Testing optical surfaces by high precision diffractive Null lenses with integrated reference surface

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ABSTRACT

Fizeau interferometers with an additional diffractive optical element are frequently used for measuring spherical and aspherical surfaces. We present a new design, were the Fizeau principle is now perfectly fulfilled, by generating reference and measuring wavefront on the last optical surface, carrying a diffractive optical element. Several advantages of this design are discussed and proved experimentally.

Keywords: *Optical testing, interferometry, Fizeau interferometer, computer-generated holograms, diffractive elements, asphere.*

1. INTRODUCTION

Diffractive optical elements (DOEs) or computer-generated holograms (CGHs) are very powerful instruments for interferometric measurements of aspherical surfaces because they can transform an incoming wavefront into nearly any arbitrary numerically or mathematically defined shape. Such CGHs, which consist of patterns of lines or rings, are now easy manufactured using equipment from the microelectronics industry or precision task-oriented circular laser writing systems optimized for CGH fabrication [1]. The precision of the CGH fabrication affects the accuracy and validation of measured results. Errors and uncertainties during the CGH fabrication processes however, result in errors in the diffracted wavefront created by the hologram. When using the final hologram for optical testing, the precision of the measurement will be affected consequently. The accuracy of the hologram structure fabrication by means of present-day equipment reaches several nanometers that allows to form steep enough wave fronts with an peak-to-valley error of PV ~l/20 waves and even less [2]. The certification of the writing process of the CGH fabrication, which can reveal random errors of the writing process, had been demonstrated [3]. The application of these innovations has allowed to create precision CGHs for interferometric measurements of large aspherical optics e.g. 6.5-m *f*/1.25 and 8.4-m f/1.14 paraboloidal primary mirrors [4]. In the last years new types of diffractive elements, such as combined (or split, cellular, multiplexed, dual-wave e.g.) CGHs [5], which represent the alternate encoding of two or more wavefronts on the CGH aperture split into regular strips or rings, had been presented. Such CGHs can transform one input wavefront into several independent output wavefronts. These new kind of elements were widely investigated for testing optical surfaces and certification of wave fronts generated by the CGHs [5, 6, 7]. However these diffractive elements also have properties of wavefronts splitting and can be used as the basic component of the interferometer – a beam splitter of the measuring and reference beam.

This paper presents a new design, were the principle of a Fizeau interferometer is now perfectly fulfilled, by generating reference and measuring wavefront on the last optical surface, carrying a diffractive optical element. Several advantages of this design are discussed. We present a simple and general method of aspheric figure metrology using a combined CGH placed in the output beam of a conventional Fizeau interferometer. This method has been examined experimentally by testing a reference *f*/0.68 spherical mirror. The experimental results we obtained by the proposed method agree well with those obtained by using a Fizeau interferometer with a standard transmission sphere.

2. OPTICAL TESTING WITH CGH

Interferometers operate by generating two laser beams, one as a reference and one as a test beam. The test beam interacts with the optics under test, the reference beam is reflected by a reference surface. Test and reference beams overlay each other inside the interferometer in the plane of CCD camera. Usually the reference surfaces are flat or spherical, hence only spherical and plane surfaces can be measured.

For testing aspherical surfaces, an additional CGH is usually introduced in the test arm, acting as a Null lens. The CGH Null operates in double path, first producing an aspheric test wavefront and then recollimating the reflected wavefront from the surface under test. This technique is used for measuring aspheres with existing Fizeau interferometers [8]. A common configuration for using a CGH for optical testing with a Fizeau interferometer is shown in Fig.1.

