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Channel polymer optical waveguides embedded in glass: Design, fabrication and characterization

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ABSTRACT

In this work, the design, fabrication and experimental evaluation of new channel polymer optical waveguides embedded in glass are reported. We show that high quality microchannels in glass, without roughness on the walls, make possible the fabrication of new channel optical waveguides by filling the microchannels with a polymer. Guided light through those new optical waveguides is demonstrated experimentally. The commercial software OlympIOs was used to design multimode and monomode channel polymer optical waveguides. The microchannels in glass substrate were fabricated by using a laser lithography system and wet-etching procedures. The spin-coating technique was applied to deposit the polymer inside the microchannels. The end-coupling method was implemented for the waveguides characterization. Theoretical and experimental results have confirmed light confinement as well as guided modes propagation by these new channel optical waveguides.

1. Introduction

Developments in polymeric optical waveguides have experienced a large growth over the last years due to their handling simplicity and low cost production [1–3]. Currently, channel optical waveguides are being fabricated with different polymers [4–6]. On the other hand, the scientific collaboration between the Integrated Optics and Immunoelectroanalysis laboratories, at University of Oviedo, made possible the fabrication of high quality microchannels in glass substrates, showing walls with negligible roughness (less than $\lambda/10$) [7,8]. The possibility to fill these microchannels with a specific polymer allows manufacturing a new structure in the field of integrated optics: the channel polymer optical waveguides embedded in glass[1] (CPOWEG). In this paper, soda-lime and borofloat®33 were used as glass substrates, and NOA 61 and PMMA as polymers.

The commercial simulation software OlympIOs was used to simulate the light propagation in this kind of channel optical waveguides. The core dimensions of CPOWEG were calculated to verify multimode and monomode condition.

After selecting the channel dimensions, a metallic mask was fabricated with a laser lithography system implemented in the laboratory [9]. Then, the mask pattern was transferred to the substrate to obtain an empty microchannel in glass. A specific wet-etching technique was developed to engrave the microchannels, and a profilometer was employed to verify the microchannel profile (dimensions and roughness). Finally, the spin-coating method was used to deposit the polymer inside the microchannels. Soda-lime and NOA 61 were chosen to manufacture multimode CPOWEG, and borofloat®33 and PMMA for monomode CPOWEG. In order to simulate theoretically, and with great accuracy, the true optical waveguide, this fabrication procedure makes possible the knowledge of the real geometrical and physical parameters, consequently, monomode and multimode CPOWEGs can be simulated and manufactured on demand.

To experimentally characterize the manufactured CPOWEG, the end-coupling method [10] was implemented. This characterization technique provides the electromagnetic field distribution. The simulations and experimental results agree very well.

2. Design

The design of CPOWEG requires the determination of the electromagnetic field distribution, both for monomode and multimode regime, and the calculation of the transverse dimensions of the microchannel, which constitutes the core of the CPOWEG. Thus, the design depends on the refractive indices of glass and polymer,

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[1] CPOWEG: Channel Polymer Optical Waveguide Embedded in Glass.

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wavelength, and monomode or multimode performance of the optical waveguide. The simulation results were obtained by using the commercial software OlympIOs, which allows to know all the fabrication parameters. Fig. 1 shows a scheme of the simulated CPOWEG.

In order to perform the simulations, it is necessary to know with great accuracy the refractive index of the glass substrate, n_s, and the refractive index of the polymer, n_f. For that purpose, refractometry techniques were employed to measure n_s, while the evaluation of n_f was carried out by means the Longitudinal Section Electric (LSE) (E^x_{pq} and quasi-TE) and Longitudinal Section Magnetic (LSM) (E^y_{pq} and quasi-TM) guided modes formulation, which was specifically developed by the authors in order to calculate refraction index and thickness of polymeric microlayers [11].

E^x_{pq} (quasi-TE) and E^y_{pq} (quasi-TM) guided modes in CPOWEG were simulated. In both cases, a good and similar agreement between the numerical and experimental results was obtained. In order to simplify the results presentation, the E^x_{pq} (quasi-TE) modes are chosen.

2.1. Multimode waveguides

For this kind of waveguides, soda-lime glass (n_s = 1.512 at λ = 632.8 nm) was chosen as substrate and NOA 61 (n_f = 1.557 at λ = 632.8 nm) as polymer, which has good optical properties to fabricate multimode CPOWEG.

The design, fabrication and characterization of CPOWEG are a new challenge in integrated optics. Therefore, the first step was to verify whether this new optical waveguides make possible guided light propagation. Initially, and in order to make the fabrication process in our laboratory, large dimensions for width, *d*, and height, *h*, were chosen. The thickness, *b*, of the NOA 61 polymer can be varied from 3 μm to 6 μm, approximately. Taking into account these considerations, several multimode CPOWEG were simulated. As an example, Fig. 2 contains the cross section of a multimode CPOWEG which was designed with the following parameters: *b* = 6 μm, *h* = 16 μm and *d* = 90 μm. Also, Fig. 2 shows the electromagnetic field distribution, calculated for the fundamental mode, E^x_{00} (TE_{00}), using the finite difference method [12] with the software OlympIOs. As for the rest of the simulated multimode CPOWEG, practically 100% of the electromagnetic field energy is confined in the core of the waveguide. Furthermore, the energy propagated in the thin layer of polymer, which covers the sample, is negligible in comparison with the energy inside the core.

