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Photochromic point-diffraction inteferometer

Martino Quintavalla [a,b], Giorgio Pariani [a], Giuseppe Crimi [a], Chiara Bertarelli [b], Andrea Bianco [a,*]

[a] INAF-Osservatorio Astronomico di Brera, via Bianchi 46, 23807 Merate, Italy
[b] Politecnico di Milano, Dipartimento di Chimica, Materiali ed Ingegneria Chimica, Piazza L. da Vinci 32, 20133 Milano, Italy

A R T I C L E I N F O

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A B S T R A C T

We demonstrate a versatile and fully adaptable point-diffraction interferometer (PDI) for optical testing which is based on a thin photochromic film. Pinholes are optically written in the photochromic layer, and sizes are easily customized to test optics with a wide range of focal ratios. The transparency of the layer can be tuned to optimize the contrast between the pinhole and the surrounding area and maximize the fringe visibility. Accuracy and repeatability of the photochromic PDI are determined; moreover the results are compared with those obtained with a standard Fizeau interferometer.

1. Introduction

The reversible light-induced change of color of a chemical species, known as photochromism [1], has been exploited for more than 40 years to produce photochromatic lenses, where the optical density is the result of the equilibrium between coloration and fading induced by sunlight absorption and ambient temperature [2]. Accordingly, photochromic layers are tuneable filter, as the color variation turns into a light-induced change in their transmittance in a specific spectral region. This color variation is accompanied by the modification of many physical–chemical properties of the materials [3] which leads to the development of smart light controlled devices, such as rewritable optical memories [4], tuneable masks, amplitude holograms, and volume gratings [3]. Recently, we have used photochromic materials to develop adaptable tools for testing the quality of optical elements, specifically rewritable amplitude Computer Generated Holograms (CGHs) based on the strong modulation of transparency in the visible region of photochromic polyurethane layers [5]. Going forward with this idea, we herein demonstrate a point-diffraction interferometer (PDI) based on thermally irreversible photochromic materials. The PDI, which is a common path interferometer invented by Linnik in 1933 and further developed by Smartt in the 70s [6], has found a widespread use in the optics industry due to its ease of implementation and operation, stability to vibrations and low sensitivity to air turbulence in comparison to other interferometers [7–10]. Such features make the PDI the ideal interferometer for an in situ metrology of even very large optics in hard environments. Moreover, the PDI being a self-referencing interferometer, it does not require an expensive reference surface. This is not the case of the Fizeau interferometer. Basically, the PDI consists of a semi-transparent substrate with a pinhole or an opaque dot, on which the converging test beam is focused (Fig. 1).

If the size of the pinhole is of the order of half the size of the Airy disc, part of the incident light is diffracted and generates a nearly perfect spherical wavefront that acts as the reference beam. The portion of light passing through the semi-transparent surrounding area (which contains the information about the optics surface figure) is attenuated and makes interference with the reference beam. The analysis of the resulting interferogram provides the characterization of the optics under test and its aberrations. The size of the pinhole and the transparency of the outer region are the two key parameters governing the relative intensities of the reference and the test beams and, accordingly, the quality of the interferogram, expressed in terms of fringe visibility. The visibility V is defined as follows [11]:

$$V=\frac{I_{max}-I_{min}}{I_{max}+I_{min}} \tag{1}$$

where I_{max} and I_{min} are the intensities of the bright and dark areas, respectively. In particular, the size of the pinhole affects the angular aperture, intensity, and accuracy of the reference beam [8]. Indeed, the larger the pinhole, the higher the light intensity, but the lower the precision of the wavefront, which is more affected by shape errors of the pinhole [10,12,13]. Usually, the pinhole diameter is fixed and is determined by the production

* Corresponding author. Tel.: +39 0395971060; fax: +39 0395971001.
E-mail address: andrea.bianco@brera.inaf.it (A. Bianco).

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method of the PDI itself (typically photolithography, etching or random-dot filtering [9,14,15]). This means that different PDIs are required to test optics with different focal ratios. The semi transparency of the regions outside the pinhole is also fixed so the fringe visibility cannot be optimized. Some attempts toward the improvement of visibility have been made, e.g., by using polarization-sensitive filtering where a pinhole is etched into a polarized plate whose rotation determines the intensity of the test beam [14,15].

The possibility to easily tune the transparency of photochromic materials is a powerful methodology to develop versatile PDIs. The opaque state of the photochromic layer is induced by UV light, then transparent pinholes of different sizes can be optically written by locally converting the layer using a visible light source. In this way the PDI can be adapted to test optics with different features. This conversion phenomenon can also be exploited to bleach, in a controlled fashion, the opaque outer region to increase its transparency and balance the intensities of the two interfering beams. This turns into a maximization of the fringe visibility. Moreover, the reversibility of the photochromic reaction makes the system completely rewritable, thus further enhancing the versatility of photochromic PDIs.

