Femtosecond writing and characterization of waveguides

Sofia Ferreira Teixeira

Department of Physics and Astronomy, Faculty of Sciences of University of Porto

10th of November of 2015

Abstract

In this paper, it is presented a method of fabrication of waveguides using femtosecond writing. This method uses a 220 fs pulse laser with a pulse repetition rate of 500 kHz, a pulse power of 10 W and at a wavelength of 1030 nm, in its 2nd harmonic (λ=515 nm). The material where the waveguides were written was a fused silica glass substrate. It was written 7 linear waveguides at 100 μm below the surface of below the surface of the sample, with a varying power of the laser beam in the range of [50,200] mW. Furthermore, the characterization studies carried out with the written waveguides are described. These studies include an analyse of the propagation loss as a function of the power of writing and an examination of the intensity profile. The studies were made with an infrared laser of a wavelength 1.5 μm and by coupling the fabricated waveguides with single mode optical fibres (SMF). It was verified that the optimal waveguide was written with a power of 125 mW, having a loss of 1.62 dB. All waveguides had a Gaussian mode profile equivalent to the optical fibre profile used. The optimal waveguide written had a mode profile with a width of, approximately, 7.50 μm in the X direction and 7.35 μm in the Y direction. The coupling loss was equal to 0.48 dB.

1 Introduction

Many areas of scientific research need a high level of miniaturization of optical devices. Integrated optical and photonics circuits can find applications in communications, medicine and in a collection of other areas. With the invention of the laser, this light source has been the base of micro-fabrication processes. Femtosecond lasers (ultrafast laser pulses) allow fabrication of three-dimensional integrated optical circuits with sub-micrometer resolutions.

The process that occurs when a femtosecond laser is focused inside a transparent dielectric material is a non-linear interaction between light and matter. Peak intensities can be of the order of TWcm^{-2}. Such intensities produce non-linear absorption. This is verified by the production of a free electron plasma, which is formed by photo ionization (non-linear and avalanche). After the formation of the plasma, the electrons transfer their energy to the lattice of the dielectric material, therefore changing the physical properties of the materials. This modification is not well understood, but it can be divided in three outcomes, depending on the energy associated with the pulse. For low and intermediate energies, there is an isotropic or birefringent refractive index change, respectively. With sufficiently high energy, there is void formation. These material modifications and the physical interaction that occurs with the femtosecond laser are illustrated in Figure 1.1 [4].

Consequently, it is possible to write regions with permanent different physical properties directly inside a dielectric material. With this, simple writing processes can be developed to fabricate three-dimensional optical elements, such as waveguides. The dielectric material of choice is fused silica, due to its high transparency and stable physical properties. Furthermore, optical devices with low loss and stable optical properties are produced with fused silica.

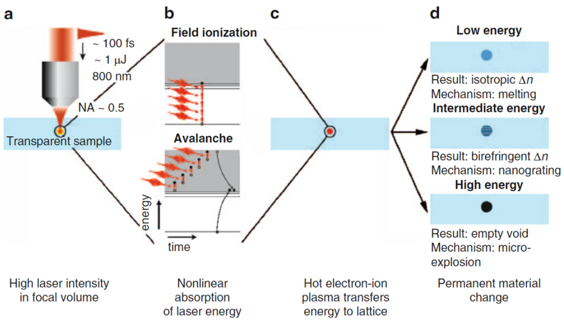

Fig. 1.1: Illustration of the physical process and of the modification of material properties caused by the interaction between femtosecond pulse and dielectric materials.

Waveguides can therefore be fabricated with femtosecond writing. It has been verified that properties of waveguides highly depend on the writing parameters, such as pulse power, writing speed and pulse duration. These properties are, for instance, the propagation loss and the mode profile. It is then possible to tune the different parameters to obtain some intended property.

This paper proposes a method for femtosecond fabrication of waveguides inside a fused silica substrate. Characterizations of waveguides are also discussed and its properties studied.

2 Femtosecond fabrication of waveguides

In this work, a 220 fs pulse laser, with wavelength of 1030 nm, a pulse repetition rate of 500 kHz and a pulse power of 10 W, was used to fabricate waveguides[1]. The laser was linearly polarized. In order to take advantage of the previously described physical process (non-linear absorption), an experimental setup was optimized and a repeatable method was used to fabricate waveguides.

[1] The waveguides were fabricated on the 20th of October of 2015.

