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Spectral and temporal properties of diode-pumped Er, Yb: glass laser

G.I. Ryabtsev [a,*], T.V. Bezyazychnaya [a], V.V. Parastchuk [a], A.G. Ryabtsev [a], M.V. Bogdanovich [a], A.I. Yenzhyieuski [a], L.L. Teplyashin [b], V.V. Kuznetsova [b], I.P. Petrovich [c], A.S. Kraskovskii [c], S.N. Titovez [c]

[a] *Stepanov Institute of Physics, National Academy of Sciences of Belarus, F. Skoryna Ave. 68, Minsk 220072, Belarus*
[b] *Institute of Molecular and Atomic Physics, National Academy of Sciences of Belarus, F. Skoryna Ave. 70, Minsk 220072, Belarus*
[c] *JSC "Peleng", Makaenka Street, 23, Minsk 220023, Belarus*

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Abstract

The peculiarities of spectral and temporal properties of diode-pumped Er, Yb: glass laser emission are investigated. Two groups of lines at 1535 and 1543 nm in lasing spectra of Er, Yb: glass laser have been observed. The competing dynamic behavior of the lasing lines groups has been registered. The obtained data are treated in the context of existence of two different active center assemblies with the Stark splitted energy levels masked by inhomogeneous broadening of the luminescence and absorption spectra. The variations in the lasing line number during changing pump power have been observed and explained in the terms of changing the number of the active center assemblies involved in a laser action.

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Keywords: Eye-safe laser; Er-doped glass; Diode-pumping; Active center assembly; Laser spectroscopy

1. Introduction

Erbium-doped glass lasers pumped by laser diodes (LDs) or LD arrays are of considerable interest as the eye-safe radiation sources for many practically vital areas [1–5]. Spectroscopic (fluorescence lifetime, stimulated emission

* Corresponding author. Tel.: +375 172840398; fax: +375 172840879.
E-mail address: ryabtsev@dragon.bas-net.by (G.I. Ryabtsev).

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cross-section, etc.) as well as laser (threshold, slope efficiency) characteristics of different Er, Yb: glass active media are studied intensively [2–11]. Nevertheless, output parameters of the present-day Er, Yb: glass light emitters are quite far from the application demands. With this in mind, it is important to look into the details of excitation and emission mechanisms of different optical centers in the glass active medium, and evaluate correctly the role of these centers in the operation regimes of eye-safe laser systems.

In this work, some peculiarities of the spectral and temporal performance of the solid-state laser on the base of erbium-doped boro-silico-phosphate glass transversely pumped by LD arrays have been revealed and investigated. The main attention is focused on a detection of the active center assemblies with the Stark splitting energy level structures in the erbium-doped boro-silico-phosphate glass and studying their influence on the spectral–temporal properties of the diode-pump eye-safe laser.

2. Experiment and results

Cylindrical Er, Yb: glass rod (3 mm diameter × 11.5 mm long) with antireflecting coating at wavelength $\lambda = 1.54$ μm prepared at the Institute of General Physics, Moscow [12], was studied. The concentrations of Er^{3+} and Yb^{3+} dopant ions in the glass were 5×10^{19} and 4×10^{21} cm^{-3}, respectively.

The Er, Yb rod absorption spectrum measured with the CARY-500 spectrophotometer for the 870–1050 and 1475–1560 nm spectral regions is presented in Fig. 1. As may be seen from Fig. 1(a) and (b) (solid curve), two distinct maxima ***A*** (915 nm), ***B*** (980 nm) and a small bulge ***C*** (1002 nm) are manifested in the 870–1050 nm absorption band as well as three maxima ***D*** (1490 nm), ***E*** (1535 nm), ***F*** (1543 nm) are found in the 1475–1560 nm absorption band. The luminescence spectrum of Er, Yb: glass rod excited by LD array unit (the emission wavelength $\lambda = 955$ nm) is presented in Fig. 1(b) (dashed curve). Two maxima in the luminescence spectrum are disclosed and arranged near the

