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Aluminium barium phosphate glass laser emitting at $\lambda = 1.54$ μm

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A series of samples with various chromium ion concentrations as sensitizing additive have been prepared and studied with respect to manufacturing of active laser elements made of erbium-activated phosphate glass. The spectral, luminescence, and laser characteristics were measured. It has been shown that the synthesides glasses provide high enough laser efficiency attaining about 1.3 % in the free-running mode.

С целью создания активных лазерных элементов из фосфатного эрбиевого стекла была изготовлена и исследована серия образцов с различными концентрациями сенсибилизирующих добавок ионов хрома. Измерены их спектральные, люминесцентные и лазерные характеристики. Показано, что синтезированные стекла обеспечивают достаточно высокую эффективность генерации в свободном режиме ~1,3 %.

It is known that there exists a great interest in development and application of lasers for the 1.5 to 1.6 μm range [1,2]. This range corresponds to the atmospheric transparency window and the eye-safe spectral region, therefore, it is applied in some fields of science and technology such as remote laser diagnostics and spectroscopy, medicine, fiber-optics communication, and ranging. Erbium glass lasers with flashlamp pumping emitting at wavelength of 1.54 μm are the easiest and the most widespread sources of high power radiation in this region.

In erbium glasses erbium ions obtain practically the whole of non-monochromatic pump energy via non-radiating channels from ytterbium ones. The latter are the main sensitizing additive [3] in this case. The erbium phosphate laser glasses now in production have high enough operating characteristics [4]. The full laser efficiency for these glasses is within limits of 1 to 3 %, that is comparable with that of Nd-glass laser (2 to 5 %). The aim of this work was to improve the technique for manufacturing of erbium glass and to determine its photophysical features and laser characteristics of active elements made of this glass.

To prepare erbium glass, we have used barium phosphate matrix with introduced erbium ions as an activator and ytterbium and chromium ones as sensitizing agents. Since the optimum concentrations of erbium and ytterbium ions were known [5–7], our task was to determine that for chrome ions. For this purpose, we have synthesized ytterbium-erbium glasses with various chromium ion concentrations. The glasses were fused in silit furnaces using a modified two-stage technique. Special purity grade starting materials were used. The initial blend was boiled thoroughly in a 0.5 dm^3 crucible made of a "Stekrit" type glass ceramics. Then the glass mass was poured in refined platinum crucible of the same volume, where the next techno-

Table 1. Main characteristics of LFS-E glass

Parameter	Value	Notes
Erbium concentration	$1.79\cdot10^{19}$ cm^{-3}	—
Ytterbium concentration	$(1.6\div2.6)\cdot10^{21}$ cm^{-3}	—
Chromium concentration	$8.6\cdot10^{18}$ to $6.0\cdot10^{19}$ cm^{-3}	0.02 to 0.14 wt %
Refraction index, n_e	1.573	—
Luminescence decay duration, τ_l	$7.8\cdot10^{-3}$ s	For chromium conc. up to $5.1\cdot10^{19}$ cm^{-3}
Density	3.38 g/cm^3	—
Thermal expansion coefficient	$8.0\cdot10^{-6}$ (°C)$^{-1}$	For temperature range 20–120°C

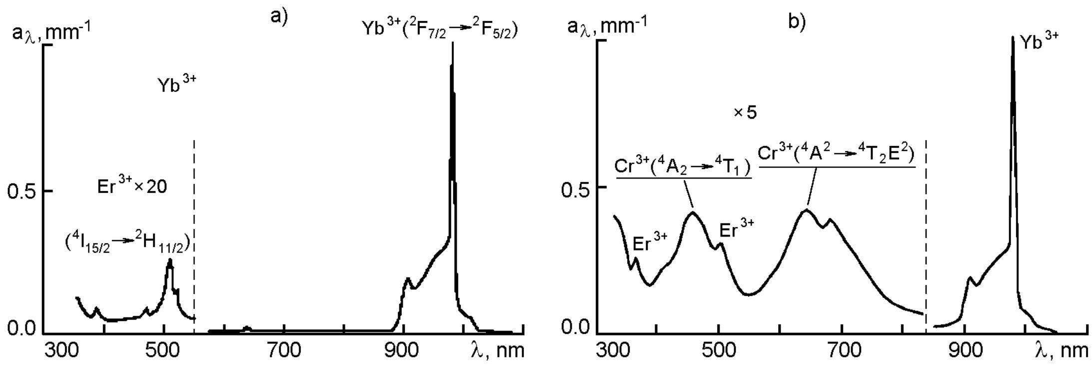

Fig. 1. Absorption spectra of erbium glasses: (a) without chromium ions; (b) with 0.06 wt % Cr_2O_3.

