High repetition rate UV ultrafast laser inscription of buried channel waveguides in Sapphire: Fabrication and fluorescence imaging via ruby *R* lines

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Abstract: We report on the fabrication of buried cannel waveguides in Sapphire crystals by 250-kHz high repetition rate ultrafast laser inscription with 385 nm pulses. The propagation properties of the waveguides were studied as a function of the writing conditions. The micro-fluorescence analysis of the *R* lines generated by trace Cr^{3+} dopant in Sapphire is used to elucidate the micro-structural modifications induced in the crystal network. It is revealed that waveguide has been formed due to local dilatation of the Sapphire network generated in the surroundings of the focal volume. The refractive index increment due to the dilatation induced electronic polarizability enhancement has been estimated to be of the order of $\Delta n \approx 10^{-4}$.

OCIS codes: (180.2520) Fluorescence Microscopy; (230.7370) Waveguides

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1. Introduction

After more than a decade of research and development efforts [1], ultrafast lasers have evolved into powerful tools in manufacturing photonic waveguide components in transparent substrates. With respect to other fabrication techniques, the ultrafast laser inscription is a flexible and cross-platform technique enabling the fabrication of three-dimensional devices in a wide array of substrates. While most of earlier works employ kHz repetition rate laser systems to write waveguide devices in glass and crystalline materials, recent reports on low-loss embedded waveguide formed by high-repetition (>250 kHz) ultrafast lasers have gained significant attention [2–5]. The residual heating effect from high repetition laser pulses produce local melting around the laser focal volume, which enhances waveguide symmetry and reduces scattering loss. The fabrication of low optical loss waveguide using high repetition rate ultrafast lasers has been reported in both amorphous materials such as fused silica and BK7 glasses [6] as well as nonlinear optical crystals such as $LiTaO_3$ [7] and $LiNbO_3$ [8].

In this work, we have extended high repetition rate ultrafast laser waveguide inscription studies in Sapphire crystals. This work is motivated by many potential applications of sapphire crystals in high temperature harsh environment sensing [9] and super continuum generation in the mid-IR range [10]. Doped with transition metal ions, sapphire is a well-known material for solid-state lasers and optical amplifiers. Several methods have already been applied for the fabrication of channel waveguides in Sapphire crystals. These include ion in-diffusion, pulsed laser deposition, reactive ion etching an ion beam implantation [11–13]. Very recently, channel waveguides in Ti-doped sapphire crystals have also been fabricated by ultrafast laser inscription with a low repetition rate (1 kHz) infrared (750 nm) laser [14]. However, the possible optimization of these waveguides based on the benefits of bulk heating from high-repetition rate ultrafast laser pulses is still unexplored.

In this paper we report the fabrication of channel waveguides in sapphire using high repetition rate (250 kHz) UV (385 nm) ultrafast laser pulses. The use of UV irradiation reduces the order of the multi-photon excitation process and, hence, the laser intensity required for permanent index modification of the sapphire crystal. The basic propagation properties of the obtained waveguides as a function of the writing conditions (such as pulse energy and writing speed) are reported and discussed. In addition, and in order to get a further insight on the laser-matter interaction in these irradiation conditions, the spatial and spectral analysis of the micro-fluorescence generated from Cr^{3+} traces has been analyzed to elucidate the waveguide's formation mechanism as well as to estimate the refractive index change induced by the laser irradiation.

2. Experimental

The waveguides studied in this work were fabricated with a Coherent MIRA oscillator and a RegA regenerative amplifier system. The output from the RegA was frequency doubled to produce 150 fs pulses at a wavelength of 385 nm and a repetition rate of 250 kHz. The writing beam was focused into a nominally pure (0001) oriented Sapphire sample (Crystal Systems

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Inc.) at a depth of 150 µm with a 40X aspheric lens (N.A. = 0.68). The Sapphire sample was mounted on a three-axis motorized stage and translated at speeds ranging from 0.2 to 5 mm/s allowing inscription of waveguides parallel to the A-axis (1120) crystallographic axis. Pulse energy was varied from 100 to 500 nJ.

