# Ultrafast laser writing and characterization of waveguides

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**Abstract.** In this paper, a method for micromachining in a silica substrate is presented, through nonlinear absorption processes of femtosecond energy pulses. Waveguides were produced with this method, using increasing writing power, 220fs pulses at 500 kHz and a writing velocity of $400\mu$m/s. They were further characterized in terms of modal profile, propagation losses and coupling losses (to a single mode fibre Corning SMF-28). Those losses were found the be uncorrelated and the best waveguide was produced with 246 mW of optical power, having minimal total losses of 4.4 dB, divided in attenuation of 1.363 dB/cm and modal profile mismatch losses of 0.156 dB per coupling. Its modal diameter was measured with a method of beam expansion and incidence on CCD, yielding $9.65 \pm 1.13\,\mu$m, with an aspect ratio of 1.239. The best aspect ratios occured for greater writing power, as a consequence of increased isotropic thermal diffusion. The losses had a nonlinear evolution with writing power, exhibiting the existance of a global maximum at 185 mW (for propagation losses) and a W shaped curve (for coupling losses).

## 1 Introduction

It is difficult to believe that Theodore Maiman, back in 1960, could have ever guessed the ruby laser he had invented would have such a distinct technological impact in so many different areas.

More recently, the possibility of generating ultrashort pulses represented a decisive change of gear in terms of the possibility of reaching optical intensities as high as ever, allowing us to enter the realms of nonlinear optics and its strange frequency changing phenomena or, more in the scope of this work, the possibility of "writing" optoelectronic components in all three dimensions, with a conceptual simplicity of undegraduate optics.

## 2 Concepts

Waveguides are no more than structures, constructed with highly discrepant dimensions (transverse sections of microns and longitudinal length of a few centimeters), that guide light. For this to happen, they exploit the fact that light "prefers" travelling in higher refractive index media, so it suffices to somehow increase the reffractive index in a prismatic like region inside a slab of glass, for instance.

This is precisely what an ultrafast laser allows us to do. When ultrashort light pulses are focused inside an homogenous material, non linear absorption phenomena are

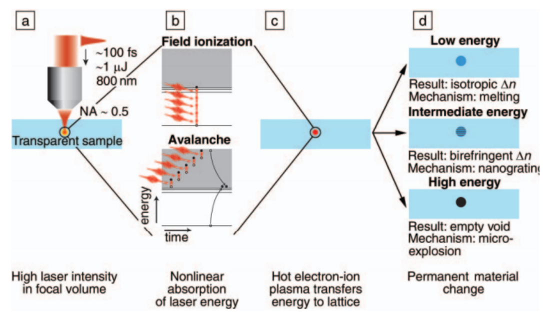


**Figure 1:** Nonlinear absorption mechanisms due to ultrashort pulses incident in homogenous media, such as silica (glass). Reproduced from Ref.[1].

likely to occur, which comprise impact ionizations due to avalanche phenomena or regular field ionizations. These phenomena locally raise the energy of electrons, which are now in the conduction band, and results in a localized alteration of the refractive index, as summarized in Fig.1.

The final step involves the control, whether manual or automatic, of the point to be written, by using a stage with, preferrably, three degrees of freedom for the possibility of accurate 3D micromachining.

Key parameters in the writing process are the writing velocity (of tipically some hundred $\mu$m per second) and the energy involved in the process. Not all energies pro-

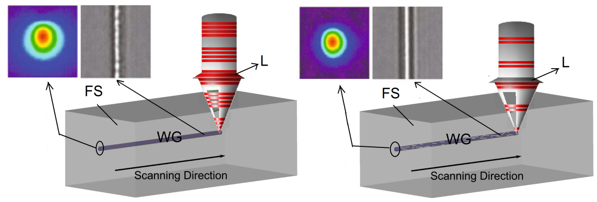


**Figure 2:** An illustrative example of the difference in using the same optical power exiting the laser and the same period in the laser, but different duty cycles, that is, a different percentage of time in which there is, in a given fixed time, actual sample exposure to laser light (duty cycle is increased from left to right). The scheme is based on Ref.[4] and the images were originally published in Ref.[2].

duce the change in index as desired, and even amongst the range that does, the uniformity of the waveguide is affected, especially if the energy control is performed by altering the duration of laser bursts.

