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Optical channel waveguides in a chalcogenide (Ga:La:S) glass fabricated through short wavelength (λ=244nm) illumination

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Abstract: Chalcogenide optical glass is an interesting material, for both fibre and planar technologies, as it offers possibilities for a wide array of devices suitable for use in both non-linear applications and as IR sources. Channel waveguide structures were directly written into bulk gallium lanthanum sulphide glass via above-bandgap (λ=244nm) illumination. Focused fluence of 1.5 – 150 J/cm^2 from a UV-laser was applied, inducing giant-photocompaction and photochemical changes. A typical channel waveguide had attenuation < 0.3 dB cm^{-1} and was spatially single-mode at 1 μm. The damage threshold for fabricating such devices in this glass system is also discussed.

Key Words: Amorphous semiconductor, Optical writing, Channel waveguide

I. INTRODUCTION

Optical components are essential if the boom in telecommunications is to experience further growth. The biggest breakthrough in fibre optic technology came with the successful development of a long-haul fibre optic amplifier. This significant invention was the Er^{3+}-doped fibre amplifier (EDFA), capable of inherently amplifying optical signals at the coincident wavelength of 1.55 μm [1]. If not for the optical transparency of these 'strands of sand', generation and influencing the behaviour of light in crystals, glass and semiconductors would not have been possible. It might possibly be that silica (SiO_2) is the ultimate inert and stable optical material that will always be relied upon for its ability to transmit light over large distances. However, the inability of optic fibre to assimilate several components and functions onto a single compact platform has had researchers exploring a concept first proposed in 1969 [2].

First conceived by S.E Miller, integrated optics (IO) proposed the incorporation of multiple devices such as transmitters, receivers, modulators, signal amplifiers and lasers onto a single photonic chip. This was generally understood to be the ultimate in miniaturization and functionality. Silica based materials were among the initial demonstrations of passive and active IO devices [3-5]. However, active planar devices based on this material suffer from concentration quenching effects caused by high rare-earth (RE) concentration, which is necessary to compensate for the short interaction length. Despite the dramatic impact silica glass has had on telecommunications, it does have limitations in active planar operation. It can function only weakly as an optic switch and is unable to transmit radiation much beyond 2 μm. The mindset in telecommunications has always been to exceed current state of art and to provide advanced solutions for present and future applications. Research into diverse fabrication techniques for a plethora of host materials that offer capabilities surpassing silica glass led to the development of new non-oxide vitreous materials. Fluoride and chalcogenide glasses (ChGs) have an optical cut-off at longer wavelengths and are manufactured from low-phonon energy materials possessing heavier ions with weak bond strengths [6-7]. The unique optical properties found in ChGs make them very interesting for IO devices. Multiple radiative transitions for RE ions are possible due to low phonon energies (W_p = 325 - 425 cm^{-1}) which are quenched in other amorphous materials. In addition, the high IR transparency, inherent photosensitivity and high non-linear refractive index are only some advantages of ChGs [7]. Notable previous works for planar and channel devices in ChGs can be found in several publications [7-11]. A good overview of planar channel devices in fluoride glasses can be found elsewhere [6]. In this paper, we discuss a method for fabricating channel waveguides in bulk gallium lanthanum sulphide (Ga:La:S) glass. The channel geometry can be beneficial for achieving low laser thresholds, circular spatial outputs and compatibility with optical fibre. For this demonstration, we have directly written channel waveguide structures with above-bandgap illumination provided by a focused UV-laser beam (λ = 244 nm). Section II details channel waveguide fabrication by UV illumination and photoinduced effects resulting in material modification. Some of these effects are present in the form of giant-photocompaction and photochemical modification. Section III discusses the damage threshold for waveguide fabrication and optical characterisation. Finally in section IV, our concluding remarks are given.

II. FABRICATION AND PHOTOINDUCED EFFECTS

The gallium lanthanum sulphide (Ga:La:S) glass system is a vitreous chalcogenide material first discovered in 1976 [12]. Since then, interest has been maintained over the years primarily due to its exceptional and unusual optical properties. These glasses have a wide transmission window between 0.6-7 μm and are classed as an amorphous semiconductor with bandgap energy 2.6 eV (475 nm). The non-toxicity, high transition temperature, excellent REsolubility, low-phonon energy, high non-linearity, highly photosensitive and well documented spectroscopic properties make it an interesting candidate for research into planar waveguide devices [13].

Fabrication of Ga:La:S glass, with a typical molar ratio 65 Ga_2S_3 : 32 La_2S_3 : 3 La_2O_3, was carried out from prepared batches of powders. These glass precursors were loaded into a vitreous carbon crucible while in a controlled atmosphere. The precursors are non-volatile at the glass melting temperature (1150°C for up to 24h) and were heated in an open (argon purged) atmosphere, after which the melt was quenched and annealed. The glass was cut into slabs (20 x 17 x 2 mm) and polished on the top and bottom faces. An optically flat polish is required on the writing surface to minimize scattering of laser light during writing. After laser writing, the sample was polished at both end faces to allow optical coupling.

