Computer generated holograms: fabrication and application for precision optical testing

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ABSTRACT

An overview of recent results in fabrication and application of new types of high precision CGHs for interferometric aspherical testing is presented.

Keywords: computer generated holograms, direct laser writing, aspheric testing

1. INTRODUCTION

At the present time computer-generated holograms (CGH) are state-of-the-art components in optical systems, especially in the field of interferometry for testing aspherical surfaces. In this paper we give an overview of recent developments in fabrication of high precision CGHs using our latest version of a circular laser-writing system (CLWS)[1]. The problem of optimizing the writing strategy in order to reduce wavefront errors is discussed. Methods for measuring the writing process parameters during CGH fabrication, which allows us to estimate independently the error distribution of the diffractive microstructures in the radial and angular coordinates, are considered. We also present practical results in CGHs fabrication using our modernized laser-writing system at the IA&E SB RAS (Novosibirsk, Russia)

2. CIRCULAR LASER WRITING SYSTEM

Circular writing system was developed at IA&E SB RAS [1,2] to fabricate diffractive optics in different light-sensitive materials. It is a highly universal tool for the fabrication of optical elements such as computer-generated holograms, diffractive lenses, microlens arrays, gratings, optical scales, etc. The simplified diagram of the CLWS is shown in Fig. 1. The system can be subdivided into five main units: rotation unit (motorized air-bearing spindle with rotary encoder, rotation controller), the radial positioning unit (motorized air-bearing stage, laser interferometer and motion controller), the writing power control unit (laser power control, modulation control, two acousto-optic modulators AOM1 and AOM2), and the optical writing head (focusing lens, autofocus sensor, reflection photodetector, calibration photodetector, electromagnetic deflector, electromagnetic shutter, writing head controller). All opto-mechanical units are mounted on granite base with pneumatic vibration isolation system.

The substrate for patterning is fixed on faceplate of a precision air-bearing spindle. The high accuracy rotary encoder is mounted on the spindle axis. The rotary optical encoder forms signals (SYNC – incremental signals and FSYNC – reference mark signal at beginning of revolution or frame sync) for rotation controller stabilizing rotation speed. Motion controller of radial positioning unit has increment less than 1 nm and allows us to get 20 nm rms accuracy. Writing is carried out by step-by-step movement a writing head along radial direction at 600-700 rpm rotation speed of the spindle. Radial step between adjacent circular tracks is normaly set in range of 0.25-0.5 μm. Laser radiation is modulated by acousto-optic modulators and enters to the focusing objective through the optical system mounted on the motorized precision air-bearing stage. The objective forms a spot on the substrate surface. The spot diameter is about 0.6 μm (FWHM). Autofocus control system maintaining the constant size of light spot consists of an electromagnetic actuator with a focusing objective and a defocus sensor (AF) with a diode laser (780 nm) and bi-cell photo detector. The focused spots of a diode and writing lasers are separated by about 50 μm in the radial direction. The separation allows the AF system to avoid an error caused by recording film surface deformation or damage at thermal action of writing laser beam.

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The objective focusing the writing laser beam is used also in an optical scheme for visual control of the substrate surface and the AF adjustment. Electromagnetic deflector (EMD) permits to deflect the writing beam in radial direction by angle of up to ±0.5'. It is needed for compensating a spindle runout, measured previously[3]. Processed runout function is loaded to pattern generator of EMD control unit at the beginning of writing process. The pattern generator forms compensating signal for EMD synchronously with spindle rotation. Electromagnetic shutter (EMS) prevents parasitic exposure of recording film during temporary breaks in writing process.

