Optimising zero-order suppression in ion-exchanged phase gratings

Carlos Montero-Orille[1,*], *Héctor* González-Núñez[1], *Xesús* Prieto-Blanco[1], *Vicente* Moreno[1], *Dolores* Mouriz[1], *María C.* Nistal[1], and *Jesús* Liñares[1]

[1]Quantum Materials and Photonics Group, Department of Applied Physics, Faculty of Physics / Faculty of Optics and Optometry, University of Santiago de Compostela, Campus Vida s/n, E-15782, Santiago de Compostela, Galicia, Spain

Abstract. Ion-exchange in glass is a well-known technique to fabricate phase optical elements. For elements with reduced dimensions, the side diffusion, intrinsic to ion-exchange processes, can affect the performance of these elements if it is not taken into account. Here we present a procedure to optimise the zero-order suppression of ion-exchanged phase gratings.

1 Introduction

Ion-exchanged phase gratings are very versatile optical elements [1]. They can be used in spectrometry, wavelength division multiplexing, power division or optical pulse compression. On the other hand, ion-exchange is a well established technique to modify the refractive index of a substrate. This modification can be made in different areas by using appropriate masks. Ion-exchange has several advantages, namely, simplicity, low cost and easy control of the fabrication parameters. Moreover, the flat surface of the elements fabricated by ion-exchange permits straightforward cleaning and antireflection coating. The fabrication of high performance elements with reduced dimensions by ion-exchange is a delicate task. In particular, it is essential to take into account the side diffusion inherent to any thermal ion-exchange process which produces a transition region [2]. If this is not done, the phase profile of the grating as well as its performance will be affected.

Here we present the design and fabrication by ion-exchange of a phase diffraction grating with its zero-order suppressed. Removal of the zero-order of diffraction is desirable in most applications, including digital holography, spatial light modulation and grating fabrication [3, 4]. As it is known, a binary phase grating does not have zero-order if its phase profile is antisymmetric and its phase step is π. However, this is not the case for an ion-exchanged grating due to the mentioned side diffusion (see Fig. 1). Therefore, in this work, we show how to compensate the phase introduced in the transition region by a proper design of the ion-exhange process and the mask (lithographical process) used to produce the diffraction grating.

2 Materials and Methods

Soda-lime glasses of 1 mm thickness and refractive index n_s=1.5103, for λ=632.8 nm, have been used as substrates. The grating fabrication was made in these substrates by thermal ion-exchange and using aluminium layers as a mask for the ions. A binary grating pattern was translated from a sheet of heavy paper to the substrate by a two-step photolithographic process. The binary pattern was designed taking into account the side diffusion inherent to the ion-exchange process. The first photolithographic reduction was made by a lens Schneider XENON Sapphire 4.5/95, using a magnification of M=-1/14.1. In the second step a Zeiss S-Planar 1.1/68 lens performing a reduction 1:5 was used. The final result was an aluminium binary grating on the substrate. As for the ion exchanges, we used a salt mixture 5% mole $AgNO_3/NaNO_3$ at 340 °C. The ion-exchange modification produced by this salt in these glasses was analysed by using the in-

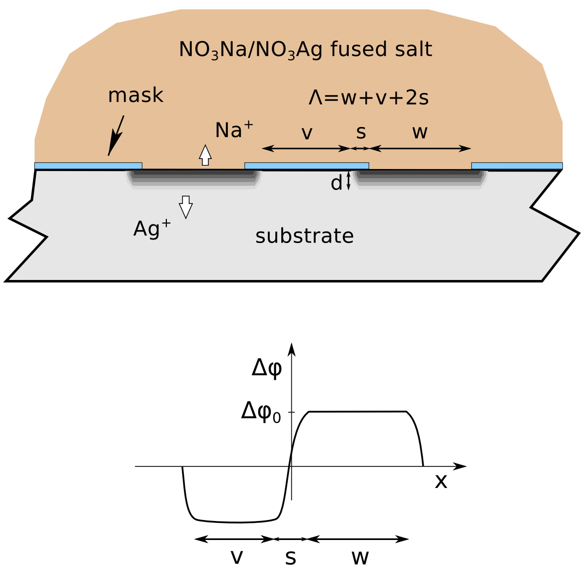

Figure 1. Scheme of an ion-exchanged grating and its phase profile. The side diffusion gives rise to a gradient in the phase profile.