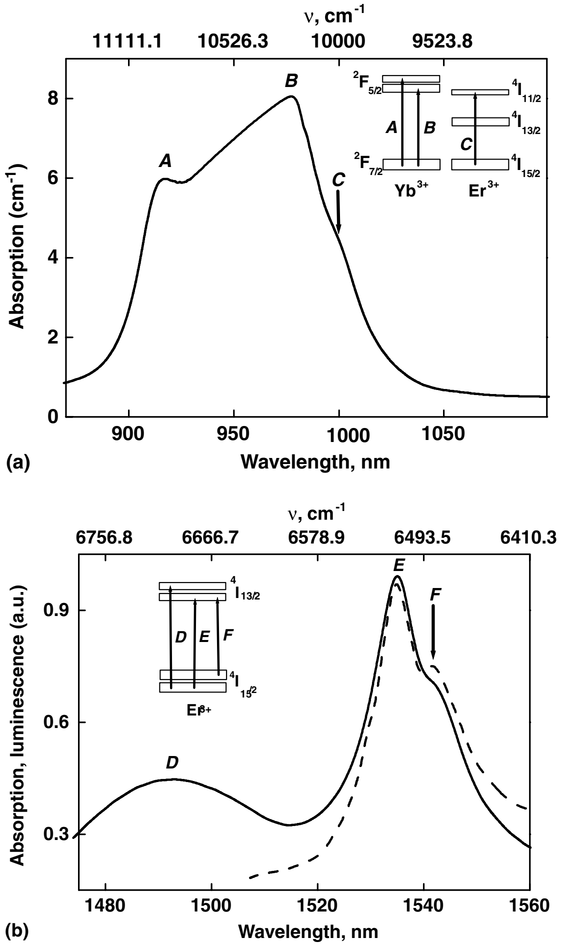

Fig. 1. Absorption (solid) and emission (dashed curves) spectra of the Er, Yb: boro-silico-phosphate-glass: (a) absorption spectrum in the spectral region of 870–1050 nm; (b) absorption and emission spectrum in the spectral region of 1475–1560 nm.

same wavelength region as the maxima ***E*** and ***F*** of absorption band, see Fig. 1(b).

The Er, Yb: glass rod was employed as an active medium of the solid-state laser transversely pumped by two or four LD arrays. The 7.5 cm long optical cavity was composed of a concave high reflectivity (the reflectivity coefficient $R = 100\%$ at $\lambda = 1.54$ μm) mirror with radius of curvature $r = -0.5$ m and a flat output mirror ($R = 98\%$ at $\lambda = 1.54$ μm). The relatively long resonator allows the optional use of some intracavity optical components, such as Co^{2+}:$MgAl_2O_4$ crystal as a saturable absorber for the passive Q-switch laser operation regime. The laser rod was pumped transversely by the custom-made laser diode array unit. The emitting facets of the LD arrays were positioned closely to the rod side surface. Each laser diode array delivered up to 250 mJ optical energy at 5 ms pump pulse duration and current of 80 A. The electrical power was supplied by a current driver which allowed us to form square electrical pulses with pulse duration of 1–5 ms and repetition rate of 0.5–20 Hz.

The lasing spectra of the Er, Yb: glass laser for the free-running operation regime at different pump levels are shown in Fig. 2. Two different spectral line suites can be found from the lasing spectra. The first (group I) and second (group II) suites of the spectral lines are located in the vicinity of the maxima ***E*** and ***F*** of the absorption spectra respectively. At the threshold pump power (about 30 W) only a single lasing line is observed in the vicinity of maximum ***E*** (the spectrum a in Fig. 2). Additional lasing lines concerning the group I (1535 nm) as well as the lines concerning the group II (1543 nm) are appeared with increasing the pump power up to 60 W, see the spectrum b in Fig. 2. An increase of the pump power up to 100 W changes the line intensity distribution within each of the two spectral groups. Synchronously with that, the number of the lasing lines is increased for each group. As a rule, a decrease (increase) of the line intensities in the group I correlates with an increase (decrease) of the line intensities in the second one (the spectrum c in Fig. 2).

The spectrum of the Er, Yb: glass laser radiation at the passive Q-switch regime was measured also. The Co^{2+}:$MgAl_2O_4$ crystal was used as a saturable absorber. In this case the lasing spectrum is similar to that for the free-running operation regime at the 30 W pump power level. In other words only a single lasing line is observed in the vicinity of the maximum ***E*** (the spectrum a in Fig. 2).

The temporal behavior of each above-mentioned spectral line groups was detected for the free-running laser operation regime using the germanium photodiode. The radiation pulse temporal profiles related to the group I (solid curve) and group II lines (dashed curve) averaged per 100 pulses are presented in Figs. 3 and 4 for the pump power 40 and 100 W, respectively. As may be seen from the given temporal profiles the lasing starts at the wavelength corresponding to a short-wave suite of the lines (group I). It can be noticed that the energy redistribution between two groups of the emission lines takes place during the lasing pulse.

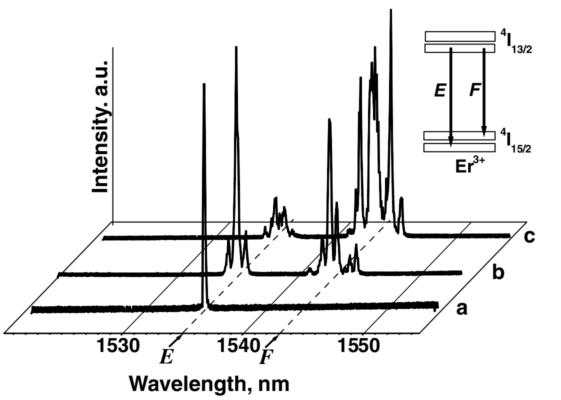

Fig. 2. Spectrum of lasing for the free-running Er, Yb: glass laser operation at the pump power of about 1–30, 2–60, 3–100 W.