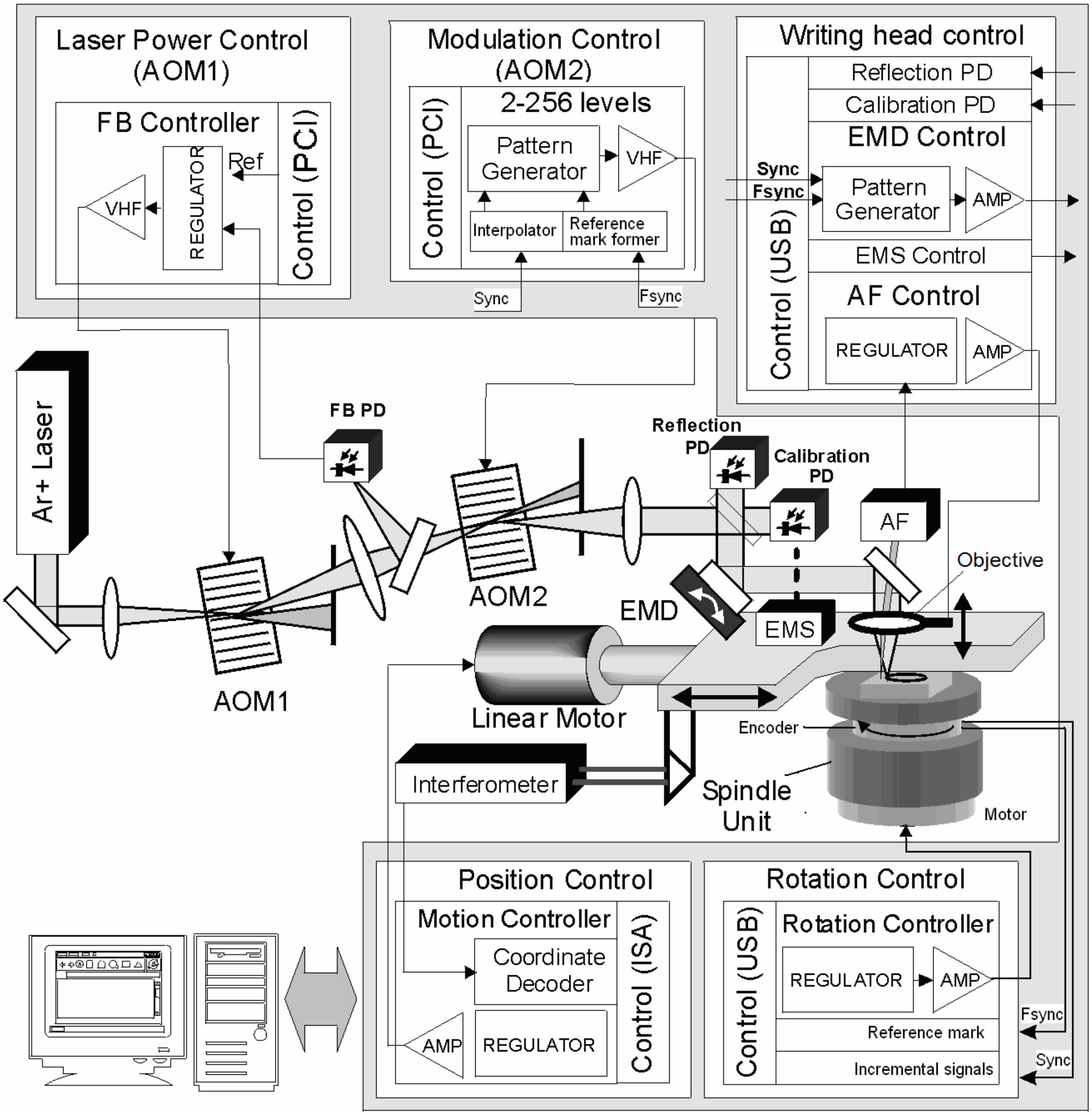

Fig. 1. Schematic layout of the circular laser writing system.

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Accurate writing beam power control is critical point for direct laser writing of continuous relief DOEs on photoresist[4] and gray-scale masks[5]. To ensure high modulation range, long-term stability, and reduce intensity noise we realized optical channel with two modulators. First of them is controlled by feedback circuit using signal from photodetector (FB PD). AOM1 is used for power stabilization and power attenuation (12 bits) depending on radial position. Second AOM is intended for high-speed binary and analog modulation synchronized with interpolated signals from angular encoder. Accuracy of this synchronizing is 1 arc.sec (rms). AOM2 has no permanent feedback loop, but its transfer function is calibrated before writing by using a signal from calibration photodetector (Calibration PD) installed on linear air-bearing stage. Table 1 specifies main parameters of circular laser writing system developed at IAE.

Table 1. Performance and Specifications of the laser writing system.