Energy can arrive to the substrate in single pulses or in bursts [2], which is proven to be more effective. The duration of these bursts, each comprising some laser pulses, can be controled with the duty cycle of an acousto-optic modulator (AOM). This mechanism allows, therefore, for the production of structures like gratings.

The AOM principle of operation is the alteration of refractive index of a material as an acoustic wave propagates through it, and the consequent deflexion of light that traverses such medium. Light then diffracts, constructively interfering in preferencial directions, thus splitting the initial power with a controlable ratio. This mechanism allows for power control, by inputting femtosecond pulses and grabbing the appropriate beam from the AOM output. Further, the AOM can temporally sample a femtosecond laser beam, acting as a shutter that is opened a percentage of time in a period of modulation, that percentage being the duty cycle. It is widely documented that duty cycles [3] affects the quality of produced gratings, as seen in Fig.2.

For the characterization of waveguides, a typical optical loss evaluation setup may be employed, for the measurement of both the modal propagation and the coupling losses. Suppose light is coupled from a laser source to an optical fibre, and from there to the waveguides fabricated as described.

With the aid of an optical amplification system, light leaving the fibre or the waveguide can be magnified and studied with a CCD camera appropriately placed, showing the average photon count in each point (or space bin, for that matter) of the transverse section of the beam. From those image profiles, and upon calibration with the modal profile of the fibre, it is possible to estimate propagation and coupling losses.

# 3 Experimental setup

## 3.1 Waveguide fabrication

The experimental setup which was utilized for femtosecond laser writing is described in its fullest detail in Ref.[4] and represented in Fig.3. We briefly detail some important features of the apparatus.

*Generation module.* Light from the ultrafast laser device (FL, Satsuma by Amplitude Systèmes) is subject to a nonlinear process (second harmonic generation, SHG) through which wavelength is halved from 1030nm to 515nm.

*Power control module.* The half-wave plate (HWP, $\lambda/2$) serves as an analyser, thereby controling the fraction of power which is used in the writing process, after an appropriate disposal of the unwanted output beam, via the beam dump (BD). The Brewster angle polarizer (BP) serves the purpose of beam splitting, maintaining the polarization direction of light which enters the optical writing module. Their combined action allows for selection of polarization direction and power control.

*Entry module.* Here, light will be driven through the air from the BAP output to a periscope comprising $M_2$ and $M_e$ and then to an optical system comprising two lenses (for beam expansion) and another HWP, for polarization selection. From there, it passes through an apperture (A) and is reflected from a mirror ($M_w$) to the sample (S).

*Writing module.* The sample (S) which is to be written is placed in a holder. Now, light will be focused by a converging objective lens (OL) and incide the sample placed at $f_w$, the focal distance of the lens, with the possibility of reflection, encountering another mirror ($M_c$), which directs it toward the calibration module.

*Calibration module.* The control module comprises another converging lens ($L_c$) which focuses light in the CCD camera placed at the focal distance of $L_c$, from where data then follows to an appropriate viewing software. Since rays will be, at a point, focused into the CCD, an attenuator (At, Altechna watt-pilot) was used in order not to damage said device.

It should be noted that all mirrors mentioned are not (nearly) perfect reflectors, which is in fact an essential condition for propagation of light from the sample to the control unit to happen. Their transmissivities are of about 91%.

## 3.2 Waveguide characterization

As outlined in Sec.2, two different experiments were conducted.