2.1 Experimental setup

The experimental setup used is represented in Figure 2.1. The pulse laser was coupled to an harmonic generator in order to be used in its 2nd harmonic, with a wavelength λ=515 nm. It was used in the 2nd harmonic because it was verified [5] that at this wavelength, the refractive index had a larger change. The setup can be divided in 5 parts, each one with a certain function to optimize the writing process. These parts are the following:

1. The first half-wave plate (HW1) and Brewster angle polariser (BAP) were used to vary the power of the beam. The HW plate was computer controlled. The BAP works as a polarization beam splitter. With the change of angle of polarization by the HW plate, the power of the beams splitted could be tuned while maintaining the linear polarization. One of the beams splitted was then used and the other was guided to a beam dump.

2. A telescope composed of two lenses (L1 and L2) (Thor Labs) was used to amplify the beam size. This amplification allows for maximum incidence at the lens which focused the beam at the sample (L3).

3. The second HW plate (HW2) was used to change the polarization of the beam to the writing direction. From previous results [1], it was verified that the best waveguides were obtained with the polarization in the direction of writing.

4. In order for the beam to be focused at the sample, an aperture (Melles Griot) and a third lens (L3) were used. To reduce the beam size to fit the full width of the lens, the aperture had the same opening as the lens. This lens was the objective lens that focused the beam at the sample.

5. For the process to be seen and small alignments to be done, a CCD camera coupled to a filter and a fourth lens (L4) was used. The fourth lens collimated the beam at the camera. The filter had to be used to reduce the intensity, because

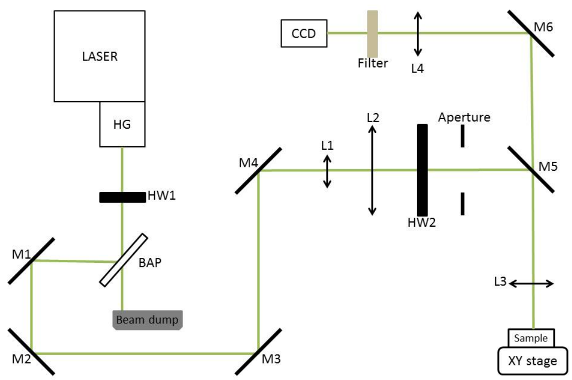

Fig. 2.1: Diagram of the femtosecond writing setup. (HG: harmonic generator, HW: half-wave plate, BAP: brewster angle polariser, M: mirror, L: lens, CCD: CCD camera)

the original beam had an intensity that could damage the camera.

Having the setup optimized, the laser and the setup were aligned. First, all the mirrors had to be align for a beam reflected at the sample to follow exactly the same return path. Second, the last mirror before the objective lens (M5) must be aligned such that the beam is perpendicular at the sample. The sample holder and the third lens also had to be perpendicular to the beam. With this, the writing process is uniform throughout the sample and the aberration produced by the air glass interface is reduced. These aberrations can change the shape of the waveguides and deform the intensity profile.

With the CCD camera, it was possible to know when the beam was focused at the surface of the sample. With all the alignments well made, if the beam was focused at the sample surface, a reflection occurred and the reflected beam was well interfered at the camera, where a point was then observed. It was possible to see the two reflections corresponding to the two surfaces of the sample perpendicular to the beam.

The sample was hold by vacuum in the computer controlled air-bearing XY stage (Aerotech ABL10100). The velocity and length of each step could be adjusted. The controller programme used was also connected to the laser. With this, the movement and the laser were coupled and the writing was more precise and could be done without any problems with the sample and with the laser operation.

2.2 Experimental method

With the setup aligned and the sample placed in the XY stage, the writing process could begin. To start with, the computer controlled HW plate was calibrated to find the angles of maximum and minimum power of the laser beam arriving at the sample. With the plate calibrated, the power could be selected automatically.

The sample was made of fused silica glass and had the geometry represented in Figure 2.2, with dimensions of 21 mm width and 1 mm thickness[2]. The waveguides intended to write were lines across the width of the sample. Considering the geometry of the sample, it was decided that the waveguides written would be separated by 125 μm and at an height of 100 μm below the surface of the sample substrate The height inside the sample was measured from the top surface, using a pressure micrometer (Mitutoyo). The top surface was found from the reflections observed at the CCD camera. Furthermore, in order for the writing process to be more stable and safe, the laser would be turned on 2mm before and turned off 2 mm after the sample. With this, it is certain that the full width of the sample is written. This is also represented in Figure 2.2.

The sample was moved in the writing direction with a writing velocity of 200 μms^{-1}. The mode of operation was Single Waveguide, in which the laser is turned on and off at the beginning and end of each step, respectively. This mode was selected in the controller programme of the XY stage. With these considerations the process of writing was the following:

[2] The total length of the sample is unknown because the sample was shared with colleagues and each region of writing available was different.

