Synthesis of an optical waveguide in bulk silica with a femtosecond laser inscription and wet etching treatment

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Femtosecond laser pulses are more and more spread for the micro/nano-machining of various materials. The objective of our work is to create an optical structure within a bulk silica substrate thanks to the commercial device Femtoprint. This optical structure will be able to transmit a signal through silica glass and limit its loss so that it can further be used for sensing applications. In this article, we report our experimental achievements obtained with the machine for the creation of waveguides. We highlight the parameters that were optimized to produce them in planar substrates.

Introduction

During the last decades, femtosecond pulses lasers have been widely used for several applications [1]. The one we are focusing in our work is the creation of optical waveguides within planar silica substrates. The overall quality of the latter depends on the energy deposited by the femtosecond pulses laser on the surface of the material. The energy of deposition is described with the following equation [2]:

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

where Φ_d (in J/m²) represents the energy of deposition, E_p (in nJ) is the energy of the pulse, f (in Hz) is the repetition rate, v (in mm/s) is the speed of inscription and ω_{nl} is the non-linear beam waste [3]. Depending on the value of the energy of deposition, three types of defaults can be generated [4,5]. For small Φ_d values, a densification of the silica glass will be obtained, which induces a local modification of its refractive index. This is precisely what is required for the creation of optical waveguides. Another possible default is the creation of nano-gratings. They appear at higher deposition energy. Same energy levels as for the creation of nano-gratings are used for the creation of mechanical structures, provided that an etching process is conducted in KOH solution. The third type of defect is the direct ablation obtained at even higher energy values. The latter is not used in our work.

Our experimental work aims to create optical waveguides and optical fiber holders directly within a silica glass plate. The holder is very important for the alignment of the in-build optical waveguide with a connecting optical fiber. To create these two structures, we used the Femtoprint machine [6], which is fully automated on three different axes. The advantage of this process is that all the different parameters of the energy deposition (cf. Eq. (1)) can be defined before the inscription. The next section will introduce the different experimental set-ups used for the inscription and characterization of the different optical structures.

Experimental set-up

Figure 1a depicts the Femtoprint machine. Its operating principle is illustrated in the scheme of Fig. 1b while Fig. 1c shows the inside of the Femtoprint. It is important to note that the femtosecond pulses laser comes from the bottom to hit the surface of the silica glass plate placed on the 3-axis moving plate. This machine is used both for the synthesis of the optical waveguide and the holder to connect optical fiber on silica glass.

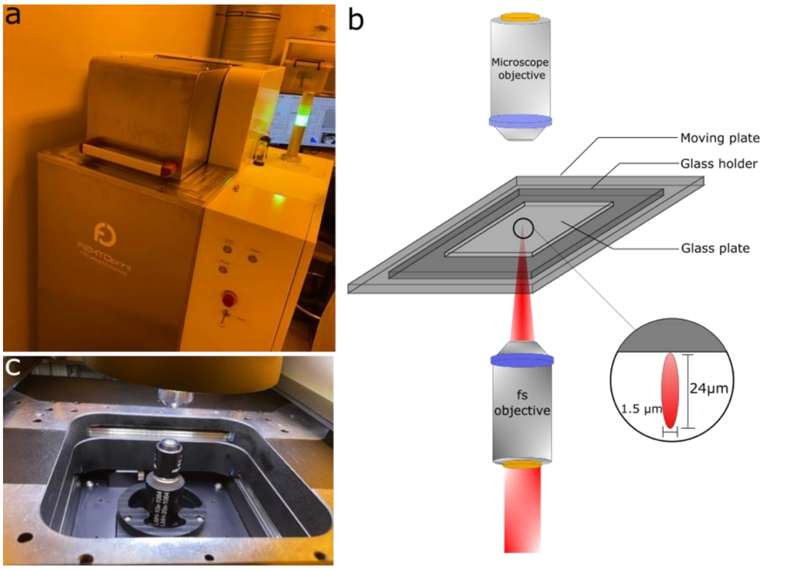

Figure 1. Picture of the Femtoprint machine from the outside (a), Sketch of the operating principle showing the glass substrate placed on a holder fixed on the moving stage and located above the laser objective (b), Picture showing laser objective located at the bottom and the microscope objective at the top used to calibrate the position and orientation of the glass substrate (c).

The optical characterization set-up is represented in Fig. 2. The input part, located on the left, comprises the InfraRed or the red beam that is used for injection within the manufactured optical waveguide. The latter is put on a second block that can move on three different axes and be easily adjusted so that the optical coupling can be optimized. The last block holds the connecting optical fiber that can move in two different directions, also for a proper alignement. This fiber allows an analysis of the waveguide performance thanks to its connection with an optical spectrum analyser (OSA).

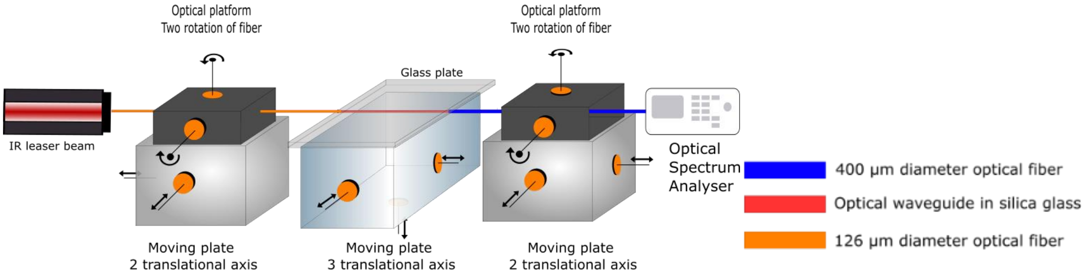

Figure 2. Experimental set-up for the determination of the transmission signal.