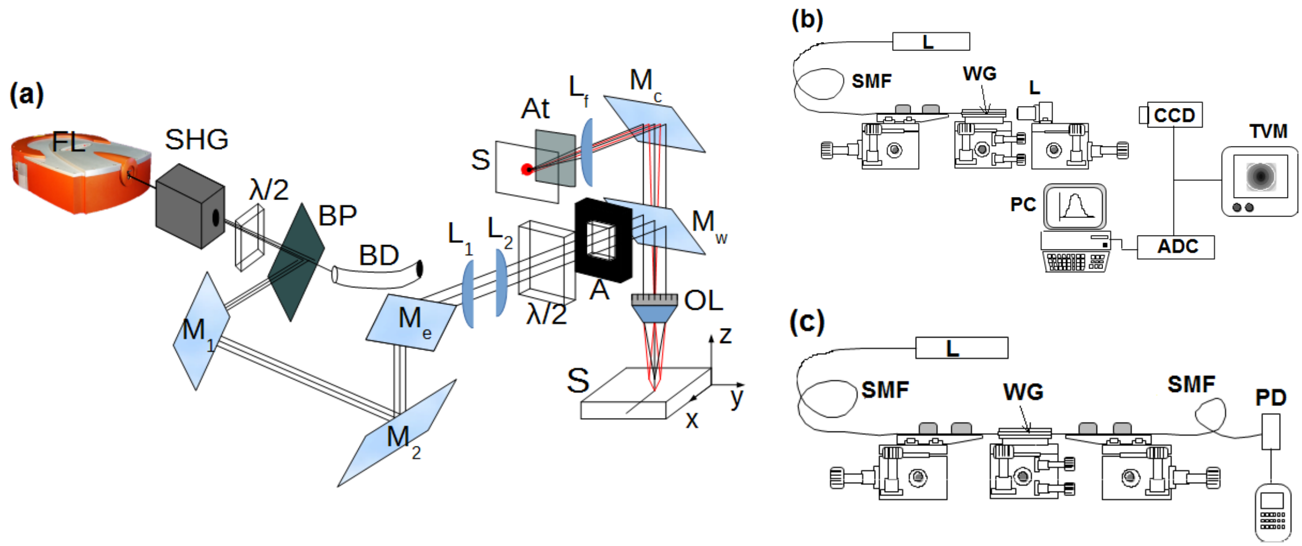


**Figure 3:** Experimental setups. (a) Femtosecond writing setup, based on [4], where the ray tracing is only accurate from the writing module forward, and where the CCD/PC for monitoring is replaced by a screen (S). Notice the refraction of light inside the sample and the two spots formed by red/black rays (laser focusing off/on the sample surface). (b) and (c) Setups for, respectively, the acquisition of modal profiles and the measurement of total losses in the path of light from the laser to the detector (both images obtained from a support document, related to to the femtosecond experiment, to the course of Técnicas Laboratoriais Avançadas II in Faculty of Sciences of Porto).

Firstly, the mode profiles were determined, using the setup in Fig.3(b). Light from a Santec TSL-210V tunable laser, at 1.5 $\mu$m, was coupled to a single mode optical fibre (SMF), propagating through it reached the interface between the fibre and the waveguide (WG). The choice of the fibre, the model SMF-28 by Corning, was made aiming for one mode propagation, assuring that no modal dispersion occurs and, as such, that the modes between fibre and guide are as close as possible.

In order to determine propagation losses, the setup in Fig.3(c) was used. It comprises the same components as the previous setup, but after the waveguide, another segment of fibre is placed, conducting light towards a photodetector (PD), where optical power can be measured.

# 4 Methods

## 4.1 Fabrication technique

The high sensitivity of the writing experiments, even though a decisive advantage of the writing process, requires special cares in terms of allignment of the system. The apparatus at our disposal was already alligned up until the writing module.

Prior to any writing process, the two types of calibrations presented were performed. First, it was assured that the beam was being focused in the upper surfase of the glass slab. For that, we moved the objective lens in the z direction until the spot size seen in the CCD reached a minimum. From there, we made sure that the surface was the upper one, by finding the second surface with appropriate movements in the lens' stage. Second, the sample was moved in the x and y directions, in order to check changes in spot size, which occured, not because of misalignment of the system, but because the slab was defective and posessed two non paralell surfaces. This was tested by changing slabs, and the alignment was validated.

Another relevant verification was that of the horizontality of both surfaces of the substrate, which was done by varying the x and y position in the sample stage seen in the CCD and verifying if the spot changes its size, and if there is astigmatism of the beam in the CCD, which it should not happen if both surfaces are paralell between themselves and perpendicular to the beam, respectively.

