Fabrication of Telecom Grade Active Waveguides by Femtosecond Laser Pulses

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High quality waveguides are fabricated in Er:Yb-doped glasses by means of femtosecond laser pulses. Shape control of the transverse profile and optical gain in the whole C-band are demonstrated in single-mode active waveguides.

Keywords: Integrated optics, active waveguides, laser micromachining

Introduction

Permanent modifications of the refractive index in transparent materials can be obtained by tightly focusing femtosecond laser pulses [1, 2]. A hot electron plasma is generated by a combination of multiphoton absorption and avalanche ionization; transfer of the plasma energy to the lattice allows to increase the refractive index in a small volume of the material surrounding the focus [3]. Exploiting this index gradient, a wide variety of waveguide devices, both active and passive, can be produced [4, 5]. Advantages of the femtosecond technique with respect to other standard techniques, such as ion exchange or glass on silicon, are the capability of direct device writing without any photolithographic process and the possibility of fabricating three-dimensional waveguide structures.

Two laser systems can be used for waveguide fabrication: low repetition rate (1-100 kHz) amplified Ti:sapphire systems, with pulse energy of a few μJs, and high repetition rate (5-20 MHz) long cavity Ti:sapphire oscillators [6, 7], with pulse energy of a few tens of nJs. In the latter case very high processing speeds are possible, but the short working distances required by tight focusing limit the flexibility and the three-dimensional capabilities. For the low-frequency systems, two different writing geometries are possible: longitudinal, in which the sample is translated along the beam propagation direction, and transverse, in which the sample is translated perpendicularly to the beam propagation direction. The longitudinal geometry produces intrinsically symmetric waveguides, but their length is limited by the focal length of the focusing objective and their quality is degraded by spherical aberrations, which vary with the depth of the focus inside the glass. The transverse geometry provides more flexibility to the system and allows to write waveguides of arbitrary length, but gives rise to an intrinsic asymmetry in the waveguide cross section. This asymmetry becomes particularly severe when the waveguide dimensions are increased, as required to achieve waveguiding at 1.5 μm, thus greatly reducing the efficiency of fiber butt coupling in conventional telecom setups.

The novel approach that we are proposing is based on astigmatic shaping of the femtosecond writing beam, which allows both the elimination of the waveguide asymmetry in the transverse geometry and the control of its size. We apply this method to the fabrication of waveguides in erbium-ytterbium doped glasses and demonstrate single-mode waveguiding and amplification in the telecom window at 1.5 μm.

Nonlinear absorption modeling

In low repetition rate systems, as the one we are using, the local index gradient is produced essentially by the single pulse and cumulative effects can be neglected. To determine the size and shape of the material volume modified by the femtosecond pulse, one can, to a first approximation, calculate the density profile of free electrons *n(t)* generated by the ultrashort pulse inside the medium and assume that the refractive index profile follows the electron density profile. The evolution of *n(t)* in a medium exposed to an intense laser pulse can be described by the following rate equation [8]:

$$\frac{dn}{dt} = \alpha I(t) n(t) + \sigma_k I^k(t) \tag{1}$$

where a is the avalanche coefficient, s_k is the k-photon absorption coefficient, and *I(t)* is the pulse temporal profile. k is chosen as the smallest integer such that k times the photon energy exceeds the bandgap of the material. By solving (1) in different points of the focal volume and plotting the asymptotic value $n(\infty)$ as a function of x,y,z, one can obtain a map of the free electron density generated inside the material. The simulations presented in this work have been calculated by using the parameters of a barium aluminum borosilicate glass (k = 3, a = 1.2 cm^2/J, s_3 = 7×10^{17} cm^{-3} ps^{-1} (cm^2/TW)^3) [8].

Set-up and experimental results

We have experimentally demonstrated the above described technique by fabricating active waveguides in erbium-ytterbium doped glass substrates. We have used a standard amplified Ti:sapphire laser (model CPA-1 from Clark Instrumentation), generating 150-fs pulses at 1 kHz repetition rate at the wavelength of 790 nm. The beam had a nearly TEM$_{00}$ symmetric transverse profile and energies ranging between 0.5 and 5 μJ were used for the micromachining. The experimental setup is shown in Fig. 1.

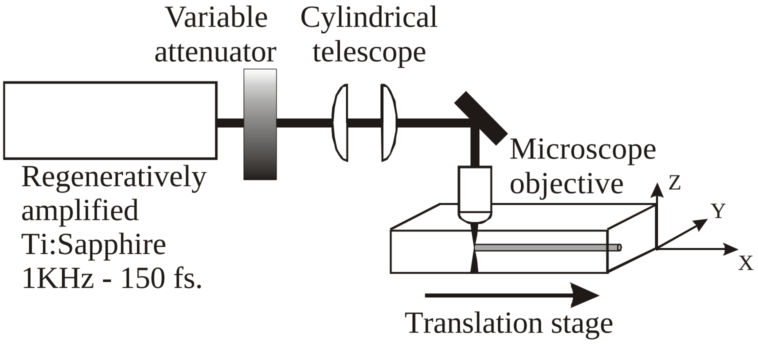

Figure 1. Setup for waveguide writing.

The laser beam was focused by a long working distance 20× microscope objective, with 0.3 numerical aperture. Waveguides were written in a 25-mm long phosphate glass base, doped with both Er and Yb with a total absorption of ≈5.5 dB at 1534 nm and ≈37 dB at 976 nm.

The first waveguides have been realized without the cylindrical telescope (see Fig.1). Figure 2a shows a microscope image of the exit face of a waveguide manufactured by 0.5 µJ pulses focused to a waist of $w_0 = 3$ µm, together with the simulation obtained from the previously described model.