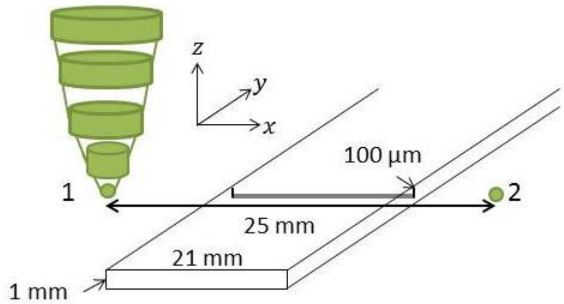

Fig. 2.2: Sample geometry and important points in fabrication method.

1. The sample stage was moved to the starting point (point 1 in Figure 2.2) of the writing step at a velocity of 20mms^{-1}: first, it was moved in the x direction, the direction of writing, and then moved the distance of waveguide separation in the y direction. This step was done without the laser on.
2. The power was adjusted for the intended power of writing.
3. The velocity of writing, 200 µms^{-1}, was selected. With the laser turned on in the mode already referred, the sample stage was moved 25 mm in the x direction. When it reached the ending point (point 2 in Figure 2.2), the laser was turned off. The process was then repeated until all the intended waveguides were written.

Using the process described, 7 waveguides were written with a varying power in the range [50,200] mW. The fabricated waveguides are summarized in Table 1.

Waveguide	$P_{writing}$(mW)
1	50
2	75
3	100
4	125
5	150
6	175
7	200

Tab. 1: Waveguides fabricated and writing power.

3 Waveguide characterization

A waveguide can be characterized by its propagation loss and by the intensity profile. These studies were made with the fabricated waveguides[3]. Two measurement setups were used and are represented in Figure 3.1 and Figure 3.3. Both experimental setups used two lasers: a red laser with a wavelength of 633 nm for alignment and an infrared laser (Santec TSL-210V) for measurements with λ=1.5 µm. The infrared laser is used due to the transmission spectrum of silica, which has a maximum in the infrared region [1].

[3] Studies made on the 27th of October.

3.1 Propagation loss

The loss was studied using the setup represented in Figure 3.1. The waveguides written were coupled to two single mode optical fibres (SMF), one connected to one of the lasers (input of the system) and the other one to a detector that measured the power (output of the system). The sample was positioned in a workstation precision stage (Elliot Martock MDE881) under a microscope (Leica) and it was hold by vacuum. The SMFs were placed in precision stages in the same workstation. This stages could be controlled by piezoelectric elements with a nanometre precision (Elliot Science E-2100). The sample stage could be moved in the X direction and the fibres stages in the X,Y and Z directions. The directions are represented in Figure 3.1.

Each waveguide was then coupled to the fibres. This coupling was made by the alignment of the positions of every stage and by a index matching liquid (Cargille Series AA) to improve the coupling even further. The alignment was made in two phases. First, it was made with the red laser to see if guidance was happening and by the movement of the stages on the micrometre scale. Second, using the infrared laser and the measurement of the output fibre signal as

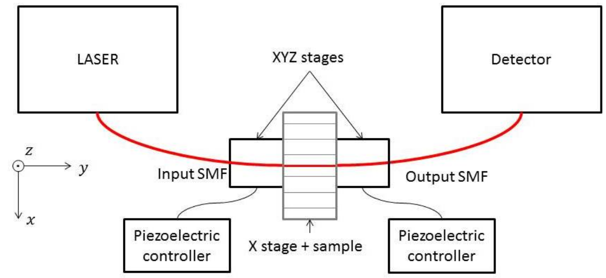

Fig. 3.1: Diagram of waveguide propagation loss measurement setup. (SMF: single mode optical fibre).

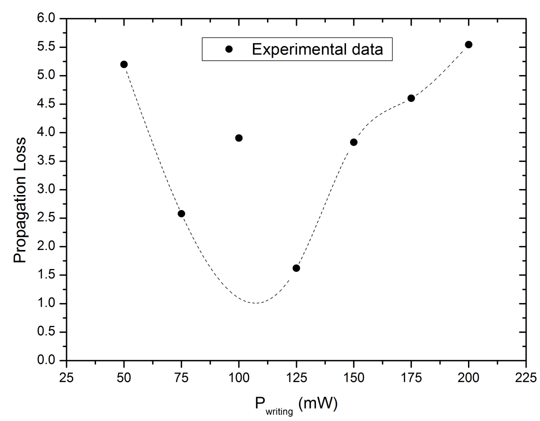

Fig. 3.2: Loss as a function of the writing power of each waveguide P.

orientation, the piezolectrics were used to make the final adjustments.

