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Phase-shift mask fabrication at micrometric scale by ion-exchange in glass for astronomical wavefront sensors

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Abstract. Photolithography combined with ion-exchange in glass is a well-known technology that can be applied to develop many different optical devices. In this work, we present the complete procedure to generate small circular phase-shift masks with diameters of only a few microns and high control in the phase change produced. It is a strategic element in applications such as optical astronomy.

1 Introduction

Binary phase-shift masks elements have multiple applications in different fields and present remarkable advantages with respect to diffractive amplitude elements. They can be used in complex optical tasks (sometimes combined with binary amplitude masks) such as apodization, super-resolution imaging, coronography or (de)multiplexing in optical communications among others [1–3]. They are also at the core of a new quaternary adaptive optical system for astronomical telescopes based on a point diffraction interferometer (PDI) [4]. Its diffracting element is a $\pi/2$-phase disk a few micrometers in diameter. Phase-shift masks usually generate the phase difference by changing the optical thickness of a transparent medium. However, it is also possible generate a phase change through the modification of the refractive index in different areas of the medium. The technique of ion-exchange in glass can be used to perform this task [5, 6]. In this work, a phase-shift element to be used in a PDI is designed, fabricated by silver-sodium ion-exchange in glass and characterized by the m-lines method for guided optical modes and by differential interference contrast (DIC) microscopy. The rest of the work is presented as follows: Section 2 outlines the materials and methods used; experimental results are presented and analysed in Section 3; and finally Section 4 summarizes the conclusions of this work.

2 Materials and Methods

Soda-lime microscope slide glasses of 1 mm thickness (*Gold Seal™*) are used as a material substrate, since they present enough regularity in their surface and thickness. The glasses are thoroughly cleaned and aluminized (about 0.25 μm thick layer) in a vacuum chamber (*Balzers BAE 250 Coating System*). Next, the positive photoresist *MICROPOSIT™ S1813 G2* is deposited above the aluminium layer. A binary mask printed on paper and transferred to the photoresist by using a Schneider Xenon-Sapphire 4.5/90 lens, which is optimized for a 14:1 reduction. The object is illuminated with four 125 W Hg lamps for several hours. Then, the sample is developed, etched in acid and cleaned in acetone. The result is an intermediate mask that acts as an object for an old photomicrographic lens Zeiss S-Planar 1.1/68 that performs a second reduction step (1:5). We built a transmission lighting system that consists of a 75 W Hg lamp, a diaphragm, an interferential filter (436 nm) and lenses that conjugate the diaphragm in the input pupil of the Zeiss lens. The final aluminium mask on glass is obtained similarly to the intermediate one but the exposure time is reduced to a few minutes.

The ion-exchange process takes place in molten salt bath inside a oven with stabilized temperature. We choose the eutectic mixture $Ag_{0.05}Na_{0.475}K_{0.475}NO_3$ at 300 °C in order to obtain a slow penetration and a high index change in the unmasked region. A carefully calibration of the diffusion time is required to adjust the exact phase change. After the ion-exchange process, the aluminium mask is removed although some regions are left as references to locate the phase-shift mask.

The exchanged layer normally also forms a several mode waveguide. We measured its effective indexes with a *Metricon 2010/M* by the prism coupling technique. From them, the gradient index profile can be recovered and integrated to obtain the cumulative phase difference between masked and unmasked regions when the element is perpendicularly illuminated [3]. This procedure provides the phase-shift at 632.8 nm, but we can extend it to a different wavelength taking into account the exchanged-glass dispersion [6]. Finally, the spatial characteristics of the mask

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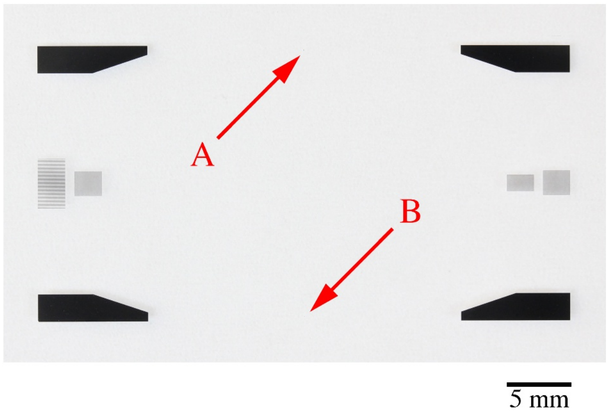

Figure 1. Picture of the intermediate mask made of aluminium on a 75 x 50 mm glass.