Paralelly, some good practice procedures were assured, such as the centering of the beam in the glass slab in order to use as little material as possible.

## 4.2 Characterization of coupling losses in the interface fibre-waveguide

First, the modal profile which propagates in the fibre was determined, and so were its parameters, defined as the $1/e^2$ width of the intensity profile seen in the CCD (because we are dealing with squared powers, a decrease of $1/e$ in power is a decrease in $1/e^2$ in intensity).

The coupling of light from the fibre to the waveguide is limited by the method used, which was not at all rigorous and consisted of manually aligning the two structures, and verifying the image on the CCD. This method introduces error much more significantly than the assumption of gaussian modes for waveguides, so uncertainty bars were chosen not to be represented in the graphic conserning losses in Fig.4. These uncertainties are enhanced by the fact that sub-milimeter precision is required in the position matching between the fibre and the guide, since the overlap in their transverse section is no more than a few squared microns, in the best case scenario of full alignment.

In order to improve alignment, a 632.8 nm laser (in the visible region of the spectrum) was used in order to perceive the adjustment between fibre and guide, prior to using the infrared laser, in both coupling and propagation experiments.

Before capturing each profile, the power supplied to the laser was varied, so that there would be no saturation of the CCD camera, when the number of photons recorded is not be proportional to the number inciding in the receiver, introducing error. We must assume that the power of the laser has no direct influence on the size of the mode, in order for comparisons to be made.

For the measurement of the waveguide optical losses, the program OpenView was used. It consists of a platform for data acquisition from CCD cameras and further processing from the relative brightness of the image in order to retrieve detailed information about the mode. In order to characterize the assymetry of the profiles obtained, the procedure was to, for a given waveguide, measure six $1/e^2$ diameter values of the modes with a tool provided by OpenView, and varying the orientation of the axis along which they were measured.

The actual lengths of the modes were computed with the calibration factor obtained from the modal width of the fibre and the value of the mode provided by the manufacturer, without the need of extra calculations with the magnification factor and the display factor intrinsic to OpenView.

Using the values obtained for modal sizes, it is straightforward to determine an adimensional parameter $\eta$, which characterizes the efficiency of coupling. In order to obtain $\eta$, it was assumed that the corresponding modes were gaussian $\mathrm{TEM}_{00}$, which are symmetric about the axis containing the propagation vector of the mode. In these conditions, having measured the beam diameters in the directions paralell to the edges of the transverse section of the guides, $w_x$ and $w_y$, it is possible to obtain [5]

$$\eta = \frac{4rw_xw_y}{(w_x^2+r^2)(w_y^2+r^2)}. \tag{1}$$

Using this parameter, an important figure of merit was computed, the coupling losses, defined as

$$\mathrm{CL} = -10\log_{10}\eta. \tag{2}$$

The expression for coupling efficiency allow us to determine the amount of loss that is due to coupling, that is, the fractional amount of energy lost in a change of medium. Devising a setup that measures the loss in an optical system that couples light into the waveguides, it is therefore possible to subtract coupling losses to obtain the propagation losses due to the optical fibre (which are of simple measurement if information from the manufacturer is not to be trusted), to the connector from the laser output to the optical fibre and, as an ultimate goal, the propagation losses due to the fabricated waveguides.

## 4.3 Characterization of propagation losses inside the waveguide

The second part of the experiment involves switching setup to the total loss measurement setup. For the expression of propagation loss from coupling loss and total loss, a model was used where power is attenuated exponentially with the length inside an optical component, and where power is attenuated of $\eta$ everytime there is coupling between waveguide and fibre. The following expression may be derived for total losses,

$$\mathrm{TL} = 2\,\mathrm{CL} + (\alpha_{\mathrm{f}}l_{\mathrm{f}} + \alpha_{\mathrm{wg}}l_{\mathrm{wg}}), \tag{3}$$

where $\mathrm{TL} = -10\log_{10}P_{out}/P_{in}$ is calculated from the setup in Fig.3, and $\alpha$ is positive for appropriate exponentially decreasing power inside the fibre/waveguide, and expressed in dB/m. For the sum in parenthesis, the most significant contribution comes from the waveguide term, as $\alpha_{\mathrm{wg}} \gg \alpha_{\mathrm{f}}$, so that the term referring to the fibre will be ignored. We will call propagation losses (PL) to the value of $\alpha_{\mathrm{wg}}$.

