Available online at www.sciencedirect.com

ScienceDirect

Applied Surface Science 254 (2007) 1121–1125

applied surface science

www.elsevier.com/locate/apsusc

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

A. Ferrer [*], V. Diez-Blanco, A. Ruiz, J. Siegel, J. Solis

Laser Processing Group, Instituto de Optica-CSIC, Serrano 121, 28006 Madrid, Spain

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.

Keywords: Femtosecond; Waveguide; Glass; Micromachining; Chirp; Fused silica; Phosphate glass; Slit shaping; Spherical aberration

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 λ the laser wavelength. The transverse dimensions of the beam at the focus scale as $2\omega_{0xy} = 2\lambda/\pi NA$, where ω_{0x} (ω_{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,

---

[*] Corresponding author. Tel.: +34 915616800; fax: +34 91 564 55 57.
E-mail address: a.ferrer@io.cfmac.csic.es (A. Ferrer).

0169-4332/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.apsusc.2007.09.084

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 $2\omega_{0y}$ increases to a size comparable $2Z_R$. 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]:

$$\Delta Z_{SA} \approx d\left(\sqrt{\frac{1-(\mathrm{NA}/n)^2}{1-\mathrm{NA}^2}}-1\right) \tag{1}$$

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 (ΔS_y), 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 trough 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 $\mathrm{NA}_x = 0.18$. 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.).

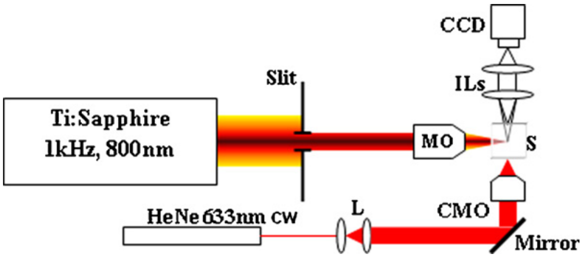

Fig. 1. Scheme of the experimental setup used for waveguide writing and characterization where S is the sample, MO is the focusing microscope objective, ILs are the imaging lenses, L is the collimation lenses and CMO is the coupling microscope objective.

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 ΔS_y 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 ΔS_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 ΔS_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 ΔS_y to achieve circular waveguides in our conditions ($\mathrm{NA} = 0.26$, $R_x = 3.7$ mm, $n = 1.45$), would be 320 μm according to next equation:

$$\Delta S_y = R_x\sqrt{\frac{\ln 2}{3}}\frac{\mathrm{NA}}{n} \tag{2}$$