Figure 1 (top line) shows the optical microscope cross-section images of the laser-induced modification produced in the Sapphire sample with different pulse energies and translation speeds. The propagation direction of the UV irradiation pulses is indicated by arrows. Note that the length of the modificated region decreases with decreasing pulse energy and increasing translation speed. The waveguiding properties of the obtained structures were examined by end-coupling a 632 nm He-Ne laser into the laser damage sites. Guiding regions were found few microns below damage sites. Within the explored processing window, guiding regions were found for all the writing speed (0.2 – 5 mm/s) at the highest pulse energy of 500 nJ. As the pulse energy is reduced the maximum translation speed ensuring waveguide formation decreases constantly. This fact is depicted in Fig. 1 (bottom line) in which it is clearly noted that for the intermediate pulse energy of 350 nJ, waveguiding was only observed in the structure fabricated with the minimum translation speed of 0.2 mm/s.

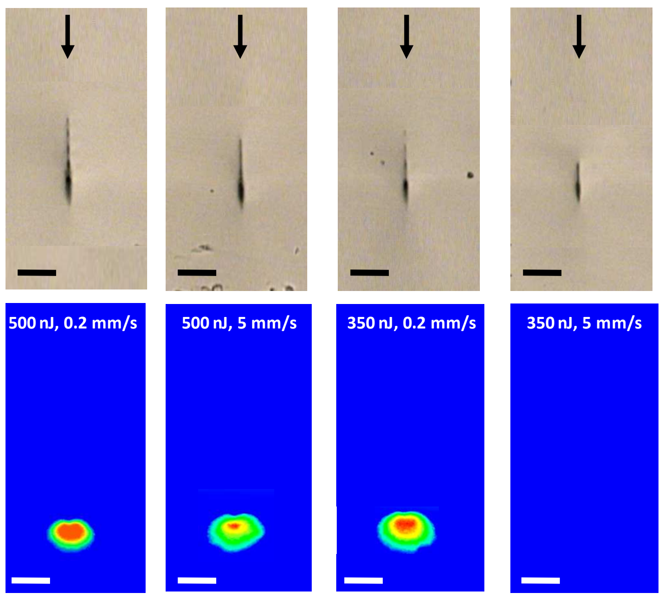

Fig. 1. Optical microscope images of the end face of the irradiated Sapphire sample as obtained for different pulse energies and translation speeds. The propagation direction of the UV irradiation pulses is indicated by arrows. The waveguide's fundamental propagation modes at 632 nm obtained in each case are shown in the bottom line. Note that for the case of 350 nJ pulse energy no waveguiding was obtained for the maximum translation speed. Scale bar is 20 microns. Aspect Ratio is 1:1.

None of waveguide fabricated in this work were able to guide at 1.5 µm. It could be due to a weak index change and/or to a small index modification region. The relative location of guiding regions in respect to the laser damage sites is, indeed, very similar to the case of the Sapphire waveguides fabricated with low repetition rate IR ultrafast laser pulses [14].

In order to gain a further understanding of the waveguide formation mechanisms to optimize waveguide performance, the micro-fluorescence properties of laser affected area generated by the presence of Cr^{3+} traces in the sapphire samples was analyzed. The trace Cr^{3+} ions concentration has been estimated to be not higher than 0.1 at.%. For this purpose the micro-fluorescence generated from the laser affected areas was analyzed with a scanning confocal microscope equipped with a 100X (0.9 N.A.) microscope objective. This objective was used for both focusing the 488 nm excitation beam and for collecting the fluorescence light from trace Cr^{3+}. After passing through a confocal aperture, the fluorescence signal was

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focused into a fiber connected to a high resolution spectrometer. Figure 2(a) shows a typical micro-luminescence spectrum obtained in our experimental conditions in which the two sharp, and well characterized, *R* lines of Cr^{3+} ions are properly labeled [15].