2. Methods and materials

According to the description of the PDI, the most important parameter to consider is the contrast of the photochromic layer at the test wavelength, *CT*, which is defined as the ratio between the transmittance of layer in the colored and uncolored states:

$$CT = \frac{T_{\text{uncolored}}}{T_{\text{colored}}} \cong \frac{1}{T_{\text{colored}}} = 10^{A_{\text{colored}}} = 10^{\varepsilon CZ} \quad (2)$$

where ε is the absorption coefficient, C the concentration of the photochromic moiety and Z the film thickness. Since the uncolored form is transparent in the visible region, it is possible to assume

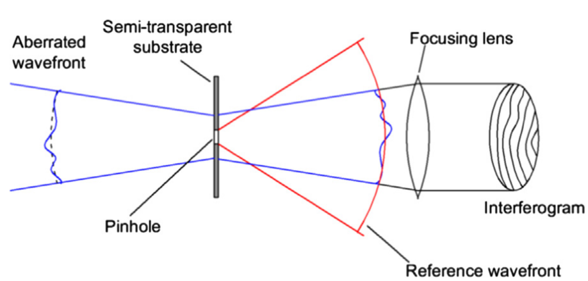

Fig. 1. Functioning scheme of a Point Diffraction Interferometer (PDI).

$T_{\text{uncolored}}=1$. Therefore, the contrast is only a function of the transmittance of the colored state. As T_{colored} determines the maximum opacity of the semi-transparent area the larger this parameter the wider the possibility of tuning the fringe visibility. According to the Lambert–Beer's law (Eq. (2)), high contrast means thick films (Z) with a large content of photochromic dye (C), and a high absorption coefficient (ε) in the colored state. From the various strategies available to produce a photochromic substrate fulfilling these requirements, we have focused our attention on the synthesis of polymers with photochromic units in the main chain. Such polymers allow us to maximize the sensitivity of the layer [16].

To produce the photochromic substrate we referred to a diarylethene-based polyurethane coating we recently developed for optical applications; this coating shows a notable contrast and good optical quality (Fig. 2) [17]. The formulation enables the optical properties of the photochromic layer to be customized by varying the chemical structure and the amount of the photochromic monomer. The solution containing the reactants is cast on functionalized borosilicate glass substrates by spin or control coating, and the complete polymerization is achieved after a heat treatment of 12 h at 120 °C. The thickness of the resulting layers, measured by spectral reflectance (Filmetrics F20EXR), depends on the casting parameters and can be varied from 1 to 10 μm. Photochromic films show uniform thickness, high homogeneity, and contrasts up to 10^4 at 633 nm. Ultra violet (UV)-vis absorption spectra of a layer with an active unit content of 30 wt% under different exposures to UV light (366 nm) are reported in Fig. 2.

Once the photochromic layer is converted to the opaque form with UV light, the pinholes are optically written with a custom-made apparatus consisting of a He–Ne laser source (633 nm) properly attenuated by a polarizing filter and focused onto the photochromic substrate, providing a minimum spot size of 2 μm. The substrate is mounted on a rotating and translating stage to write both pinholes and auxiliary alignment markers. Since the photochromic conversion is a non-linear process [18] (i.e. the conversion becomes faster as the light intensity increases), it is possible to write pinholes in a wide range of dimensions by keeping the spot size constant and varying the photon dose (namely, exposure time and light intensity) with a single laser pulse. Simulations of the photochromic conversion under a Gaussian beam exposure of constant size clearly show that the pinhole diameter increases while increasing the photon dose [19], as shown in Fig. 3(a). In Fig. 3(b), microscope images of pinholes experimentally obtained at the same conditions confirm this behavior. This feature is worth noting since it makes the writing procedure very simple and unaffected by any parameter other than the optical quality of the focusing lens. The pinholes diameter

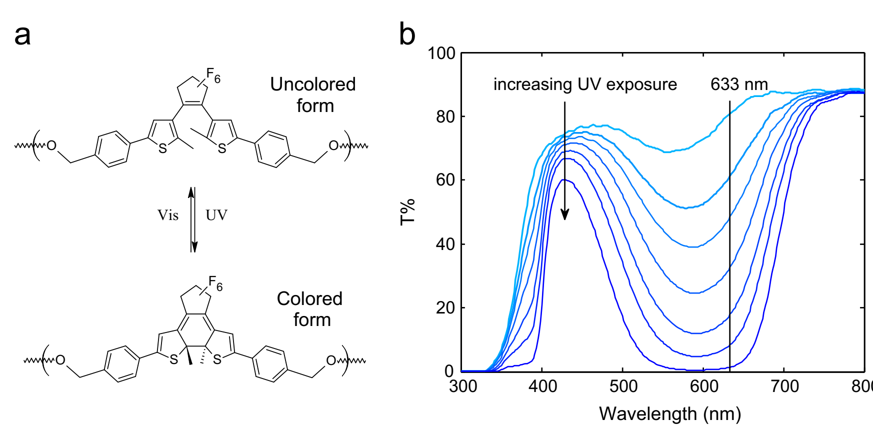

Fig. 2. (a) Photochromic reaction of the diarylethene unit in the polyurethane coating; and (b) UV–vis absorption spectra of a photochromic film with a content of photochromic units of 30 wt% (right).