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New ytterbium-phosphate glass for diode-pumped lasers

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***Abstract*. A new ytterbium laser glass based on an alumoborophosphate composition is developed. It is shown that the chemical and thermal stabilities of this glass are record-high for phosphate glasses and that its spectral and luminescent characteristics compare well with popular laser glasses. A mould of laser-quality glass doped with ytterbium with a concentration of 5×10^{20} cm^{-3} is synthesised. Active laser elements $5 \times 5 \times 2$ mm in size are prepared from this glass for longitudinal diode pumping. These elements were used to fabricate a laser, whose output power in the cw regime reached 783 mW and maximum slope efficiency was 28.9 %. Pulses with a duration of $\sim$ 150 fs and a peak power of about 5 kW are obtained in the passive mode-locking regime.**

Keywords: *laser glass, ytterbium, femtosecond laser*.

Laser materials doped with trivalent ytterbium ions Yb^{3+} are of great interest for development of compact, reliable, and efficient laser sources in the spectral region near 1 μm. The advantages of ytterbium-containing laser materials compared to neodymium-containing media include the simple two-level energy diagram, which is responsible for the absence of losses caused by the absorption from the excited state and by the up-conversion [1], and a low ($\sim 4\,\% - 5\%$) quantum defect (difference between the frequencies of the absorbed and emitted photons), which leads to low thermal losses in the active medium and, hence, to higher output powers. The intense absorption bands in the region of 980 nm allow one to pump such lasers by commercial laser diodes, which considerably decreases the cost and increases the reliability of these lasers. It should be also noted that the cost price of glass materials is much lower than that of laser crystals, while the wider and smooth stimulated emission bands are favourable for producing tunable and ultrashort-pulse lasers. In some works, lasing in ytterbium glasses was demonstrated upon pumping both by solid-state [2] and diode [3] lasers, but the output power was only of about 0.5 W.

As is known, the most important drawbacks of phosphate laser glasses are the low mechanical strength and thermal resistance, which limits the average output power, as well as the low resistance to atmospheric moisture. The main structural components of phosphate glasses are the PO_4 tetrahedrons with strong covalent bonds between the central ion and oxygen anions. The glass properties are substantially determined by the number of chemical bonds between the tetrahedrons. A well-known example of glass with a high thermal resistance and mechanical strength is fused quartz, in which each of the SiO_4 tetrahedrons is bound to the four neighbouring tetrahedrons by bridging oxygen ions, i.e. by ions which form bonds with two neighbouring glass-forming ions. This results in a stable three-dimensional structure, which determines the excellent thermomechanical properties of fused quartz. In the case of phosphate glasses, the PO_4 tetrahedrons are bound only to 2 – 3 neighbouring ones, because of which the thermomechanical strength and chemical stability of these glasses are low.

The idea of development of high-strength and chemically stable phosphate laser glasses, used by us previously in [4], consists in what follows. It is known that trivalent ions of small radii (B^{3+}, Al^{3+}) also can form strong tetrahedron complexes with oxygen. In the BPO_4 and $AlPO_4$ crystals, the alternating PO_4 and BO_4 (or PO_4 and AlO_4) groups form a strong three-dimensional lattice similar to the quartz structure with four bridging oxygen ions in each tetrahedron. Similar to crystals, the glasses of mixed borophosphate and alumophosphate compositions also can have an enhanced thermomechanical strength and chemical stability compared to purely phosphate glasses owing to better bonds between glass-forming tetrahedrons. Using these considerations and the results of [4], we chose the following molecular composition of ytterbium laser glass with a mixed alumoborophosphate glass-forming matrix: Li_2O (9 %), Al_2O_3 (7 %), B_2O_3 (12 %), $La_2O_3 + Yb_2O_3$ (7 %), P_2O_5 (65 %). Our investigations showed that such properties of this glass as the moisture resistance, hardness, thermal expansion coefficient, and thermal resistance are similar to the properties of much harder and chemically stable silicate glasses, while the ytterbium absorption and luminescence spectra and cross sections are almost the same as those of pure phosphate glasses. The physicochemical properties of the high-strength alumoborophosphate laser glass are given below.