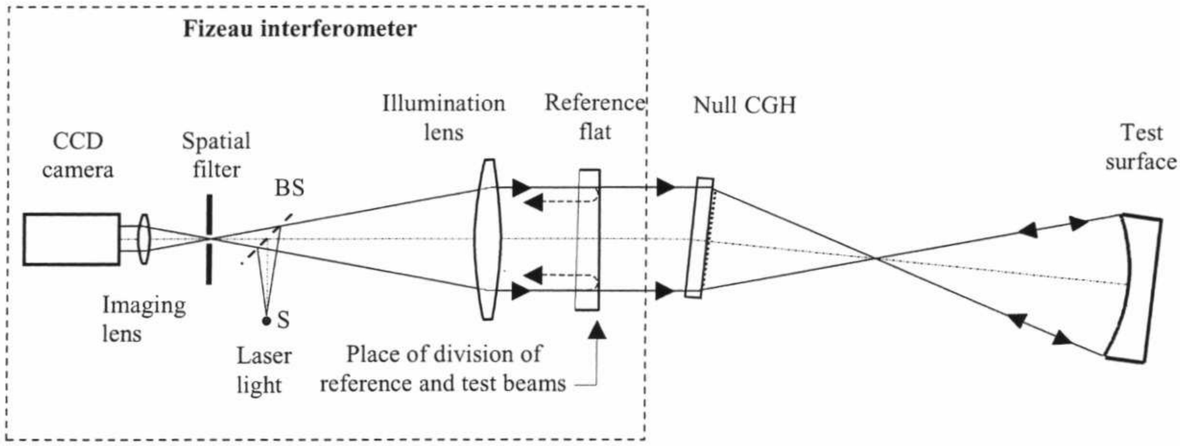


Fig.1 Configuration for CGH Null test of asphere with Fizeau interferometer.

In this configuration on-axis or off-axis CGH Nulls can be used . If the interferometer operates with a plane output wavefront , the CGH Null is usually tilted by a small angle (less then 1 degree) with respect to the optical axis, so that the various diffraction orders will be separated. The tilt of the CGH Null is necessary in order to eliminate the direct reflection (zero-order) from the CGH surface as well.

This interferometer measures the combination of the CGH Null *and* the asphere, so the accuracy of the test depends on the quality of the CGH Null. In the presented case, the major source of error is the surface of the reference flat of the Fizeau interferometer and the *transmitted wavefront distortion* (TWD) of the CGH substrate [8, 9]. In practice, the TWD of the CGH substrate limits the measuring precision of this type of interferometric measurement. Typical CGH substrate errors show low spatial frequencies, and these surface figure errors are responsible for the low spatial frequency wavefront aberrations in the diffracted wavefront [9]. One method of eliminating the substrate error is to measure its flatness before. The CGH substrate errors can be measured using the zero-order diffraction beam. However, the zero-order diffracted wavefront is extremely sensitive to duty-cycle variations of the phase CGH pattern [9]. This phase error overwhelms the effect of the CGH substrate error in the zero diffraction order and prohibits the substrate figure measurement. Thus the direct elimination of the TWD of the CGH substrate leads to significantly improved measurement accuracy.

3. DESIGN CONCEPT

Our basic idea of increasing the accuracy of the interferometric measurement consists in the elimination of the influence of the CGH substrate figure error. For this purpose we propose to use an off-axis combined CGH, which is situated on the external plane of the substrate, in relation to interferometer, as shown in a Fig. 2. The combined CGH consists of two independent CGHs: One part of the hologram is generating a plane wave (reference beam) and one other part (Null CGH) a test wavefront (test beam). In this case, both test and reference wavefronts are formed by means of diffraction and by one single CGH. This CGH can be composed of e.g. a linear grating and a Null CGH. The formation of a combined CGH is shown in Fig. 3. The first component (Fig.3a) is built as a phase CGH in order to achieve a maximum of diffraction efficiency . The second component (Fig. 3b) is a reflective grating. The combination of these two elements leads to an amplitude-phase CGH (Fig. 3c).

This test method is a *hybrid* of the two optical measurement methods, Fizeau test plate interferometry and the use of Computer Generated Holograms. The accuracy of the test is limited only by the quality of a single flat optical surface and the accuracy of the CGH structure location. Both can be produced with high accuracy. This method is close to the CGH test plate technique developed by J. Burge and D. Anderson [10].