Maximum diameter of the writing field	280 mm
Substrate thickness	1.5–30 mm
Recording spot diameter	0.6 μm
Spindle rotation speed	300–800 rpm
Accuracy of radial coordinate positioning (rms)	20 nm
Accuracy of angular coordinate measurement (rms)	~1 arc sec
Recording wavelength	457–514-nm, Ar laser
Pattern generator dimensions/Weight	1.5 x 1 x 1.4 m^3/1.2t

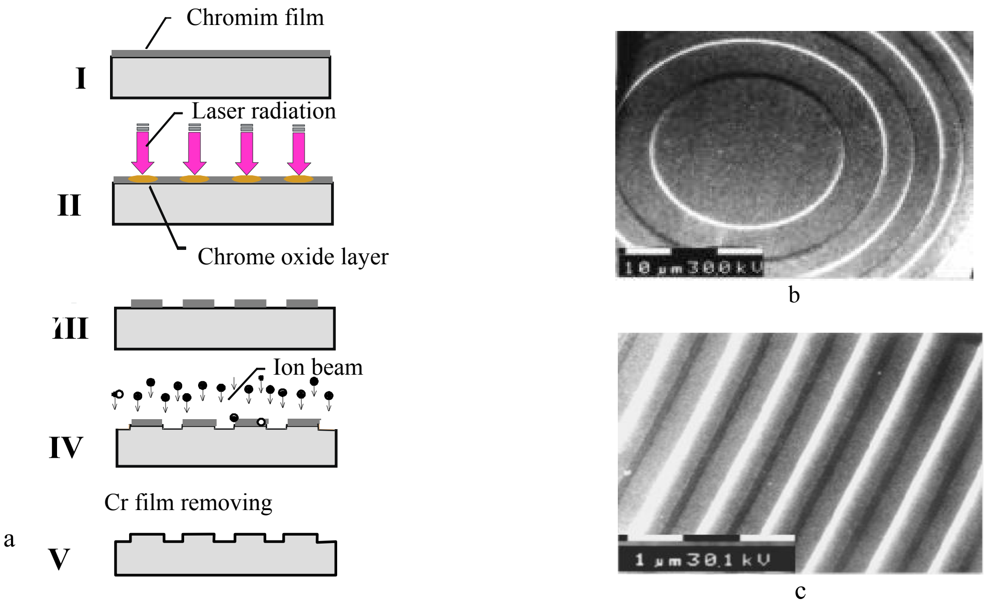


Fig. 2. Methods for fabrication of binary (a) and continuous relief (b) DOEs and typical examples (c, d) of DOE surface.

3. METHODS OF CGH FABRICATION

The CLWS allows us to fabricate CGHs with binary or continuous-relief microstructure onto large-diameter and thick optical substrates. The CGH patterns can be created using an exposure of photoresists and also a direct writing method based on thermochemical effect of laser heating on chromium films[6] as shown in Fig. 2a. Laser heating of chromium film causes build-up of a thin oxide layer (stage I in Fig. 2a). After it is exposed, immersing the substrate in a caustic bath develops the pattern (stage III). The bare chromium is dissolved much more quickly than the chromium oxide. After the development process, a pattern of chromium remains where the laser beam had exposed the surface and created the oxide layer. Chromium film can be easily deposited to curved surface. It allows writing diffractive structures on concave/convex surfaces. Ion etching is used for fabrication of phase binary CGHs (Stage IV). This thermochemical effect allows the direct generation of patterns with spatial resolution better than 1000 mm^{-1} onto bare chromium films (Fig. 2 b,c). The dynamics of the laser writing is chosen to build up enough oxide where the laser had scanned with minimal thermal broadening. This method permits the direct formation of chromium patterns with spatial resolution better than 1000 mm^{-1} without resist.

4. SPECIFIC SOURCES OF CLWS ERRORS.

The writing process introduces errors in CGH structure[7, 8]. These errors have two components: the difference between the calculated and real coordinates of diffractive zones in CGH, and the difference in shape between the calculated and actually fabricated zones.

The absolute error of the coordinate depends on the accuracy of writing beam displacement with respect to the substrate. Coordinate error results in an additional phase shift of the wavefront of the light flux transmitted through the fabricated CGH. The phase shift is similar to the phase shift caused by disturbance of the periodicity of grooves in a usual diffractive grating and leading to the appearance of parasitic diffraction orders. The phase shift (in fractions of light wavelength λ) can be defined as [6]:

$$\Delta W(x,y) = -m\lambda\varepsilon(x,y)/S(x,y), \quad (1)$$

where m is the diffraction order; S(x,y) is the local center-to-center ruled fringe spacing; $\varepsilon(x,y)$ is CGH position error in direction perpendicular to CGH ruled fringes. From this equation follows that the knowledge of local CGH position error ε for whole aperture permits to certificate writing process. The problem of defining ε becomes one-dimensional for rotationally symmetric CGH written by circular laser writer. In a case if CGH position error is defined as $\varepsilon_i = r' - r$, where r and r′ are calculated and written radial coordinates of ruled fringe center.