2. Results and discussion

The analysis of the spatial variation of this well-understood spectral feature emerges as an exceptional tool to understand the ultrafast laser interaction with the Sapphire network and waveguide forming mechanisms [15]. For this purpose, we have scanned the 488 nm excitation spot over the cross section of the four structures shown in Fig. 1. In all the cases we have found that the intensity of these *R* lines was strongly reduced at the focal volume. This was accompanied, for all cases, by a slight spectral broadening as shown in Fig. 2(b) and 2(c). Both figures correspond to the structure fabricated with pulse energy of 500 nJ at a translation speed of 0.2 mm/s.

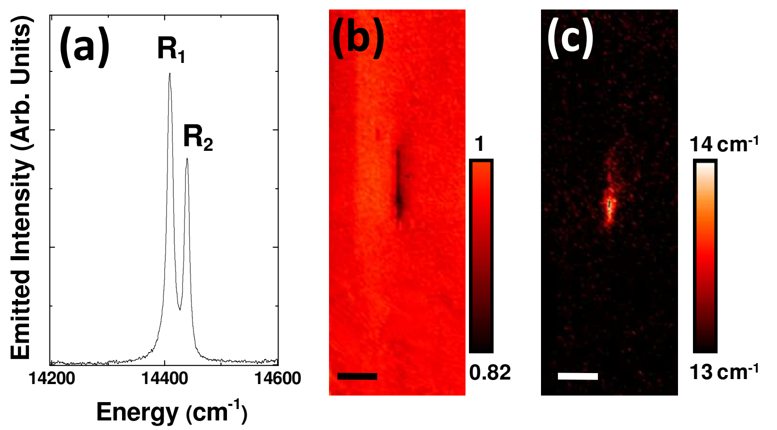

Fig. 2. (a).- Micro-Luminescence spectrum obtained from the micro-structured Sapphire sample as obtained after 488 nm excitation. The R_1 and R_2 lines generated by Cr^{3+} traces are labeled. Spatial dependence of the R_1 line intensity and bandwidth as obtained from the damage track obtained with a pulse energy of 500 nJ and 0.2 mm/s translation speed, respectively ((b) and (c), respectively). Scale bar is 20 microns. Aspect Ratio is 1:1.

This simultaneous reduction and broadening of the *R* lines denote a partial damage/disordering of the Sapphire network at the focal volume due to the strong laser densities achieved. Just below the focal volume (where waveguides were formed there is not any significant reduction (nor broadening) of the Cr^{3+} lines. This indicates that the laser-induced waveguide is located at an undamaged area.

More relevant information can be obtained from the fluorescence images obtained based on the spatial variation of the spectral shift induced in the *R* lines. Figure 3 maps the spectral shift of R_1 fluorescence lines of the four representative structures whose microscope images and guided modes profiles are shown in Fig. 1 [16]. Similar images were obtained when the R_2 line was analyzed as well.

We have found that for the three structures showing waveguiding (those obtained with 500 nJ pulse energy and that obtained with 350 nJ pulse energy at the minimum translation speed) the fluorescence images present a clear contrast. These three structures are characterized by a red-shift of the R_1 line at the focal volume and by a clear blue shift of the R_1 line at the waveguide's location just below the focal volume.

Taking advantage of the well known behavior of the R_1 line in the presence of a compressive/tensile stress we can conclude that in those structures capable of waveguiding a local dilatation of the Sapphire network is induced just below the laser damage track, in which a local compression has been produced. This is consistent with prior reports [15,17,18], in

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which it was concluded that the refractive index of sapphire increases when a tensile stress is applied (i.e. when the local density is reduced) as a consequence of the dominant contribution of the electronic polarizability enhancement over the atomic density reduction.

