Deep subsurface optical waveguides produced by direct writing with femtosecond laser pulses in fused silica and phosphate glass

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Abstract

In the present work, we have analyzed the use of elliptical beam shaping along with low numerical aperture focusing optics in order to produce circular cross-section waveguides in different materials at large processing depths by direct femtosecond laser writing (100 fs, 800 nm, 1 kHz). A variable slit located before the focusing optics allows to generate a nearly elliptical beam shape and also to reduce the effective numerical aperture of the beam along the shat axis of the ellipse. The focusing optics allows to focus the beam deep inside the sample, which is translated at a constant speed transversely to the writing beam direction. The influence of several experimental parameters (energy per pulse, slit width, processing depth) on the properties of the produced waveguides has been analyzed. The influence of the intrinsic properties of the material (refractive index, composition) has been analyzed by comparing results obtained in fused silica and Er:Yb co-doped phosphate glass. The results obtained show that this approach leads to the successful production of deep subsurface (up to 7 mm) waveguides with circular cross-sections. Preliminary results using chirped pulses in the phosphate glass suggest that temporal pulse shaping can be used as an additional parameter to optimize the guided mode symmetry.

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1. Introduction

Non-linear processing of dielectrics using femtosecond laser pulses has been widely studied over the last years [1]. During the process, the dielectric material, transparent to the irradiation at low powers, experiences multi-photon absorption and avalanche ionization if a powerful laser beam is tightly focused inside it. The energy coupling of the laser inside the material can lead to a variety of localized structural modification processes amongst which the modification of its refractive index is one of the most widely studied, as it allows producing a variety of photonic elements in a 3D configuration. Waveguides [2], Y-couplers [3], amplifiers or lasers [4], have already been produced by this technique. Still, the production of these elements is generally limited to a shallow region close to the surface due to the approximately linear increase of the spherical aberration (SA) with depth caused by the refractive index mismatch at the air–dielectric interface [5–7]. The main effect of SA is to stretch the focal volume along the beam propagation direction, leading to modified structures with elongated cross-section and also to a corresponding decrease of the volume of transformed material as the energy is deposited over a much larger focal volume.

The finite numerical aperture (NA) of the focusing optics also causes ellipticity of the focal volume. In absence of SA (for instance at shallow processing depths) and for powers within a regime where non-linear propagation effects are negligible, the dimension of the focal volume along the propagation axis (z-axis) is given by the Rayleigh range \( Z_R \): \( \Delta Z = 2Z_R = 2n\lambda/\pi NA^2 \), \( n \) being the refractive index of the material and \( \lambda \) the laser wavelength. The transverse dimensions of the beam at the focus scale as \( 2\omega_{0x,y} = 2\lambda/\pi NA \), where \( \omega_{0x} \) (\( \omega_{0y} \)) are the \( 1/e^2 \) intensity radius along the \( x(y) \) axis. The focal volume is thus an ellipsoid with an aspect ratio \( AR = Z_R/\omega_{0x,y} = n/NA \). In order to achieve a spherical focal volume it is thus necessary to use a NA equal to the refractive index of the sample.

The use of elliptical beams [8,9] provides though a way to generate waveguide structures with circular cross-section. The fundamental idea of this approach consists of using an elliptically shaped beam with one of its transversal dimensions,
namely x, being substantially longer than the other. The elliptical beam can be produced by using a cylindrical telescope or a slit. When this beam, propagating along the z-axis is focused, its smaller transverse dimension (y) with a much smaller effective NA gets less focused. The telescope or the slit can be arranged in such a way that \(2\omega_0\), increases to a size comparable \(2\omega_z\). The focal volume adopts then the shape of a nearly circular disk in the y-z plane. In the particular case of waveguide writing, if the sample is moved then along the x-axis the waveguide produced will show a nearly circular cross-section.