The different writing errors of CLWS were investigated. Some results are presented in Table 2.

Table 2. Sources of CLWS errors.

Error type	Methods for error reduction
The error of fixing the origin of coordinates	Accurate search of rotation axis
Drift of the origin of coordinates during writing	Periodical correction, prediction of CGH distortion
Error of circular shape of zones because of spindle runout	Real-time correction, prediction of CGH distortion
Errors of absolute radial coordinate of writing spot	System calibration, correction
Angular coordinate error	System calibration, correction

Writing strategy for non-axial-symmetric CGHs is very similar to typical step-by-step writing strategy for x-y writers. More interesting challenge is to get maximal fabrication accuracy for axial-symmetric CGHs having wide application at the aspheric optics testing. Fig. 3 depicts writing strategy for axial-symmetric CGHs realized circular CLWS at IA&E SB RAS. It is based on several principles:

- accurate formation of zone boundaries;
- multiple passes for narrow zones (not less than 3, Fig. 3 a,b)
- addition of new tracks required for increasing of zone width in center of the zone (Fig. 3 c)

Table 3 presents some peculiarities of such writing process. The offered algorithm results in an increasing the writing accuracy but also in an increase of writing time of axial-symmetric DOEs.

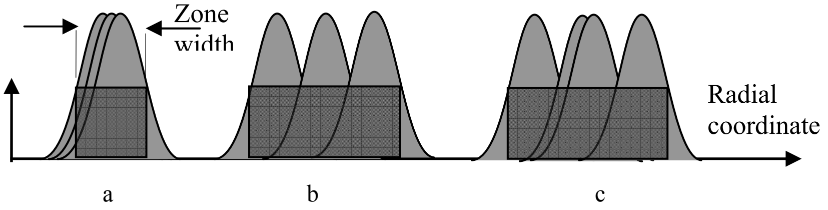


Fig.3. Writing strategy for axial-symmetric CGH.

Table 3. Methods of writing.

Method	Expected result
Circular step-by-step scanning	Less discretization error in comparison to elliptical trajectories
Multiple passes at writing of narrow diffractive zones	Uniform zone width change
Symmetric filling-in of the zones	Uniform zone width change
Scattering of the start points of circular trajectories in given angular sector	Angular uniformity of the pattern

5. CERTIFICATION OF CGH.

Since the aspheric surfaces are fabricated using the results of the test, the null CGHs define the shapes of the final optics. But there is always a possibility that the null CGH could be flawed, resulting in final shape of the optics being incorrect. Problem is that the aspheric wavefront generating by CGH cannot be tested by standard methods. Several methods of indirect CGH certification have been developed [9, 10] and used in IA&E:

- Preliminary calibration of CLWS and systematic inaccuracy compensation.
- Periodical correction of CLWS errors during writing process.
- Measurement and recording current errors of CLWS during writing and then using data to calibrate optical systems with CGH.
- Embedding special fiducial reference marks and zones in CGH.
- Writing the test zone plates and their testing before fabrication of CGH to check current state of the CLWS.
- Sub-aperture combining a test zone plate and the CGH on one substrate.
- Fabrication diffractive imitator of the tested surface.

6. BINARY PHASE CGH FOR OPTICAL TESTING

As an example of fabrication of complex diffractive structure with binary profile we present the CGH for aspheric figure metrology[11]. The idea of method was to enlarge the Fizeau area to last face of CGH (Fig.4). Then substrate will be in common path area and its inhomogeneity and surface imperfectness will be compensated. This method seriously increase precision of interferometric measurements, while elimination of substrate errors, which are the main limitation for precision asphere testing. For application of this method there is need of combined CGH that generates simultaneously test and reference wavefronts. This combined CGH was realized as combination of amplitude and phase diffractive microstructures.

