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Femtosecond laser writing of a depressed cladding single mode channel waveguide in high-purity tellurite glass

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ABSTRACT

High-purity tungstate-tellurite glasses doped with molybdenum, lanthanum or bismuth oxides were investigated from a point of view promising medium for nonlinear optical devices fabrication. A tubular-like architecture was employed for fabrication of waveguides in the of tellurite glasses, in which refractive index change is negative under femtosecond laser writing at 1028 nm. Thermal, nonlinear optical properties and optimal laser writing conditions were determined. The glasses revealed a very high stability against crystallization, high transparency in the visible, near- and mid-IR regions, large values of Kerr nonlinear coefficient that are within the range of $(4.3 \div 5.4)\cdot 10^{-6}$ cm^2/GW. The highest values of the nonlinear coefficient were found for bismuth containing glasses. The single mode waveguide with propagation loss of 0.15 dB/cm at 1064 nm was inscribed in tungstate-tellurite glass.

1. Introduction

Tellurium dioxide based glasses are characterized by low phonon energy as compared with silica glasses, possess convenient viscosity parameters and sufficient mechanical strength. High Kerr nonlinearity and large Raman gain coefficient in combination with wide band gap make them a very promising material for bulk and waveguide devices based on nonlinear optical conversions of ultra-short pulses to mid-IR. Manufacturing of tellurite glasses with an extremely low content of 3d–transition metals and hydroxyl groups, and hence with low optical loss in the near and mid-IR regions has already been demonstrated [1,2].

Waveguide architecture is highly attractive for increasing non-linear optical effects, because it allows keeping high intensity of light along long optical path that is complicated using bulk optics. The self-frequency shift of solitons, the red-shifted dispersive wave and solitonic supercontinuum generation were demonstrated in tellurite glass optical fibers [3–5].

Thus, development of a technique for manufacturing of high-quality waveguides inside bulk samples of tellurite glass is of considerable interest. Formation of waveguiding channels by ion-exchange technique is difficult due to damage of the glass surface [6]. The direct laser writing waveguides in tellurite glasses is pretended to be more attractive, because tight focusing of a laser beam in the glass volume permits to keep low intensity on the glass surface. The inscription of waveguides performed by UV irradiation of cw doubled frequency Ar^+ laser (wavelength $\lambda = 244$ nm) was described in [7]. The channels with length of 1 cm were inscribed in the regime of refractive index increase inside the channels with respect to non-illuminated region ($\Delta n = 1.5\cdot 10^{-3}$). The waveguide insertion loss was about 8 dB at $\lambda = 1550$ nm.

Refractive index modification in tellurite glasses under laser pulses exposure was investigated by Inoue and co-authors [8–10]. The sodium-tellurite based glasses ($TeO_2\cdot Na_2O\cdot Al_2O_3$, $TeO_2\cdot Na_2O\cdot GeO_2$, and $TeO_2\cdot Na_2O\cdot TiO_2$) doped with 2 mol% CoO exhibited decreased refractive index inside illuminated region after exposure to 5 ns laser pulses ($\lambda = 532$ nm, repetition rate $f = 10$ Hz, spot diameter d was about 800 μm) with average power $P = 60 \div 1000$ mW by a value $|\Delta n| = 0.05 \div 0.22$ [10]. The thermal action of the light beam is responsible for observed phenomena, i.e. the light induced local heating and cooling after stopping the irradiation results in decrease in n.

The laser writing in niobium-tellurite glass increases the refractive index [11] but the long-term result of the light action depends on pulse duration. Picosecond pulses (pulse duration $\tau = 30$ ps, $\lambda = 532$ nm, $f = 10$ Hz) modify the glass, but the modification disappears during 48 h after illumination. At the same time exposure to femtosecond pulses ($\lambda = 800$ nm, $\tau = 130$ fs, $f = 1$ kHz) results in permanent increase in refractive index, $\Delta n = 0.009$. Authors have explained the refractive index growth under fs-pulses exposure by rearrangement of

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the glass structure. Guiding of He–Ne laser light was demonstrated in the waveguide, but the inscribing procedure, characteristics of waveguide, and loss were not presented.

