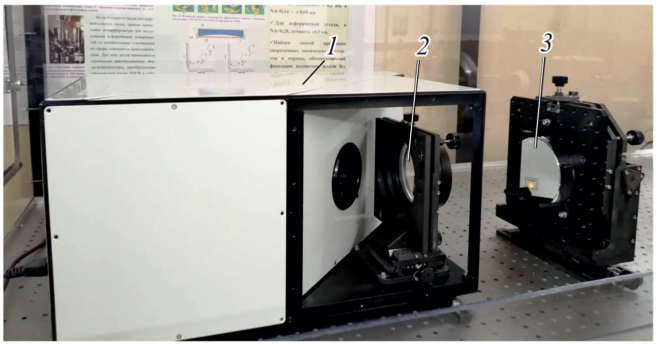

Figure 3. Scheme of measuring the wavefront corrector aberrations: *1* — PDI, *2* — corrector under study, *3* — reference plane.

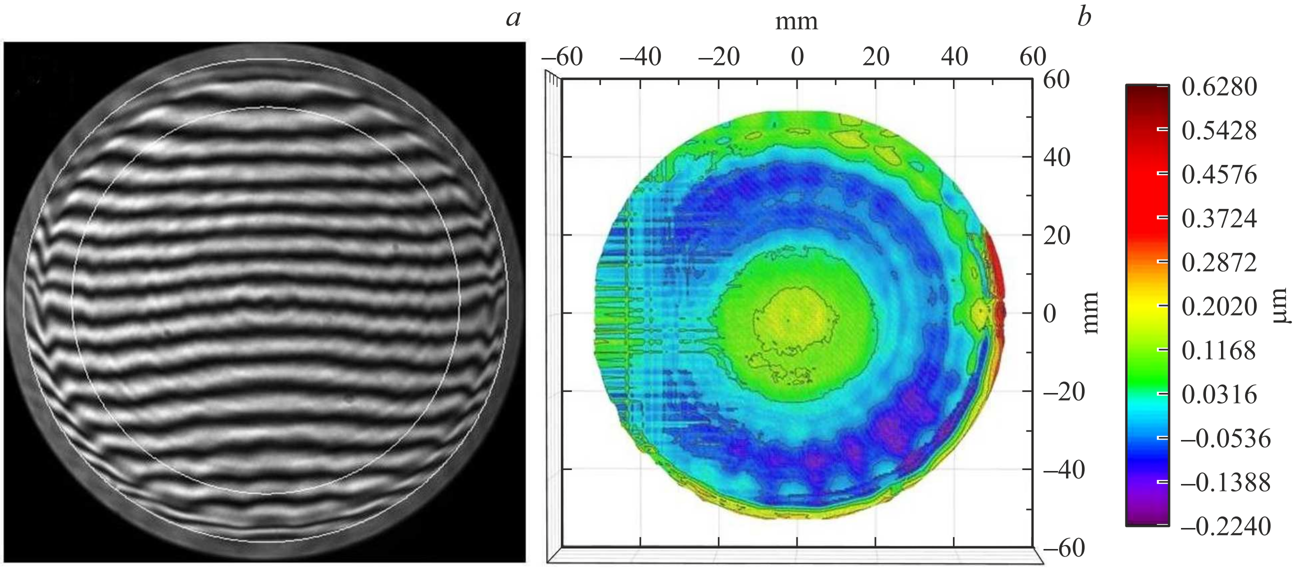

Figure 4. Interferogram (a) and aberrations map (b) of corrector. White circle shows the area with diameter of 80%.

As the interferogram and the reconstructed aberrations map show, that the wavefront contains significant share of high frequency aberrations. They have a certain symmetry, related, in our opinion, with specifics of surfaces forming using small-sized tools. There are no such structures and high frequencies on components manufactured using lapping method, for instance [14].

Also it can be noted that corrector parameters do not satisfy the Marechal's criterion for permissible aberrations for optics of diffraction quality RMS $\leq \lambda/14$ even for visible range [15].

2.2. Corrector surface improvement using ion-beam etching method

Method of ion-beam etching was used for correction of the wavefront corrector aberrations. Experiments were performed using a unit and techniques described in [16]. The only difference was that during calculation of ion beam motion path along the component the improved algorithm was used, allowing to double the spatial frequencies of irregularities, that can be processed during ion-beam etching, with the same ion beam diameter [17].

To accelerate the correction process the axially-symmetrical part of error was picked out of the total aberration and corrected using high-precision wide-aperture beam [16]. The remaining local errors had been already corrected with low-sized ion beam. Reduction of aberrations was performed using method of convex surface etching. During recalculation of the measured aberrations in the surface etching map the double light passage through the component under study was considered. Besides, unlike with mirror optics testing, the corrector material refractive index was also considered. Therefore the measured aberration Ψ is relatable to shape error through the equation

$$\Delta\Psi = 2(n-1)\Delta x, \tag{2}$$

where n is corrector material refractive index, Δx is surface profile error.