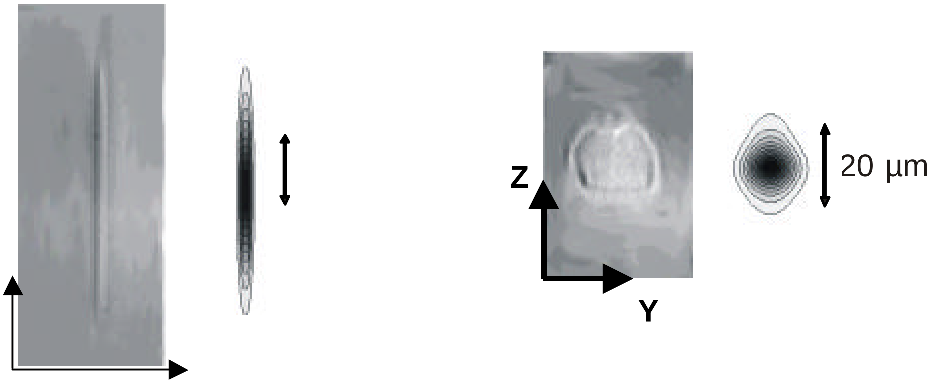

Figure 3. Comparison between microscope images of the end face of the waveguides and simulated electron density distributions for a standard (a) and an astigmatic (b) laser beam; see text for focusing conditions.

Two features are important: (i) the profile is strongly asymmetric, extending over less than 3 µm in the y direction and over 60 µm in the z direction, causing highly inefficient coupling to standard telecom fibers; (ii) the y extent of the profile is too small to support a mode at 1.5 µm. The reason for this asymmetry is essentially due to the fact that the waveguide dimension in the y direction is related to $2w_0$, while the z extension scales as twice the Rayleigh range of the Gaussian beam, $z_R = \frac{\pi w_0^2}{\lambda}$. To increase the waveguide symmetry without further decreasing the y dimension, one needs to decrease z_R independently from w_0. Here we propose to use an astigmatic beam to independently control the z and y size of the waveguide transverse profile.

In the transverse writing geometry the size of the beam along the x direction does not influence the waveguide size, because it is the direction along which the sample is translated (see Fig. 1), so that a lower writing velocity can compensate for a tighter focusing. We can exploit this fact to focus very tightly in the x direction so as to reduce the z waveguide extension by decreasing z_{Rx}, while simultaneously choosing the focal spot size in the y direction to optimize the waveguide y dimension. To achieve perfect circularity, one needs to increase the ratio w_{0y}/w_{0x} to about 10. A simpler approach consists in slightly offsetting the two waist positions along z, in this case the waveguide cross section becomes nearly perfectly symmetrical with w_{0y}/w_{0x} of about 3 and a z_0 offset of about 200µm (Fig.2b) [9]. To produce the astigmatic focus, the beam size along the y direction was reduced by a cylindrical telescope, providing a magnification by a factor 2.5 in the focus of the objective. The relative position of the waists along the z direction was finely controlled by translating one of the cylindrical lenses.

We have tested the performance of the waveguides at the wavelengths of 0.633 µm and 1.5 µm. The waveguide in Fig. 2b is single-mode at 1.5 µm. By a comparison between the mode profiles of the waveguide and of the standard telecom coupling fiber we estimated coupling losses of 2.4 dB; a measurement of the transmitted power allowed to evaluate propagation losses of 0.6 dB, corresponding to 0.24 dB/cm. Symmetric waveguides obtained with this technique exhibited enhancement and internal gain when used in a standard optical amplifier setup [10], but due to the very high Yb doping only short waveguide can be pumped in their entire length. Optical gain results for a 9mm sample are reported in Fig. 4.

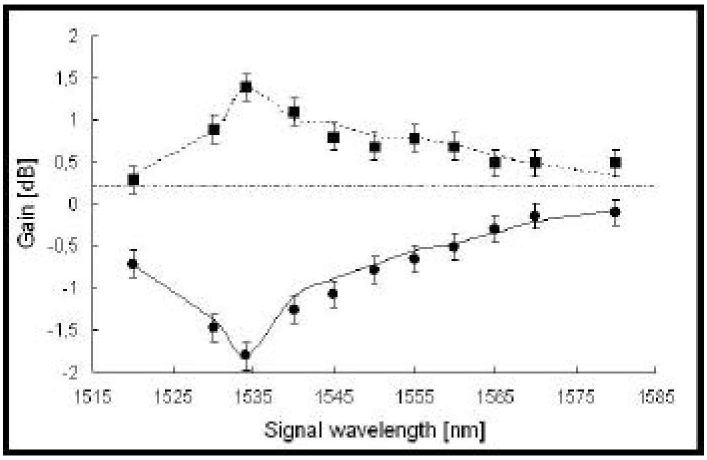

Figure 4. Absorption and optical gain for a 9mm long waveguide in the telecommunication C-Band.

It is worth noting that for the first time optical gain has been demonstrated in the whole C-band for a waveguide fabricated by means of femtosecond laser pulses. Despite further optimization of the Er:Yb doping is needed, this result is very promising in view of the realization of waveguide amplifiers and lasers with this technique.

Conclusions

A novel approach to waveguide writing with femtosecond pulses based on astigmatic beam focusing has been introduced and experimentally demonstrated. By controlling both the spot size asymmetry and the relative position of the beam waists, we can achieve symmetric waveguides which are single mode at the optical communication wavelength of 1.5 μm. For the first time optical gain has been observed on the whole C-band, with 1.4 dB peak value, in a 9mm waveguide written with femtosecond laser pulses.

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