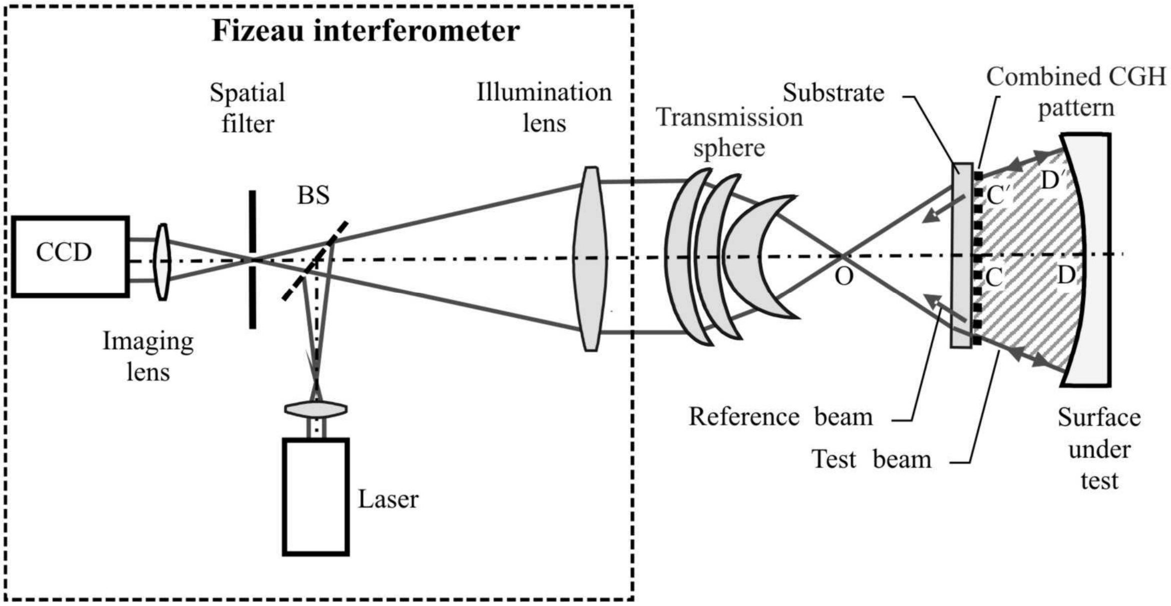
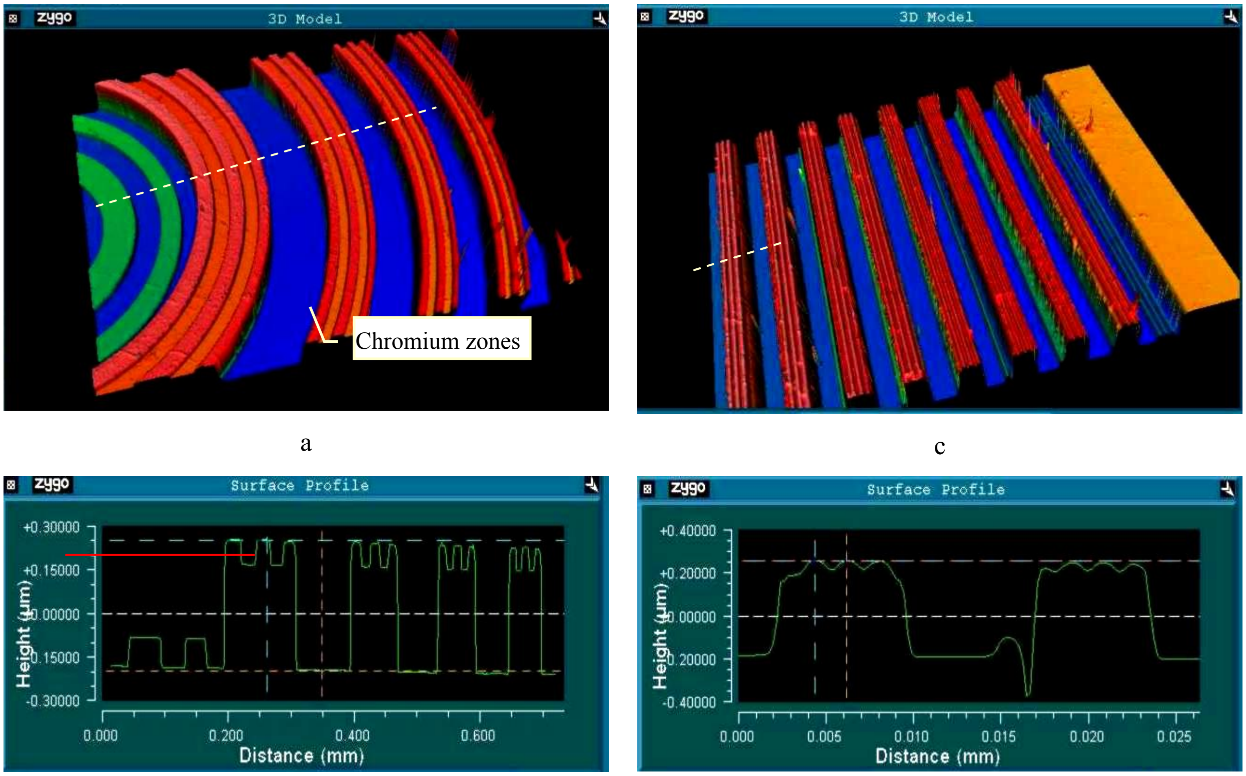