This approach is valid, provided that the processing depth and the NA are small. Otherwise SA effects cannot be neglected, leading to a further elongation of the focal volume (beyond \(Z_R\)). The elongation increases with processing depth and can be estimated according to the following expression [7]:

\[
\Delta Z_{SA} \approx d \left( \frac{\sqrt{1 - \left( \frac{\text{NA}/n}{} \right)^2}}{1 - \text{NA}^2} - 1 \right)
\] (1)

From the above description it turns out that in order to minimize the dimension of the focal volume along the propagation axis at a given depth a compromise is required between decreasing \(Z_R\), by using high NA optics, and decreasing SA effects, by using low NA optics. However, even if this compromise is reached, the cross-section of the focal volume would still be elliptical, unless this approach is combined with elliptical beam shaping yielding a circular cross-section as proposed in this paper. We investigated this approach using slit shaping in two different materials (fused silica and Er:Yb co-doped phosphate glass) under different experimental conditions in terms of pulse energy (\(E\)), slit width (\(\Delta S_x\)), processing depth (\(d\)), . . . in order to optimize the performance of the produced waveguides. The work includes also some preliminary results regarding the potential use of temporal pulse shaping as a tool for optimizing the guided mode symmetry.

2. Experimental details

A scheme of the experimental setup used for producing waveguides is shown in Fig. 1. The laser source is a commercial fs-amplifier operating at a wavelength of 800 nm and providing 100 fs laser pulses at 1 kHz repetition rate. The horizontally polarized amplified beam passes through a variable slit located at a distance of 21 cm from the focusing optics. The longer axis (x) of the slit lies in the horizontal plane. The focusing optics is a 10×, long working distance (30 mm) microscope objective with focal length \(f = 20\) mm, and a nominal NA = 0.26. The output beam of the amplifier has a diameter (1/e\(^2\)) of 7.4 mm, making the effective NA along the x-axis to be \(\text{NA}_x = 0.18\). During irradiation the samples are scanned along the x-axis at a constant speed of 100 μm/s in order to generate waveguides with a length of 2 cm. The samples are commercial glass blocks 1 cm × 1 cm × 2 cm of fused silica (Lithosil from Schott), and phosphate glass doped with 2.2%Er\(^{3+}\) and 2.5%Yb\(^{3+}\) (wt.%) (MM2 from Kigre Inc.).

In the case of phosphate glass, the use of chirped pulses (obtained by detuning the compressor section of the amplifier system) in order to improve the properties of the waveguides was also investigated. In this case, an additional transversal imaging system is employed to record images of the emission of the plasma generated inside the material. A microscope objective coupled to a tube lens and a CCD camera was used for the purpose (see Fig. 1). In this way real time images of the plasma emission in static conditions were acquired while using different \(\Delta S_x\), or amounts of chirp in order to generate a plasma volume with best circular symmetry. The optimal conditions thus found were then used to produce the waveguides by translating the sample at the same speed as the fused silica sample.

After polishing the end surface of the samples, the written waveguides were characterized using a He–Ne laser (633 nm) and a microscope objective to couple the light into the waveguides (see Fig. 1). Near field images of the guided mode light distribution at the exit plane of the waveguides were recorded using a standard imaging system. Further details regarding the experimental setup and the characterization of the waveguides can be found elsewhere [10].

3. Results and discussion

3.1. Influence of the processing depth, slit width and pulse energy

In order to study the different factors affecting the properties of the waveguides produced, we concentrate on the results obtained in fused silica. In this case the study has been focused on the specific roles of \(d\) and the \(\Delta S_y\). The study of the influence of \(E\) was confined to a regime in which non-linear propagation effects are negligible. Fig. 2 shows several illustrative examples of near field images at 633 nm of the intensity distribution at the exit plane of waveguides produced in fused silica for different \(\Delta S_y\) and \(d\). The slit width has been typically varied from 200 to 500 μm. This range has been chosen because in a rough approximation [9], the expected \(\Delta S_y\) to achieve circular waveguides in our conditions (\(\text{NA} = 0.26\), \(R_s = 3.7\) mm, \(n = 1.45\)), would be 320 μm according to next equation:

\[
\Delta S_y = R_s \sqrt{\frac{\ln 2 \text{ NA}}{3 n}}
\] (2)

