Mem. S.A.It. Vol. 86, 400

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An adaptive interferometer for optical testing

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Abstract. Interferometry is a well-established technique to test optical elements. However, its use is challenging in the case of free-form and aspheric elements, due to the lack of the reference optics. The proposed idea concerns the development of a versatile interferometer, where its reference arm is equipped with a reprogrammable Computer Generated Hologram. This principle takes advantage from our study on photochromic materials for optical applications, which shows a strong and reversible modulation of transparency in the visible region. The encoding of the desired hologram can be done off-line, or directly into the interferometer, and different patterns may be realized sequentially after the erasing of the previous hologram. We report on the present state of the research and on the future perspectives.

Key words. interferometry, CGH, photochromic materials

1. Introduction

The interferometric null test of aspheric or free-form optics needs a non-standard reference surface, called null corrector, able to adapt the incoming wavefront to the test surface. Null correctors are usually obtained with a train of lenses, but, more recently, amplitude or phase diffractive optics, such as Computer Generated Holograms (CGHs, see Fig. 1) have been proposed. The use of CGHs for performing interferometric optical tests is a visionary idea of J. Wyant (Wyant & Bennett 1972), and in recent years CGHs are finding application also in the field of astronomical instrumentation (Burge 1995; Burge et al. 2008).

In this framework, we showed how to exploit the reversible transmittance modulation of photochromic materials in the visible region to produce amplitude CGHs for the interferometric test of aspheres (Pariani et al. 2011a). Thanks to the reversibility of the photochromic reaction, it is possible to write and erase different patterns on the same substrate according to the requests. Moreover, the hologram is ready to use after the light exposure, without any chemical post-processes. Our research in this field aims to get further inside the possibilities offered by photochromic CGHs, mainly concerning: *i)* an adaptive interferometer, i.e. a Twyman-Green interferometer, by substituting the reference flat mirror with a re-programmable CGH able to generate the desired reference wavefront; furthermore, the writing process may be directly carried out inside the instrument, providing a fully adaptable instrument to test aspheric elements; *ii)* multiplexed CGHs, for performing simultaneous

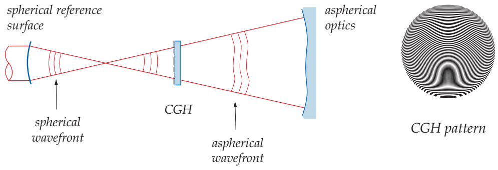

Fig. 1. Scheme of a null interferometric test of an aspherical mirror with a CGH.

and independent interferometric measurements of complex optics (e.g. aspheric segments) at different wavelengths.

2. Photochromic materials

Photochromic materials change reversibly their colour when exposed to light. Our particular interest is devoted to diarylethenes (Irie 2000), which show interesting photochromic properties such as large fatigue resistance (they survive after many switching cycles), good thermal stability and quantum yields. In order to maximise the optical response of the layer, we synthesized a series of different photochromic polymers (polyurethanes), varying the amount and the species of functionalized diarylethenes (Pariani et al. 2011b): depending on the concentration of the photochromic monomer in the formulation, the maximum optical density of the film in the visible region ranges between 0.1 and 5, and, by acting on the chemical structure of the photochromic monomer, the position of the absorption peak is varied between 500 and 700 *nm*. The procedure also allows to conveniently vary the thickness of the coatings between 0.1 and 10 μm. Since the polymerization reaction is carried out in situ, the coatings show good surface quality, bulk homogeneity, and surface flatness, which make them suitable for application in interferometry (Pariani et al. 2011a).

Considering amplitude diffraction elements, their diffraction efficiency is directly linked to the film contrast CT, defined as

$$CT(\lambda) = \frac{T_A(\lambda)}{T_B(\lambda)} \sim 10^{Abs_B}$$

where T_A and T_B are the transmittances of the film in the transparent and opaque forms, respectively (Bianco et al. 2012). Setting a minimum threshold value of $CT = 100$, photochromic polyurethanes provide easily such values thanks to the large change in transparency and high photochromic content.