logical stages (deuteration, the melt bubbling with oxygen, homogenization of the fluid glass, etc.) were carried out. The glass cast in a mould was annealed in electrical resistance furnace in accordance with the preset temperature-time schedule. The samples for determination of physicochemical properties and spectral and luminescence parameters as well as the laser active elements (∅4×60 mm^2) with certain chromium concentrations were prepared from this glass casts. The main characteristics of the LFS-E glass are cited in Table 1 and characteristic absorption spectra thereof measured using an SF-20 spectrophotometer are shown in Fig. 1. The absorption bands of erbium are rather narrow and low-intense. This is one of the main obstacles for its efficient lasing in glass without additional sensitizers. Moreover, the 550–900 nm spectral range in which a significant fraction of flashlamp pumping energy is radiated, is not utilized even though ytterbium ions are used as a sensitizer. Therefore, the lasing threshold for ytterbium-erbium glasses is rather high. Introduction of chromium ions as an additional sensitizer (Fig. 1b) enables to increase the use factor of flashlamp pumping radiation and to reduce the laser generation threshold as a result. The absorption spectrum of chromium ions in phosphate glass consists of two wide bands with maxima near 460 nm and 650 nm, overlapping the visible spectral range. The luminescence band of chromium encompasses a wide spectral region of 750–1000 nm with maximum near 820 nm. This region overlaps with that of ytterbium absorption, thus, an efficient energy transfer from chrome to ytterbium is provided as a result.

The erbium ion luminescence lifetime τ_l and amplitude of its intensity I_l for all studied samples of the glasses have been measured with disk τ-meter of TI-28 type. Fig. 2 shows the results of these measurements. The increasing chrome content in glass is seen to amplify sensitization effect, so the erbium ion luminescence rises more than by a factor 1.5 as a result. This indicates the efficient chrome-ytterbium-erbium energy transfer, whereas the optimal chromium concentration range amounts is 0.1 to 0.14 wt. %.

One of the main channels of the ion erbium luminescence quenching is the exchange of the activator electron excitation energy for stretching vibration of the oxyhydryl groups $(O_n–H_m)^-$ as an acceptor. The hydroxyl groups $(O–H)^-$ have the strongest quenching effect among them. The induc-

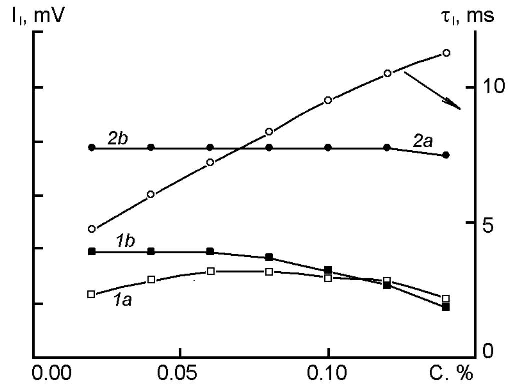

Fig. 2. Dependences of luminescence pulse amplitude I_l (a) and its decay duration τ_l (b) on Cr^{3+} concentration for deuterated (*1*) and non-deuterated (*2*) glass.

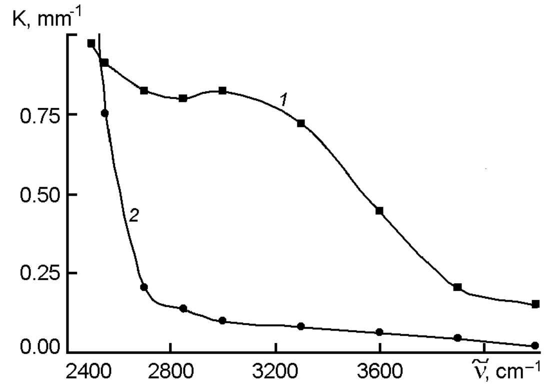

Fig. 3. Typical absorption spectra of an LFS-E glass with Cr^{3+} concentration 0.12 wt. % for deuterated (*1*) and non-deuterated (*2*) glass.

tance-resonance mechanism of non-radiating ion-vibration transfer of activator excitation causes energy degradation of erbium metastable state and reduction of quantum yield, luminescence decay time, laser efficiency and raising the lasing threshold.

One of the main ways to reduce influence of these groups is deuteration of the glass melt because the maximum of the (O–D) bond vibration spectrum has a bathochromic shift with respect to (O–H) one. Moreover, using the dehydration of the glass mass, it is possible to reduce considerably the overlapping of the erbium emission spectrum with hydroxyl absorption one and to reduce the Er^{3+} luminescence quenching as a result.

The dehydration degree of the studied glasses may be estimated qualitatively from their absorption spectra. Fig. 3 shows absorption spectra of the dehydrated (by deuteration) and non-dehydrated glass samples. The spectra were calculated from the transmission ones measured using an IKS-39 spectrophotometer. It is seen that, using the technology of glass melt deuteration, it is possible to reduce absorption with $(O–H)^-$ groups since the intensity and lifetime of the luminescence erbium ions being increased at the same time (Fig. 2). The absorption coefficient of the samples was lower than 0.15 mm^{-1} at $\tilde{\nu} = 3000$ cm^{-1} for the all chrome concentration series. This fact indicates the main fraction of hydroxyl groups to be removed.

