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Single-mode channel optical waveguides formed by the glass poling

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ABSTRACT

A novel method of channel waveguides fabrication via glass thermal poling with a profiled electrode has been proposed. The physical model and numerical simulation of channel optical waveguides formation and the guiding mode regimes have been performed. The configuration of anodic electrode and the applied voltage providing single-mode waveguide formation for different wavelengths have been found.

1. Introduction

Glasses as optical materials have been used for centuries and still are under intensive study. The main advantages of them are good optical properties, transparency, easy manufacturing, low cost, and variability of properties via changing the glass composition and structure. Glass is a fundamental component of many passive and active photonics and integrated optics devices, such as optical waveguides [1,2], arrayed waveguide gratings [3], filters [4], splitters [5], and laser arrays [6,7]. Glass-based optical devices can be fabricated by either evaporation/sputtering processes or glass refractive index modification. The latter technique can by realized by diffusion processes, i.e. ion exchange or ion implantation [8], or by selective irradiation by a UV or fs-laser beams [9,10]. Among these techniques, ion exchange is the simplest and the cheapest one. It is the process when the ions in the glass sample are exchanged with those from the salt melt. Ion exchange allows to enrich the subsurface layer with “alien” ions, and since this process results in the local change of glass refractive index due to the difference in ionic polarizabilities, it is widely used for the formation of optical waveguides [11], gradient index lenses [12], diffraction gratings [13] and other structures.

One more technique of local modification of the glass properties in the subsurface region is thermal poling, the process when a glass sample is heated below glass transition temperature under the voltage applied. The poling process causes the charge dissociation at the anodic side of the glass sample, and the drift of positive ions towards the cathode. It has been suggested that negative ions also play a role in this process and migrate towards the anode [14]. The process of glass poling leads to the change of glass composition [15], refractive index [16], surface relief [17], and induces optical nonlinearity due to the break of glass centrosymmetry [18,19]. It can be used for enhancing surface reactivity in bioglasses and ceramics [20] and surface affinity to atmospheric water [21]. Glass poling with a profiled anode can be used for the modification of material properties at submicronic scale [22,23] and for the formation of linear and nonlinear optical devices such as waveguides and diffraction gratings [24–26].

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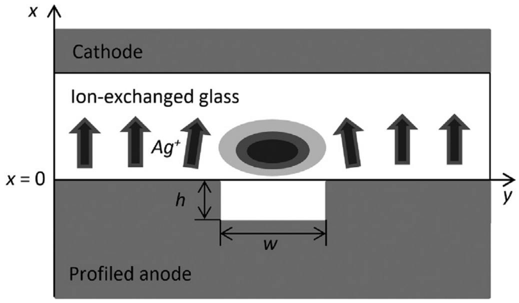

Fig. 1. Scheme of the process. The region with high silver content after the poling is indicated with an ellipse.

Both ion exchange and glass poling may be used to fabricate optical waveguides, the basic components of integrated optics and photonics. In such structures the high refractive index regions are surrounded by low index regions and thus can provide the propagation of light confined in one (planar waveguide) or in two dimensions (channel waveguide). For the most of photonics applications, there is a need in single-mode waveguides suitable for coupling with lasers and optical fibers. Single-mode regime can be realized in channel waveguides, when the high-index region is confined in two dimensions. This can be implemented by ion exchange through a slit (diffused waveguides) [27,28], by placing a high-index strip (or a ridge) on the top of a low-index planar structure (ridge waveguides) [29,30], or by surrounding a high-index waveguiding core in a low-index surrounding medium (buried waveguides) [31,32]. All these techniques require "wet" lithographic process that includes multiple steps: deposition of resist, exposition, development, and one or two steps of etching.

In this work, we propose a novel method of channel waveguide fabrication via thermal poling of preliminary ion-exchanged glass with a profiled electrode that is electric field imprinting of the waveguides. In this case, the anodic electrode (stamp) can be used multiple times, and only one technological step is needed for the poling process. To explore the possibility to obtain "imprinted" channel waveguides that support single-mode regime, we performed numerical modeling of the diffusion and ionic drift processes, found the concentrations of ions participating in the poling process and corresponding refractive index change in the glass. Having done this, we calculated the mode spectra of the waveguides formed, and found the anode parameters and voltage regime leading to the formation of single-mode channel optical waveguides.

2. Model

In our work we modeled the process of poling for common soda-lime glasses underwent the preliminary Na^+-Ag^+ ion exchange, the process when the sodium ions from glass sample are exchanged with the silver ions from the salt melt. The ion exchnage enriches the subsurface glass layer with silver ions, the maximum of silver concentration being just beneath the sample surface. The concentration profile of a diffusing ion can be described as $C(x) \sim \mathrm{erfc}(x/2d)$, where d is a characteristic penetration depth, x – distance from the sample surface [1].

If we apply electric field with a profiled electrode to the glass sample after ion exchange process, silver ions from the subanodic layer will move to the cathode in the areas, where the electric voltage is applied (see Fig. 1). Under the electrode groove there will be no ionic drift, and this area will still contain silver ions after the poling process. As far as silver ions demonstrate higher polarizability than sodium ions, this region will have higher refractive index if compared to the neighboring areas, and this will allow guiding of a light wave confined in x and y directions (see Fig. 1).

A complete description of the glass poling is still to be found. It should take into account all the species participating in the process and strongly depends on the poling conditions, i.e. poling with blocking and non-blocking electrodes. In blocking electrodes conditions, only the species present inside the glass before poling participate in the process. In non-blocking electrodes process charged species like protons or hydronium ions can be injected into the glass from the anodic side [33,34]. In this paper we develop a numerical model of the formation of channel optical waveguides under the glass poling in non-blocking electrode regime, when protons can penetrate into the glass sample from the anodic side.

To find the concentration profiles of species participating in the poling process one has to solve a set of Fick equations

$$\frac{\partial C_{Ag+}}{\partial t} = D_{Ag+} \Delta C_{Ag+} - \mu_{Ag+} \nabla \cdot \left(\mathbf{E} C_{Ag+} \right), \tag{1}$$

$$\frac{\partial C_{Na+}}{\partial t} = D_{Na+} \Delta C_{Na+} - \mu_{Na+} \nabla \cdot \left(\mathbf{E} C_{Na+} \right), \tag{2}$$

$$\frac{\partial C_{H+}}{\partial t} = D_{H+} \Delta C_{H+} - \mu_{H+} \nabla \cdot \left(\mathbf{E} C_{H+} \right) \tag{3}$$