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Systematic control of optical features in aluminosilicate glass waveguides using direct femtosecond laser writing

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ABSTRACT

Low loss optical waveguides inside aluminosilicate glasses have been successfully fabricated using direct femtosecond laser writing. To establish the influence of pulse energy and host variations on the optical waveguides have been tentatively explored and systematically studied with the help of different spectroscopic techniques. Isochronal annealing treatment effectively reduces the insertion losses to 1.01 ± 0.28 dB at 632.8 nm. A red shift of the Raman band has been observed with increasing Al_2O_3 content due to the bond angle variations. The point defects such as non-bridging oxygen hole centers have been corroborated by the photoluminescence studies and significant red-shift has also been documented with increasing Al_2O_3 content. In addition, there is no NBOHC defects perceived after isochronal annealing treatment inside the glass waveguides. Our results envisage that the present glass waveguides should be promising and potential for applications in passive waveguides and integrated photonic devices.

1. Introduction

The micromaching on the transparent dielectric materials using ultrafast laser technology have received considerable attention to develop new photonic devices with outstanding precision and high functionality during the last two decades [1–6]. One of the fascinating and emerging technology i.e., femtosecond laser that has to employ for making three dimensional (3D) volume material processing [1–6]. Consequently, it can be adopted to establish micro and nano patterns, in a space selective manner, through a unique attempt [1–6] compared with other matured technologies, namely the diffusion of metal ions [7], ion implantation and X-ray lithography [8,9], respectively. In fact, the driving of non-linear energy transfer processes in the laser-matter interaction have attested as an obvious material modification, surface and volume crystallization as well as elemental redistributions within the materials [1–6,10]. Indeed, they strongly relied on the main laser parameters, namely, pulse energy, repetition rate and writing speed as well as the compositional variations [1–6,10,11]. Accordingly, this attests significant enhancement in the rate of dissolution of the laser irradiated zone as compared to an unexposed region of the bulk materials [12]. In particular, there are three types of modifications (type-I, type-II and type-III) clearly distinguished in silica based materials that makes them as a backbone of any versatile photonic device functionality [1–6,10–12]. The permanent positive index change (type-I), negative index change (type-II, birefringence, which is commonly known as Nanogratings) and void formation (type-III) took place, in a 3D architecture, inside silica glasses including point defects generation [1–6,10–12].

Researchers have focused on the development of low-loss waveguides in a wide-range of materials (like, glasses [2,4,12–14], polymers [15,16] and crystals [1,5,6,12,17]), which have found successes prevalently with type-I, type-II and depressed cladding techniques using the ultrafast laser technology. There are few examples of low-loss waveguides in the materials as per literature, as follows. Eaton et al. reported that there is no such appreciable reduction in the propagation losses, according to the repetition rate inside fused silica [14]. However, they have controlled guiding properties through varying writing speeds in the silica using frequency doubling technique [4]. Low et al. reported that the lowest propagation losses (<1.0 dB/cm) have achieved due to an increase

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of the densification as evidenced by the Raman spectroscopy and refractive index as well as a 1 × 4 beam splitters also demonstrated in aluminosilicate glasses (Corning 1737) using Ti: Sapphire laser writing [18]. Recently, Lapointe et al. has shown in Ref. [13] that low loss optical waveguides (<0.15 dB/cm at 1550 nm) were successfully established in chalcogenide glass tapes using a similar technique. Furthermore, the lowest propagation losses as low as 0.3 dB/cm were accomplished in poly (methyl methacrylate) (PMMA) polymer straight and s-curved waveguides using multiple parallel tracks accompanied by a larger index change (Δn) as noted by Patzold et al. [15].

A simple and promising alternative route is to control the material guiding properties through compositional variations, which is scarcely available in the literature. The superior properties of silica based glasses compared with other materials (polymers [15,16], chalcogenide [13] and phosphate [19]) include high thermal stability, good chemical durability, high resistance and high thermal conductivity that makes them to apply in many industrial purposes [20,21]. These extraordinary material properties make it a very attractive candidate to ameliorate not only low loss optical waveguides, but also other photonic devices. In this work, we have investigated low loss optical waveguides inside aluminosilicate glasses through varying pulse energy, compositional variations and isochronal annealing treatment. The lowest insertion loss is being estimated to be 1.0 ± 0.2 dB in aluminosilicate glasses. Thus, these glasses are promising and/or potential candidates to implement in integrated photonics and telecommunication applications.

