Effect of Net-Fluence on waveguide formation in ultrafast laser inscribed chalcogenide glass

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Abstract: Waveguides were fabricated on GeGaSEr chalcogenide glass using ultrafast laser inscription method. The thermal diffusion model is discussed for understanding the light matter interaction and shown the effect of net-fluence in waveguide formation on chalcogenide glass.

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1. Introduction

Chalcogenide glasses are attractive because of its transparency in mid-IR region, photo-sensitivity [1], high third order non-linearity, chemically and thermally stable, easy to dope with rare earth ions due to the high solubility and low phonon energy [2,3]. Direct laser writing method employs multi-photon absorption by focusing its sub band-gap energy [4] into the material to produce high energy to cause structural changes in the material for fabricating devices like waveguides, lasers and amplifiers on bulk transparent dielectric material. A major advantage of fabricating waveguides using femtosecond micromachining is the ability to create 3-D structures inside the transparent materials [5].

Bulk GeGaSEr glass prepared by vacuum sealed conventional melt quenching technique. The amorphous nature of the sample was confirmed by X-ray diffraction. In this work, controlling the waveguide cross section by solving the heat diffusion model by finite difference method is discussed. From this model, we compared the theoretical values with the experimental results for waveguide cross-section.

2. Waveguide fabrication and Charecterization

We fabricated waveguides on GeGaSEr chalcogenide glass using Yb-doped femtosecond fiber laser. A circularly polarized sub-picosecond pulse laser of 1047 nm wavelength, 350 fs pulse duration at repetition rate of 100 kHz were set for inscription. Waveguides were fabricated using high intensity laser pulses. The laser pulses were focussed using aspheric lens having 0.68 NA at a distance of 100 μ m below the surface of the GeGaSEr glass sample. Each waveguide is separated by 50 μ m to avoid the overlapping or stress influence on the subsequent waveguide. The various range of powers from 94 mW to 30 mW by 85 % step down and different translation speeds of 18 mm/s, 10 mm/s, 6 mm/s and 4 mm/s 1 mm/s and 0.1 mm/s were used to inscribe the waveguide.

The near field image of the waveguide was captured at a wavelength of 1550 nm, using IR camera with 0.65 NA objective lens. The optically induced structure was captured by an optical microscope at 50x magnification. The corresponding images are provided in Fig. 1.

3. Modeling

The temperature distribution during waveguide formation was calculated with a finite-difference thermal diffusion model governed by the thermal diffusion partial differential equation with spherical symmetry

$$\frac{\partial}{\partial r} \left(r^2 \frac{\partial T}{\partial r} \right) = \frac{r^2}{D} \left(\frac{\partial T}{\partial t} \right) \quad (1)$$

Fig. 1. (a) Optical microscope image of single mode waveguide and (b) its corresponding near field image at 1550 nm

The laser dissipation was treated as a spherical Gaussian distribution with energy volume density $E(r) = E_0 \exp(-r^2/w_0)$ with beam waist w_0 set to the $1/e^2$ radius of the focused laser beam waist. The value of E_0 depends on the absorbed laser pulse energy, which was inferred from measurement of the transmitted laser power. The values of E_0 were varied by changing the laser power, scan speed, and repetition rate. The temperature profile was augmented by an instantaneous temperature rise $T(r) = E(r)/C_p\rho$, each time a new laser pulse arrived. To model the effect of net fluence on waveguide diameter, specific heat capacity (673 J/g°C), thermal diffusivity (0.0026 cm²/s) and density (2761.1 kg/m³) of the material were calculated using modulated DSC, a custom made photothermal diffusivity instrument and Metler Toledo density Kit respectively.

Fig. 2. The relation between Waveguide diameter and net fluence for experimentally observed and theoretically calculated values

4. Discussion

The waveguide near field image at 1550 nm wavelength was captured using IR camera with 0.65 NA objective lens and the optically induced structure are captured with the help of optical microscope with 50x magnification (Fig.1). We calculated the waveguide diameter by comparing pixel values of the near field images of the standard telecommunication

fiber and the waveguide.

The finite-difference heating model is used to find the waveguide spatial formation [6]. To compare this model with the experimental results, net fluence (NF) is calculated for each energy and translation speed. The net fluence is calculated using the following relation,

$$NF = \frac{2R}{\pi\omega_0} \frac{E_p}{v} \quad (2)$$

where ω_0 is the beam waist, R is repetition rate and v is the translation speed and E_p is the incident laser pulse energy.

Fig.2 shows the relation between the net-fluence and the diameter of the waveguide from solving the thermal diffusion equation [6,7]. We have taken three energy with four different translation speed for the modeling. The model best fits the experimental data with 70%, 80% and 90% absorption for 580, 803 and 945 nJ of incident pulse energies respectively. For the incident pulse energies 580 nJ, 803 nJ, and 945 nJ the corresponding absorbed laser energies were 406 nJ, 674 nJ, and 850 nJ respectively. This suggest that with increase in incident pulse energy the absorption also increases, which further leads to an higher initial temperature. As expected, the transverse waveguide diameter increases with increasing net exposure, through decreasing scan speed. With increase in absorbed energy, larger waveguide diameter were observed (Fig. 1a). This could be attributed to the strong heat diffusion effects owing to an increases photoionization rate. There is a fine agreement between theoretical and experimental values of waveguide diameter. The theoretical model data goes well with experimental data within 7% error at 945nJ pulse energy. At 803 nJ and 580 nJ pulse energy the estimated values vary about 18% and 13% respectively from the experimental results.

5. Conclusion

We presented the waveguide formation in GeGaSe chalcogenide glass due to the thermal diffusion using ultrafast laser inscription method at low repetition rate. The relation between the net fluence and waveguide cross section diameter was verified using these experimentally measured physical properties. The theoretically predicted values are in agreement with the experimental values.

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