Femtosecond laser writing of the depressed cladding buried channel waveguides in ZnS crystal

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Abstract: We report the first direct laser-writing of buried channel waveguides in ZnS. A depressed cladding waveguide with propagation loss of 0.62 dB/cm at 1030 nm allowed to obtain spectral broadening under femtosecond-pumping at 1030 nm.

OCIS codes: Guided waves (130.2790) ; Laser materials processing (140.3390); Infrared and far-infrared lasers (140.3070).

1. Introduction.

The channel waveguide architecture is promising for the mid-IR supercontinuum generation in media with high Kerr nonlinearity. Recently we reported the first experiments on supercontinuum and frequency comb generation from Cr:ZnSe and Cr:ZnS lasers using various nonlinear fibers such as e.g. germanate and chalcogenide fibers[1,2] as well as chalcogenide nanospikes[3]. The direct femtosecond laser writing paves the way towards uniqe opportunities opening up upon formation of such waveguides as it will make the supercontinuum source not only extremely compact but also will allow operation at high repetition rates in excess of 10 GHz, which is highly attractive for high resolution and high sensitivity spectroscopy using coherent mid-infrared frequency combs. This work will also open up the way towards highly efficient compact few optical cycle frequency comb sources around 5 microns – the work similar to the one previously done with bulk Cr:ZnSe[4] or Yb- and Tm-fiber lasers[5]. In this paper we report on the first steps towards creation of a single mode channel waveguide in highly non-linear ZnS single crystal and using it for supercontinuum generation.

2. Optimization of direct laser writing in ZnS crystal.

A Yb:KGW femtosecond laser system with a regenerative amplifier operating at wavelength $\boldsymbol{\lambda}$ = 1028 nm was used for direct laser writing in standard setup, where the focused laser beam is perpendicular to the direction of the sample scanning. An objective length with NA=0.85 was used for focusing at depth of 100 μm under the polished crystal surface. Trial writing of tracks was done with different pulse duration, pulse repetition rates and scatting velocity of the sample. Refractive index change in the tracks was investigated with QPm technique. At first dependence of refractive index change upon pulse duration was obtained with repetition rate $\boldsymbol{f}$ and scanning velocity $\boldsymbol{V}$ fixed at 5 kHz and 0.25 mm/s correspondingly (Fig.1).

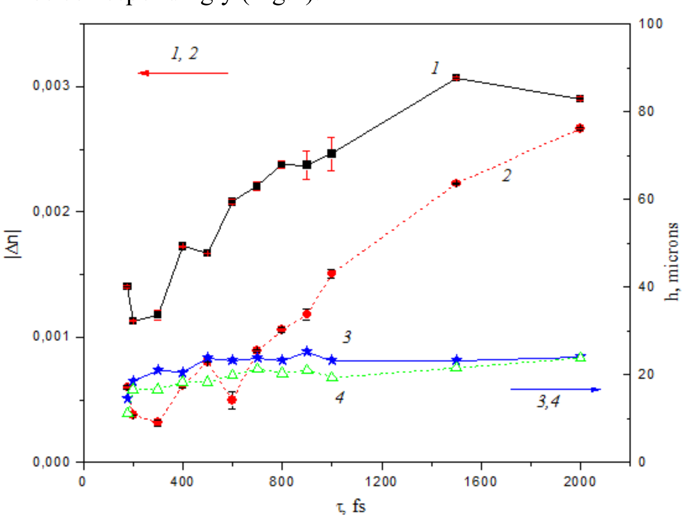

Fig.1. Dependencies of the refractive index change |$\boldsymbol{\Delta n}$| (1,2) and the track height *h* (3,4) on the pulse duration *t* (f = 5 kHz, E_p = 960 nJ, V = 0.25 mm/s). *1, 3* – Polarization $\boldsymbol{E}$ is perpendicular to the scanning direction $\boldsymbol{s}$, *2, 4* – $\boldsymbol{E}$ is parallel to $\boldsymbol{s}$.

All obtained tracks have the decreased refractive index with respect to non-modified regions of the crystal. The tracks were fairly smooth and homogeneous under pulse duration not exceeding 1000 fs, and visible inhomogeneity was observed in microscope as pulse duration increased over 1000 fs. The refractive index change grows significantly with pulse duration while the rack height remains almost unchanged and equal to $\boldsymbol{h} \approx 20$ µm. Refractive index change $|\boldsymbol{\Delta n}|$ produced by the beam with polarization perpendicular to the scanning direction is larger than $|\boldsymbol{\Delta n}|$ produced by the beam with polarization parallel to the scanning direction. Pulse duration of 800 fs was chosen as a compromise between high refractive index change and homogeneity of a track in experiments for further optimization of writing on the pulse energy, repetition rate and scanning velocity. The tracks were slightly rugged at high repetition rates and writing velocities. So, the intermediate conditions ($\boldsymbol{f}$ = 100 kHz; $\boldsymbol{V}$ = 5 mm/s) were selected for waveguide writing in order to avoid any inhomogeneity in the tracks.

3. Characterization of the depressed channel waveguide.

We used depressed cladding architecture with a tube-like cladding for channel waveguide writing [6,7]. Depressed cladding. Series of waveguides differed by number of tracks in the cladding and distance between tham were written. The waveguide possessing a nearly single mode behavior at wavelength of 1030 nm is shown in Fig.2.

(a) (b)

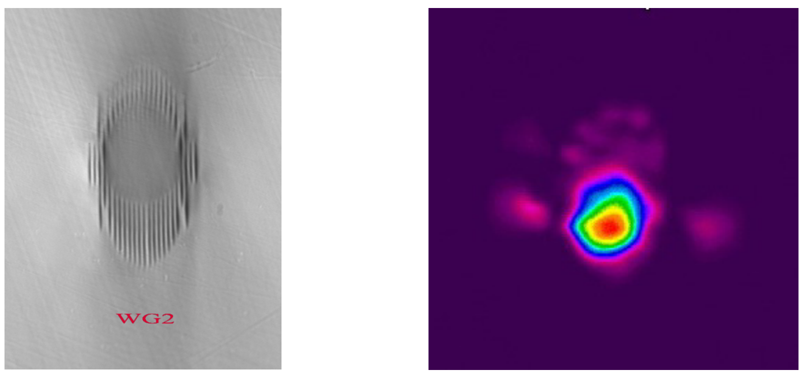

Fig.2. (a) End view of the channel waveguide inscribed in ZnS single crystal by femtosecond laser beam at $\boldsymbol{\lambda}$ = 1028 nm, pulse duration of 800 fs, $\boldsymbol{f}$ = 100 kHz, $\boldsymbol{V}$ = 5 mm/s, pulse energy of 500 nJ. Core diameter is equal to 40 µm; (b) Experimental distribution of intensity at the waveguide output. Mode diameter is equal to nearly 35 µm.

The waveguiding loss for inscribed structures was as low as 0.62 dB/cm. It was found that the structure guides the light with multimode regime, when coupled with femtosecond pulses with pulse duration of 300 fs and laser the average power exceeding 1 mW. Correspondingly we have found a broadening of the spectrum at the waveguide output at this level of average power. The increase of the beam power results in growth of spectral width up to 70 nm, which was obviously restricted because of strong positive GVD in the spectral region of investigations.

4. Conclusion

Direct laser writing was shown to be a promising technique for manufacturing of low loss single mode channel depressed cladding waveguides in ZnS single crystal. It opens up unlimited opportunities to fabricate both passive as well as active ion doped ZnS/ZnSe based waveguides for integrated photonic devices.

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