Spectral and kinetic properties of Er³⁺, Yb³⁺ : Yb₃Al₅O₁₂ crystals at high temperatures

B.I. Galagan, B.I. Denker, V.V. Osiko, S.E. Sverchkov

Abstract. **The spectral and kinetic properties of yttrium – aluminium garnet crystals co-doped with Er³⁺ and Yb³⁺ are studied in the range from room temperature to 800 °C. It is found that the lifetime of the $^4I_{11/2}$ level of the erbium ion decreases approximately by a factor of twenty with increasing temperature and the efficiency of nonradiative energy transfer from Yb³⁺ to Er³⁺ increases considerably. Analytic expressions describing the spectral and temperature dependences of the absorption and emission cross sections for the transition between the $^4I_{13/2}$ and $^4I_{15/2}$ levels of the erbium ion are proposed.**

Keywords: yttrium – aluminium garnet, yttrium – erbium laser, IR laser.

1. Introduction

Erbium lasers emitting at ~ 1.5 µm $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition of Er³⁺ ion are attractive for a number of applications because their radiation is relatively eye-safe, the earth atmosphere and silica fibres are transparent in the region of their emission, and there exist highly sensitive uncooled photodetectors in this spectral region such as germanium and InGaAs photodiodes. At present the only matrix for active elements of these lasers is in fact a phosphate glass co-doped with Yb³⁺ and Er³⁺ ions. Yb³⁺ doped into these glasses at concentrations exceeding the erbium concentration by one – two orders of magnitude is used a sensitiser which absorbs the pump radiation in the region $0.9 – 1$ µm and transfers the excitation energy to erbium ions (see the energy level diagram in Fig. 1).

Phosphate glasses combine a high quantum yield (close to 100 %) of luminescence from the upper $^4I_{13/2}$ laser level of the Er³⁺ ion (whose lifetime τ_{2Er} is ~ 6 ms) with a rather short lifetime ($\tau_{3Er} \sim 1 - 3$ µs) of the $^4I_{11/2}$ level. Due to a rapid multiphonon relaxation of the $^4I_{11/2}$ level of the Er³⁺ ion in phosphate glasses, the reverse energy transfer from the $^4I_{11/2}$ level of the Er³⁺ ion to the resonance $^2F_{5/2}$ level of the Yb³⁺ ion and parasitic up-conversion process are drastically reduced.
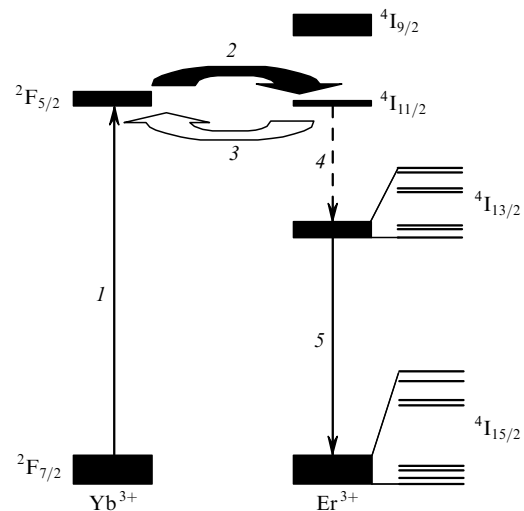
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Figure 1. Energy level diagram of the Er³⁺ and Yb³⁺ ions and the energy transfer scheme: (*1*) optical pumping; (*2*) direct process; (*3*) reverse process; (*4*) multiphonon relaxation; (*5*) laser transition.

A disadvantage of phosphate glasses as a laser matrix is their low heat conduction and low mechanical strength, which are much worse than for many known crystals. As a result, these glasses can be comparatively easily thermally damaged by pump radiation, which restricts the average output power of such lasers.