The test wavefront (I_2) passes the Null CGH twice in the 1st order of diffraction. The reference wavefront (I_1) is generated by diffraction (in reflection) on the linear grating with the spacing $S_{grat}=\lambda/2\varphi$, where φ is the angle of inclination of the CGH substrate (Littrow angle). The CGH is designed to diffract this reference beam to match an ideal test wavefront. The combined CGH should be designed in a way, that its diffraction orders are spatially separated in the plane of pinhole (spatial filter). If θ is the full angular size of the pinhole, the spacing S, defining the period of alternation of CGH 1 and CGH 2, is derived by $S < \lambda/\theta$.

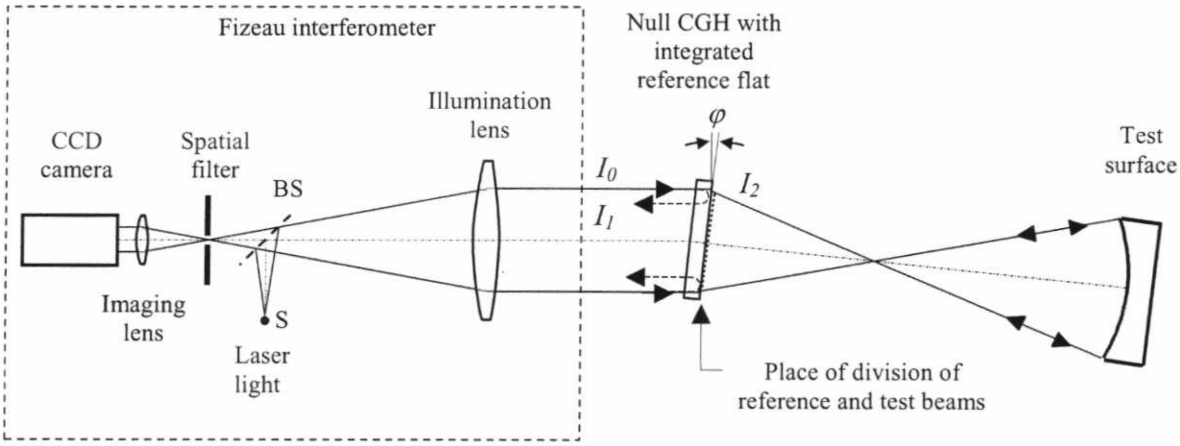


Fig.2 Layout for measuring aspheres with a Null CGH with integrated reference flat.

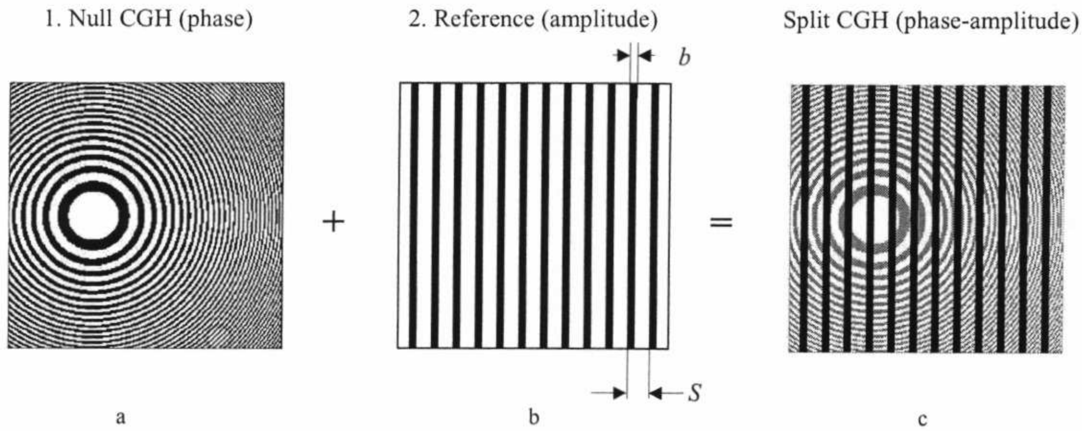


Fig.3 Formation of the combined CGH Null:

