Production of an optical waveguide in planar glass substrate fabricated with Femtoprint

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Femtosecond laser pulses are more and more spread for the micro/nano-machining of various materials. While Bragg gratings are routinely patterned within optical fibers using the point-by-point or line-by-line technique, the objective of our work is to produce Bragg grating sensors within planar glass substrates. As a first step towards this objective this paper reports the inscription of an optical waveguide in planar glass substrates. These achievements have been obtained with the so-called Femtoprint machine, a commercial device created to engineer glass materials. We report the parameters that were used to produce cylindrical waveguides in planar substrates, the experimental set-up, and the first experimental results.

Introduction

In a concern of miniaturization of photonic devices[1] or for quantum photonics applications[2], there is a growing interest in integrating or embedding optical components in transparent glass or crystals. In recent years, ultrashort pulses (< 2ps) laser inducing permanent and specific damage in materials has been demonstrated to be a robust and precise technology for micromachining of fused silica glass or waveguides inscription [3]. However, despite the various research dedicated to femtosecond (fs) pulses induced refractive index modification in silica glass[4],[5], the non-uniform or asymmetric refractive index distribution in the waveguide, which can induce propagation losses is still a problem to face. In this work, we used the commercially available Femtoprint[5] machine to design and inscribe optical waveguides in silica glass. We demonstrate that for a given laser beam polarization, a good equilibrium between the scanning speed and repetition rate to correctly adjust the pulse accumulation in silica glass allows to control the refractive index modification in the material. Besides, we used different inscription designs to inscribe cylindrical waveguides. The latter were characterized and show elliptical profile and transmission with reasonable loss.

Experimental setup and results

For the inscription of the waveguides, we used a standard BK7 glass and a femtosecond inscription process based on the commercial Femtoprint device[5]. This machine, shown in Fig. 1, is composed of a femtosecond laser, high numerical aperture microscope objectives, and high precision translation and rotation stages allowing a perfect alignment of the sample under test. The laser is emitting 300 fs pulses at 1030 nm with variable repetition rate and pulse energy from 1 kHz to 2 MHz and from 60 nj to 700 nj, respectively. These parameters are easily adjustable and linked to a computer-aided design software (Alphacam).

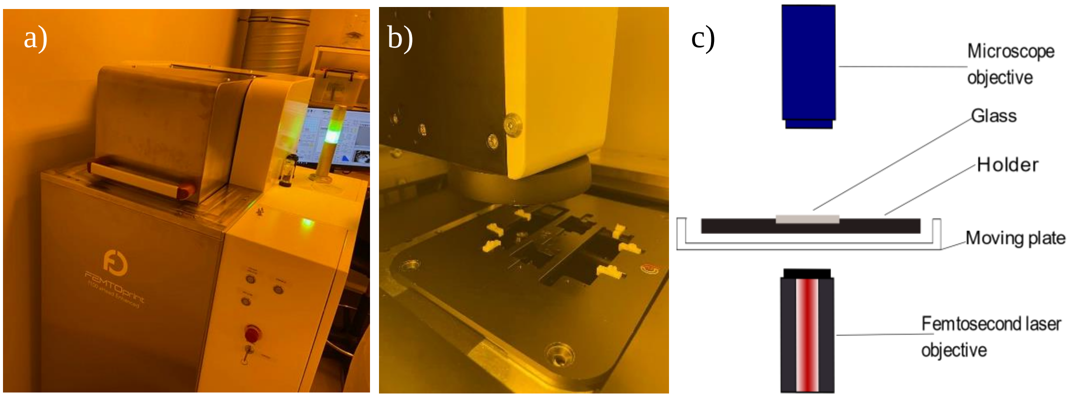


Figure 1. Picture of the Femtoprint: external view of the machine (a), inner view on the microscope and holder (b) and schematic explaining the inscription part (c).