Unfortunately, no technological crystals that would have the above-mentioned combination of lifetimes of the excited $^4I_{13/2}$ and $^4I_{11/2}$ states of the Er³⁺ ion have been found so far among the known laser matrices, and the search for new Yb³⁺ – Er³⁺ laser crystals is being continued [1 – 5]. Researches call attention from time to time to yttrium – aluminium garnets (YAG) crystals, which offer the advantages of a high mechanical strength and a high heat conduction, the possibility of doping with ytterbium at high concentrations, and a high (close to 100 %) quantum yield of luminescence from the $^4I_{13/2}$ level of Er³⁺. Another attractive feature of YAG crystals is a strong splitting of the $^4I_{15/2}$ and $^4I_{13/2}$ levels of the Er³⁺ ion in a crystal field, so that the room-temperature luminescence spectrum of erbium ions exhibits a number of narrow lines in the region between 1.45 and 1.66 µm (Fig. 2a). Upon pumping into the absorption band of ytterbium [1], lasing was achieved at 1.61 and 1.64 µm with the efficiency ~ 7 %. This became possible due to the quasi-four-level lasing scheme realised upon the transition from the metastable $^4I_{13/2}$ level of the Er³⁺ ion to the upper Stark components of the ground $^4I_{15/2}$
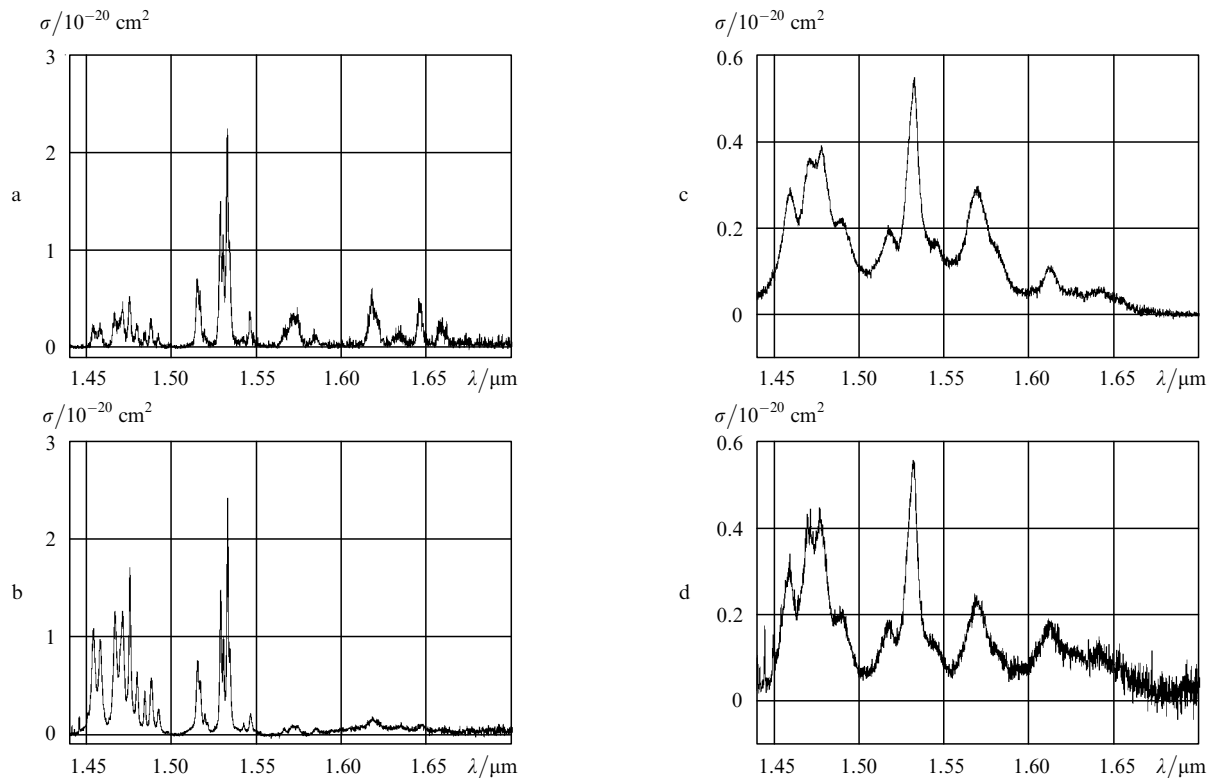
Figure 2. Luminescence (a, c) and absorption (b, d) spectra of an Er^{3+} (0.5 %) : YAG crystal at room temperature (a, b) and 800 °C (c, d).

level. To achieve the population inversion at room temperature in this case, it is sufficient to excite only 10 % – 15 % of erbium ions. To obtain lasing at a wavelength of 1.536 μm [the most intense line in the luminescence spectrum (Fig. 2a) corresponding to the transition to the lower Stark component of the $^4I_{15/2}$ level of the Er^{3+} ion], it is necessary to excite already 50 % of erbium ions. However, upon pumping into the absorption band of Yb^{3+}, the production of such inverse population at room temperature is prevented by reverse energy transfer from the relatively long-lived $^4I_{11/2}$ level of the Er^{3+} ion ($\tau_{3Er} \sim 100$ μs) to the $^2F_{5/2}$ level of the Yb^{3+} ion.