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Refractive index n	1.53
Heat expansion coefficient	
at $T = 20 - 40\,^{\circ}\mathrm{C}/10^{-7}\ \mathrm{K}^{-1}$	72
$\mathrm{d}n/\mathrm{d}T$ at $T = 20 - 40\,^{\circ}\mathrm{C}\ /10^{-7}\ \mathrm{K}^{-1}$	27
Thermooptical coefficient $W = \mathrm{d}n/\mathrm{d}T + \alpha(n-1)\ /10^{-7}\ \mathrm{K}^{-1}$	66
Density at $20\,^{\circ}\mathrm{C}\ /\mathrm{g\ cm}^{-3}$	2.83
Melt density at $1350\,^{\circ}\mathrm{C}\ /\mathrm{g\ cm}^{-3}$	2.67
Thermal conductivity $/\mathrm{W\ m}^{-1}\mathrm{K}^{-1}$	0.83 ± 0.04
Heat capacity $/\mathrm{J\ cm}^{-3}\mathrm{K}^{-1}$	2.06 ± 0.05
Knoop hardness $/\mathrm{kgf\ mm}^{-1}$	702 ± 30
Weight loss in boiling water $/10^{-5}\ \mathrm{g\ cm}^{-2}\ \mathrm{h}^{-1}$	<1
Acid resistance (GOST 13917-82) group	1
Moisture resistance (GOST 13917-82) group	U
Deformation temperature $/^{\circ}\mathrm{C}$	755
Heat shock resistance $/^{\circ}\mathrm{C}$	
without ion exchange strengthening	165–175
with ion exchange strengthening	285–315

The spectral and luminescent studies showed that the developed glass exhibits a pronounced quenching of ytterbium luminescence by OH^--groups, which inevitably exist in phosphate glasses. Figure 1 presents the dependence of the ytterbium luminescence decay rate W_{OH^-} on the concentration of OH^--groups for the maximum technologically possible ytterbium concentration $1.7 \times 10^{21}\ \mathrm{cm}^{-3}$, which corresponds to the 100 % substitution of lanthanum by ytterbium ions. The observed anomalously strong quenching imposes some restrictions on the concentration of ytterbium in a glass to be used as an active laser material. It is experimentally found that at the best dehydration achievable under our technological conditions, which corresponds to the absorption coefficient $\sim 1.5 - 2\ \mathrm{cm}^{-1}$ at the wavelength 3.3 μm, the ytterbium concentration must not exceed $(5-7) \times 10^{20}\mathrm{cm}^{-3}$. Under these conditions, the lifetime of Yb^{3+} in the excited state is close to the radiative lifetime (1.2 ms) and the decay rate W_{OH^-} does not exceed $0.2\ \mathrm{ms}^{-1}$.

We developed an original technology for moulding high optical quality glass with an ytterbium concentration of $5 \times 10^{20}\ \mathrm{cm}^{-3}$, from which we prepared laser elements in the form of plane-parallel plates $5 \times 5 \times 2$ mm in size for longitudinal diode pumping.

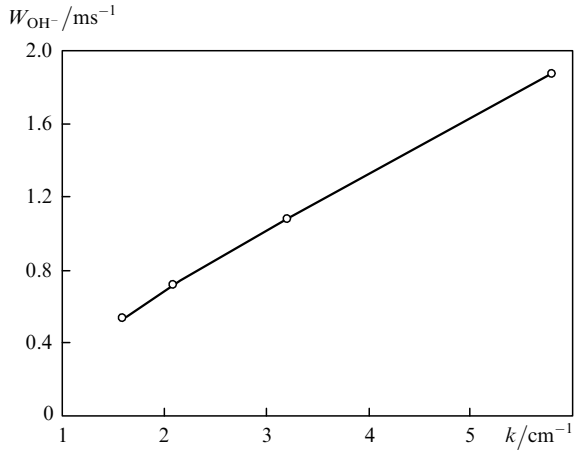

Figure 1. Dependence of the rate of quenching of the ytterbium luminescence by hydroxyl groups W_{OH^-} on the absorption coefficient k at a wavelength of 3.33 μm; k is proportional to the concentration of OH^--groups.

The experiments on cw lasing were performed in a cavity shown in Fig. 2. The input mirror M1 was coated with a dielectric coating with a transmittance exceeding 98 % at the pump wavelength of about 980 nm and a high reflectance ($R > 99.9\,\%$) at the lasing wavelength of 1020–1100 nm. Mirrors M2 and M3 also had a high reflectance at the lasing wavelength. As output mirrors, we used plane-parallel mirrors M4 with the transmittance $T = 1.5\,\%$, 4 %, and 5.7 % at the laser wavelength. The pump beam waist diameter in the active element was about 80 μm (at the level $1/e^2$). The best laser output parameters were achieved at the beam waist diameter in the cavity of about 60 μm.

