Proton Beam Writing of Chalcogenide Glass: A New Approach for Fabrication of Channel Waveguides at Telecommunication O and C Bands

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***Abstract*—We report on proton beam writing of chalcogenide glass for the fabrication of channel waveguides. The focused proton beam at an energy of 1 MeV induces positive refractive index changes, forming channel waveguide structures in the irradiated region. The channel waveguides support both the TE and TM polarizations from the visible to near-infrared telecommunication O and C bands. Based on the maximum value of the refractive index contrast achieved by measuring the numerical aperture of the waveguide channels, we reconstruct the refractive index distribution and calculate the modal profiles of waveguides in the near-infrared wavelengths. The calculated modal profiles are in very good agreement with the experimental results. The minimum propagation loss is measured to be ∼2.0 dB/cm at the wavelength of 1064 nm.**

***Index Terms*—Chalcogenide glass, channel waveguides, proton beam writing.**

I. Introduction

Chalcogenide glasses are radically novel semiconductor materials with very promising properties, such as wider infrared transparent band than silica and fluoride glasses. Chalcogenide glasses are composed of covalently bonded heavy elements, in contrast to oxides, their interatomic bonds are weak. So the bandgap of chalcogenide glasses is red-shifted to the visible or near infrared (NIR) region of the spectrum [1]–[4]. That is to say, chalcogenide glasses are transparent for the MIR. Moreover, these glasses also have some unique optical properties for nonlinear and waveguide optics, which can be applied in phase-change memories, solar cells, sensors and photonics [5]–[9]. Gallium lanthanum sulfide glass (GLS) is a major member of chalcogenide glass family and has significant advantages over other chalcogenide glasses: wider transmission window (0.5–10 μm), higher refractive index ($n \sim 2.2767$), excellent thermal and mechanical stabilities, larger Kerr nonlinear coefficient, lower toxicity, and higher solubility of rare-earth ions. As a consequence, GLS glass can be used as a bulk platform for optical devices, such as compact waveguide-based devices for trace gas sensing or infrared imaging and detection in space [1]. Waveguide structures have been achieved in GLS chalcogenide glass by proton implantation and femtosecond laser inscription [10], [11].

In the traditional way, two dimensional (2D) confined channel or ridge waveguides could be fabricated by the combination of ion implantation and other technologies, for example, the mask technology, precise diamond blade dicing, and femtosecond laser inscription [12]–[20]. Moreover, 2D waveguides have been realized in a number of materials, including glasses, single crystals, polycrystalline ceramics, semiconductors and organic materials [20]–[22]. Nevertheless, such techniques require two-step processing of the samples. Alternatively, a direct-write ion beam technique has been applied to produce channel waveguides in optical materials, i.e., proton or He^+ ion beam writing. Such focused light ion beams, typically at energy of 1–3 MeV and fluence of 10^{13}–10^{16} cm^{-2}, has been rapidly growing to a powerful technique for the micro-manufacture of channel waveguides [19], [20], [23]–[34]. The proton or He^+ ion beam writing is based on the controlled scanning of proton or He^+ beam within the material. Some controlled micro-modifications occur in the scanning area. Concerning the optical properties, in most of the glasses [30], [33], [34] and some crystals (e.g., Nd:YAG and Nd:GGG) [27], [28], the proton or He^+ induces an increase of the refractive index in the scanning volume, typically located at the end of the ion track. This feature enables construction of buried waveguides instead of surface ones in some optical materials. However, the ion beams may also induce volume compression in the irradiated region along the whole trajectory of ions in some materials (e.g., silicate glass [35]), which results in formation of surface channel waveguides.

In this work, we report, for the first time, on the fabrication of channel optical waveguides in GLS chalcogenide glass by the proton beam writing. The guiding properties of GLS channel waveguides are investigated at the NIR telecommunication O (1.3 μm) and C (1.55 μm) bands.