In this paper, we studied changes in the spectral and kinetic properties of Yb^{3+}, Er^{3+} : YAG crystals with increasing temperature by a few hundreds of degrees with the aim of obtaining the conditions that would be more favourable for lasing at ~ 1.5 μm.

2. Samples and experimental methods

The YAG crystals doped with Yb^{3+} or Er^{3+} ions and concentration series of crystals co-doped with both ions were grown by the zone melting method [5, 6]. The atomic concentrations in series were varied from 0.25 % to 1 % for erbium and from 3 % to 12.5 % for ytterbium. Crystals of diameter 5 mm and length 50 mm were synthesised from oxides of elements of purity 99.99 % and had satisfactory optical quality.

Spectroscopic studies were performed in the range from room temperature to 800 °C. We investigated the temperature dependences of the absorption and luminescence spectra of erbium ions, absorption spectra of ytterbium ions, and decay of luminescence from the excited states of both ions. To reduce the error of measuring the kinetics of

luminescence decay for ytterbium caused by reabsorption, we used samples of size smaller than 0.5 mm. In addition, samples were plunged into an immersion liquid (glycerol) at room temperature.

The absorption and luminescence spectra were recorded by using an MDR-23 monochromator. Luminescence was excited by repetitively pulsed 0.975 and 0.955-μm diode lasers, and at high temperatures also by a 0.69-μm Q-switched ruby laser. Photodetectors were FEU-62 photomultiplier and a germanium photodiode, and the experimental data were recorded with analogue-to-digital converters built in a PC.

3. Experimental results

We found that the absorption and luminescence lines at the $^4I_{13/2} \rightarrow ^4I_{15/2}$ transition of the Er^{3+} ion considerably broadened with increasing temperature from room temperature to 800 °C. Figure 2 presents the absorption and luminescence spectra of an Er^{3+} : YAG crystal (0.5 % of Er^{3+}) at room temperature and 800 °C. The luminescence spectra were normalised by using expression (4) presented in section 4. As the temperature was increased up to 800 °C, cross sections in the maximum of some spectral lines decreased approximately by a factor of five. The emission cross section at the maximum of the 1.536-μm luminescence line at 800 °C was $\sim 5.5 \times 10^{-21}$ cm², which is close to its value in laser glasses at room temperature. The maximum value of the emission cross section in the region between 1.6 and 1.65 μm decreased down to $\sim 10^{-21}$ cm². In addition, in this spectral region, absorption from the excited $^4I_{13/2}$ state to the $^4I_{9/2}$ state of the Er^{3+} ion can be expected (see Fig. 1), as well as in the case of erbium-doped phosphate glasses. For this reason, lasing in the region from 1.6 to

1.65 μm (unlike 1.536 μm) at high temperatures can be hindered even at high-power excitation of the upper $^4I_{13/2}$ laser level of the Er^{3+} ion.

Figure 3 presents the absorption spectra of an Yb^{3+} : YAG crystal (5 % of Yb^{3+}) at 20 and 800 °C. The spectrum at 800 °C is strongly broadened and smoothed. Note that noticeable absorption appears in the long-wavelength region which can be used to pump Yb^{3+}, Er^{3+} : YAG crystals by neodymium lasers at 1.05 – 1.06 μm.
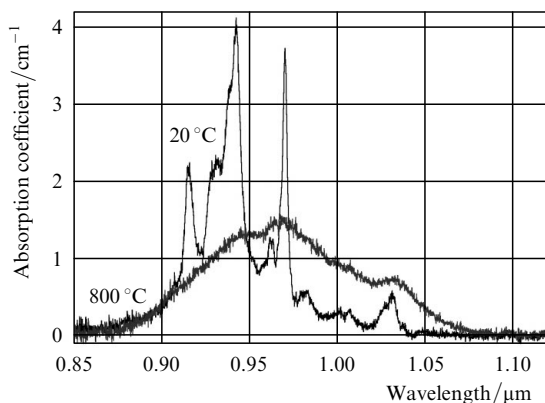

Figure 3. Absorption spectra of an Er^{3+} (0.5 %) : YAG crystal at temperatures 20 and 800 °C.