Channel waveguides with positive modification of refractive index were inscribed by femtosecond pulses in various glasses based on the tellurium oxide [12–18]. The fs-pulses induced refractive index modification in phospho–tellurite glass ($67TeO_2$–$30P_2O_5$–$1Al_2O_3$–$1.75La_2O_3$–$0.25Er_2O_3$) doped with Er^{3+} was obtained in [12] using Ti:sapphire laser (λ = 806 nm, τ = 45 fs, f = 1 MHz) and focusing objective lens with numerical aperture NA = 0.45. Waveguide channels 1 cm in length and 4 ÷ 8 μm in width were inscribed. Inscription velocity was in range V = 0.1 ÷ 0.3 mm/s, the pulse energy was E_p = 3000 nJ. Value of propagation loss was < 2 dB/cm. Besides, a decrease in La and P concentrations inside the channels and a migration of these atoms toward the periphery was found. The modulation of the Te:P ratio can explain positive refractive index change inside modified region.

Er^{3+}-doped sodium-phospho-tellurite glasses were proposed for optical amplifiers based on a channel waveguide [13,14]. Femtosecond oscillator Yb:KYW emitting at λ = 1040 nm pulses with τ = 350 ÷ 400 fs, f = 600 ÷ 1000 kHz and the objective lenses with numerical aperture NA = 0.6 or 1.4 (oil immersed) were used. The best waveguides (that showed a uniform morphology with a bright contrast of refractive index) were obtained under inscription with 1 MHz repetition rate, 130-nJ pulse energy at 4 mm/s scan velocity and objective lens with NA = 1.4 [14]. The increase of refraction index Δn inside the channel was as high as $2.5 \cdot 10^{-3}$, propagation loss at 1600 nm was 0.9 dB/cm for the 2.1-cm long waveguide under single mode guiding. Analysis of ion concentrations in the laser exposed region revealed increase in Te concentrations and decrease in Na concentrations inside regions with high refractive index [15]. For surrounding regions with decreased refractive index the ratio of ions was opposite. Local increase of Te was explained by the modification of atoms arrangement, i.e. conversion of trigonal bipyramids (TeO_4) to trigonal pyramids (TeO_3). This conversion is accompanied with increase of the packing fraction and, consequently, with glass densification.

At the same time femtosecond pulses (with pulse energy E_p = 10 ÷ 150 nJ) reduce refractive index in the $73TeO_2$–$20ZnO$–$5Na_2O$–$2La_2O_3$ glass [19]. The analogous result of lowering of refractive index was obtained for Er^{3+} doped tellurite glass under femtosecond-pulses writing (λ = 800 nm, τ = 50 fs, f = 1 kHz, the inscription velocity was set in range V = 0.02 ÷ 0.1 mm/s, the pulse energy was E_p = 100 ÷ 1000 nJ) [6]. It is obviously that single channel waveguiding in the obtained structures is impossible.

In order to get waveguiding at negative refractive index modification under direct femtosecond laser writing one should consider a depressed cladding waveguide structure [20–22]. Depressed cladding waveguide consists of non-modified core that surrounded by a number of tracks with laser-induced lowered refractive index, which constitute the cladding. Such structure has advances with respect to traditional core-modified waveguides. At first, light propagates through non-modified core, which is obviously more homogeneous medium than core-modified waveguides. Such approach permits keep low scattering loss in core and does not degrade spectroscopic properties of medium. At second, size and shape of the core can be managed depending on the requirements on composition and sizes of guiding modes.

In this paper we describe fabrication of depressed cladding channel waveguides in high-purity tellurite glasses by the femtosecond laser beam.