Experimental results

In this section, we present our experimental results. Figure 3 shows a microscope image of a waveguide written in bulk silica glass. To create this structure, the parameters of the Femtoprint were optimized following a trial and error approach. It turns out that appropriate parameters are a pulse energy of 130 nJ, a repetition rate of 1 MHz, a speed of inscription of 20 mm/min with planar movements of the tightly-focused laser beam and a space between the different laser paths of 0.5 µm.

Figure 3. Microscope picture of a waveguide (refractive index densification) created by tightly-focused femtosecond pulses laser in a planar silica substrate.

To properly connect this femtosecond laser-induced waveguide with external characterization equipment and thereby analyse its performance, a mechanical holder was designed and manufactured at one edge of the planar substrate to host the connecting optical fiber. Figure 4a shows the conceptual design that is a succession of 3 cavities of 1 mm side with a small tunnel (0.5 mm in length and 126 µm of diameter) in between to allow the easy insertion of a telecommunication-grade single-mode optical fiber. This mechanical structure was obtained with pulses of 230 nJ, a repetition rate of 1 MHz and a speed of inscription of 950 mm/min. After the laser process, a KOH (0.1 M) etching was performed for 6 hours at 85 °C. Figure 4b depicts the obtained mechanical holder.

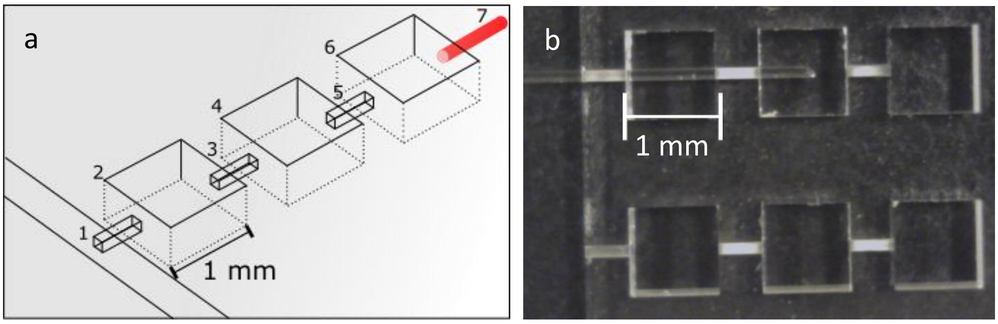

Figure 4. Scheme representing the design of the optical fiber holder at one edge of the glass plate (1,3 and 5 represent the cavity for the optical fibre whereas 2, 4 and 6 are the cavities allowing the KOH to spread more quickly) (a), Picture of the actual implementation (b).

Now that the waveguide and the optical fiber connector are produced in line within the glass substrate, they can be optically characterized. The goal of the measurements is primarily to observe the efficiency of the waveguide in terms of transmission. To do so, Bragg gratings inscribed in the connecting optical fiber are used. They are first measured directly with the fiber connected to the OSA. These measurements correspond to the blue bars displayed in Fig. 5 for 3 different gratings. The connecting fibers are then aligned with the optical waveguide made in the glass substrate and a similar characterization is performed. This yields the green bars of Fig. 5. Comparing blue and green bars reveals that the optical loss is less than 1 dB, which is very satisfactory for us as we intend to use the waveguides for sensing purposes.

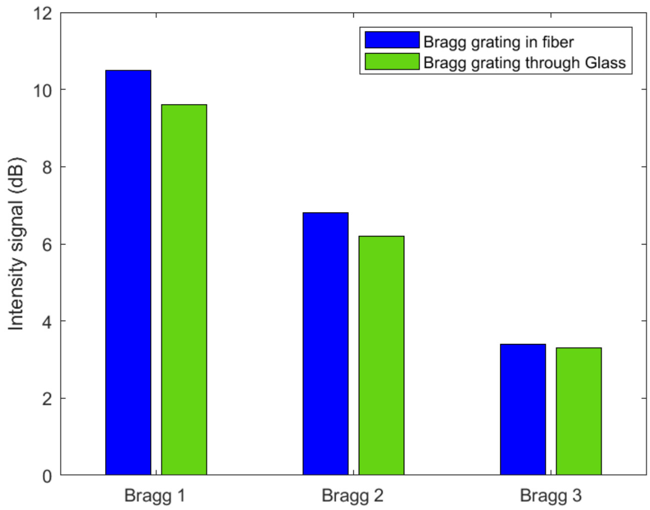

Figure 5. Optical characterization of the waveguide performance in bulk silica thanks to the use of fiber Bragg gratings written in the connecting optical fiber.

Conclusion

In conclusion, we have created an optical waveguide that is fully working and can transmit at least 90 % of the signal. The created mechanical structure allows us to properly align the waveguide and the coupling optical fiber. The next step of our experimental work is now the inscription of a Bragg grating into the core of an optical waveguide. The targeted application is mostly focused on physical sensing (temperature and strain) based on the in-built Bragg grating.

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