Figure 4 shows the temperature dependences of the excited-state lifetimes of Yb^{3+} and Er^{3+} ions measured in Yb^{3+} (0.35 %) : YAG and Er^{3+} (0.5 %) : YAG crystals. Note that the lifetime τ_{3Er} of the $^4I_{11/2}$ level of erbium drastically decreases with increasing temperature. As temperature is increased from room temperature to 800 °C, τ_{3Er} decreases approximately by a factor of twenty and becomes comparable with the corresponding lifetimes in phosphate glasses at room temperature. In his case, the lifetimes of the upper $^4I_{13/2}$ laser level of the Er^{3+} ion (τ_{2Er}) and the $^2F_{5/2}$ level of the Yb^{3+} ion (τ_{0Yb}) change insignificantly. All this gives promise that the influence of reverse energy transfer from erbium to ytterbium will decrease with increasing temperature, while energy transfer from ytterbium to the upper laser level of the erbium ion will increase.
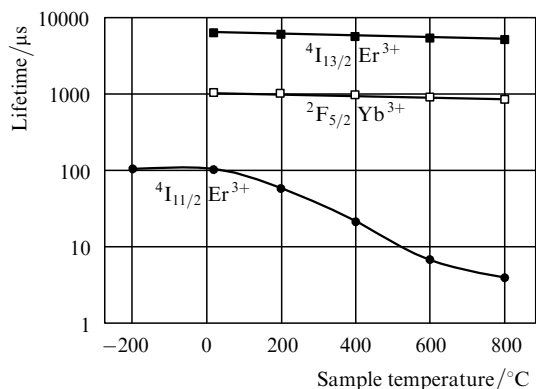

Figure 4. Temperature dependences of the lifetimes of the excited $^4I_{13/2}$ and $^4I_{11/2}$ states of the Er^{3+} ion and the $^2F_{5/2}$ state of the Yb^{3+} ion.

We studied the temperature dependence of the kinetics of luminescence of Yb^{3+} in crystals with different concentrations of erbium and ytterbium. Luminescence of Yb^{3+} ions was excited by 30-μs pulses from a diode laser. Note at once that we observed in these experiments an increase in the rate of excitation energy transfer from ytterbium to erbium with increasing temperature. Almost in all cases (except indicated below), the luminescence decay was exponential. Therefore, the rate of the Yb^{3+} → Er^{3+} energy transfer was determined from the expression $W(T) = 1/\tau_{Yb}(T) - 1/\tau_{0Yb}(T)$, where τ_{Yb} is the lifetime of excited ytterbium in samples containing Er^{3+} and T is the sample temperature. Figure 5 presents the dependences of the rate W on the erbium concentration at room temperature for three series of samples with different concentrations of ytterbium ions. One can see that these dependences are almost linear, i.e., the rate of nonradiative energy transfer is directly proportional to the concentration of energy acceptors – erbium ions.
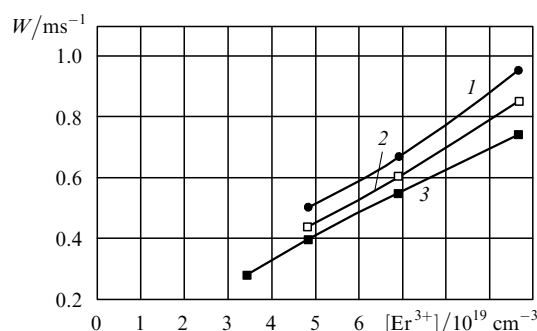

Figure 5. Dependences of the rate of nonradiative Yb^{3+} → Er^{3+} energy transfer on the concentration of Er^{3+} at room temperature in YAG crystals containing 7 % (1), 10 % (2), and 12.5 % (3) of Yb^{3+}.