3. Strategies for CGH production

In a typical route for the production of amplitude patterns, the photochromic coating is converted in the whole volume to the colored form by irradiation with UV light. Then, the layer is patterned upon exposure to visible light, which induces a selective decoloration of the film. We considered two different strategies for the substrate patterning: *i)* a scanning system, by direct laser writing (maskless lithography) and *ii)* a raster system, by mask projection based onto a spatial light modulator. Pattern distortion errors introduced by the writing process cause a wavefront error proportional to the local position error and to the gradient of the encoded phase (Wyant & Bennett 1972). As a general indication, pattern distortion errors of 100 *nm* (well in the range of commercially available machines) and a line spacing of 10 μm result into a wavefront error of $\lambda/100$ for the first diffraction order, which is the standard for commercial reference surfaces. The writing systems described hereafter must guarantee this performances.

3.1. Direct laser writing

In the first approach, the pattern is transferred to the photosensitive layer using a light beam focalized in a diffraction limited spot onto the substrate. The laser power is continuously adjusted while the substrate is scanned in the plane and exposed where necessary. Usually, an autofocus system keeps the substrate in the correct axial position to guarantee the best spot resolution. Our first CGHs were produced with a simple He-Ne laser plotter, developed in house to transfer rotationally symmetric patterns on the photochromic layer. The light wavelength of 632.8 *nm* was chosen to match the sensitivity region of the photochromic material. We hence obtained patterns with good contrast and definition, by carefully adjusting

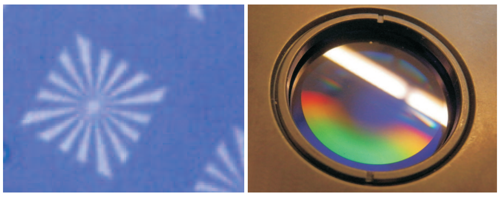

Fig. 2. Resolution test (left) and an f/1.5 Fresnel Zone Plate (right).

the writing speed (1-10 mm/s) and light power (0.5-1 mW) (Pariani et al. 2011a). In order to verify and push at the limit the production of photochromic CGHs, we performed tests with a commercial direct laser machine, in collaboration with the Institut fur Technische Optik of the Universitat Stuttgart (Pariani et al. 2012). A maskless lithography machine in polar coordinates (CLWS300) based on a 514 nm laser (which is at the limit of sensitivity of the photochromic polymer) has been used. The determination of the correct speed rate and light power turned out to be the main issue, since the facility is characterized by high speed rates (hundreds of mm/s) and very high light powers (tens of mW/m^2). Low powers were not able to completely convert the volume of the material, giving a low definition of the pattern, and high powers caused the formation of surface reliefs on the coating. Nevertheless, we produced different patterns (variable gratings with 4.0 to 1.8 μm periods and Fresnel Zone Plates, (see Fig. 2), verifying a very high resolution of the photochromic coating, which was limited only by the writing beam size to 1 μm. The results convinced us on the necessity of a custom direct laser machine for the production of photochromic CGHs, which is now in the design phase at Brera Observatory.

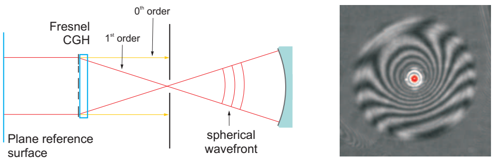

Fig. 3. Scheme of the optical test (left) and recorded fringes (right).