Fig.4. Layout of asphere testing with combined CGH

The diffractive structure for test wavefront is of low spatial frequency as optical power of surface under test can be compensated with transmission sphere (TS). From the other hand the structure for reference wavefront is of high spatial frequency while it operates in reflection and has doubled optical power of TS. Phase diffractive structure was fabricated by dry ion etching. That erodes bottoms of phase microstructure and only tops of phase microstructure are perfect. So, we produce amplitude microstructure generating reference wavefront only on tops.

This method has been experimentally examined by testing a reference spherical mirror. This mirror under test with f/0.65 (standard RS from Zygo interferometer toolkit) was measured independently and its quality was defined as PV=0.05λ, rms=0.005 λ. Before fabrication of CGH microstructure fused silica substrate with diameter of 60 mm, 8.06 mm thickness and about 1 arc sec wedge was also tested by interferometer and its flatness (side with CGH) was PV=0.05λ, rms=0.01 λ and TWD was PV=0.25 λ, rms=0.1 λ because of second surface of substrate was poor.

The combined CGH consists of two independent axially symmetric diffractive elements: One component of the CGH is generating a spherical wave (reference beam) at reflection, while the other component (null CGH) is generating a test aspherical wavefront (test beam) in transmission. The phase function of the null CGH component is derived by use of a geometrical model of rays normal to the surface under test (aspheric surface). The null CGH phase function is the optical path difference (OPD) between *OC′D′* and OCD as shown in Fig.4. The reference beam function is the OPD between *OC* and *O′C*, as shown in Fig. 4. One can see that substrate TWD is the same parts of the reference and test beams OPD. In such a way, diffractive patterns for phase null CGH (1^{st} order of diffraction) and reference amplitude CGH (3^{d} order of diffraction) were calculated.



a c

b d

Fig.5. 3D images (a, c) and plots (b, d) of the central part and periphery of the fabricated combined CGH. Zygo NewView 6000 microscope, objectives 20x (a,b) and 50x (c,d) Mirau.