The dependences of W on the ytterbium concentration are more complicated. Figure 6 presents these dependences for samples with the concentration of erbium ions 9.66×10^{19} cm^{-3} (0.7 %) at three different temperatures. One can see that the rate of energy transfer does not increase monotonically with the ytterbium concentration, as in phosphate glasses [7]. In this case, the maximum value of W is achieved at some optimal ytterbium concentration. It follows from Fig. 6 that the optimal ytterbium concentration in the temperature range 600 – 800 °C is $(10 - 14) \times 10^{20}$ cm^{-3}. In this region of temperatures and activator concentrations, the quantum efficiency of nonradiative energy transfer ($\eta = 1 - \tau_{Yb}/\tau_{0Yb} = W\tau_{Yb}$) achieves 70 % – 80 %. We assume that a considerable increase in the rate of nonradiative energy transfer from ytterbium ions to erbium with increasing temperature is caused by the increase in the rate of multiphonon relaxation of the $^4I_{11/2}$ level of the Er^{3+} ion and the decrease in the rate of reverse energy transfer from the $^4I_{11/2}$ level of the Er^{3+} ion to the $^2F_{5/2}$ level of the Yb^{3+} ion.

Another effect caused by the influence of high temperature on the kinetics of luminescence of ytterbium was reliably observed only at the maximum temperature of our experiments (800 °C). Figure 7 presents the luminescence decay curves for the Yb^{3+} ion for a sample containing 0.7 % of Er^{3+} and 10 % of Yb^{3+} obtained upon pumping by laser diode pulses of duration 30, 500, and 3000 μs. Within
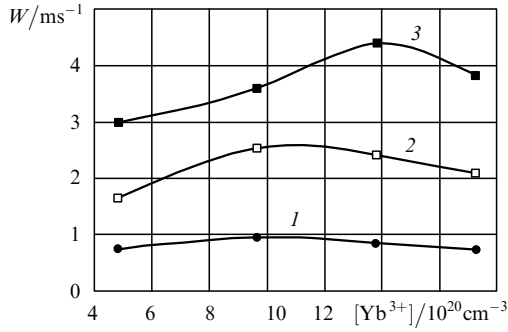
Figure 6. Temperature dependences of the rate of nonradiative $Yb^{3+} \to Er^{3+}$ energy transfer on the Yb^{3+} concentration in YAG crystals containing 0.7 % of Er^{3+} at room temperature (1), 600 (2), and 800 °C (3).

~ 400 μs after the pump pulse end, the exponential decay (with the time constant of hundreds of microseconds) is 'delayed' and changes to decay with the time constant of a few milliseconds. This effect becomes especially noticeable at long pump pulses. All the three curves in Fig. 7 can be well approximated by a sum of two exponentials with the time constants of 160 μs and 4.4–4.8 ms.
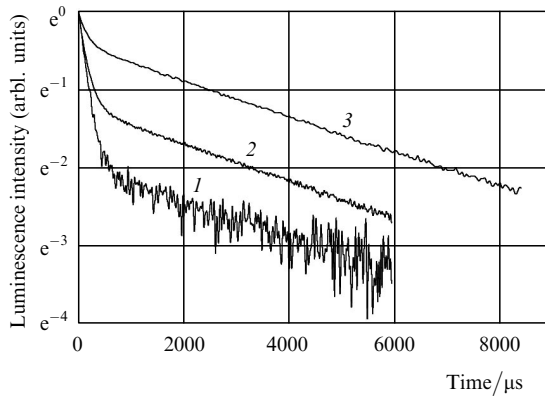

Figure 7. Luminescence decay of Yb^{3+} in Yb^{3+} (10%), Er^{3+} (07%):YAG crystal excited by 30-μs (1), 500-μs (2), and 3-ms (3) pulses.

We explain this effect by the establishment of thermal equilibrium between populations of the $^4I_{11/2}$ and $^4I_{13/2}$ levels of Er^{3+} ions along with the known effect of excitation 'trapping' between the $^4I_{11/2}$ level of the Er^{3+} ion and the $^2F_{5/2}$ level of the Yb^{3+} ion [8]. In fact, we are dealing in this case with the trapping of excitations between three excited states: the $^2F_{5/2}$ level of the Yb^{3+} ion and the $^4I_{11/2}$ and $^4I_{13/2}$ levels of the Er^{3+} ion, which relax simultaneously with the same relaxation time. Thus, the lifetime of the $^4I_{13/2}$ level measured at 800 °C was 4.8 ms in the case under study, which is lower than $\tau_{2Er} = 5.3$ ms for a sample without ytterbium.