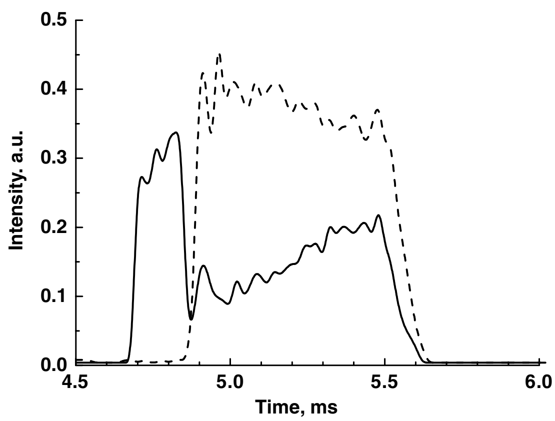

Fig. 3. Temporal profiles of the laser light pulses for 1533–1537 nm (solid) and 1541–1545 nm (dashed curves) spectral ranges averaged per 100 pulses for the free-running Er, Yb: glass laser operation at the pump power about 40 W.

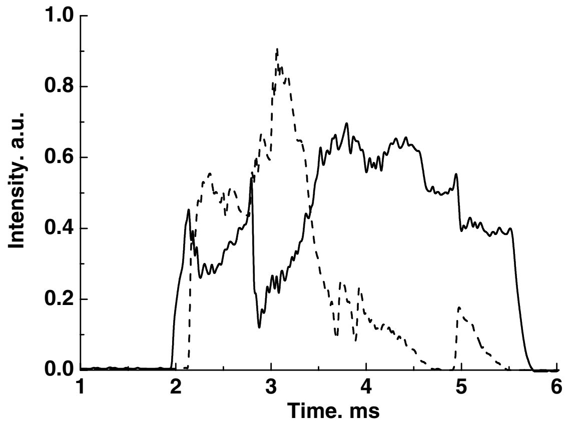

Fig. 4. Temporal profiles of the laser light pulses for 1533–1537 nm (solid) and 1541–1545 nm (dashed curves) spectral ranges averaged per 100 pulses for the free-running Er, Yb: glass laser operation at the pump power about 100 W.

3. Discussion

The maxima ***A*** and ***B*** in the absorption spectrum (Fig. 1(a)) are probably related to the optical transitions from the $^2F_{7/2}$ ground state to the two splitting components of the upper level $^2F_{5/2}$ for the Yb^{3+} ions [13]. A small bulge ***C*** on the long-wave shoulder of the 870–1050 nm absorption spectrum (Fig. 1(a)) can be associated with the superposition of a low-intensity absorption band for the Er^{3+} ions ($^4I_{15/2}$–$^4I_{11/2}$ transition) on the absorption band for the Yb^{3+} ions ($^2F_{7/2}$–$^2F_{5/2}$ transition). Three maxima ***D***, ***E*** and ***F*** in the 1475–1560 nm spectral region of the absorption spectrum (Fig. 1(b), solid curve) may be presumably concerned with absorption of the Er^{3+} ions in the $^4I_{15/2}$–$^4I_{13/2}$ channel. The short-wave maximum (***D***) is probably related to the transition from the ground state $^4I_{15/2}$ to the upper splitting component of the $^4I_{13/2}$ level. The maximum ***E*** is likely corresponded to the resonant transition between the lower splitting components of the $^4I_{15/2}$ and $^4I_{13/2}$ levels. The maximum ***F*** may be associated with the absorbing transition from the upper component of the ground state $^4I_{15/2}$ to the lower component of the $^4I_{13/2}$ level.

Two maxima ***E*** and ***F*** of the luminescence spectrum (Fig. 1(b), dashed curve) can be referred to the optical transitions from the lower splitting component of the $^4I_{13/2}$ level to the two inhomogeneously broadened splitting components of the $^4I_{15/2}$ level. The assumption that the maxima ***E*** and ***F*** are corresponded to the transitions from one component of the $^4I_{13/2}$ level to two components of the $^4I_{15/2}$ was deduced from additional luminescence decay measurements. We have experimentally obtained luminescence decay characteristic times for the emission wavelengths corresponding to the maxima ***E*** and ***F***. Characteristic times for the determined emission wavelengths are almost the same and equal to ~8 ms. Thus, the discussed luminescent optical transitions occur from the common sublevel of the $^4I_{13/2}$. The total FWHM of the luminescence spectrum is equal to 100 cm^{-1} (Fig. 1(b)).