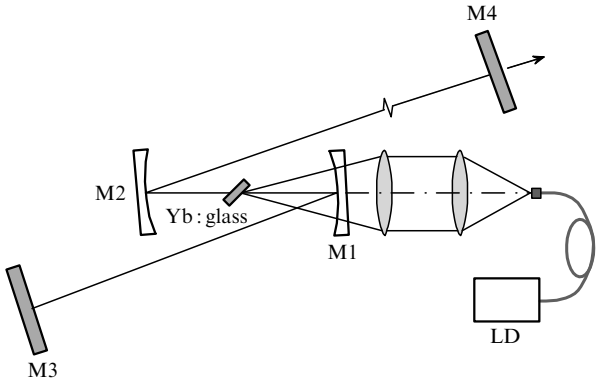

Figure 2. Cavity scheme of an ytterbium glass laser operating in the cw regime: (M1) spherical mirror (with $r = 100$ mm and antireflection coating in the region of 800–900 nm), (M2) spherical mirror ($r = 100$ mm, $R = 99.9\,\%$ at $\lambda = 1050$ nm), (M3) mirror ($R = 99.9\,\%$ at $\lambda = 1050$ nm), (M4) output mirror ($T = 1.5\,\%$, 4 %, 5.7 % at $\lambda = 1050$ nm), (LD) laser diode ($P_{ld} = 6$ W, $\lambda_{ld} = 980$ nm).

The dependences of the cw laser radiation power on the absorbed pump power for output mirrors with different transmittances are shown in Fig. 3. The output laser characteristics obtained in our experiments are listed in Table 1. The maximum output power (783 mW) was achieved for the output mirror with a transmittance of 4 %. The slope efficiency reached 28.9 %. The laser radiation spectrum measured at $T_{opt} = 4\,\%$ (Fig. 4) has several

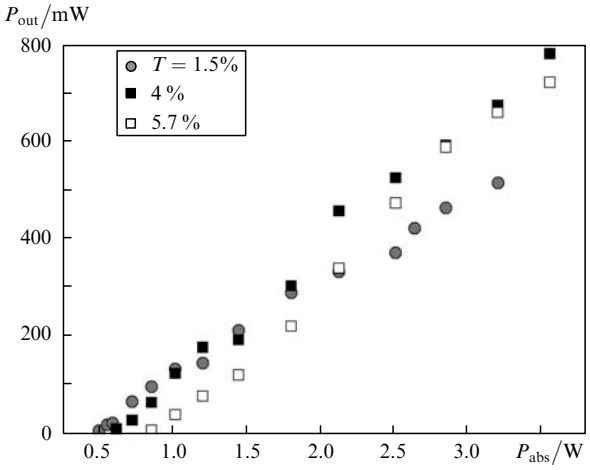

Figure 3. Output laser characteristics for different transmittances of the output mirror.

Table 1. Output laser parameters in the cw regime.

T(%)	P_{th}/mW	η (%)	P_{out}/mW	λ/nm
1.5	471	18.6	518	1056.5
4.0	633	28.9	783	1055
5.7	805.7	28.3	725	1034

Note: P_{th} is the threshold pump power; η is the slope efficiency; P_{out} is the maximum output power; and λ is the radiation wavelength.

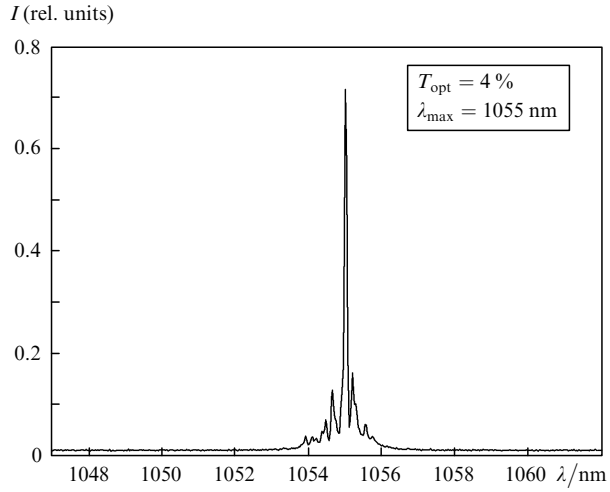

Figure 4. Emission spectrum of the laser in the cw regime.

peaks in the region of 1054 – 1057 nm with the maximum at the wavelength $\lambda = 1055$ nm.

For tuning the laser wavelength, we placed a TF8 glass prism into the cavity shoulder between mirrors M3 and M4. The tuning curve shown in Fig. 5 was measured for the output mirror with the transmittance $T = 1.5\,\%$. The possibility of laser wavelength tuning in the region of 1008 – 1080 nm indicates that this active medium is promising for generating ultrashort pulses.