Another possible approach followed by colleagues [6] was to assume background losses by determining the power loss in the case of a fibre-fibre connection (that is, removing the middle module in Fig.3(c) and bringing the fibres together). The method they used was to reference power measured in the powermeter to this background power. This approach removes the dependence on fibre parameters shown in 3, but introduces a new variable, since no splicing was performed and coupling losses between fibre are not negligible. For that reason, it was chosen to keep the method devised above and measure PL disregarding losses inside the fibre.

# 5 Results and discussion

Then, waveguides were written in the substrate using five values of writing power. The user interface of the system allowed for one to choose between setting the percentage of laser power [1] to be used in writing, or its absolute value.

The writing was performed with pulses of 220fs, occuring at a frequency of 500 kHz, and with a duty cycle of 100%, so that no grating structure would be produced, only homogenous waveguides. These typical frequencies allow for isotropic thermal recovery in the substrate, in theory improving the aspect ratio of the modal profiles. Before writing, the laser was pointed to a depth of 50$\mu$m, and all the resulting waveguides had a length of 3cm. The writing velocity was selected to be 400 $\mu$m/s. As suggested in Ref.[4], the polarization was set, via the HWP in the entry module, to paralell to the writing direction.

The widths of waveguide modes are presented in Fig.4 for several waveguides written with different powers. The values and uncertainty bars represent, respectively, the mean value and one standard deviation of the set of widths obtained for each waveguide. It is possible to see that there is no linear correspondence between wtriting power and mode diameter. The confinement is best for the waveguide fabricated with 62 mW.

The results for the aspect ratio represent the maximum quotient between the six modal widths in orthogonal directions that were measured for each waveguide and the uncertainty represents the deviation of the maximum aspect ratio from the mean value of all six computed aspect ratios. The aspect ratio has the tendency to be improved with increasing writing power, showing the increase of isotropic thermal effects in the amplified laser system, which reduces the "squeezing" of the mode in the direction perpendicular to the laser beam.

As outlined in Sec.4, the information from the manufacturer about the mode profile guided in the fibre allowed a correspondence between pixel lengths and "true" lengths. Dividing the modal width in the fibre, 10.4$\mu$m, by the respective pixel width, we obtained a conversion rate of $\approx 12.596$ px/$\mu$m, from which the widths and the coupling efficiencies were computed.

[1] after losses due to the optical system, which are significant since the power of the writing pulses is 10W – the power control module attenuates this value of about 4 orders of magnitude.

Compared to data from other research groups [6], we determined a much more significant mismatch between fibre and waveguide modes, therefore an increased amount of coupling losses. With the data extracted from our own experiments, and even considering that attenuation inside the fibre is negligible, we obtain $\alpha_{\mathrm{wg}} < 0$, that is, the waveguides behave as amplifiers, which is unphysical. From that, we conclude that data concerning the modal profile inside the fibre was poorly extracted.

In what follows, all data from the optical fibre was requested to colleagues [6]. From there, the calibration factor had to be computed again, just like new coupling losses. In Fig.4, to the left, it is possible to see the difference in modal profiles of the fibre obtained by colleagues and by us (check caption for details).

The results shown in Fig.4, to the right, exhibit the quality of produced waveguides as a function of writing power. The results in the coupling losses reflect directly the proximity between waveguide and fibre modes.

The evolution of the losses with power depends heavily on the type of losses. When considering propagation losses, they increased until reaching a maximum, and then decreased for the maximum power tested (246 mW).

Finally, the W shaped curve for coupling losses shows, in comparison to other work [7], that perhaps an error in measurement might have occured.

What seems to be visible, at least in part, is a tendency for the higher number of photons to generate less dispersed statistics in terms of where they hit the silica, thus confining the mode, and providing lesser couping losses. However, the behaviour for higher power seems not to be explained by this interpretation.