Of course, this effect prevents the efficient population of the $^4I_{13/2}$ level of the Er^{3+} ion because it favours in fact the reverse energy transfer from the upper $^4I_{13/2}$ laser level of the Er^{3+} ion to ytterbium ions. The stationary distribution of the excitation energy over the levels of Er^{3+} and Yb^{3+} at 800 °C can be estimate from the experimental data available.

The population ratio for the $^4I_{11/2}$ (N_3) and $^4I_{13/2}$ (N_2) levels of erbium ions can be found from the Boltzmann distribution: $N_3/N_2 = \exp(-\Delta E/kT)$. This ratio is ~ 1 %. By assuming that all energy losses in the $Yb^{3+} - Er^{3+}$ system are determined only by radiative losses from the $^4I_{13/2}$ level of Er^{3+} and $^2F_{5/2}$ of Yb^{3+}, we can write the equation

$$\frac{N_2}{\tau} + \frac{N_{Yb}}{\tau} = \frac{N_2}{\tau_{2Er}} + \frac{N_{Yb}}{\tau_{0Yb}}$$

for excited ions in the 'trapping' regime. Here, $\tau = 4.4$–4.8 ms is the total relaxation time of excited erbium and ytterbium ions; N_{Yb} is the concentration of excited ytterbium ions; $\tau_{2Er} = 5.3$ ms and $\tau_{0Yb} = 0.86$ ms are the corresponding lifetimes of excited Er^{3+} and Yb^{3+} ions in the absence of co-dopants. Then, the population ratio for the $^4I_{13/2}$ level of Er^{3+} and the $^2F_{5/2}$ level of Yb^{3+} for the Er^{3+} (0.7 %), Yb^{3+}(10 %) : YAG crystal under study will be

$$\frac{N_{Yb}}{N_2} = \frac{1/\tau - 1/\tau_{2Er}}{1/\tau_{0Yb} - 1/\tau} = 0.03 \pm 0.01.$$

In other words, the concentration of excited ytterbium ions for this sample in the stationary regime at 800 °C is 2 % — 4% of the concentration of erbium ions at the upper laser level.

4. Analytic expressions for the spectroscopic characteristics of Er^{3+} in YAG

The experimental data considered above show that the spectroscopic characteristics of Er^{3+}, Yr^{3+} : YAG crystals strongly change in the temperature range studied. In this section, we will estimate analytically the luminescence, absorption, and gain cross sections for erbium ions in YAG crystals as functions of temperature. Unfortunately, the data concerning the $^4I_{13/2} \leftrightarrow ^4I_{15/2}$ transition in the Er^{3+} ion in YAG crystal available in the literature ambiguously describe the energy and number of the Stark components. The total number of transitions between seven Stark components of the upper level and eight components of the lower level in YAG should be 56, but the resolution of Stark components is complicated due to their spectral overlap.

Our model is based on the results of detailed room-temperature studies of the absorption spectra of Er^{3+} in a $Y_2Al_5O_{12}$ crystal [9]. In particular, we used the energy level diagram from this paper, as well as the oscillator strengths and bandwidths for transitions between the Stark levels of the $^4I_{13/2}$ and $^4I_{15/2}$ states. In addition, according to data obtained in paper [10] devoted to the study of the properties of Er^{3+} in various garnets at low temperatures, we assume that the seventh Stark component of the $^4I_{13/2}$ level of Er^{3+} (absent in the energy level diagram presented in [9]) is located higher by 5 cm^{-1} than the sixth component. As a result, we compiled the table of transition probabilities A_{ji} between the Stark levels (Table 1). Note that the formal decomposition of absorption spectra into separate lines by using data [9] leads to good agreement with the experiment. However, to describe more accurately luminescence spectra as well, some changes should be introduced for some transitions (see note to Table 1). The probabilities A_{ji} were calculated as in [9]:

Table 1. Probabilities A_{ji} (s^{-1}) and linewidths Δv_{ji} (cm^{-1}) of spontaneous transitions between the Stark components of the $^4I_{13/2}$ (energy E_{2j}) and $^4I_{15/2}$ (energy E_{1i}) levels of the Er^{3+} ion in a Er^{3+} : YAG crystal at room temperature.