The loss in dB in a waveguide is given by equation (3.1). The P_{ref} is the reference power that is detected when the two fibres are coupled together without the waveguide and the P_{out} is the output power measured when the waveguide is coupled to the two fibres. With this measurement, the loss obtained include the loss at the waveguide, at the fibres and at the coupling between the fibres and the waveguide. The reference power P_{ref} gives information about the loss at the fibres and at the coupling. The power guided through the waveguide P_{out} includes the same losses plus the loss at the waveguide. The input power of the infrared laser was 1 mW and the output power was of the order of 100 µW (P_{ref}=860 µW)

$$Loss = -10 \log \frac{P_{out}}{P_{ref}} \tag{3.1}$$

In Figure 3.2, it is pictured the propagation loss as a function of the writing power of each waveguide $P_{writing}$. It is verified that the waveguide with the smallest losses is the waveguide that was written with a power of 125 mW, having 1.62 dB of propagation loss. It is seen that the waveguide made with 100 mW had some problems. It can be concluded that this waveguide could have been badly written or that the sample was dirty in the location of this waveguide. Due to this, the tendency line of the loss was obtained without considering this point. The overall results indicate that the best waveguides are obtained with powers between 110 and 125 mW. Furthermore, the overall propgation losses are small when compared to other waveguides written with similar methods[4].

3.2 Mode profile

The mode profile of the waveguide and of the SMF was measured using the setup represented in Figure 3.3. As in the previous study, the sample was mounted on the movable stage and hold by vacuum. The input signal was delivered by a fibre also placed in the piezoelectric stage already referred. In this study, the output of the system was a lens (L1) (Nikon) that collimated the beam at a CCD camera connected to a computer. The lens was also placed in the piezoelectric stage and, as in the previous study, could be moved in the X, Y and Z directions represented in Figure 3.3.

Two measurements were performed with the infrared laser and by varying its power. The power was adjusted to prevent saturation of the camera image. First, the mode profile of the fibre was obtained. For this. the sample was removed of its stage and the fibre was

[4] This results were compared with results obtained by other groups.

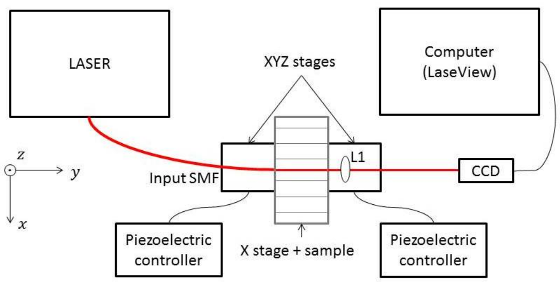

Fig. 3.3: Diagram of intensity profile measurement setup. (SMF: single mode optical fibre, L: lens, CCD: CCD camera)

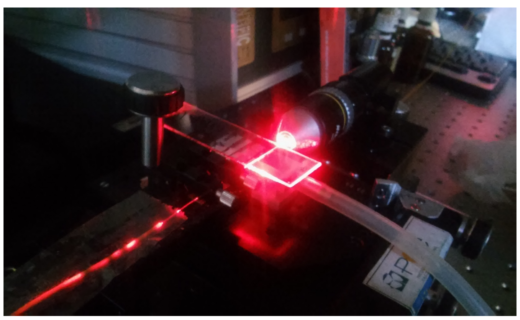

Fig. 3.4: Red laser beam guidance with the coupled system of the optical fibre and one waveguide written.

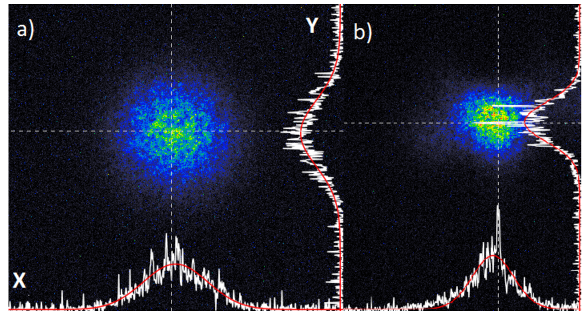

Fig. 3.5: Images taken from the CCD camera and fits obtained with the LaseView programme when it was being guided the infrared laser wave: a) SMF (single mode optical fibre; b) waveguide written with 125mW.

	a_x	a_y	a	d_x	d_y
Fit	81.75	79.92	80.84	58.33	57.10
Real	10.5	10.3	10.4	7.50	7.35

Tab. 2: Intensity widths at $1/e^2$obtained with the LaseView software fit and its conversion to the real Gaussian mode size.

coupled to the lens. To obtain the intensity profile of the waveguides, they were coupled to the input fibre and the lens, following the same steps as in the previous study. Figure 3.4 is a picture of the guidance of the red laser beam in the SMF coupled to one waveguide. It is visible the absorption and loss both at the SMF and at the waveguide.