II. Experiments in Details

The GLS chalcogenide glass was cut to the dimensions of $9.0\ (x) \times 10\ (y) \times 2.0\ (z)$ mm^3, and the largest and the two edge faces of the sample were optically polished. The fabrication of the channel waveguides in GLS chalcogenide glass by proton beam writing was carried out using the facility at the Centre for Ion Beam Applications, National University of

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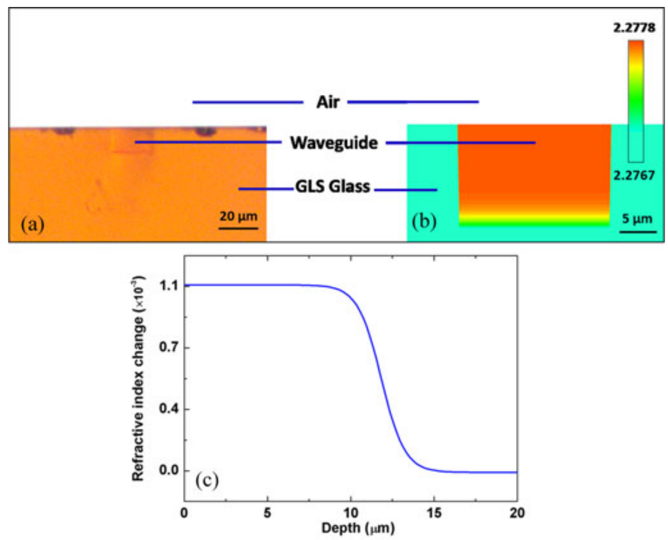

Fig. 1. (a) Cross-sectional microscopic image of channel WG3 fabricated in GLS chalcogenide glass by proton beam writing, taken with an optical microscope in transmission illumination. (b) The reconstructed refractive index of the channel WG3 for TE polarization. (c) The refractive index change along z direction of WG3 for TE polarization in GLS glass.

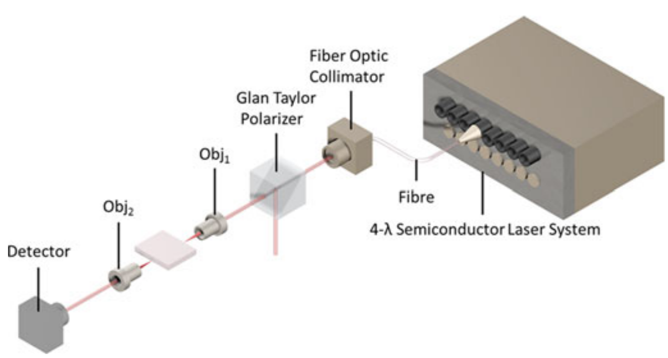

Fig. 2. Schematic of the end-face coupling arrangement employed to investigate the optical properties of channel waveguides in GLS glass.

Singapore. The proton beam with energy of 1 MeV was focused down, on one of the two large surfaces of the GLS sample. The GLS chalcogenide glass was mounted on a motorized stage (Exfo inch-worm stage), which can move linearly at different speeds. During the writing process, the proton beam was scanned along x axis of the sample, forming four channel waveguides, at fluences of 4×10^{15}, 6×10^{15}, 8×10^{15}, 1×10^{16} cm^{-2}, respectively (synthetically referred as WG1–WG4 hereafter). The cross sections of the four channel waveguides are similar, and the photograph of WG3 is shown in Fig. 1(a). The photograph was imaged by an optical microscope (Axio Imager, Carl Zeiss) operating in transmission mode. The chipping at the edge of GLS glass is visible. If the chipping is very close to the waveguide, the chipped edge may scatter the light to some extent, increasing insertion losses.

The end-face coupling arrangement, depicted in Fig. 2, was employed to investigate the near-field modal profiles of the channel waveguides. In order to reconstruct the refractive index distributions, we also utilized the improved end-face coupling arrangement, adding a large square glass for altering the incident angle of the laser placed after the Glan–Taylor polarizer, to determine the value of the maximum refractive index contrast. The incident light is generated in the 4-λ semiconductor laser system (GCSLS-O, China Daheng Group, Inc.), which can launch four kinds of laser with different wavelengths (405, 635, 1310, 1550 nm). The launched laser can be coupled into a fiber cable. Subsequently, by using the fiber optic collimator (GCX-L, China Daheng Group, Inc.), the divergent laser can be collimated. Afterwards, the output laser for the TE or TM polarization, passing through the Glan–Taylor polarizer, was focused by a NIR microscope objective lens (Numerical Aperture $(\mathrm{N.A.}) = 0.4$, $20\times$) to be coupled into the channel waveguide. The output light at the other facet of the sample was collected by using another microscope objective lens. A visible-NIR CCD camera (MicronViewer 7290 A, Electrophysics Corp., USA) was employed to map the coupled light from the channel waveguide structure. Consequently, the experimental near-field modal profile of the waveguide structure could be measured. Instead of the CCD camera, it is possible to measure the power of the output light with a power meter. By utilizing the improved end-face coupling arrangement, the N.A. of the waveguide was measured in order to get the maximum value of refractive index change of channel waveguides, by rotating the large square glass to adjust the position of the incident coupled light. Moreover, the 1064 nm laser also was employed to investigate the optical properties of the waveguides.