3.2. Mask projection

The second approach consists in the projection of a mask onto the photochromic substrate. This approach is currently under investigation, in collaboration with the Laboratoire d'Astrophysique de Marseille, within the Opticon Project (EU, FP7). In this setup, the photochromic plane is conjugated with an intermediate focal plane, where a Spatial Light Modulator (SLM) is placed: here the illumination light is focalized. The SLM is a device able to control and modulate even the intensity or the phase of a light beam. The image impressed onto the SLM is transferred, through some intermediate optics, to the sample surface. SLMs available on the market show resolutions up to 1920x1200 pixels, with a pixel size of about 8 μm, which means an active area of about 200 mm^2. The large pixel size is the main limitation of the system, forcing the line pitch to 30-50 μm. On the other side, the SLM guarantees a high versatility of the system in terms of patter generation capabilities. Up to now, a 1 to 1 system is under construction, but some demagnification can also be introduced in the process, according to the optics used, to increase the pattern density. In this case, a stitching process shall be foreseen to cover large areas.

4. First results

In order to prove the applicability of photochromic materials to produce amplitude CGHs for the optical metrology, we designed and produced amplitude FZPs, as prototypes of more complex CGHs. In the interferometric test, the photochromic FZP was the optical element under test, compared to the reference spherical surface in a double pass setup. The interference fringes obtained with a 200 mm focal length FZP were well visible, thus indicating that the CGH satisfied the contrast requirement described above (Fig. 3). The overall transmission of the CGH was 36.3% and the contrast 200 at 632.8 nm. The diffraction efficiencies of the zero order and of the first converging order were 30.1% and 9.0% respectively, approaching the theoretical values of

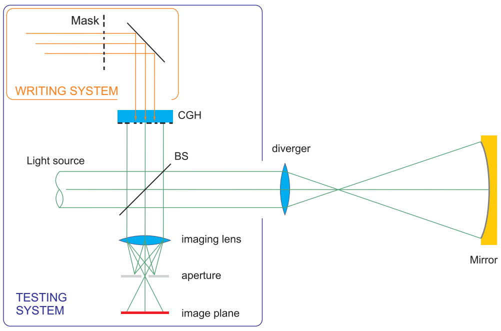

Fig. 4. Scheme of the TGI interferometer, showing both the CGH writing and the testing systems.

25% and 10.1% for amplitude patterns with infinite contrast (Pariani et al. 2011a). Actually, surface flatness errors (not accounted for during the hologram design phase) and pattern distortion errors were introduced in the CGH production, giving an overall accuracy of the element of 3λ PV and $\lambda/2$ RMS.

5. Perspectives

Photochromic CGHs, being binary amplitude holograms, are less efficient than phase holograms. For this reason, the classical double pass Fizeau interferometer can hardly be used. To overcome this limitation, the idea proposed by Burge et al. (Burge 1995) may come into help, i.e., to apply CGHs in single pass in a Twyman-Green Interferometer (TGI). Two are the possibilities for placing the CGH in single pass: *i)* on the reference beam, *ii)* after the two beams recombination. The first possibility may be the best choice in the case of photochromic materials. Actually, the photochromic CGH may be directly obtained on the reference flat mirror, by coating the metal mirror with the photochromic layer. Thanks to the re-writability of photochromic layers, different holograms can be designed, written and erased on the referencee mirror, adapting in any case the reference beam to the test optics. Even more challenging, an all-in-one writing-testing device may be foreseen (see Fig. 4): using a multilayer coated reference mirror to reflect the measurement light and transmit the other visible wavelengths, the hologram may be written from the backside directly in the measuring system. In this way, the interferometer becomes a really versatile and adaptable instrumentation to test aspheric optics, since the reference optics is quickly built on demand directly at the correct place inside the interferometer.

Concerning the feasability of photochromic multiplexed CGHs, we demonstrated photochromic films, bearing two monomers with separated absorption peaks in the visible region, that could be selectively addressed to obtain two independent patterns active at different wavelengths in the visible region (Pariani et al. 2011b). New photochromic monomers are now designed and synthesized, in order to increase the band separation between them. This feature may open to multiplexed photochromic CGHs, for the testing of complex segmented mirrors in two different spectral region simultaneously, with the same optical setup.

Acknowledgements. This work was partly funded by the UE (Opticon-FP7), by INAF (TECNO-INAF 2010) and Progetto Premiale T-REX.

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