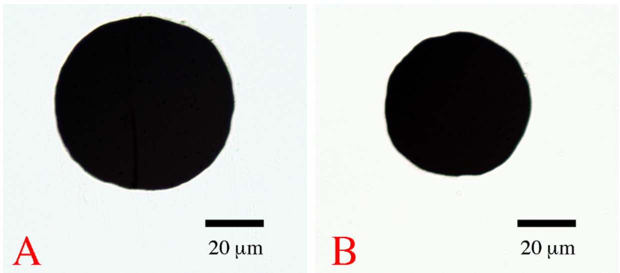

Figure 2. Images of the circular dots of the intermediate mask shown in Figure 1.

were investigated with a commercial high-resolution DIC microscope (*Nikon Eclipse Ni-U*).

3 Experimental Results

Next, we show the performance of the technique in the fabrication of a circular binary mask with a diameter in the range 5–10 μm and a phase-shift difference of $\pi/2$ rad for 632.8 nm. We must stress that this is a strategic element designed for astronomy applications (such as shown in ref. [4]). The phase pattern can be made from any of the following masks: an aluminium layer on the entire surface except for a hole, or only an aluminium dot on a clean surface. We use the second one to avoid phase defects arising from digs, scratches, pores… in the aluminium layer.

Figures 1 and 2 show the intermediate mask which includes some reference patterns to help the localization of the two dots defining the desired binary mask. Figure 3 shows the final phase elements as viewed through a DIC microscope where the brightness is related to the partial derivative of the phase along a diagonal. The inner diameters of these masks are (A) 6.1 μm and (B) 4.1 μm. The phase shift achieved is 0.47π rad after a diffusion time of 10 min 45 s. Therefore, the phase-shift error is less than $\lambda/66$ for λ=632.8 nm. We could even increase the accuracy with a better diffusion time adjustment.

As shown in the pictures, the mask is not purely binary. The side diffusion generates a ramp of approximate 2 μm for this phase shift. Normally, this does not affect for certain applications although it imposes a limit on the minimum spatial size of the mask that can be fabricated.

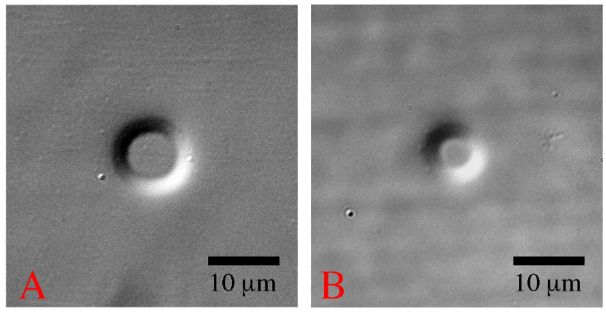

Figure 3. Pictures of the final two circular phase-shift masks obtained in the fabricated element. The images were obtained with a DIC microscope in a transmission configuration with a Nikon TU Plan Fluor 100×/0.9 objective.

4 Conclusions

High quality micrometric-size phase-shift masks can be produced with the technique described in this work. These elements can be used in numerous applications where the need for a very accurate phase-shift is required. These phase-shift masks made by ion-exchange also presents several advantages over other techniques based on thickness modifications, as for example, a more robust element because it is inside the glass substrate. The main limitation of this technique is the side diffusion which prevents to achieve sub-micrometric patterns.

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