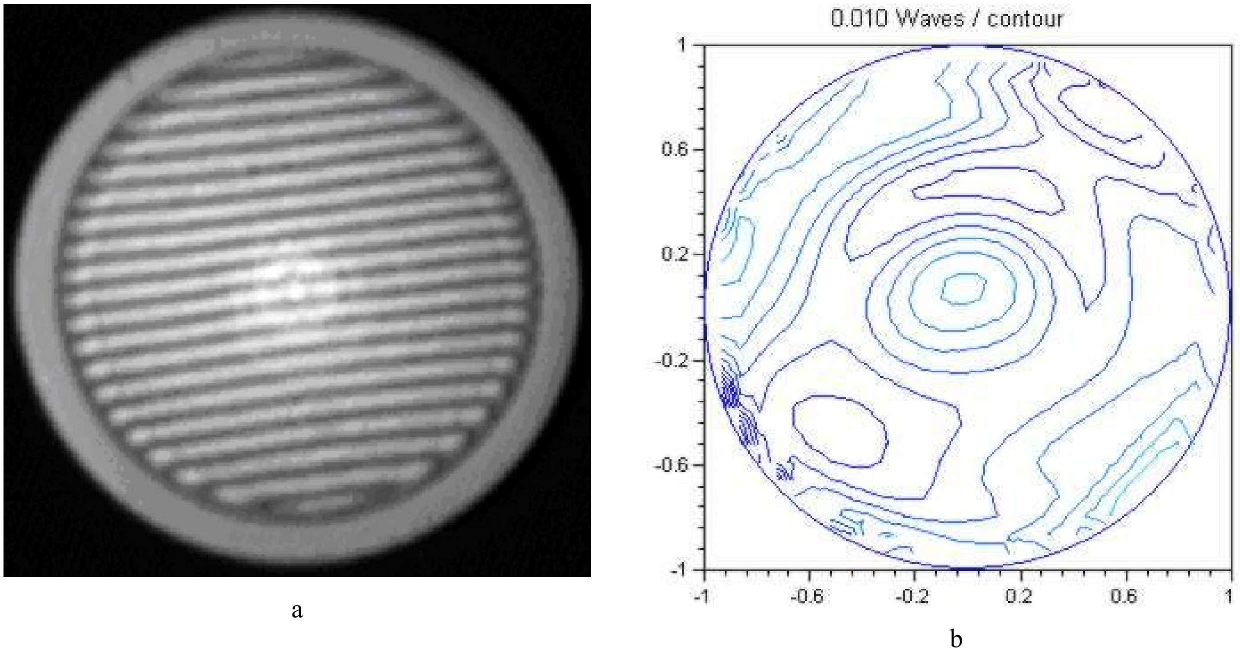
The combined CGH was fabricated by using the circular laser writing system, built by the Institute of Automation and Electrometry in Novosibirsk, Russia[1]. The combined CGH (phase-amplitude) has been processed in the following way. A chromium layer (about 80 nm thickness) was deposited onto the high-quality surface of substrate and then was structured using a resistless technology by direct laser writing. Chromium film after exposure was developed in selective developer. This amplitude pattern was transferred into the fused silica substrate by ion etching in order to get appropriate phase relief. After etching, protective chromium film was removed from substrate surface, excepting areas of reference amplitude hologram.

Fig. 5 shows images of the central area (a) and outer zones (c) of the fabricated combined CGH after ion etching and after removal of the chromium layer from the phase CGH zones. Images were taken with a NewView 6000 white-light interferometric microscope and processed in a three-dimensional (3D) representation. Plots (phase profiles) of corresponding areas are shown in Fig. 5b, d. One can see that fabricated CGH looks like as two-level structure. Axial-symmetric chromium zones with about 80 nm thickness are superimposed on the top of axial-symmetric phase zones with about 400nm thickness. Every phase zone contains 2-4 chromium zones which reflect back and diffract light formed reference beam. Hence, an amplitude-phase CGH has been fabricated with approximately 30% diffraction efficiency into the first order of diffraction for test beam and 1% efficiency in reflection into the third order of diffraction for reference beam.

Axial-symmetrical design of combined CGH allows to increase of accuracy of wavefront formation. The wavefront error produced by the CGH pattern is given by (1). Thus, with m=1, S_{min}=15 µm, ε=0.1µm (see Fig.5d) the maximum fabrication error of the test wavefront of the fabricated CGH is about 0.006 λ (PV), and the error of the reference wavefront is about 0.05 λ (PV).

Reference spherical mirror was tested with fabricated experimental DFNL by Fizeau interferometer with f/0.65 TS. To eliminate influence of reflected light beam, TS was slightly tilted. In that way TS was used as a focusing objective only.

A typical interferogram produced by testing a *f* /0.68 spherical reference mirror is shown in Fig.6a. A plot of the phase map is shown in Fig. 6b.The intensity distribution of the reference beam shows very good uniformity, and the contrast of the fringes is good enough. Measured wavefront errors were 0.13 λ (PV) and 0.014 λ (rms). That is in two times less than TWD of used substrate. Hence, we can conclude that substrate inhomogeneity does not affect measurement results.



a

b

Fig.6. Interferogram (a) and phase map(b) of a reference spherical mirror with *f* /0.68, measured with the combined CGH null: RMS = 0.014, Peak-Valley = 0.13.

CONCLUSIONS

The present paper has reviewed some techniques and equipment for the fabrication of binary and continuous-relief DOEs developed at IA&E SB RAS during last years. We demonstrated the laser writing systems with circular scanning are a highly universal tool for fabrication of computer-generated holograms for optical testing. They have several important advantages over traditional x-y writing systems:

- high writing speed due to continuous scanning on angular co-ordinate,
- reduction of noise introduced into diffracted wavefront by quantization in traditional x-y systems,
- reduction the number of writing data for circular zone plates fabrication,
- possibility of multiplication of images along angular coordinate.

Some from the large number of CGHs fabricated with CLWS were presented and excellent quality was demonstrated.

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