2. Experimental details

Transparent aluminosilicate glasses with the composition of (100-X) SiO_2 - X Al_2O_3 (X = 3, 10 and 15 wt. %) were directly purchased from the Green-ray Company, China. Hereafter, these glasses had labeled as SA3, SA10 and SA15 glasses and selected glasses were dissected into 10 (x-axis) × 10 (y-axis) × 1 (z-axis) mm^3 dimensions. Optical waveguides were fabricated inside aluminosilicate glass plates using an optical fiber laser emitting linearly polarized light with a central wavelength of 1031 nm (Origami-10 XP, Onefive GmbH, Switzerland), a pulse duration of 420 fs and repetition rate varying from 1 k Hz to 1 M Hz. A slit was 800 μm width that is placed before focusing an objective lens in order to regulate the focused spot size of the laser beam (symmetric waveguides) in the transverse direction. Further, it was directly focused into the aluminosilicate glass plates 150 μm below the surface through a 40 × microscope objective aspheric lens with a numerical aperture (NA) of 0.6. Subsequently, the laser pulse energy was measured after 40 × microscopic objective focusing the laser beam into the aluminosilicate glass plates. Finally, the selected glasses were translated normal to the laser focusing direction by a computer controlled XYZ three-axis program. Here, the laser inscription was made with different pulse energies (0.8–2.85 μJ) at a constant writing speed of 5.6 mm/s, repetition rate of 100 kHz and the distance between two successive laser written waveguides in all glass plates are of 100 μm. The fabrication of waveguides are followed by the laser polarization along x-axis is normal to the writing direction along y-axis and z-axis is the light propagation. After laser inscription, the end-facet of the glass waveguides are polished in order to minimize the scattering losses.

After femtosecond laser inscription, the end-face coupling technique was applied to ensure the mode formation correspond to guiding properties of the waveguides were studied. The schematic illustration of the near-field modal profile setup are described elsewhere [2,20,22,23]. The intensity distribution of the glass waveguide mode profile images at 632.8 nm is presented in Fig. 1(B–E). Micro-Raman spectra were recorded in the

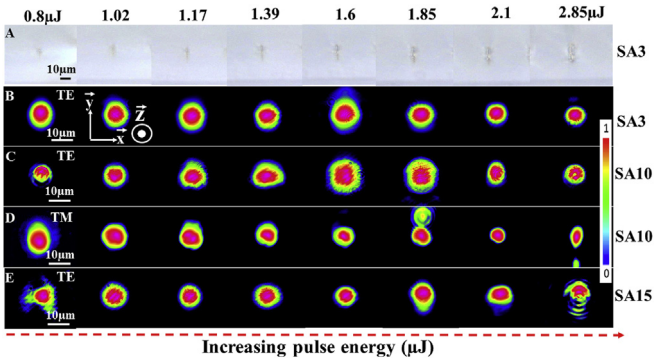

Fig. 1. **(A)** Typical SA3 glass waveguide end-facet cross-sectional images for various pulse energies. Near-field intensity distribution of the aluminosilicate glass waveguides as a function of the pulse energy (horizontal row) **(B)** SA3 (TE), **(C)** SA10 (TE), **(D)** SA10 (TM) and **(E)** SA15 (TE) glasses.

wavenumber range of 50–1500 cm^{-1} using micro-Raman LABRAM-HR800 (HORIBA Jobin Yvon) spectrometer, which was equipped with optical microscope through a 50 × focusing objective laser beam at operating wavelength of 632.8 nm focusing on the glass plates. Photoluminescence measurements were carried out using a confocal optical microscope (Nanofinder FLEX2, Tokyo Instruments, Inc) under 532 nm green laser, as an excitation source with a power of 0.75 mW. Further, the laser was focused on the aluminosilicate glass waveguides directly through a 50 × microscope objective with a 0.25 NA. All spectroscopic measurements were carried out at room temperature (RT).

3. Results

3.1. Optical properties of waveguides

Fig. 1(A) illustrates the typical aluminosilicate (SA3) glass waveguide cross-section using optical microscope (Axio Imager, Carl Zeiss) for various pulse energies. There is a straight and thin single striations commonly referred as the formation of type-I waveguides. It is assessing the diameter (about 2–8 μm) and depth (~37–140 μm) of waveguide cross-section amplified with increasing pulse energy varied between 0.8 μJ and 2.85 μJ. On the other side, it can be seen that there is a significant increment in the cross-sectional line diameter perceptibly, when increasing concentration of Al_2O_3 from 3.0 wt. % to 15 wt. % at fixed pulse energy.

The near-field intensity distribution images of the aluminosilicate glass waveguide modes for TE polarization as a function of Al_2O_3 (vertical column) versus pulse energies (horizontal row) and typical SA10 glass waveguide modes for TM polarization are depicted in Fig. 1 (B–E). Fig. 1 discloses the experimentally characterized mode seeming to be circular and symmetric features as well as slight decrement in the resultant mode diameter as increasing pulse energy along the laser polarization direction (E). Below the laser pulse energy of 0.8 μJ, we were unable to detect waveguide mode by dint of an insufficient index change in the modified region perhaps under this conditions [22,23]. On the contrary, to higher pulse energies (typically >2.0 μJ), it has been clearly shown that the larger mode diameter represents lessening of the refractive index change inside the waveguide core [4]. Above 3 μJ of pulse energy, we could not see circular waveguide mode formation in all three studied glasses due to the lessening of the refractive index. With increasing Al_2O_3 (vertical row) content, we have observed significant reduction in the diameter of the resultant mode inside aluminosilicate glass waveguides. This observation can be elucidated by the fact that an improvement in the index of