E_{1i}/cm^{-1} \ E_{2j}/cm^{-1}	$E_{21} = 6543.4$	$E_{22} = 6593.5$	$E_{23} = 6600.5$	$E_{24} = 6777.2$	$E_{25} = 6796.7$	$E_{26} = 6877.2$	$E_{27} = 6882.2$
$E_{11} = 0$	$A_{j1} = \textbf{9}$	13.9	30.2	29.9 (**25**)	48.0 (**45**)	58.5 (**50**)	**20**
	$\Delta v_{j1} = \textbf{5.5}$	5.5	6.4	5.1	6.6	8.0	**8.0**
$E_{12} = 18.5$	$A_{j2} = 60.6$	2.14	5.27	24.3	35.5 (**33**)	53.7 (**50**)	**10**
	$\Delta v_{j2} = 3.3$	3.7	4.7	5.2	4.5	7.6	**7.6**
$E_{13} = 58.6$	$A_{j3} = 2.56$	28.4	49.8 (**40**)	12.4	16.6	79.8	**10**
	$\Delta v_{j3} = 5.1$	3.7	3.9	4.9	4.2	7.6	**7.6**
$E_{14} = 75.3$	$A_{j4} = 10.3$	28.1	**3**	10.4	21.7	43.6	**15**
	$\Delta v_{j4} = 6.9$	4.1	**3.9**	4.8	5.5	6.4	**6.4**
$E_{15} = 410.3$	$A_{j5} = 3.3$	30.4	8.0	40.1	31.0	**5**	–
	$\Delta v_{j5} = 8.8$	10.2	11.0	13.2	10.9	**5**	–
$E_{16} = 423.1$	$A_{j6} = 17.2$	22.2	16.5	32.9	12.4	4.4	–
	$\Delta v_{j6} = 15.6$	14.3	20.5	17.7	11.4	12.0	–
$E_{17} = 520.8$	$A_{j7} = 6.8$	27.2	24.5	11.9	6.6	53.2	–
	$\Delta v_{j7} = 10.8$	15.4	10.7	15.5	11.9	14.2	–
$E_{18} = 565.5$	$A_{j8} = 7.5$	18.7 (**16**)	4.85 (**10**)	19.5	7.8	74.4	–
	$\Delta v_{j8} = 8.8$	13.0	8.4	22.8	14.7	15.6	–

N o t e . The values presented in the table were calculated from expression (1) by using data [9]. When the corresponding data were absent in [9] or were inconsistent with our experimental results, the values of A_{ji} and Δv_{ji} (in bold) were fitted to the absorption and luminescence spectra observed in our experiments.

$$A_{ji} = \frac{8\pi^2 e^2 n^2 g_i}{mc\chi g_j} v_{ji}^2 f_{ij}. \qquad (1)$$

Here, $v_{ji} = E_{2j} - E_{1i}$; E_{2j} and E_{1i} are energies of the Stark components (in inverse centimetres) of the $^4I_{13/2}$ and $^4I_{15/2}$ levels of the Er^{3+} ion, respectively; g_j and g_i are the statistical weights of these components; f_{ij} are the oscillator strengths for the corresponding transitions; m and e are the electron mass and charge; c is the speed of light; $n = 1.82$ is the refractive index of YAG; and $\chi = 9n(n^2 + 2)^{-2}$ is the correction for the acting field for electric dipole transitions (for magnetic dipole transitions, $\chi = 1/n$ and the difference between these quantities is only 5%).

Taking into account that the statistical weights of the Stark levels are $g_i = g_j = 2$, the absorption and emission cross sections for a Lorentzian line of width Δv_{ij} can be written in the form

$$\sigma_{ij} = \sigma_{ji} = \frac{A_{ji}}{4\pi^2 n^2 v_{ij}^2 \Delta v_{ij}}. \qquad (2)$$

The spectral dependences of the absorption and emission cross sections are written as

$$\sigma_{\text{abs}}(v, T) = \sum_{i,j} \frac{\sigma_{ij} F_{ij}(v) \exp(-E_{1i}/kT)}{B_1}, \qquad (3)$$

$$\sigma_{\text{emiss}}(v, T) = \sum_{i,j} \frac{\sigma_{ji} F_{ji}(v) \exp[-(E_{2j} - E_{21})/kT]}{B_2}, \qquad (4)$$

$$F_{ij} = F_{ji} = \frac{\Delta v_{ij}^2/4}{(v - v_{ji})^2 + \Delta v_{ij}^2/4}, \qquad (5)$$

where

$$B_1 = \sum_i \exp\left(-\frac{E_{1i}}{kT}\right); \quad B_2 = \sum_j \exp\left(-\frac{E_{2j} - E_{21}}{kT}\right).$$

