Single-step fabrication of surface waveguides in fused silica with few-cycle laser pulses

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Abstract

Direct laser writing of surface waveguides with ultrashort pulses is a crucial achievement towards all-laser manufacturing of photonic integrated circuits sensitive to their environment. In this Letter, few-cycle laser pulses (with a sub-10 fs duration) are used to produce subsurface waveguides in a non-doped, non-coated fused silica substrate. The fabrication technique relies on laser-induced microdensification below the threshold for nanopore formation. The optical losses of the fabricated waveguides are governed by the optical properties of the superstrate. We have measured losses ranging from less than 0.1 dB/mm (air superstrate) up to 2.8 dB/mm when immersion oil is applied on top of the waveguide.

Photonic integrated circuits (PICs) can be broadly defined as devices involving several integrated optical components [10]. Thanks to their outstanding versatility, PICs are used in a wide range of applications including optical communications [29], biosensing [20, 7], and quantum optics [18, 26]. Waveguides constitute a fundamental building block of PICs. Beyond their ability to transport light, straight and curved waveguides can be combined to create functional passive elements (e.g. splitters, microinterferometers, multiplexers, lenses) [9] as well as active optical devices [1].

Several fabrication techniques may be used to produce waveguides in glass substrates [11]. Among these, laser writing of waveguides is especially attractive because it does not require a cleanroom environment, is cost-effective, and offers a high throughput [11]. Two direct laser fabrication techniques have been demonstrated: UV- and fs-laser writing. UV-laser writing relies on a photochemical reaction to induce a permanent refractive index change. This method...
requires the deposition of a photosensitive layer on top of the target substrate such as a germanosilicate thin film \cite{5}, restricting the applicability of UV-laser writing to the surface of the sample. Since the individual photo-sensitive reaction is the result of the absorption of a single UV photon, the pulse duration is unimportant in UV-laser writing. Conversely, fs-laser writing enables full 3D waveguide fabrication in many host materials, including pure fused silica. However, using this technique on or near the surface is challenging. The main reason is that direct fs-laser writing traditionally relies on pulse-to-pulse heat accumulation to induce controlled, localized heating of the substrate. After cooling, high-refractive index regions with light-guiding capabilities appear. In this scheme, the magnitude of the stress load produced upon thermal relaxation is a major limitation. Attempts in non-toughened glasses have resulted in surface swelling \cite{4}, cracking \cite{16} and ablation \cite{27}.

In this Letter, we describe the direct fabrication of surface waveguides in fused silica with the help of few-cycle laser pulses. Our method does not rely on pulse-to-pulse heat accumulation, but instead is based on the type 1 laser-matter interaction regime \cite{19}. Modifications induced in the type 1 regime exhibit a smooth, uniform and positive index refractive index change $\Delta n$, in contrast to type 2 modifications which are characterized by a strong birefringence due to the presence of periodic nanogratings in the irradiated region. Furthermore, we demonstrate the existence of a strong coupling between the refractive index of the superstrate ($n_s$) and the optical transmission of these waveguides and discuss potential applications.

The experimental setup is depicted in Fig. 1. Few-cycle pulses (sub-10 fs duration) from a high repetition rate (400 kHz), non-collinear optical parametric amplifier \cite{8} were focused with a gold-coated refractive objective (numerical aperture 0.5) on the surface of a fused silica sample. Using reflective optics enables preserving the temporal structure of the laser pulse in the focal plane \cite{21}. The fused silica samples are parallelepipedic and polished to optical quality on all sides. A stepper motor is used to translate the sample along the laser beam direction at a constant speed of 60 $\mu$m s$^{-1}$.

We first examined the influence of the entrance pupil of the focusing objective on the laser energy deposition. The sample was irradiated for 10s at a 400 kHz repetition rate without moving. A 10x microscope objective formed an image of the sample surface on a camera sensor. A bandpass filter (transparent in the 655 nm $\pm$ 15 nm region) placed before the detector enabled visualizing the plasma luminescence which is otherwise overwhelmed by laser light scattering on the sample surface. For a fixed distance between the laser objective and the entrance face of the sample, two regions of interaction $RI_1$ and $RI_2$ appear. The results reported in Fig. 1(b) are obtained for $d = 500 \mu$m, where $d$ is the distance from the air/glass interface to the matched-medium focus. The laser beam filled the back aperture of the reflective objective, with a $\approx 13 \text{ mm}$ diameter at $1/e^2$. By design, the effective entrance pupil of the reflective objective was annular, with a resulting transmission factor $T \approx 36\%$. $RI_1$, on the left hand side of Fig. 1(b), is formed by the laser radiation traveling through air only. The length of $RI_1$ along the laser propagation direction is $\approx 70 \mu$m. $RI_1$ is
Counts