[*]e-mail: carlos.montero@usc.es

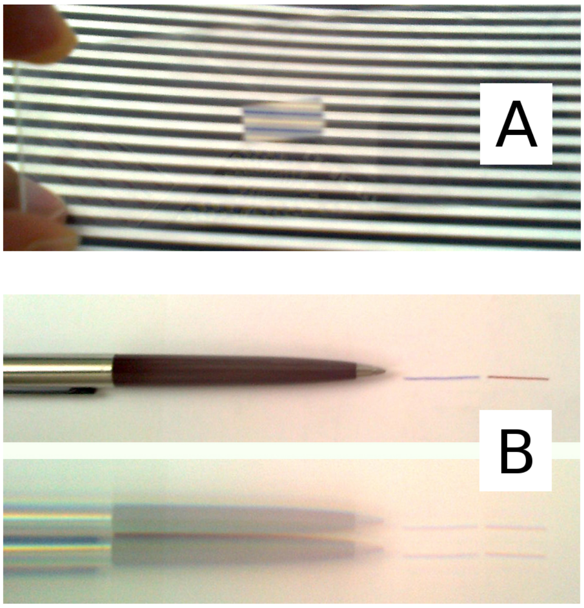

Figure 2. Image through one of the gratings fabricated of: A) a black and white object and B) a long object.

verse Wentzel–Kramers–Brillouin (IWKB) method. As it is known, this method recovers the gradient index profile following an ion-exchange process, which can be represented by a function $n = n_s + \Delta n(x/d)$ for a 1D ion-exchange, with d an effective depth [5]. After determination and integration of this profile, the phase step ($2\Delta\varphi_0$) generated by the ion-exchange can be calculated.

With regard to the design of the grating, we recall that our goal was to minimise its zero-order. As we said, the phase profile must be antisymmetric for this purpose. This means w=v (see Fig. 1) and hence the period of the grating must be Λ=2(w+s). On the other hand, due to the isotropic nature of the ion exchange, the size of the side diffusion (s) is similar to the size of the in-depth diffusion ($s \approx d$). Moreover, both effective depths are proportional to the maximum phase step ($2\Delta\varphi_0$) and this phase step must be set properly. Indeed, for a moderate side diffussion, we must look for a maximum phase step slightly bigger than π to compensate for the minor phase step that the side region gives. Therefore, the design of both the aluminium mask and the ion-exchange process are linked and must be done together. After fabrication of the aluminium mask, we fabricated several gratings by changing the ion-exchange time in order to find the optimal one: the grating with the minimum zero-order. The performance of these gratings was assessed by measuring the efficiency of their zero-order through two methods: 1) directly, by using a He-Ne laser and a power meter, and 2) by measuring their spectral transmittance with a spectrometer.

3 Experimental results

We fabricated two gratings designed to suppress the zero-order at λ=632.8 nm. We chose their periods to be Λ=60 μm and Λ=30 μm. Hence their dimensions were w=v=25 μm and w=v=10 μm, respectively, because we estimated that an in-depth diffusion $d \approx 5 \mu$m was needed. In order to look for the properly phase step, a calibration of the ion-exchange process was made based on the diffusion time [5]. We found that an ion-exchange time of t=12.6 min gives rise to $2\Delta\varphi_0 = \pi$ in the glasses used. Because a bigger than π maximum phase step should be necessary to minimise the zero-order, we made several gratings with longer times and measured their performance by the two methods commented in the previous section. We found that ion-exchange times of t=15.5 min, for the grating with period Λ=60 μm, and t=28.2 min, for the grating with period Λ=30 μm, gave the best results: gratings with a zero-order efficiency T_0<0.5%. The phase steps of both gratings were $2\Delta\varphi_0 = 1.11\pi$ and $2\Delta\varphi_0 = 1.52\pi$, respectively, supporting these results our initial hypothesis.

We show, in Fig. 2, the image of two objects through the grating of Λ=30 μm. In Fig. 2A the grating can be seen in the central rectangular region of the microscope slide used as a substrate, where the zero-order suppression is observed. The white region of the object that is behind becomes blue at the zero-order, because we did the design for red light. On the other hand, Fig. 2B shows a pen without (up) and with (down) the grating in front of the camera lens. The double image proofs that the ±1 orders are the most relevant ones.

4 Conclusion

We have presented the fabrication by thermal ion-exchange of phase gratings with their zero-order suppressed. The design of these gratings has been made by taking into account the side diffusion inherent to any thermal ion-exchange process. In particular, a specific design of the mask needed for the fabrication must be done. The removal of the zero-order that we achieved is excellent: its efficiency falls below 0.5%.

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