The duty cycle of the linear grating is defined on base of the parity condition for the intensities of the test and reference beam. The intensity of the diffracted reference beam is defined by the diffraction amplitude of the linear grating:

$$I_1 = I_0 \rho_{grat} D^2 sinc(mD)^2 ,$$

where ρ_{grat} is the reflectance of the linear grating material, m the diffraction order, and D is the grating duty-cycle defined by $D = b/S$. The intensity of the test beam (after double pass through the CGH) is defined by the zero order diffraction efficiency [11]:

$$I_2 = I_0 \eta_1^2 \rho_{test} D^4,$$

where η_1 is the diffractive efficiency of CGH 1 (Null CGH) in +1st order and ρ_{test} is the reflectance of the surface under test. The relative intensities of the test- and reference beam as a function of the duty-cycle of the linear grating are shown in Fig. 4, based on the parameters η_1=0.4, η_2=0.1, R=0.8 and ρ_{test}=0.4 (curve 1), ρ_{test}=0.1 (curve 2), ρ_{test}=0.05 (curve 3). For these given values the optimal duty-cycle is D=0.16. In this case the light transmission of test and reference arms of the interferometer is about $I_2/I_0 = I_1/I_0 = 1\%$. One can see that by changing the duty cycle of the grating, it is possible to reach an optimal contrast of the final interferogram for a variety of materials with different reflectance (e.g. glass, silicon, germanium, metallic mirrors, optical ceramics etc.).

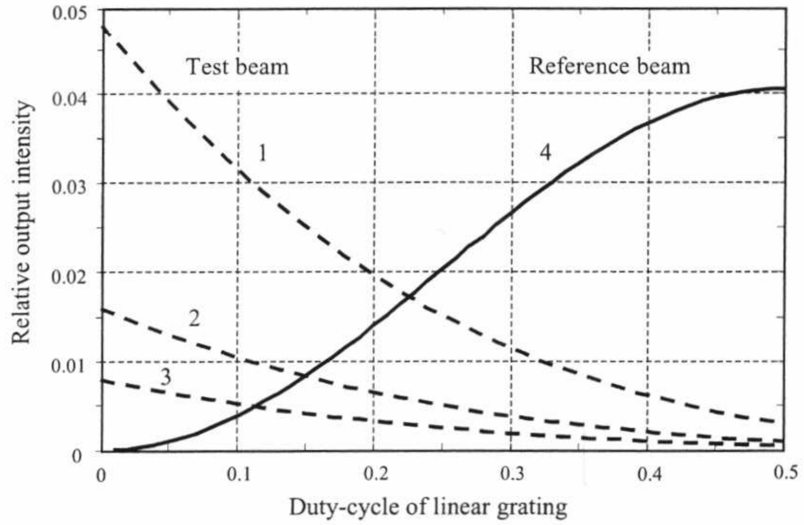


Fig.4 Relative output intensities of the test beam (curves 1,2,3) and reference beam (4) as a function of the duty cycle of the linear grating. The reflectance of the tested surface is ρ_{test}=40% (1), ρ_{test}=10% (2), ρ_{test}=5% (3).

4. CGH FABRICATION PROCESS AND EXPERIMENTAL RESULTS

The aim of the experiments was the verification of the proposed CGH design. The test was performed using a Phase Shifting Fizeau type interferometer (Zygo GPI). The CGH has been designed and fabricated with the following parameters: Diameter D=50mm, focal length f=150mm, tilt angle φ=0.25° degrees. As a surface under test we used a standard reference sphere *f*/0.68 (from Mark IV toolkit).