In the experiments in the passive mode-locking (PML) regime, the highly-reflecting mirror M3 in the cavity was replaced by a SESAM passive Q-switch (modulation depth 0.8 %, saturation energy density 30 J cm^{-2}). To obtain a negative group velocity dispersion, we used a pair of TF8 glass prisms in the cavity shoulder between mirrors M2 and M4. The negative dispersion was varied by changing the distance between the prisms.

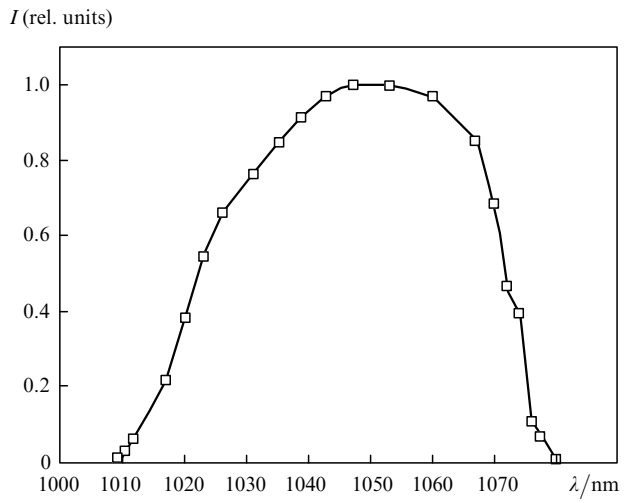

Figure 5. Tuning curve of the ytterbium laser wavelength.

The mode-locking regime was achieved when the waist diameter of the TEM$_{00}$ mode at the Q-switch was about 180 μm and the distance between the prisms was 39 cm. The spectrum and autocorrelation function of laser pulses in the PML regime are shown in Fig. 6.

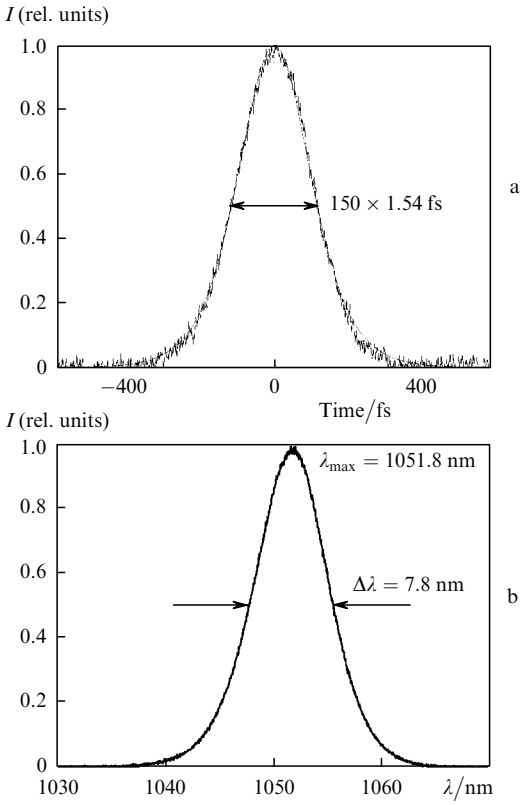

Figure 6. Autocorrelation function (a) and spectrum (b) of ytterbium glass laser pulses in the PML regime.

The product of the pulse duration (about 150 fs) and their spectral half-width (7.8 nm), i.e., $\tau_{pulse}\Delta\nu_{gen}$, was 0.317, which indicates that the shape of the output pulses was close to the shape of transform limited (sech^2) pulses, for which this product is 0.315 [5]. The maximum average output power in the PML regime was 100 mW at the pulse repetition rate of 117 MHz, which corresponds to the pulse peak power of 5 kW. The output beam quality factor M^2 was smaller than 1.2.

A further increase in the pump power lead to a destabilisation of the PLM regime, which manifested itself in the generation of several transverse modes. This was caused by imperfect matching between the pump beam and the TEM$_{00}$ cavity mode in the active element. The output power can be further increased by using a pump laser diode with a better output beam quality and by increasing the heat removal efficiency.

Thus, we have developed an ytterbium laser glass based on an alumoborophosphate composition, which has the record-high (for phosphate glasses) chemical and thermal stability and whose spectral and luminescence characteristics are comparable with those of popular laser glasses. From

the synthesised glass, we prepared active laser elements $5 \times 5 \times 2$ mm in size for longitudinal diode pumping and obtained in them lasing in the cw regime and in the passive mode-locking regime. The cw radiation power reached 783 mW at a wavelength of 1055 nm, and the maximum slope efficiency was 28.9 %. In the passive mode-locking regime, we obtained pulses with a duration of about 150 fs and a pulse peak power of 5 kW.

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