# 6 Conclusive remarks

A femtosecond laser was used with varying MOD efficiencies providing different writing powers in the range for the writing of waveguides in fused silica. The waveguides were then characterized in terms of extraction of modal profiles, of coupling efficiencies and propagation losses.

The writing occured at a speed of 400 $\mu$m/s and the lengths of the waveguides were of 3 cm.

The optimal waveguide produced, with a power of 246 mW, had minimum total losses of 4.4dB, which are a balanced combination of low loss in propagation (1.363 dB/cm) and in coupling (0.156 dB) to a single mode fibre (SMF). Its modal diameter was found to be $9.65 \pm 1.13\,\mu$, and the assymetry measure of the propagant mode in the guide was quantified with an aspect ratio, that was of 1.239 for the optimal guide.

The minima of propagation (1.363 dB/cm) and coupling

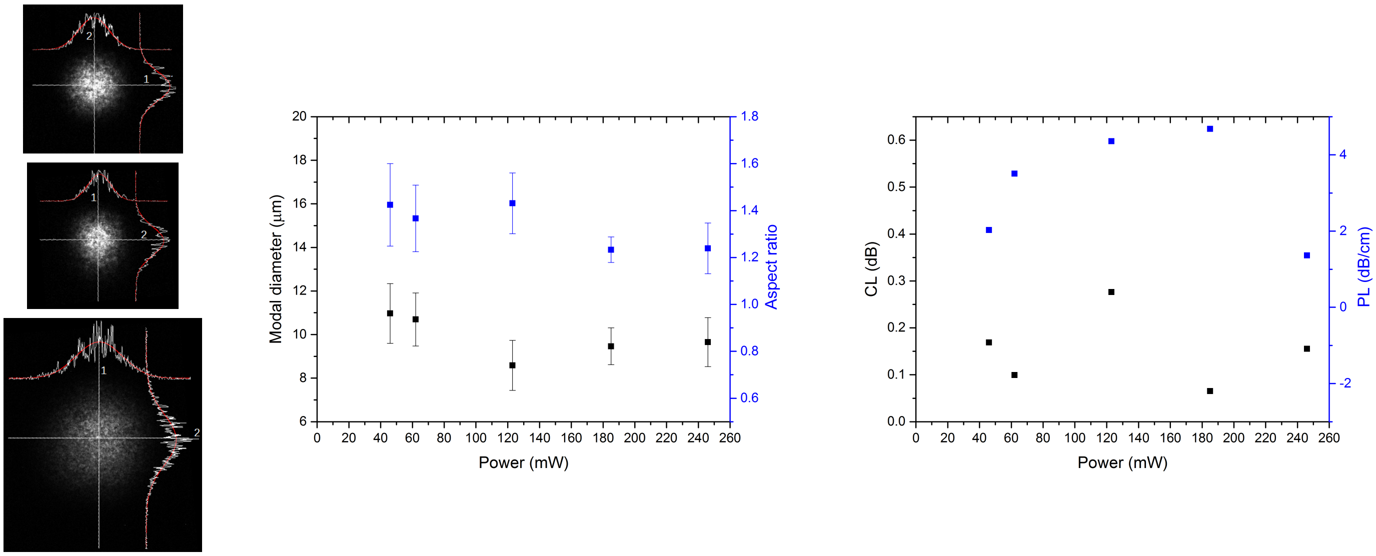


**Figure 4:** Experimental results. In the left are representations of modal profiles obtained with OpenView overlapped with the original CCD image (from top to bottom, the fibre mode obtained in [6], the guided mode and the fibre mode obtained by our group). In the middle, modal characterization of the waveguides (see text for information on error bars). In the right, coupling losses (CL) and propagation losses (PL) as a function of writing power.

(0.065 dB) losses did not coincide, and those parameters were uncorrelated in the context of this experiment.

As further work, focusing on waveguides, the next step would be the a more accurate coupling between fibre and waveguide, in order to find the practical limit of coupling efficiency. The variation of other parameters, such as writing velocity, should also be tested, always with the aim of optimizing the devices produced. Finally, other structures could be produced by this method, so a full range of work is at disposal in order to prove feasibility of the method for other structures.

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