Four cylindrical exemplars of active elements were fabricated with the following parameters: diameter of 4.0 mm, length of 65 mm, Cr_2O_3 concentration of - 0.08, 0.1, 0.12, and 0.14 mass % for laser researches.

The elements were tested in two laser pumping systems (LPS) with INP-5/60 type flashlamps used in the 1st system and INP-3/45 type ones in the 2nd. There was applied the forming circuit of flashlamp discharge calculated as described in [8] to increase its light output and provide the spectral matching of pump radiation with absorption band of the laser active medium. A quartz reflecting enclosure with diffuse coating was used in the 1st LPS. The pumping light pulse duration therein was $\tau_{0.5}\approx 2$ ms (FWHM). Laser cavity of 300 mm length was formed by two plane dielectric mirrors with the reflection coefficients $R_1 = 99.5$ % and $R_2 = 90$ % at $\lambda = 1.54$ μm. The studied samples differ noticeably neither in the pumping threshold W_{thr} nor in lasing energy W_{las} under the same pumping energy of 343 J. An insignificant distinction was probably connected with the presence of inhomogeneities in the samples.

A quartz reflecting enclosure with mirror coating was employed in the 2nd LPS. Its geometric proportions were matched with dimensions of the examined samples considerably better than for the 1st system. The testing with respect to energy parameters demonstrated that optimal reflectivity of output mirror in the 2nd LPS was equal $R_2\approx 70$ %.

We have measured the output laser energy at the same charge energy of laser capacitor bank but at different parameters of its discharge loop to clear up the influence of

Table 2. Laser energy under fixed pumping energy W_p = 63 J and for different durations of its pulse $\tau_{0.5}$ (FWHM) in the 2nd system

$\tau_{0.5}$, ms	0.8	1.4	1.5	1.7	2.1	2.75	3.6
W_{las}, mJ	428	475	490	485	490	449	415

pumping duration upon laser efficiency of the samples. The results of these measurements for the sample with 0.14 wt. % Cr_2O_3 under pumping energy W_p = 63 J are represented in Table 2. The sample efficiency is seen to vary weakly in the duration range of 0.8 to 4 ms. Some increase of the laser output energy at the pulse duration increase from 0.8 ms to 2 ms may be connected with relatively long time of energy transfer from Yb^{3+} to Er^{3+} [9] being manifested in this case. The insignificant decrease of W_{las} at pulse durations $\tau_{0.5} > 2.1$ ms was probably caused by losses due to the additional inductance that was used in this case. Delay time of the laser pulse with respect to the pumping one for all the duration values turned out to be nearly equal to rise-up portion of the pumping pulse, similar to the 1st system. This result agrees with other researches [3].

Fig. 4 shows a typical dependence of laser radiation energy W_{las} on the pumping one W_p for the glass with 0.08 wt. % Cr_2O_3 in the 2nd system with output mirror $R_2 \approx 70$ %.

The presented results demonstrate that the obtained samples of the erbium glass provide a rather high laser efficiency attaining about 1.3 % in the free-running mode that is comparable with the known analogues.

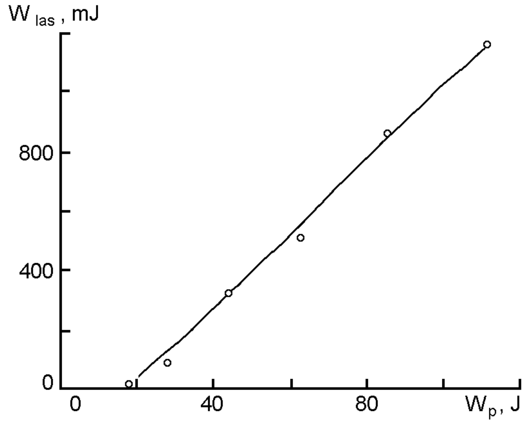

Fig. 4. Dependence of laser radiation energy W_{las} on pumping one W_p for glass with Cr_2O_3 concentration of 0.08 wt. %; the 2nd system.

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Лазер на фосфат-алюміній-барієвому склі, що генерує на λ = 1,54 мкм

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З метою створення активних лазерних елементів з фосфатного ербієвого скла виготовлено та досліджено серію зразків з різними концентраціями сенсибілізуючих добавок іонів хрому. Виміряно їх спектральні, люмінесцентні та лазерні характеристики. Показано, що синтезовані стекла забезпечують достатньо високу ефективність генерації, яка досягала ~1,3 % у вільному режимі.