The radiative lifetime of the $^4I_{13/2}$ level is determined from the expression

$$\frac{1}{\tau_{2\text{Er}}} = \sum_j \frac{A_{ji} \exp[-(E_{2j} - E_{21})/kT]}{B_2}. \qquad (6)$$

Assuming that the values of A_{ij} do not depend on temperature, but spectral lines broaden and shift with increasing temperature, we should introduce correcting factors into expressions (2)–(5) which take into account these temperature variations:

$$\Delta v_{ji}(T) = \Delta v_{ji}[1 + 4.5 \times 10^{-3}(T - T_0)],$$

$$E_{1i}(T) = E_{1i}[1 - 6 \times 10^{-5}(T - T_0)],$$

$$E_{2j}(T) = E_{2j}[1 - 7 \times 10^{-5}(T - T_0)],$$

$$E_{21} - E_{11} = (E_{21} - E_{11})[1 - 7 \times 10^{-7}(T - T_0)].$$

Here, $T_0 = 300$ K is room temperature.

These expressions allow us to estimate analytically temperature changes in the spectroscopic characteristics of transitions between the $^4I_{13/2}$ and $^4I_{15/2}$ levels of the Er^{3+} ion in YAG crystals. For example, the calculation of the radiative lifetime of the $^4I_{13/2}$ level by expression (6) yields values 6.55 and 6.06 ms for room temperature and 800 °C, respectively, which is close to the experimental values 6.4 and 5.3 ms that we obtained. A larger shortening of the lifetime $\tau_{2\text{Er}}$ observed in experiments can be explained by the increase in the transition probabilities A_{ji} and increase in the rate of luminescence quenching by uncontrollable impurities with increasing temperature.
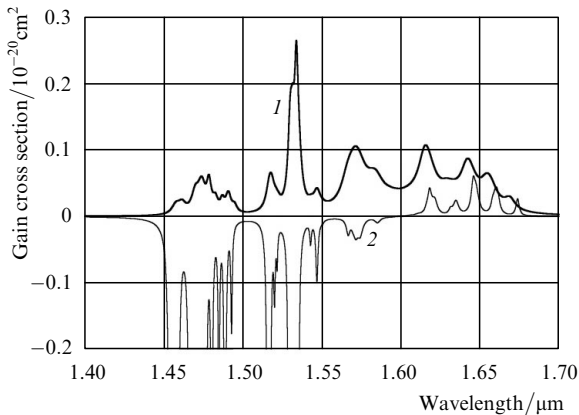
Figure 8.   Spectral dependences of the gain cross section at the $^4I_{13/2} \leftrightarrow ^4I_{15/2}$ transition of the Er^{3+} on in YAG calculated for the excitation level $x = 0.65$ and temperature $600\,°C$ (*1*) and $x = 0.2$ at room temperature (*2*).

Our model also gives the analytic temperature dependence of an important parameter of the active medium – the gain cross section $\sigma_{ampl}(v, x, T) = x\sigma_{emiss}(v, T) - (1 - x) \times \sigma_{abs}(v, T)$, where x is the fraction of excited erbium ions. Figure 8 presents the gain cross section calculated at $600\,°C$ for $x = 0.65$ and room temperature for $x = 0.2$.

5. Conclusions

Our studies have shown that the lifetime of the excited $^4I_{11/2}$ level of the Er^{3+} ion considerably decreases and the efficiency of nonradiative energy transfer from Yb^{3+} to Er^{3+} increases with increasing temperature from room temperature to $800\,°C$. These results give promise that efficient lasing may be obtained at $\sim 1.54\,\mu m$ in Yb^{3+}, Er^{3+} : YAG crystals pumped into the absorption band of ytterbium at high temperatures.

Based on the analysis of the absorption and luminescence spectra, we have obtained analytic equations for calculating the absorption, luminescence, and gain cross sections for Er^{3+} ions in YAG crystals at the transitions between the $^4I_{13/2}$ and $^4I_{15/2}$ levels in the range from room temperature to $\sim 800\,°C$.

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