With the camera connected to the computer, an image of the intensity profile was obtained. Furthermore, a fit of the intensity was calculated using the software LaseView. It was verified that all the waveguides had similar profiles. These profiles were also similar to the optical fibre profile, which is Gaussian.

In Figure 3.4, it is pictured the images obtained with the camera of the intensity profile of the SMF and of the optimal waveguide found in the previous study (P=125 mW) and the fits obtained with the software. From these fits, the widths at an intensity equal to $1/e^2$ were obtained and are presented in Table 2. The profile of the fibre is used to calibrate the image scale[5]. The mode size of the fibre is known to be 10.4 µm at the wavelength used (1.5 µm) [1]. With this, the mode size of the waveguides can be estimated. The value is 7.50 µm in the X direction and 7.35 µm in the Y direction.

Having estimated the mode profile width, it is useful to obtain the mode mismatch losses. This exists due to the difference between the mode field diameter of the fibre and of the fabricated waveguides. The mode mismatch losses can be quantized by the coupling efficiency, η, that depends on the electric field mode distribution of the coupling fibre and waveguide. For

[5] In order to obtain the mode sizes more precisely, the camera and the software used should be automatically and more precisely calibrated by the intensity profile of the fibre. This could not be done, because the characteristics of the camera were not fully known.

Gaussian mode profiles, the efficiency can be simplified and given by equation (3.2), depending on the mode diameter of the single mode fibre a and on the mode diameters of the waveguide, d_x and d_y.

$$\eta = \frac{4a^2 d_x d_y}{(d_x^2 + a^2)(d_y^2 + a^2)} \tag{3.2}$$

Using equation (3.2), it is obtained that the coupling efficiency of the fibre with the waveguide fabricated with 125 mW is 0.89. The coupling losses, in dB, can be obtained by equation (3.3) using the coupling efficiency. The value obtained for the optimal waveguide is 0.48 dB.

$$CL = -10 \log(\eta) \tag{3.3}$$

4 Conclusion

In this work, it was developed and optimized a setup and a method for femtosecond writing of waveguides into a glass substrate. With this method, seven waveguides were fabricated. They were written with a varying power in the range [50,200] mW.

Characterization studies were carried out with the written waveguides. It was verified that the best waveguide was written with 125 mW, having a loss of 1.62 dB. It was concluded that in order to obtain waveguides with the smallest loss, the writing power should be between 110 and 125 mW.

Furthermore, it was observed that the waveguides have a Gaussian intensity profile. With the waveguide written with 125 mW, it was verified that it had a similar mode profile as the SMF, with an intensity size of 7.50 µm in the X direction and 7.35 µm in the Y direction.. It was obtained, for this waveguide, a coupling efficiency of 0.89 and a coupling losses of 0.48 dB.

To conclude, the method used allows one to fabricate good quality waveguides inside materials as fused silica glass. It is therefore possible to develop three dimensional photonic structures and to produce integrated optical circuits that can find diverse applications in today's technological world.

References

[1] Luis Andre Fernandes. *Birefringence and Bragg grating control in femtosecond laser written optical circuits*. PhD thesis, Department of Physics and Astronomy of Faculty of Sciences of University of Porto, 2012.

[2] Rafael R Gattass and Eric Mazur. Femtosecond laser micromachining in transparent materials. *Nature photonics*, 2(4):219–225, 2008.

[3] Stefan Nolte, Matthias Will, Jonas Burghoff, and Andreas Tünnermann. Ultrafast laser processing: new options for three-dimensional photonic structures. *Journal of Modern Optics*, 51(16-18):2533–2542, 2004.

[4] Roberto Osellame, Giulio Cerullo, and Roberta Ramponi. *Femtosecond Laser Micromachining: Photonic and Microfluidic Devices in Transparent Materials*, volume 123. Springer Science & Business Media, 2012.

[5] Lawrene Shah, Alan Arai, Shane Eaton, and Peter Herman. Waveguide writing in fused silica with a femtosecond fiber laser at 522 nm and 1 mhz repetition rate. *Optics Express*, 13(6):1999–2006, 2005.