Figure 1: (a): Cross-sectional view of the experimental setup. The part of the laser beam represented in bright red propagates through air only and forms the region of interaction $RI_1$. The beam blocker can be put in the beam path to prevent the part of the laser beam represented in transparent red to form the region of interaction $RI_2$. The microscope objective (15x, NA=0.5) is gold-coated. $d$: distance from the air/glass interface to $RI_1$. (b): Left: Shape of the effective entrance pupil when the objective is completely illuminated by the laser beam. The transmission $T$ is 0.36. Right: Intensity map observed after a bandpass filter (central wavelength of 655 nm) during laser exposure. (c): Same as (b) using the beamblock and iris shown in (a).

accompanied by a second region of interaction $RI_2$ with a 140 µm length. $RI_2$ is formed by the optical rays propagating through the bulk sample. The presence of a planar air/glass interface in the optical path of the laser beam producing $RI_2$ induces spherical aberrations which lead to a shift and elongation of the focal volume [15]. The magnitude of the pulse distortion varies with $d$, suggesting that the irradiation conditions in $RI_2$ cannot be kept constant as the sample moves along the laser propagation. In order to limit the irradiation to the part of the beam traveling through air only, we placed a beam blocker to cover the lower half of the back aperture of the objective, thus providing a half-annular entrance pupil. Furthermore, the entrance of the beam diameter was slightly
reduced with the help of an iris to optimize the plasma distribution in the focal region [Fig. 1(c)]. In this case, the incident laser pulse does not interact with glass before reaching the focal plane and the irradiation conditions remain invariant when translating the sample along the direction of the laser beam. The fabrication of a single line-shaped microstructure is then straightforward. It suffices to irradiate the surface of the substrate continuously from edge to edge by translating the sample over a distance of at least the sample width. In what follows, the laser pulse energy was constant with a value of $E = 530 \text{nJ}$ after the microscope objective. For higher pulse energies, intense laser light scattering occurred and the irradiated region exhibited a mix of negative and positive refractive index changes (not shown). These features are indicative of the type 2 interaction regime characterized by the formation of nanopores [3, 19].

In Fig. 2(a) we show the laser footprint on the exit facet after sample polishing, using optical transmission microscopy (111x optical magnification). The laser-induced microstructure has a width $w \approx 2 \mu m$ and a height $h \approx 6 \mu m$. Diagnostics of the top surface with an atomic force microscope (AFM) are presented in Fig. 2(b), and reveal the presence of a shallow surface topography variation ($< -10 \text{nm}$, about $430 \text{ nm FWHM}$) on top of the laser-induced microstructure. The negative sign of the topology variation is indicative of a volume reduction (and hence a density increase) in the irradiated area, and is the opposite to what happens when microprocessing is performed in the type 2 regime, with longer (35 fs) and more energetic (about $2 \mu J$) laser pulses where surface swelling as high as $250 \text{ nm}$ was measured [4]. An inversion in the sign of the surface topography is consistent with recent observations reporting a volume reduction of glass cantilevers irradiated in the type 1 regime and a net volume increase of cantilevers irradiated in the type 2 regime [3]. We emphasize that the absence of recast in the AFM pictures hints towards a purely non-ablative process. The phase shift distribution $\Delta \phi$ across the laser-induced microstructure presented in Fig. 2(c) was measured by spatial light interference microscopy [30]. As expected from a local density increase, $\Delta \phi$ is positive in the irradiated volume [25]. The corresponding spatial average of the laser-induced refractive index change $\Delta n = \frac{\lambda_c \Delta \phi}{2 \pi h} \approx 0.006$, where $\lambda_c = 550 \text{ nm}$ is the central wavelength of the illumination source (an halogen light bulb in our case), $h = 6 \mu m$ is defined in Fig. 2(a) and $\Delta \phi = 0.43 \text{ rad}$ is the phase shift measured at the center of the microstructure. We emphasize that the magnitude of $\Delta n$ obtained exceeds the value of $10^{-4} - 10^{-3}$ usually measured in the bulk for type 1 modifications [19].

Recently, micro-Raman measurements in the bulk of irradiated fused silica samples have revealed that the relative increase of the D2 peak is directly proportional to the refractive index change [19]. To further confirm our conclusion on the laser-induced compaction and refractive index increase, micro-Raman investigations were performed on the pristine and irradiated material, as shown in Fig. 2(d). The spectra were normalized with respect to the amplitude of the $\omega_3$ band [23]. They reveal an increase of the D2 peak (centered at $600 \text{ cm}^{-1}$) in the irradiated volume, confirming a local laser-induced compaction [2, 3]. These micro-Raman measurements were carried out on the top surface of the sample and might not necessarily correspond to the maximum of compaction, presum-
Figure 2: Characterization of the laser-induced optical structures. (a): Side view of the sample acquired with an optical transmission microscope. The sample is illuminated with an halogen lamp. (b): Surface topography (top view) measured with an atomic force microscope (AFM). (c): Phase shift across the microstructure, measured with a spatial light interference microscope (SLIM). (d): Micro-Raman investigations of the irradiated zone (purple line) and of the pristine sample (grey line). The spectra were normalized with respect to the $\omega_3$ band.
Figure 3: (a): Near-field intensity profile at the exit of the laser-induced microstructure at a wavelength of 633 nm. The mode field diameters in the p- and s- directions are indicated in the picture. (b): Transmitted intensity as a function of the analyzer angle for linear input polarizations in the p- and s- directions (left) and for an arbitrary linear input polarization (right).

ably located in the center of the laser-induced microstructure (i.e. ≈ 3 µm away from the surface).