4.1 CGH FABRICATION

The CGH has been written using the circular laser writing system (CLWS), built at the Institute of Automation and Electrometry in Novosibirsk, Russia [12]. The CLWS is capable of writing 250-mm diameter holograms with an absolute accuracy of 100 nm across the full diameter. The machine rotates the substrate with 600-800 rpm and uses an interfereometrically controlled linear air bearing writing head, with a positioning precision of several ~1 nm. This machine also writes arbitrary patterns that do not have circular symmetry using a coordinate transformation software and a high quality angular encoder with an rapid writing beam switching. The hologram is written with a resistless technology by direct writing in chromium films [2].

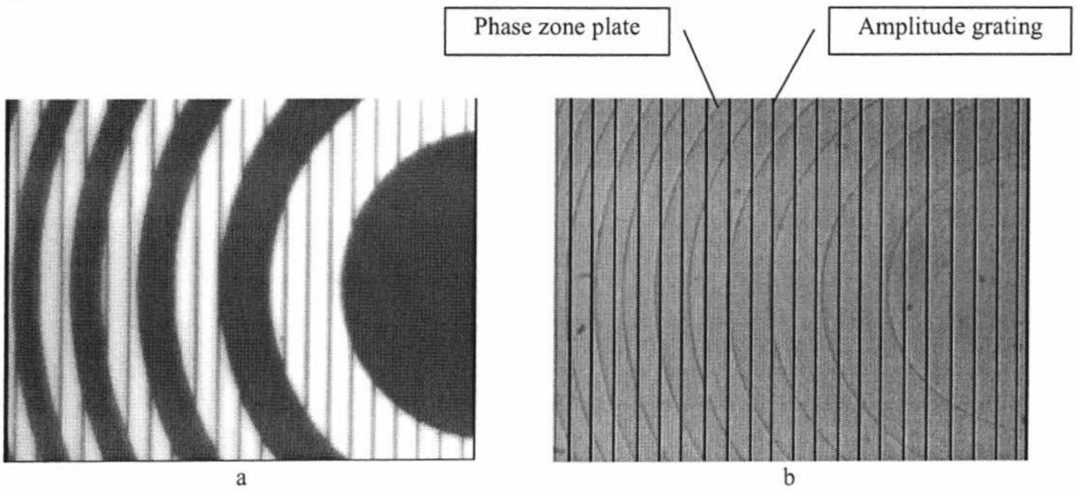


Fig.5 Central part of chromium mask (a) fabricated by CLWS and amplitude-phase CGH (b)

The CGH had been fabricated on a 60mm fused silica substrate with a surface quality of 1/20 wave peak-to-valley (P-V). The second surface has about 1-2 wave P-V quality. The substrate wedge is about 4-5 minutes. A chromium layer has been deposited onto the high quality surface. Fig. 5a shows a photograph of the chromium pattern of the CGH Null, fabricated by direct writing with the CLWS. The linear grating has about D=72 μm spacing and b=18 μm line width.

The CGH-Null-part formed in chrome on glass diffracts approximately 10 percent into the first order in transmission, and the linear grating diffracts 1 percent into the first order in reflection. This CGH can be used for testing surfaces with high reflectivity.

Fig. 5b shows a photograph of the same part of the final CGH after ion etching and after removing the chromium layer from the phase CGH area. Hence, an combined amplitude-phase CGH has been fabricated with approximately 40 percent diffraction efficiency into the first order of diffraction and 1 percent efficiency in reflection. This CGH can be used for testing surfaces with low reflectivity.

4.2 CHARACTERIZATION OF THE CGH NULL.

To prove the feasibility of the concept, the fabricated CGH Null was mounted into a standard Zygo type bayonet housing and was fixed at place of the transmission sphere in an Zygo GPI interferometer (Fig. 6a). The optical test layout was chosen according to Fig. 2. As a first step, the alignment procedure (tilt of CGH at 0.25 degree) was made. Fig. 6b shows the "view" mode of the alignment pattern. One can see several orders of diffraction, caused by the linear grating of the CGH.