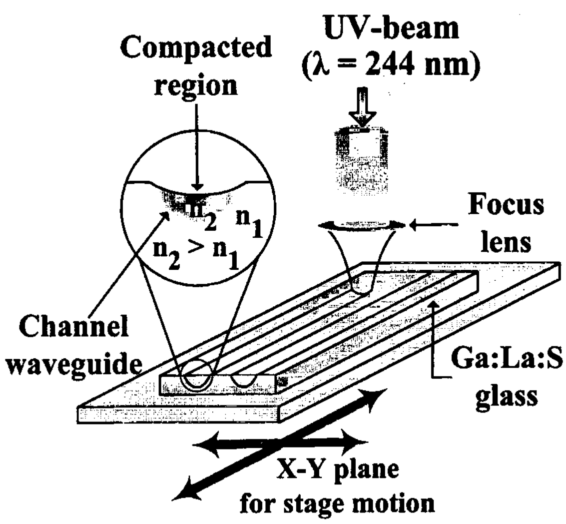

Fig. 1. Schematic diagram of the set-up used to directly write channel waveguides into Ga:La:S glass.

The direct-UV writing set-up shown in Fig. 1 consists of a frequency-doubled UV-laser (Coherent FRED Sabre 500) with 200 mW of CW output at 244 nm. A UV grade spherical fused silica lens (35 mm focal length) provides a focused writing spot from the spatially filtered laser beam. The UV-beam size ($1/e^2$ radius of intensity) is approximately 3.1 mm and the measured spot size of the focused waist is 3.3 μm. The sample, held in place by a vacuum chuck, was attached to a computer controlled translation stage. The stage, which provided the 2D movement of the sample (X and Y dimensions), has a maximum scan velocity of up to 5 cm/s and relative position resolution of 0.1 μm. The quality and dimension of a channel waveguide was determined by both the intensity (I_{UV}) of the focused laser beam and the scan velocity (V_{SCAN}). The average laser fluence (F) applied to the glass surface may then be expressed as [4]:

$$F = \frac{I_{UV}.a}{V_{SCAN}} \tag{1}$$

where a is the spot size. Fig. 1 also indicates photostructural change in the form of giant-photocompaction with material densification. The ability of an irradiated region (channel waveguide) to confine a laser beam suggests a positive change in refractive index ($n_2 > n_1$). For our experiments, the UV spot size was varied between 25 – 50 μm, by adjusting the sample to focus distance, providing laser intensity of I_{UV} = 1.5 – 10.2 kW/cm^2 over the applied area. Scan velocity was varied between 0.2 – 5 cm/s. Hence, a fluence in the range of 1.5 – 130 J/cm^2 was applied to the glass surface. Micrographs of the channel waveguides were obtained using an analytical scanning electron microscope (SEM, JEOL 6400) to which an energy dispersive X-ray microscope (EDAX), allowing compositional analysis, was attached. The channels indicate varying degrees of photocompaction. A channel directly written with UV-laser fluence of 10.8 J/cm^2 had undergone photoinduced changes in the form of giant-photocompaction (1.2 μm). Physical dimensions of the channel were 13 μm by 6 μm. Measurements within the photomodified region revealed variations in elemental ratios, with an increase in lanthanum content and decrease in gallium and sulphur. This photochemical modification contributes to densification by creating a region of raised refractive index, which is the waveguide core. The physical size as well as the chemical change within the photoinduced region varied largely with changes in scan velocity and applied laser intensity, as would be expected. This physical and chemical change in turn varied the attenuation as well as modal size and shape of the waveguide output. The maximum measured refractive index change in these channels was $\Delta n \approx +10^{-3}$.

Amorphous semiconductors (ChGs) can experience structural changes, with modification of physical and chemical states, when exposed to light. Chalcogenide glasses are widely regarded as a "soft semiconductor" because of their inherently quasi-stable atomic structure. The flexible and viscous structure is due to the chalcogen atoms having a two-fold coordination. Electronic mobility as seen in a semiconductor produces asymmetric motion of atoms and this can be paralleled to explain some of the photoinduced effects in ChGs. However, it is certainly plausible that there are contributions from both electronic and thermal phenomena to these photoinduced effects [14]. In the case of As_2S_3, exposure to near-bandgap illumination, macroscopic photoexpansion ($+\Delta V/V \sim 0.5\%$) was observed and could be thermally recovered [15]. This photoelectronic excitation with near-bandgap light with $\hbar\omega \approx E_g$, where $\hbar\omega$ is the photon energy and E_g is the optical bandgap energy of the ChG semiconductor, induces photodarkening and produces structural transformations. Volume changes were even more remarkable with below-bandgap ($\hbar\omega < E_g$) exposure causing giant-photoexpansion ($+\Delta V/V \sim 5\%$), leading to development of As_2S_3 microlenses [16]· Above-bandgap illumination ($\hbar\omega > E_g$) with photon energies lying within the Urbach-tail region can have far more prominent volumetric effects, due to considerably greater material absorption, than that of $\hbar\omega \leq E_g$ illumination. Permanent optical and geometrical changes caused by above-bandgap illumination can potentially be beneficial for fabrication of IO components [14].