In order to examine the ability of the microstructures to guide light at optical frequencies, the fundamental mode of a CW He-Ne beam (λ = 633 nm) was focused onto the entrance facet of the laser-induced microstructures with a microscope objective (numerical aperture 0.42). A second microscope objective formed a 111-fold magnified image of the end facet on a camera sensor. Figure 3(a) shows the obtained output intensity distribution. It corresponds to a TEM00 mode and demonstrates that these laser-induced microstructures are single-mode optical waveguides at 633 nm. A modal analysis in the directions parallel (p-) and perpendicular (s-) to the surface of the sample (see Figure S1) provides a mode field diameter (MFD, defined as the 1/e² decay of the maximum mode intensity), of 4.3 and 6.0 µm in the p- and s- directions, respectively. The influence of the input polarization was examined by placing the waveguide between a polarizer and an analyzer. The transmission of the waveguide was measured as a function of the relative angle between the polarizer and the analyzer [see Fig. 3(b)]. The polarization is maintained for input fields with a linear polarization in the s- and p- directions (see thick transparent lines...
in Fig. 3(b) left). However, an input field with a linear input polarization in another direction becomes elliptically polarized upon propagation in the waveguide, which indicates that s- and p- polarized fields have different propagation constants.

Having confirmed the waveguiding capabilities of the laser-induced microstructures and their polarization-maintaining properties, we now examine the possibility to control the propagation losses by varying the refractive index of the superstrate $n_s$. By applying the optimum end-fire coupling method [13], losses $< 0.1 \, \text{dB mm}^{-1}$ were measured for $n_s = 1.00$ (in air). The losses obtained when applying a drop of immersion oil on top of the waveguide are shown in Fig. 4. The diameter of the oil droplet was controlled by using a graduated microsyringe.

A first order exponential fit of the experimental data indicates that the

![Figure 4: Evolution of the optical transmission at 633 nm as a droplet of immersion oil ($n_{\text{oil}} = 1.516$) with a variable diameter is placed on top of the laser-induced surface waveguide. The dotted line represents a fit of the experimental data using a single exponential decay. The presence of oil induces an attenuation of $2.83^{+0.48}_{-0.66} \, \text{dB mm}^{-1}$.](image)

superstrate-induced leakage is as strong as $2.83^{+0.48}_{-0.66} \, \text{dB mm}^{-1}$. The uncertainties were obtained from fits of the lower and upper bounds of the experimental values. In the so-called ray-optic approach of guided mode theory [28], the light propagating through a waveguide is described as a sum of oblique rays experiencing total internal reflection at the boundary of the waveguide. Changing $n_s$ changes the conditions for total internal reflection. When $n_s$ increases, the minimum angle for total internal reflection decreases and the steepest rays escape the waveguide [22]. The large attenuation coefficient deduced from the numerical fit indicates that the optical structures are sensitive to the refractive index of their environment and can thus be employed as refractive index sensors, with significant potential for lab-on-chip applications. These waveguides may for
instance constitute the sensitive part of optical biosensors microsystems that are used for label-free bio-sensing [24]. The optical structures presented in this letter may also be used as efficient photon/plasmon couplers to interface photonic and plasmonic architectures [12], or as the backbone for the fabrication of compact stationary-wave integrated Fourier-transform spectrometers [17]. Furthermore, the ability to control the losses in a waveguide is a critical achievement towards the fabrication of reconfigurable optical networks-on-a-chip [6].

In this Letter, we have presented a method to print waveguides directly on the surface of a pure fused silica substrate with the help of few-cycle laser pulses. This is the first time that surface waveguides are directly photoinduced on the surface of fused silica without need for pre- (e.g. deposition of a photosensitive material) or post-processing of the target substrate. The optical structures produced correspond to type 1 modifications, support waveguiding at optical frequencies, possesses polarization-maintaining properties and exhibit a core refractive index change of $\Delta n \approx +0.006$ on average. AFM measurements and Micro-Raman investigations indicate that laser-induced microcompaction is at the origin of the observed refractive index change. The waveguides are sensitive to their environment, extending the capability of the direct laser write method to the rapid prototyping of compact optical microsystems taking advantage of all the well-known benefits (small size and weight, low power consumption, improved reliability and vibration sensitivity [14]) of integrated optics devices.

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Supplemental Documents
See Supplement 1 for supporting content

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