![Fig. 1. Scheme of the experimental setup used for waveguide writing and characterization where S is the sample, MO is the focusing microscope objective, ILS are the imaging lenses, L is the collimation lenses and CMO is the coupling microscope objective.](image-url)
Fig. 2a shows the image corresponding to a waveguide produced with \( \Delta S_y = 200 \, \mu \text{m} \) at 8 \( \mu \text{J/pulse} \) and a depth of 1.45 mm. It can be seen that the mode is elliptical with its long axis oriented along the \( y \)-axis. In this case effect of the slit is to produce an excessive stretching of the focal volume along the \( y \)-axis, which is larger than the dimension of the focal volume along the propagation axis (\( z \)), including both, the \( Z_R \) and the SA induced elongation. On the contrary, if \( \Delta S_y \) is too wide (i.e. \( \Delta S_y = 500 \, \mu \text{m} \) shown in Fig. 2b), the stretching of the focal volume along the \( y \)-axis is insufficient. The effect of an optimal \( \Delta S_y \) can be seen in Fig. 2c (\( \Delta S_y = 350 \, \mu \text{m} \)), with the stretching of the focal volume along the \( y \)-axis matching the combined effect of the \( Z_R \) and the SA, leading to nearly perfect circular cross-section in the propagated mode.

Although these results suggest that \( \Delta S_y \) requires an extremely careful adjustment for a given processing depth, actually, once an optimal width is determined for a given depth, the shape of the waveguide mode is nearly circular over a large processing depth interval. This is illustrated in Fig. 2d where the optimal value (\( \Delta S_y = 350 \, \mu \text{m} \)) for a depth of 1.45 mm has been used to produce a waveguide at a 7.25 mm depth. It can be seen that even at such large depths the AR of the waveguide is essentially circular. The influence of SA at this large depth is relatively small due to the low NA optics used. This is illustrated also by the fact that the same pulse energy was used in the waveguides of Fig. 2c and d. A further confirmation of this conclusion is given in Fig. 3 where the AR of the mode (\( y \)-axis dimension/\( z \)-axis dimension) is plotted as a function of the writing depth for \( \Delta S_y = 350 \, \mu \text{m} \) and several writing pulse energies. It can be seen that once the slit has been optimized at a certain depth (i.e. \( \sim 4.5 \, \text{mm} \), AR \( = 1 \)) the AR changes only within the range of \( \sim 20\% \) while the depth is nearly doubled or reduced to less than a half. At this point it is worth noting that in absence of a slit, the dimension along the \( z \)-axis of the structures produced is about 90 \( \mu \text{m} \) for a processing depth of 7.25 mm. This value is in excellent agreement with the value that can be obtained from Eq. (1), for a NA of 0.18 and a refractive index...
of 1.45 (fused silica at 800 nm) indicating that the slit not only stretches the focal volume along the y-axis but also reduces strongly the effective NA of the beam, reducing substantially the SA effects at large processing depths.

3.2. Influence of the material parameters

In order to understand the role of the material parameters in the production of deep subsurface waveguides, the behavior of a commercial phosphate glass (MM2, Kigre Inc.) co-doped with erbium and ytterbium (2.2%Er and 2.5Yb% (wt.%)) has been also investigated. In this case the processing depth was maintained constant (1.56 mm), and the temporal profile of the pulse were varied.

Fig. 4 shows several examples of near field images at 633 nm of the intensity distribution at the exit plane of waveguides produced in the phosphate glass. Fig. 4a corresponds to a waveguide produced with an optimal $D_{Sy}$. As in the case of fused silica, a mode with circular cross-section can be achieved. The small difference in the refractive index induced of fused silica (1.45) and the phosphate glass (1.56) leads to comparable $Z_R$ and SA focus elongation. As a consequence, the optimal $D_{Sy}$ found is similar. However, when comparing Figs. 2c and 4a, it is worth noting that the size of the guided mode is substantially smaller in the phosphate glass despite the higher pulse energy used. This confirms that both materials have different transformation thresholds and structural modifications mechanisms, which play an important role in defining the size of the refractive index modified region.