2. Experiment

2.1. Glasses samples preparation

High-purity tungstate-tellurite glasses modified with bismuth, molybdenum or lanthanum oxides were chosen for the study by the criteria of high transparency in the visible and near-IR ranges, rather high stability against crystallization, good mechanical properties and high values of optical nonlinearity. The codes and corresponding compositions of the samples are presented in the Table 1.

Table 1
Composition of the tungstate-tellurite glasses, glass transition temperature T_g and Kerr nonlinear coefficient γ.

Code	Composition (mol. %)	T_g, °C	γ, cm^2/GW
TWL-1	$72TeO_2$–$24WO_3$–$4La_2O_3$	400	$4.42 \cdot 10^{-6}$
TWL-2	$69TeO_2$–$23WO_3$–$8La_2O_3$	430	$4.35 \cdot 10^{-6}$
TWLM-1	$64.8TeO_2$–$21.6WO_3$–$3.6La_2O_3$–$10MoO_3$	385	$4.64 \cdot 10^{-6}$
TWLM-2	$68.4TeO_2$–$22.8WO_3$–$3.8La_2O_3$–$5MoO_3$	395	$5.03 \cdot 10^{-6}$
TWB-1	$73TeO_2$–$22WO_3$–$5Bi_2O_3$	360	$5.4 \cdot 10^{-6}$
TWB-2	$70TeO_2$–$22WO_3$–$8Bi_2O_3$	370	$5.39 \cdot 10^{-6}$

High-quality bulk optical devices, using nonlinear optical effects, require the achievement of low optical loss in the host material. Optical loss is largely determined by the concentration of impurities in the initial chemicals and inserting impurities during preparation of a glass, and the presence of scattering inclusions, mostly of crystalline phases. Hydroxyl groups, 3d-transition metals and certain rare-earth elements impurities actively absorb in the visible and infrared ranges. High-purity oxides TeO_2, WO_3, MoO_3 were fabricated by original techniques [23–25] and commercial “superpure” grade La_2O_3 and Bi_2O_3 were used for the glasses synthesis.

The total content of 3d-transition metal impurities in the mixture of initial oxides from the data of atomic emission analysis do not exceed 0.2–2 ppm wt, the content of rare-earth elements controlled by laser mass spectrometry method is less than the detection limit of the method (< 1–2 ppm wt) [1].

The glasses were produced by melting the oxides in gold and platinum crucibles. Glasses were melted at 800 °C for several hours with recurrent stirring of the melts, and then the melt was poured into silica glass moulds and annealed during several hours at a glass transition temperature.

After annealing the founded samples were extracted from the moulds and mechanically treated by cutting, grinding and polishing into the plates of necessary sizes for measurements and waveguide writing tests.

The glasses TWL and TWB were prepared inside a sealed silica chamber in the atmosphere of purified oxygen. The applied procedure of melt drying and sample preparation allows to achieve a low concentration of hydroxyl group impurity and, accordingly, low optical loss in the mid-IR [2]. In order to compare the properties of glasses obtained by different techniques, the TWLM glasses were obtained by conventional melting-quenching process in an open furnace in a stream of non-dried oxygen. Under these conditions, the concentration of hydroxyl groups remains high, as well as optical loss in the mid-IR. Such samples are quite suitable for studies in the wavelength region of about 1 μm or less, but for mid-IR applications, especially near the hydroxyl absorption bands with peaks of ~1.5 μm, ~2.3 μm, ~3 μm, ~4.5 μm the excessive loss will impact.

2.2. Thermal properties, visible and IR spectra

Stability against crystallization is one of the main criteria for the suitability of glasses for melt-quenching forming high-quality casts for optical elements. It is usually expressed through the difference between values of the transition and crystallization temperatures (in the case of a non-optimal composition). STA - 409 PC Luxx instrument was used for investigations by differential scanning calorimetry. The accuracy of the measurement was estimated to be ± 3 °C. The glass transition temperatures were approximately determined from the point of intersection of the tangents to the curve at the inflection corresponding to the thermal effect of vitrification (Table 1).