III. DAMAGE THRESHOLD AND OPTICAL CHARACTERISATION

It was generally observed that with slower scan velocities (< 0.8 cm/s), for a constant I_{UV}, structures were clearly visible even with the naked eye due to physical damage of the glass. Material damage can lead to the formation of microcracks, which includes generation of bulk or surface cracks, common for fluencies above the damage threshold. For very slow scan velocities (< 0.2 cm/s) ablation was the dominant effect. Below the ablation and damage thresholds such damage of the glass could be avoided, with several kinds of material change being noted. Volume expansion or contraction, material densification and associated refractive index changes can however lead to residual tensile stresses within irradiated glasses [17]. An indication of the range of surface changes that can be induced by direct-UV writing into Ga:La:S glass is shown in Fig. 2.

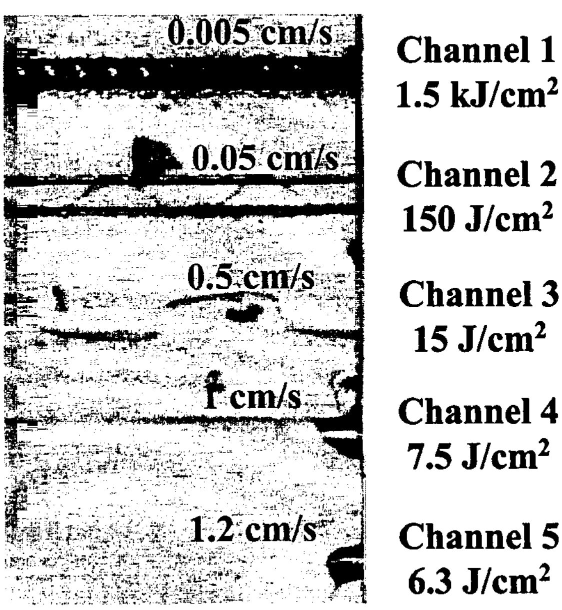

Fig. 2. Optical micrograph of directly written channels with associated scan velocity and applied fluence for constant I_{UV} = 1.5 kW/cm^2.

A general observation is physical dimensions for the resulting structures decrease with increasing scan velocity, for a constant I_{UV}. Furthermore, structures can be damaged either due to ablation (Channel 1) or microcracking (channels 2,3). However if applied fluence is below the damage threshold, structures formed (channels 4,5) will be free from severe physical defects. It should be noted that damage to a channel waveguide could also occur during the polishing process. Channels 4 and 5 show chipping at the end of the waveguide, a defect introduced during the polishing process.

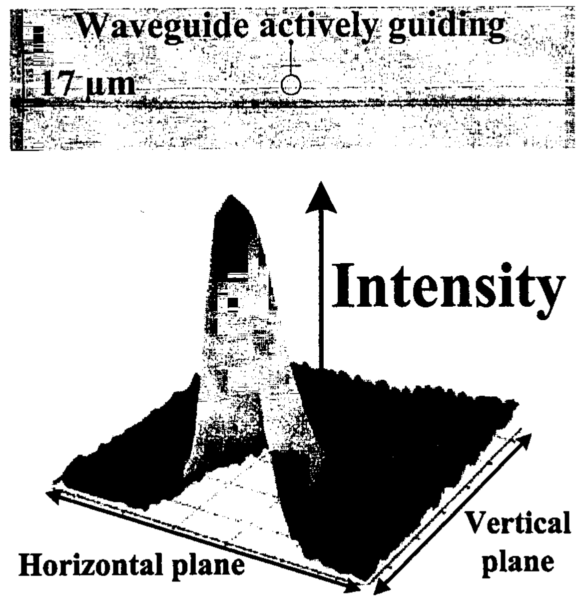

Fig. 3. Optical micrograph of a channel waveguide, actively guiding light, with compaction width 17 µm and surface plot of the near-field TM mode (λ=815 nm).