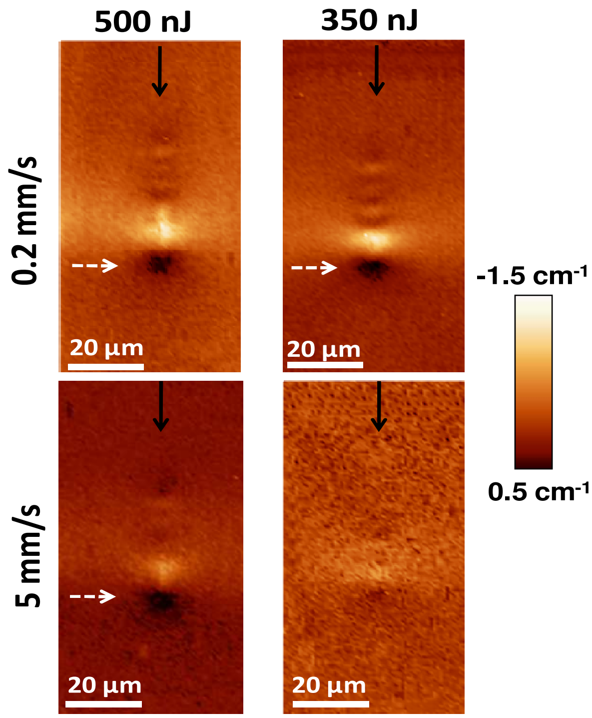

Fig. 3. Spatial distribution of the R_1 line position as obtained for four damage sites generated with different pulse energies and translation speeds. Solid and dashed arrows indicate the irradiation direction and the waveguide's location, respectively.

According to this, the fluorescence images included in Fig. 3 reveal that the guiding region, where the rise of refractive index occurs, is a locally dilated area below the laser damage track. For the case of the structure written with pulse energy of 350 nJ at 5 mm/s translation speed, no appreciable blue shift of the R_1 line has been observed. This suggests that the total deposited energy is not sufficient to create any relevant density modification in the Sapphire network for these conditions, which leads to waveguiding absence for this structure. Thus, it is clear that in our case waveguides are formed as a consequence of a local lattice dilatation, this in contrast with ultrafast laser inscribed waveguides fabricated in other systems, in which local lattice compression has been identified as the refractive index increment mechanism [6].

Using the well established pressure coefficient of the R_1 line we have estimated, from the maximum red and blue shifts of the R_1 line, a maximum induced compressive stress at the focal volume of 0.46 GPa and a maximum tensile stress of 0.25 GPa at the waveguide's location for the structure written with 350 nJ pulse and 0.2 mm/s writing speed [15,16]. This is consistent with a similar analysis based on R_2 line shift. The tensile stress of 0.25 GPa induced in the guiding region yields a density variation of $\Delta\rho/\rho_0 \approx 0.4$ and $\approx - 0.2\%$ at the focal volume and waveguide, respectively. According to S.C. Jones et al. [18], these variations in the local density would cause a refractive increment of $\Delta n \approx -0.1 \cdot (\Delta\rho/\rho_0) \approx 1 \cdot 10^{-4}$ at waveguide's location. This value is, indeed, comparable to that previous reported for the channel waveguides previously fabricated in Sapphire with low repetition rate IR ultrafast pulses ($\Delta n \approx 2 \cdot 10^{-4}$) [14], which is not sufficient to produce waveguiding at 1.5 µm telecommunication wavelength.

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3. Conclusion

In summary, channel waveguides in Sapphire crystals have been fabricated by ultrafast laser inscription using high repetition rate UV pulses. The presence of Cr^{3+} traces has been used to elucidate the mechanisms leading to refractive index change and waveguide formations. The spatial variation of the spectral properties of the *R* lines was used to analyze the lattice dilation and compaction induced by the laser irradiation.

It was found that the refractive index rise in waveguiding regions was caused by the local dilatation of the Sapphire lattice induced in the surroundings of the focal volume. This has been found to be in agreement with previous experimental measurements in which it was demonstrated that, for the particular case of Sapphire, any density reduction is accompanied by a refractive index increment. Based on the induced spectral shift of the R lines at waveguide's location, we have estimated a refractive index increment at waveguide's location of the order of 10^{-4}.

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