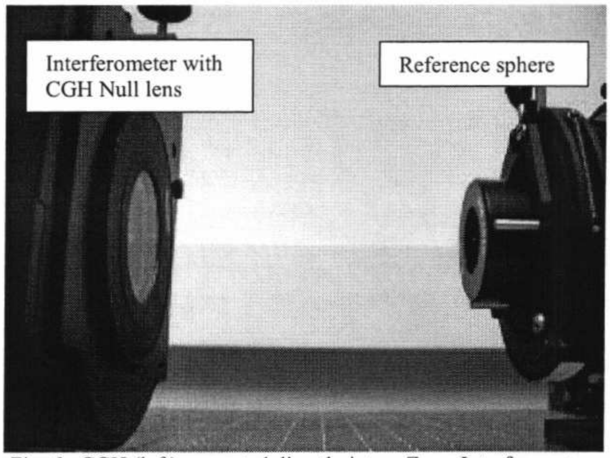


Fig. 6a CGH (left), mounted directly into a Zygo-Interferometer, and lens surface under test (reference sphere at the right)

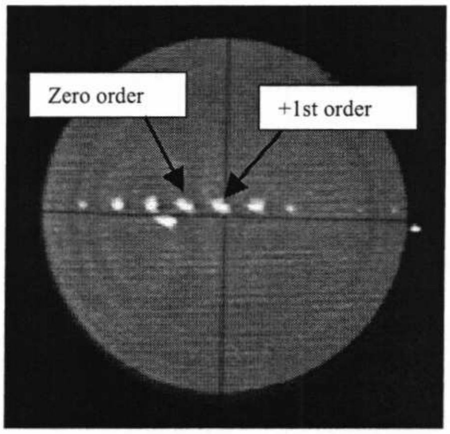
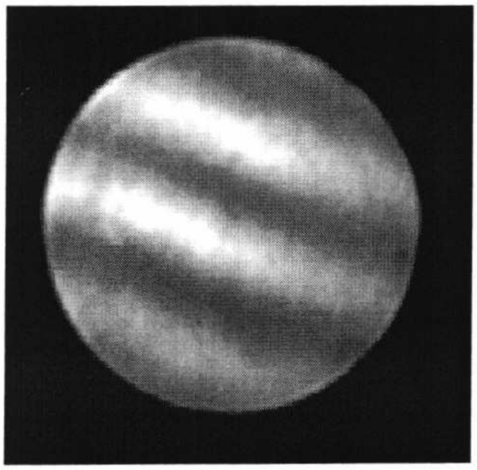
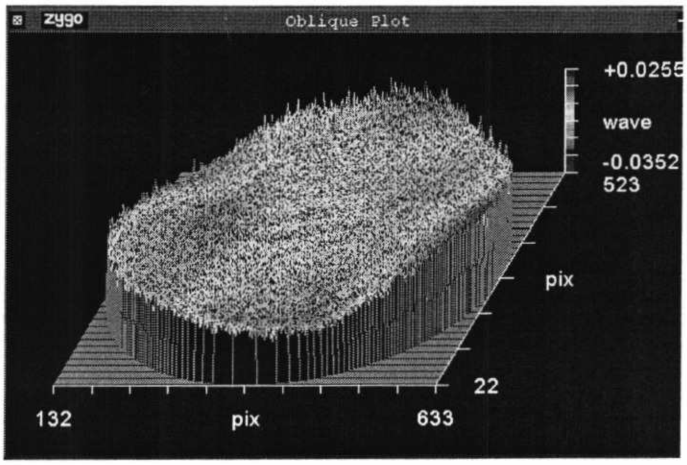


Fig. 6b Alignment pattern with CGH Null



a



b

Fig.7 Interferogram (a) and phase map (b) of a reference spherical mirror f/0.68, measured with the CGH Null.