2.2. Monomode waveguides

In this case, borofloat®33 (n_s = 1.470 at λ = 632.8 nm) and PMMA A4 (n_f = 1.490 at λ = 632.8 nm) were chosen as glass substrate and polymer, respectively. For designing monomode CPOWEG it is necessary to know, very precisely, all the geometrical parameters of the optical waveguide: *b*, *h* and *d*. For this purpose, a simulation window, centered in the core of the waveguide, with dimensions 50 μm × 20 μm was established.

Taking into account the equipment available, and the capabilities in the laboratory, the assigned values to the thickness, *b*, and the width, *d*, where: *b* = 0.2 μm and *d* = 8 μm; whereas *h* was taken as variable. Using the OlympIOs software, the effective index, n_{eff}, of the fundamental mode, E^x_{00} (TE_{00}), as well as the effective index of higher order modes, E^x_{10} (TE_{10}) and E^x_{01} (TE_{01}) were evaluated. For that purpose, the parameter *h* was modified from 0 μm to 1 μm. Fig. 3 shows the simulation results.

Each propagated mode must satisfy the guided propagation condition, $n_{eff} > n_s$. To obtain a monomode waveguide, this

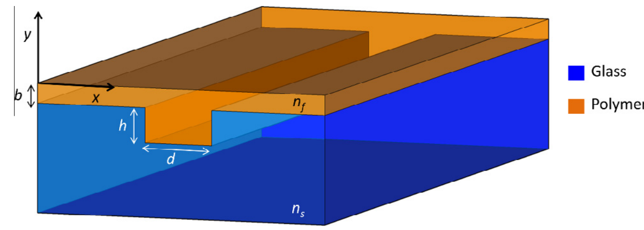

Fig. 1. Final structure of a CPOWEG.

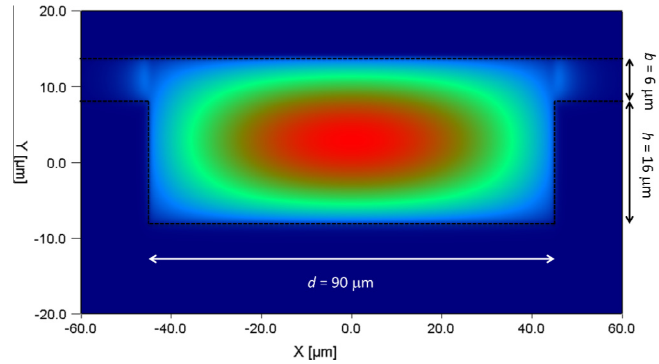

Fig. 2. Cross section and electromagnetic field distribution for the fundamental mode of a multimode CPOWEG fabricated with soda-lime glass substrate and NOA 61 polymer.

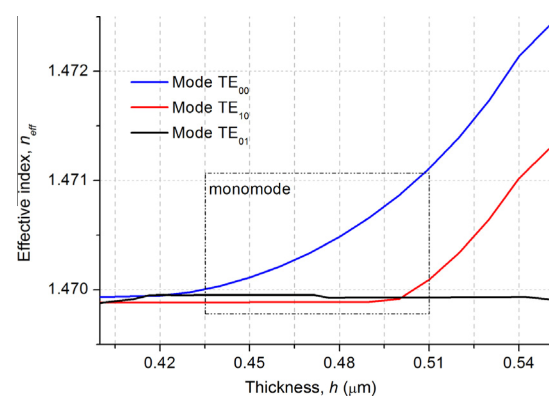

Fig. 3. Effective index, n_{eff}, obtained for TE_{00}, TE_{01} and TE_{10} modes as a function of thickness, *h*, for monomode CPOWEG, fabricated with borofloat®33 and PMMA A4.

condition must be satisfied just for the fundamental mode. As Fig. 3 shows, if *h* > 0.43 μm the fundamental mode, E^x_{00} (TE_{00}), is propagated; however, if *h* > 0.51 μm the second mode, E^x_{10} (TE_{10}), is excited. Therefore, to achieve a single-mode CPOWEG, *h* must verify the relationship: 0.43 μm < *h* < 0.51 μm.

The electromagnetic field distribution for the fundamental mode, E^x_{00} (TE_{00}), has been calculated using the software OlympIOs, as shown in Fig. 4.

Once the design parameters have been established for monomode CPOWEG, the fabrication process can be carried out.

3. Fabrication

The fabrication processes for multimode and monomode CPOWEG were similar. Fig. 5 shows a cross-section scheme with the steps to manufacture this kind of waveguides. Before starting the fabrication of CPOWEG, a metallic mask must be manufactured. In our case, a laser lithography system was implemented