As indicated above two groups of the lasing lines were observed in the vicinity of the maxima ***E*** (1535 nm) and ***F*** (1543 nm) of the luminescence spectrum. A number of the most intensive lasing lines at the pump power over 60 W is equal to 8. The interval between the neighbor lasing lines lies in the range 2.5–4.7 cm^{-1}. Intermode distance for the investigated Er, Yb: glass laser resonator is much less than the interval between the neighbor lasing lines. Thus, the observed lasing lines do not belong to the laser resonator mode structure and may be related to the Stark splitting of the level $^4I_{15/2}$ (Er^{3+}) in the electrostatic crystal field with a low symmetry [13]. A number of the most intensive lasing lines observed with increasing the pump power up to 100 W is equal to 16. Appearance of the additional lasing lines can be related to the existence of a set of different active center assemblies in the Er, Yb: boro-silico-phosphate glass. Variety of the active center assemblies in the Nd doped glasses was earlier revealed by using selective laser spectroscopy methods [14]. The increase of the lasing line number from 8 to 16 with increasing the pump power can be associated with involving an additional assembly of the active centers in the laser action. So, we can conclude that there is the set of the active center assemblies in the Er, Yb: boro-silico-phosphate glass. Each assembly from the set can be involved into the lasing action at a certain pump level. The lasing spectrum structures (Fig. 2) may be related to the existence of the set of the active center assemblies with the Stark splitting energy level components masked by inhomogeneous broadening of the proper luminescence and absorption spectra.

An alteration of the lasing conditions by changing the mirror positions and resonator configurations results in the variation of a number of the lasing lines and their relative intensities. At the same time the observed lasing lines keep the same spectral positions. Variation of lasing lines number can be explained in the terms of changing the number of active center assemblies involved in the laser action.

The simplified energy level diagram and transitions scheme of Yb^{3+} and Er^{3+} ions (Fig. 5) was defined on the basis of luminescence and absorption spectra. This scheme demonstrates the lasing possibility on the transitions from a lower component of the $^4I_{13/2}$ (Er^{3+}) level to two inhomogeneously broadened components of the $^4I_{15/2}$ level.

As may be seen from Figs. 3 and 4, the lasing starts at 1535 nm wavelength corresponding to the short-wave set of lines (group I) characterizing by a lower threshold in comparison with the group II lines. The data obtained are in accord with the data presented in Fig. 2, where there is only one spectral line related with group I at low pump power (about 30 W). Comparing temporal profiles of two groups of the lasing lines, it can be noticed that an increase (decrease) in the intensities of the lines belong to one group is accompanied by a decrease (increase) of the line intensities in the second group. It indicates the competing dynamic behavior for two groups of the lasing lines.

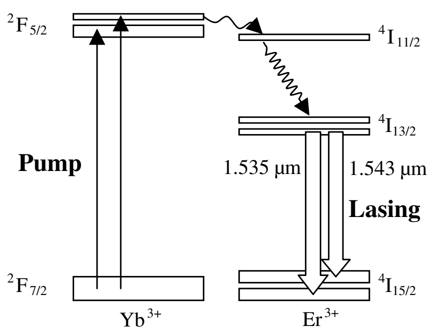

Fig. 5. Energy levels diagram and pumping scheme of Er, Yb: glass laser.

4. Conclusion

The absorption and luminescence spectra of Er, Yb-doped boro-silico-phosphate glass were measured and analyzed. The obtained data were used to compose the simplified scheme of energy levels and optical transitions for Er and Yb ions in the investigated active medium. The spectral and temporal behavior of the Er, Yb: boro-silico-phosphate glass laser emission has been investigated. Two competitive groups of the lasing lines were revealed. The group I is situated in the vicinity of 1535 nm, while the group II is located nearby the wavelength of 1543 nm. The lasing threshold pump power for the group I lines is less than that for the group II. At the pump power over 60 W a total number of the lasing lines (in both groups) is equal to 8, that is matched to a number of the Stark splitting components for the $^4I_{15/2}$ level of one active center assembly in the electrostatic field with a low symmetry. Increasing the total number of the lines in two groups up to 16 during the subsequent rise of the pump power even to the magnitude of 100 W may be concerned with involving the second active center assembly in the lasing. These distinguishing spectral and temporal features of the laser emission we associate with an existence of two active center assemblies with the Stark split energy levels in the erbium-doped boro-silico-phosphate glass.

The obtained data demonstrates a possibility of spectral selection of the set of active center assemblies disclosed in the Er, Yb: boro-silico-phosphate glass in the course of a laser emission. Closer examination of these complicated active centers is needed for further improvement of eye-safe glass laser parameters. This approach can be also applied for revealing the active center assemblies in other non-crystalline active media.

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