In Fig. 3 a channel waveguide directly written with fluence of 10.2 J/cm^2 and compaction width 17 µm is shown guiding a laser beam. The channel has a well formed structure and is without any apparent laser induced damage. Great care was undertaken during the polishing process, where the optical waveguide chip was wax bonded on each side to two similar sized Ga:La:S substrates for added polishing stability. It was also observed that the guided mode (λ=815 nm) was in the fundamental spatial-mode and measured modal dimensions were W_x = 7.2 µm by W_y = 8.2 µm for TM polarisation where W_x and W_y refer to the 1/e^2 intensity radii for the guided pump mode profile in the horizontal and vertical planes respectively.

The isolation of a single numerical figure as the lower limit for the damage threshold has proven difficult, as no clear pattern applicable to all write parameters could be identified. The appreciation for this complexity was readily understood once the parameters involved were studied. The key parameters in the direct-UV write process are laser intensity, scan velocity, UV-beam spot size and to a lesser extent surface preparation and homogeneity of glass composition. Investigation into damage threshold was conducted with variation in applied laser intensity (I_{UV} = 1.5 – 3.6 kW/cm^2) and scan velocity (V_{SCAN} = 0.5 – 5 cm/s) while maintaining a constant UV-beam spot size (a = 50 μm). Even at the lowest fluence (1.5 J/cm^2) the onset of surface compaction with depth of 0.2 μm, was observed as shown in Fig. 4. The resulting channel structure was well formed and able to guide light. When V_{SCAN} was in excess of 1 cm/s, channel structures were well formed for I_{UV} = 1.5 – 3.6 kW/cm^2. However, as V_{SCAN} approached low velocities, damage was visible in the form of severe microcracking. This could be due to residual tensile stresses causing fractures during the material relaxation cycle as well as strong absorption of laser energy. The damage threshold seemed to be specific for each applied laser intensity and was very much dependant on scanning velocity.

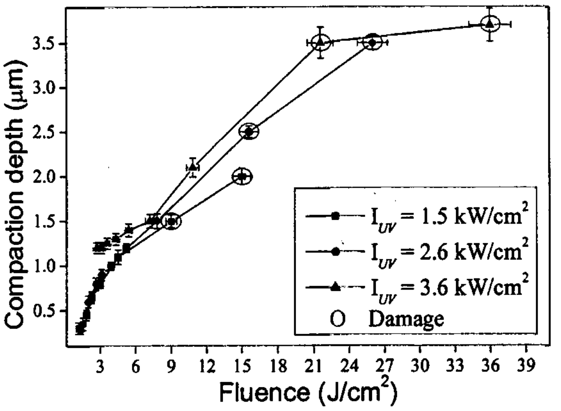

Fig. 4. Compaction depth is plotted against laser fluence for applied laser intensity (I_{UV} = 1.5 – 3.6 kW/cm^2). The graph shows six points of laser-induced damage due to slow scan velocities resulting in either ablation or microcracking.

For I_{UV} = 3.6 kW/cm^2, the channel formed with laser fluence of 10.6 J/cm^2 did not exhibit surface damage and was capable of guiding light. In contrast for I_{UV} = 1.5 kW/cm^2, the channel that was formed with a lower laser fluence of 9.1 J/cm^2 was seen to have undergone channel damage via severe microcracking. This suggests that the damage phenomenon is dependent on scanning velocity more so than it is on applied laser fluence. For a constant I_{UV} = 1.5 kW/cm^2, with applied fluence of 1.5 – 6 J/cm^2, uniform channels without any significant damage were observed. This was also true for I_{UV} = 2.6 kW/cm^2 and 3.6 kW/cm^2 with respective applied fluence of 2.1 – 8.5 J/cm^2 and 3.1 – 10.6 J/cm^2. Waveguide attenuation measurements were TM polarised at 1 μm and a tungsten lamp was used as a light source. For a channel exposed to 3.5 J/cm^2, waveguide attenuation was < 0.5 dB cm^{-1} prior to thermal annealing. The same waveguide had an attenuation of < 0.3 dB cm^{-1} following 30 minutes of thermal annealing at 400 °C.

IV. SUMMARY

Photoinduced changes can be introduced by directly writing waveguides into Ga:La:S glass through exposure to short wavelength light (λ = 244 nm). Photomodifying the physical and chemical properties allowed fabrication of a spatially single-mode channel waveguide with attenuation < 0.3 dB cm^{-1} at 1 μm. Surface compaction was observed for the lowest applied fluence with ablation and microcracking observed for very high fluencies. Photodensification was observed in the guided regions and was verified through EDAX. Maximum measured refractive index change in these channels was $\Delta n \approx +10^{-3}$. Further optimisation of glass quality and laser write parameters is expected, leading towards efficient low-loss devices for use with IO. We have already demonstrated laser operation in a neodymium-doped device [18] through this fabrication technique. The potential for developing highly nonlinear optical waveguides and erbium-doped waveguides with emission in the near-mid-IR seems promising.

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