III. Results and Discussion

The refractive index distribution of a single channel waveguide cannot be directly obtained by the conventional measuring methods, such as the m-line technology, due to the small irradiated surface area of the channel. In order to reconstruct the refractive index distributions of channel waveguides produced by proton beam writing, the N.A of the waveguides was measured in order to indirectly determine the maximum value of the refractive index contrast between the bulk material and the core waveguide structure induced by the proton beam. The maximum of refractive index contrast could be roughly approximated by using the formula

$$\Delta n \approx \frac{\sin^2 \theta_m}{2n} \tag{1}$$

where θ_m is the maximum incident angular deflection at which there is no transmitted light out of the channel waveguide structure, while n is the refractive index of the substrate [36]. According to the measured θ_m, we can roughly calculate the maximum refractive index contrast of the channel waveguide for the two transverse polarizations. The maximum refractive index contrasts of the four channel waveguides for the TE and TM polarizations are shown in Fig. 3, respectively. It can be seen that the refractive index changes along TM polarization are larger than those along TE direction, showing effect of ion beam induced birefringence in the guiding cores. In addition, based on these data of refractive index change maxima together with the shape of channel waveguide structure, we can obtain the reconstructed

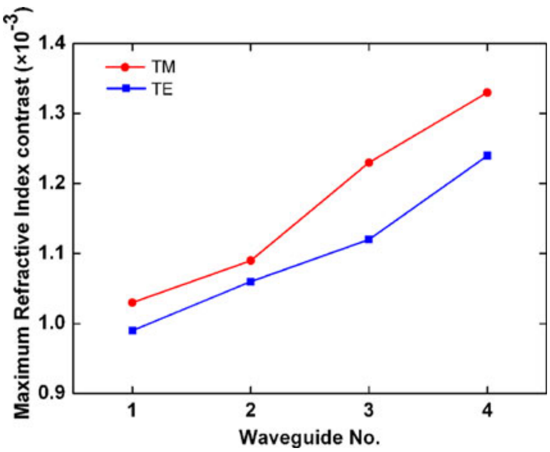

Fig. 3. The maximum refractive index contrasts of WG1–WG4 induced by proton beam writing for the TE and TM polarizations.

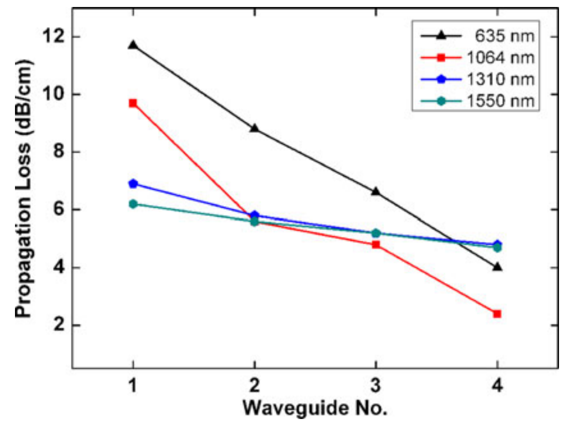

Fig. 5. The propagation losses of WG1–WG4 induced by proton beam writing for the TE polarization at the wavelength of 635, 1064, 1310 and 1550 nm.