We have also studied the role of the pulse duration/chirp of the pulses used to irradiate the phosphate glass samples. As a starting point, unchirped pulses with a duration of 100 fs were used to write a waveguide with an elliptical cross-section whose major axis lies along the y-direction (slit too narrow). This waveguide is shown in Fig. 4b. Subsequently, in a different region of the sample (and maintaining the rest of parameters of the irradiation system: pulse energy, repetition rate and $D_{Sy}$), we used the imaging setup described in the experimental section in order to image the plasma distribution generated inside the sample while chirping the pulses leaving the amplifier. The pulse chirp was induced by changing the distance between the gratings in the compressor section of the femtosecond amplifier, aiming for a plasma image with circular symmetry. The corresponding image of the optimized plasma shape is shown in Fig. 4d and corresponds to positively chirped pulses (low frequencies arrive first at the sample) with a duration of 190 fs. Fig. 4c shows the near field image of the guided mode obtained from a waveguide written with these chirped pulses. In spite of being produced with a non-optimized $D_{Sy}$, the mode shows a circular cross-section. The comparison of Fig. 4b and c clearly demonstrates that by controlling the temporal structure of the pulses it is possible to optimize the

![Fig. 4](image-url)

Fig. 4. (a–c) Near field images of propagated modes at 633 nm at the exit plane of waveguides written in phosphate glass at a fixed depth $d = 1.56$ mm with different pulse energies and slit widths, using chirped and unchirped pulses. (a) $E = 6.4 \mu$J, $D_{Sy} = 350$ μm, unchirped; (b) $E = 6.4 \mu$J, $D_{Sy} = 300$ μm, unchirped; (c) $E = 6.4 \mu$J, $D_{Sy} = 300$ μm, positively chirped; (d) plasma emission image obtained during static irradiation using positively chirped pulses as the ones in (c).
cross-section of the guided mode. We have confirmed that the use of negatively chirped pulses (with the same duration as the positively chirped ones) does not lead to an improvement of circularity. Although at present we do not have a conclusive explanation for this preliminary result, the use of the chirped pulses has already been shown to increase the ablation efficiency in dielectrics [11]. However, in that case the effect was observed for negatively chirped pulses, unlike the present situation. Also, an improvement in the efficiency of energy coupling in the material under temporally shaped pulses has been reported to occur in several dielectrics [12] and metals [13], associated to the differences in the energy relaxation mechanisms and their characteristic time scales (electron–phonon coupling strength, plasma lifetime, formation of self-trapped excitons, . . .). Also, the presence of diffraction at the slit in combination with the chirp of the pulse could lead to a situation in which the energy of the different pulse frequencies could be more efficiently concentrated in a smaller focal volume.

4. Conclusions

We have shown that the combined use of elliptical beam shaping (using an adjustable slit) and low NA optics enables the production of deep subsurface waveguides with circular modes in different materials (fused silica and phosphate glass) by direct writing with femtosecond laser pulses. The AR of the waveguide mode can be effectively controlled through $\Delta S_y$, allowing to produce circular modes or elliptical ones with the long axis oriented either in the beam propagation direction or perpendicular to it. For a given $\Delta S_y$, the AR of the guided mode is only weakly dependent on of the processing depth (over several millimeters) and the pulse energy. The most important difference in the behavior of fused silica and phosphate glass samples is the size of the guiding modes, being smaller in phosphate glass. This difference is attributed to the different transformation thresholds and refractive index modification mechanisms in both materials. It has also been shown in the case of phosphate glass that the use of chirped pulses can be used as an additional parameter to improve the mode symmetry. Although this preliminary result requires further investigation, the fact that the effect is only observed for positively chirped pulses suggests that the temporal distribution of frequencies within the pulse plays an important role in modifying either the dynamics or the spatial deposition of energy inside the material.

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