When using femtosecond pulses, three types of refractive index modification can be reached depending on the deposited energy. The first and the most interesting one in photonics, is a slight modification of the refractive index in glass material [4][5]. The two other types of damage are either provoking micro-gratings[6] or an ablation[7] of the material. The goal of this study is to identify the optimal parameters for the inscription of an optical waveguide in a glass substrate. According to the literature, the most important parameters impacting the waveguide performances are linked to the deposited energy expressed by[8]:

$$\Phi_d = \frac{4E_p}{\pi\omega_{nl}^2}M = \frac{4E_p}{\pi\omega_{nl}}\left(\frac{f}{v}\right) \qquad (1)$$

Where f is the repetition rate, v is the translation speed of the sample during the inscription, Ep is the energy of the pulse impacting the deformation of the glass, M is the nonlinear absorption beam diameter and ω_{nl} is the nonlinear beam waist given by Krol et al[9]. Besides the polarization of the laser beam, f and v are the parameters impacting strongly the homogeneity of the waveguide. The design of this latter is also an important parameter to consider. We used two design configurations for the waveguide inscription, each one describes the path of the writing laser beam: the first one is based on a helical path and the other is based on a planar configuration with very close parallel laser paths, as depicted in Fig. 2a and Fig. 2b, respectively.

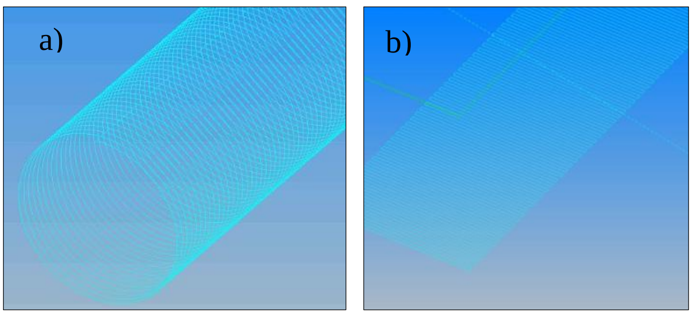


Figure 2. Screenshot of a waveguide with helicoidal laser path (a) or with a plane by plane path (b).

For the inscription of the waveguides, we used the microscope objective of 0.5 NA and select the polarization of the laser beam perpendicular to the scanning direction as it allows higher photo-ionization and more symmetrical mode field pattern of the waveguide [10]. After different tests of waveguides inscription by varying step by step the writing parameters, we found that a high repetition rate (f=1 MHz), low pulse energy (Ep < 130 nJ), and a slow inscription speed (v ranging from 20 to 500 µm/s) allow to induce refractive index modification without high damage (nano-gratings or cracks) [11],[12] of the glass substrate. We noticed that the space between the inscribed lines (laser paths) is also an important parameter to take into consideration so as to produce a homogeneous waveguide. Therefore, we tested three spacing values i.e. 1.5 µm, 1.0 µm, and 0.5 µm. The last one produces the most homogeneous refractive index profile. In Fig. 3a, we can see an example of transmission microscope image of a planar waveguide obtained by planar design, with 130 nJ pulse energy, 1 MHz repetition rate, 20 mm/min inscription speed and 0.5 µm laser paths spacing. In ref. [9], it has been reported that the refractive index modification is located slightly below the localized defect due to femtosecond pulses. Accordingly, we also checked the cross-section of the produced planar waveguide with an optical microscope, as shown in Fig 3b. This picture shows an elliptical shape of the modified area surrounding the laser path. Due to unpolished edges of the substrate. This picture provides only qualitative analysis. Additional tests have to be performed to deeply analyze the waveguide profile and the mode field.