The 1st order of diffraction indicated in Fig. 6b has to be aligned into the center of the crosshair. The process of alignment of this kind of CGH Null is comparable with the well-known procedure, when aligning commonly used refractive reference lenses or transmissions spheres.

A typical interferogram of testing a *f*/0.68 spherical reference mirror is shown in Fig.7a. The intensity distribution of the reference beam has shown a very good uniformity and the contrast of the fringes was good enough. A 3D plot of the reconstructed phase map is shown in Fig.7b. The resulting precision of the measurement is P-V = 0.06 waves and rms = 0.01 waves.

5. CONCLUSIONS

A hybrid optical measurement method had been developed, were a Fizeau test plate interferometry is combined with the use of a Computer Generated Hologram. This method enables the extreme challenges for high precision measurements of aspherical optics. The technique can be used with standard commercial interferometers. The CGH test plate can be used to measure any sphere or asphere with convex or concave shape.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

1. A.G. Poleshchuk, E.G. Churin, V.P. Koronkevich, V. P. Korolkov, etc., "Polar coordinate laser pattern generator for fabrication of diffractive optical elements with arbitrary structure" Appl. Opt., **38**, 1295-1301(1999).
2. V. V. Cherkashin, E. G. Churin, V. P. Korolkov, V. P. Kooronkevich, A. A. Kharissov, A. G. Poleshchuk, J. H. Burge. "Processing parameters optimization for thermochemical writing of DOEs on chromium films," Proc. SPIE. **3010,** 168-179, (1997)..
3. A. G. Poleshchuk, V.P. Korolkov, V.V. Cherkashin J. Burge, "Methods for certification of CGH fabrication," OSA Trends in Optics and Photonics (TOPS), OSA Topical Meeting DOMO-02, June 3-6, 2002, Tucson, USA, **75** , 438-440 (2002).
4. J. H. Burge, L. R. Dettmann, S. C. West. "Null correctors for 6.5-m *f*/1.25 paraboloidal mirrors," OSA Trends in Optics and Photonics (TOPS), OSA Topical Meeting Fabrication and Testing of Aspheres . **24**, 182-186, (1999)
5. A. G. Poleshchuk, J.H. Burge, E.G. Churin. "Design and application of CGHs for simultaneous generation several specified wavefronts," EOS Topical Meeting Digest Series (DOE-1999, Jena, Germany, August 23-25, 1999), **22**, 155-156, (1999).
6. M. Beyerlein, N. Lindlein, J. Schwider. "Dual-wave-front computer –generated holograms for quasi-absolute testing of aspherics," Appl. Opt. **41**, 2440-2447, (2002).
7. Reichelt and H.J.Tiziani: Twin-CGHs for absolute calibration in wavefront testing interferometry, Optics Communications, Vol. 220, p. 23-32, 2003
8. S.M. Arnold, L.C. Maxey, J.E. Rogers, R.C. Yoder. "Figure metrology of deep aspherics using a conventional interferometer with CGH Null," Proc. SPIE **2536**, 106-116, (1996).
9. Yu-C. Chang and J. Burge. "Error analysis for CGH optical testing," Proc. SPIE **3782**, 358-366 (1999).
10. J.H. Burge, D.S. Anderson. "full aperture interferometric test of convex secondary mirrors using holographic test plates," Proc. SPIE **2199**, 181-192 (1994).
11. A.G. Poleshchuk. "Diffractive light attenuators with variable transmission," JOURNAL OF MODERN OPTICS, **45,** 1513-1522, (1998).
12. A.G. Poleshchuk, E.G. Churin, V.P. Koronkevich, V.P. Korolkov et al. "Polar coordinate laser pattern generator for fabrication of diffractive optical elements with arbitrary structure," Appl. Opt., **38**, 1295-1301, 1999.