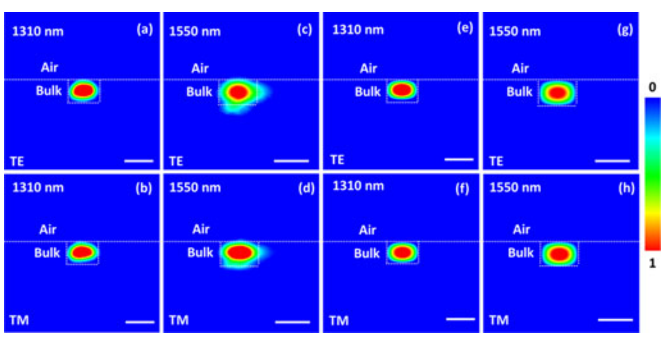

Fig. 4. The measured near-field modal profiles of WG3 for the TE (a) and TM (b) polarization, and calculated ones for the TE (e) and TM (f) polarization at the wavelength of 1310 nm; the measured near-field modal profiles of WG3 for the TE (c) and TM (d) polarization, and calculated ones for the TE (g) and TM (h) polarization at the wavelength of 1550 nm. (All the scale bars are 20 μm.)

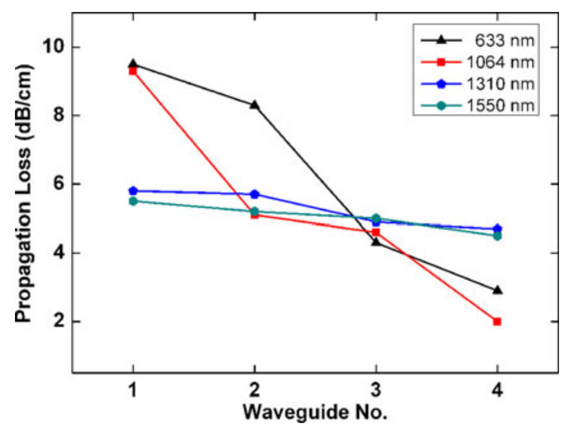

Fig. 6. The propagation losses of WG1–WG4 induced by proton beam writing for the TM polarization at the wavelength of 635, 1064, 1310 and 1550 nm.

refractive index distribution. The refractive index distribution of WG3 for the TE polarization is shown in Fig. 1(b). Moreover, Fig. 1(c) depicts the refractive index change of WG3 for TE polarization along z direction in GLS glass.

According to the reconstructed refractive index profiles, the modal profiles of fundamental TE and TM mode for channel waveguide at the wavelength of 1310 and 1550 nm can be calculated by using the finite-difference beam propagation method (FD-BPM) of the RSoft© software [37]. Fig. 4(a)–(h) depict the measured and calculated modal profiles of the channel WG3 for the TE and TM polarization at the two telecommunication wavelengths of 1310 and 1550 nm, respectively. As one can see from Fig. 4, the calculated modal profiles are in good agreement with the experimental results measured by using the end-face coupling arrangement. It also implies that the reconstructed refractive index profile can be trusted and the simulations of the modal profile based on the reconstructed refractive index profile were successful. From the calculated and experimental near-field modal profiles, it can be seen that the light of 1310 and 1550 nm guided in the channel WG3 is single-mode. Due to the low loss of the single-mode propagation, such waveguide structure can be applied in the modern NIR communication.

The propagation losses of the four channel waveguides for the TE and TM polarizations were measured by means of the end-face coupling arrangement. The results were shown in Figs. 5 and 6. As one can see, the propagation losses diminish along with the increase of the fluence. It is because larger fluence can induce higher refractive index contrast between the bulk material and the core waveguide structure. The light can be confined with higher efficiency in the high-index waveguide structure. So the wave-guiding properties could be improved by increasing the writing fluence. Based on Figs. 5 and 6, we also can find the propagation losses for the TM polarization are lower than the ones for the TE polarization. Two possible factors might be responsible for such difference. The first one is that the light for the TM polarization is confined by the air and the bulk (the one for the TE polarization is confined by the bulk): thus, the light with the TM polarization could be confined inside the waveguide structure better than the light with the TE polarization. The second one is the difference between the refractive index contrast in the waveguide structure, that is larger for the TM polarization, and it may improve the confinement properties.

IV. Conclusion

In conclusion, we have reported the fabrication of channel waveguides in chalcogenide glass by using proton beam writing. The guiding properties in the NIR telecommunication O and C bands have been investigated, showing very good performances, with single mode for both TE and TM polarizations. The lowest propagation losses of waveguides were measured at the wavelength of 1064 nm to be $\sim$2.4 dB/cm for the TE polarization and $\sim$2.0 dB/cm for the TM polarization. Such waveguide structures could be applied in the modern NIR communication.

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