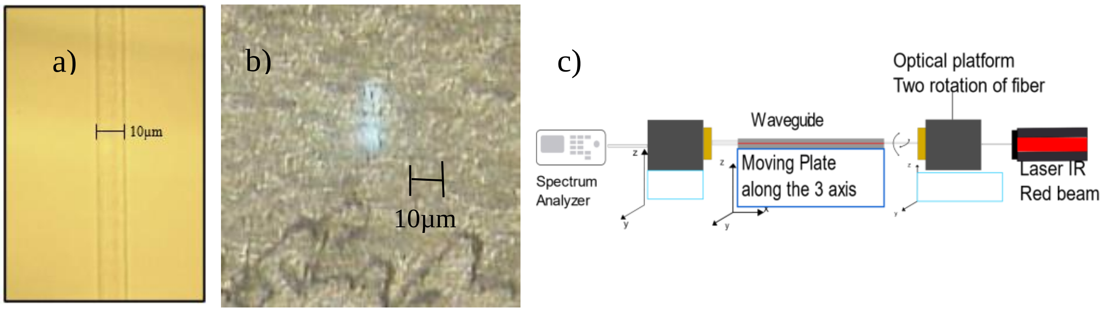
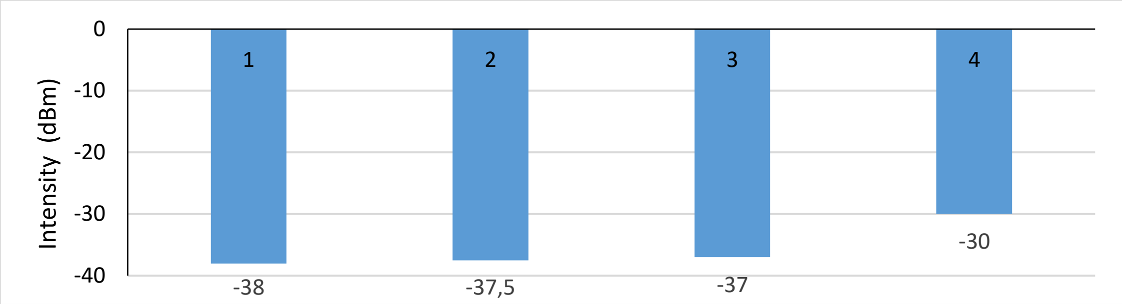


Figure 3. Transmission microscope picture of a planar waveguide (a), its cross-section (b) and scheme of the butt-coupling experimental setup (c).

The different waveguides produced by varying the parameters listed previously were then characterized. First, we performed a semi-qualitative analysis by launching a red-light beam in the waveguide and analyzing its propagation path. We therefore implemented a Matlab^{TM} code, which allows to obtain 3D plots from a 2D image showing the distribution of the beam intensity along the waveguide. This analysis allows a pre-selection of the samples. For the qualitative characterization step, we consider the setup reported in Fig. 3c to couple light in the produced waveguides. It shows the structure under test between two butt-coupling SMF-MMF fibers at the input and the output side, respectively. The setup allows determining the quality of the signal transmission by comparing the output optical power with and without the waveguide between the two butt-coupling fibers. To avoid parasitic reflections, index matching gel is used at both input and output.
The experimental results for the different produced waveguides are reported in Fig. 4. The graph shows the transmission values for 26 mm long waveguides and the table below summarizes the corresponding inscription parameters. Considering the intensity through the butt-coupling fibers without the waveguide (-24.3 dBm), sample #4 shows the lowest losses determined to be 2.2 dB/cm. This value is over-estimated because the substrate edges are not polished. However, in comparison to the other waveguides we can consider that the planar design with high scanning speed (20 mm/s) is the more adapted to produce homogeneous waveguides.



Label of structure	#1	#2	#3	#4
Pulse energy	130 nj	130 nj	130 nj	130 nj
Repetition rate	1 MHz	1 MHz	1 MHz	1 MHz
Type of inscription	Helicoidal	Planar	Planar	Planar
Speed of inscription	1 mm/min	1 mm/min	5 mm/min	20 mm/min
Space between laser paths	0.5 µm	0.5 µm	0.5 µm	0.5 µm
Loss (db/cm)	5.3	5.1	4.9	2.2

Figure 4. Graphic comparing the impact of each parameter on the loss of the signal and the associated table explaining the differences between each structure.

Conclusion

We produced different waveguides with femtosecond laser pulses delivered by the Femtoprint device. The samples were obtained by controlling the inscription parameters. First, we show that the spacing between the laser path cannot exceed 0.5µm. For a given pulse energy (<130 nJ) and repetition rate (1 MHz) we determine a scanning speed for a homogeneous and reasonable loss (2.2 dB/cm) structure to be in the window (20-500 µm/s). Finally, we show that the planar design is better that the helical one in terms of refractive index distribution and induced losses.

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