Fig. 5 shows the interferogram and the wavefront aberrations map after single procedure of axially-symmetrical and local errors correction. As shown from the figure, as in the first case, the high frequency errors dominate the aberration map. However, the aberration value dropped more than by a factor of 4 and at 100% area was: PV = 207 nm ($\sim \lambda/3$) and RMS = 19.2 nm ($\sim \lambda/33$). At 80% diameter area the values dropped to nanometric level: PV = 65 nm ($\sim \lambda/10$) and RMS = 8.3 nm ($\sim \lambda/76$).

3. Results discussion and main conclusions

The work includes study of wavefront corrector aberrations for the spherical diverging wave conversion to the plane front, that is a plane-convex lens with aspheric profile of convex surface made using method of turning with small-sized tool. The study showed the presence of significant high frequency aberrations, while the main parameters of aberrations had the following values. At 100% corrector area RMS = 79.7 nm ($\sim \lambda/8$), vertical drop PV = 849 nm ($\sim 1.3\lambda$). At 80% diameter aperture the aberrations were: RMS = 37.9 nm ($\sim \lambda/17$), vertical drop PV = 304 nm ($\sim \lambda/2$). The observed aberrations only partially satisfy the requirements to optics of diffraction quality for visible range of wavelengths in 80% diameter area.

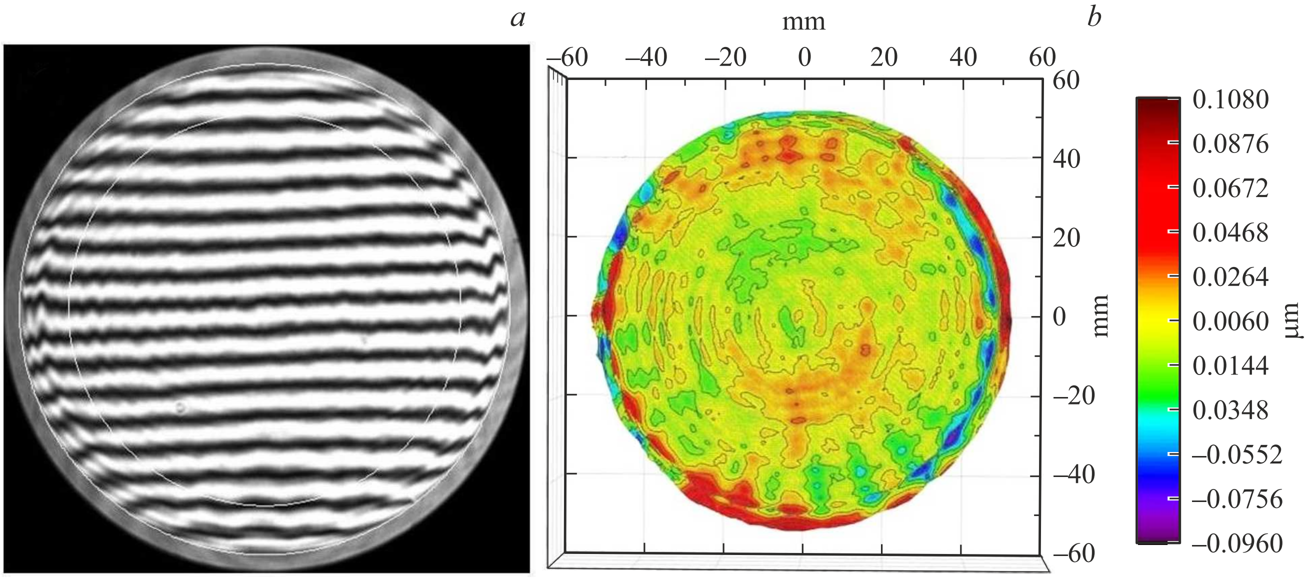

Figure 5. Interferogram (*a*) and aberrations map (*b*) of corrector after ion-beam polishing. White circle shows the area with diameter of 80%.

The principle possibility of ion-beam etching use for reduction of corrector aberrations with such „deep“ asphere was studied. Effectiveness of such approach was confirmed. It is shown that after the procedure of ion-beam etching the aberrations along the whole corrector aperture were reduced more than by a factor of 4 and in terms of vertical drop parameter were PV $= 207$ nm ($\sim \lambda/3$) and RMS $= 19.2$ nm ($\sim \lambda/33$). At 80% diameter area the values dropped to nanometric level: PV $= 65$ nm ($\sim \lambda/10$) and RMS $= 8.3$ nm ($\sim \lambda/76$). This result already allows to use corrector for studying the flat surfaces and telescope aberrations for visible and even UV ranges of wavelengths, and at 80% diameter area — even for vacuum ultraviolet.

To satisfy the requirements to optics of extreme ultraviolet range the further study of corrector wavefront quality by means of repeated procedures of local errors correction with ion beam is planned.

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Conflict of interest

The authors declare that they have no conflict of interest.

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