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Output power saturation effect in Yb – Er fibre lasers

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Abstract. **The output power saturation effect in Yb – Er fibre lasers is experimentally observed. A formula for estimating the saturation power is derived. A method is proposed for measuring the $^4I_{11/2}$ level lifetime or the concentration of Er ions based on the measurements of the saturation power.**

Keywords: *fibre lasers, Yb – Er active medium, saturation power, excited state lifetime.*

1. Introduction

High-power (several tens of watts) single-mode lasers emitting at a wavelength of 1550 nm with a linewidth of ~0.1 nm are of interest, for example, for development of on-board scanning systems [1] and atmospheric optical communication lines, in range-finding, and for second harmonic generation in periodically poled crystals [2]. Based on laser radiation at λ = 1550 nm, it is possible to obtain lasers emitting at λ = 775 nm using the second harmonic generation, at λ = 517 nm using the third harmonic generation, and at various wavelengths of the red and blue spectral ranges using the summation of the frequencies of these harmonics and radiation at λ = 1030 – 1070 nm.

A narrow (narrower than 0.1 nm) spectral line in a cavity scheme with an erbium active few-mode fibre is difficult to obtain due to a low mode instability threshold [3] and nonlinear effects leading to line broadening, especially, due to four-wave mixing [4]. To increase the mode instability threshold, it was proposed to use for pumping single-mode radiation with longer wavelength [5]. One of the main factors limiting the output power in the case of using this approach to Yb – Er fibre lasers for creating a high-power single-mode radiation source with λ = 1550 nm was the power saturation effect. Hereinafter, we will, for simplicity, call the power level to which the output laser power saturates the saturation power P_{sat}.

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The power saturation effect was previously theoretically predicted for erbium [6] and ytterbium – erbium active media [7]. In both works, this effect was explained by the existence of the so-called bottleneck limiting the pump energy transfer to the working level. As a result, an increase in the pump power leads to an increase in the level excitation rate, but the rate of the excitation transfer to the metastable level through intermediate levels almost does not change. In [6], it was shown that such a bottleneck for purely erbium media is the transition between the $^4I_{11/2}$ and $^4I_{13/2}$ levels. For ytterbium – erbium media, one more limiting factor is the rate of excitation transfer from Yb to Er [7]. It should be noted that the bottleneck effect can also exist in lasers based on other active ions with similar energy level diagrams, because of which the analysis of our results performed on the basis of general considerations and presented below can also be applied to other media.

In the present work, we experimentally study the output power saturation effect in an Yb – Er fibre laser and derive a formula for estimating the saturation power for such lasers.

2. Experimental results

Figure 1a shows the typical experimental optical scheme. We tested three optical schemes of Yb – Er fibre lasers differing by the length and parameters of the active fibre. Since our aim was to obtain linearly polarised radiation, we used only a polarisation-maintaining fibre in the optical channel. However, this fact is dispensable, because of which all results and discussions presented below are equally valid for isotropic systems. The parameters of the used active fibres are listed in Table 1. We used fibres with a phosphorosilicate matrix with concentrations n_{Yb} of Yb ions, which are an order of magnitude higher than the concentration n_{Er} of Er ions. The lasers were pumped into the active fibre core with diameter d and length L by single-mode radiation with wavelengths λ_p = 1065 and 1070 nm. The active fibre was immersed in water for cooling (otherwise, it was strongly heated and the power characteristics of the laser changed with time). The output spectrum contained, apart from the signal radiation at λ_s = 1550 nm, the unabsorbed pump radiation. Because of this, the output radiation was collimated, after which its spectral components were separated by a dichroic mirror and their powers were measured.

Based on optical scheme No. 3, we assembled scheme No. 4 by adding a piece of the active fibre, which played the role of an amplifier, at the exit of the laser. This resulted in an increase in the efficiency of pump radiation conversion to radiation at λ_s = 1550 nm (Fig. 1b).

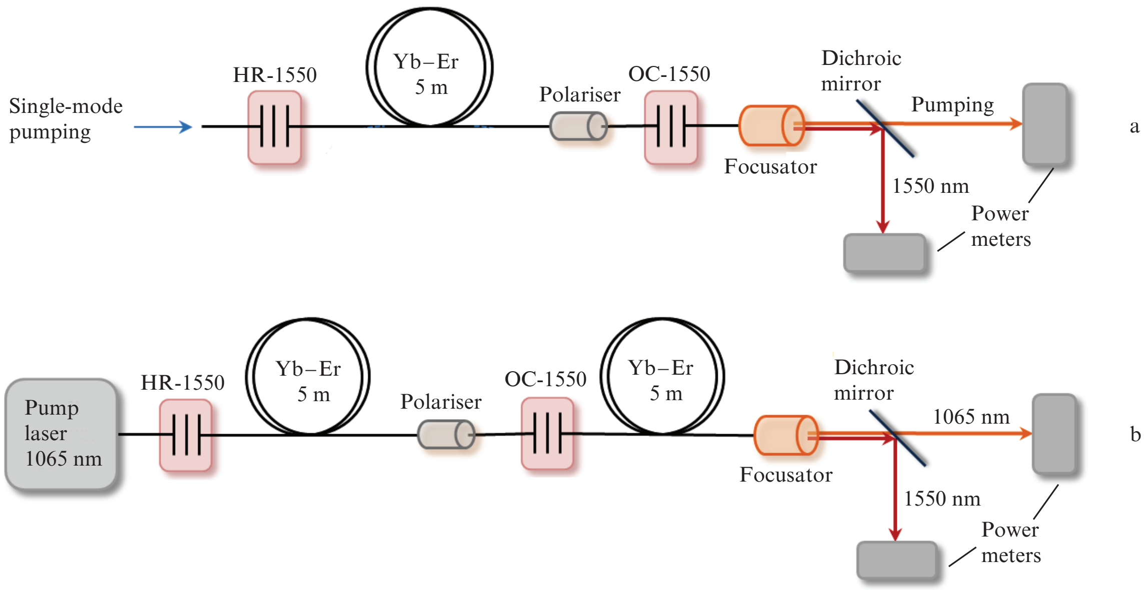

Figure 1. Optical schemes of (a) an Yb–Er fibre laser with single-mode pumping and (b) laser No. 4. HR-1550 and OC-1550 are the highly and weakly reflecting fibre Bragg gratings, respectively.

Table 1. Parameters of the used lasers.

Scheme number	L/m	d/μm	n_{Er}/ppm	λ_p/nm
1	4	9.1	230	1070
2	6	9.1	230	1070
3	5	18	300	1065
4	10	18	300	1065

Figure 2 presents the light-current and spectral characteristics of the laser with optical scheme No. 3. The output power at λ_s = 1550 nm at low pump powers increases with a slope efficiency η = 27% and reaches saturation at $P_{sat} \approx$ 15 W. At the same time, the output power of the pump spectral component (λ_p = 1065 nm) linearly increases in the saturation region.

Table 2 presents the saturation powers and slope efficiencies of erbium lasers for all used optical schemes. Power saturation for sample No. 4 was not reached due to the insufficient pump laser power.

Table 2. Experimental results.

Scheme number	η (%)	$\varkappa$ (%)	P_{sat}/W (experiment)
1	30	74	1.7
2	34	65	2.5
3	27	50	15
4	30	–	>27

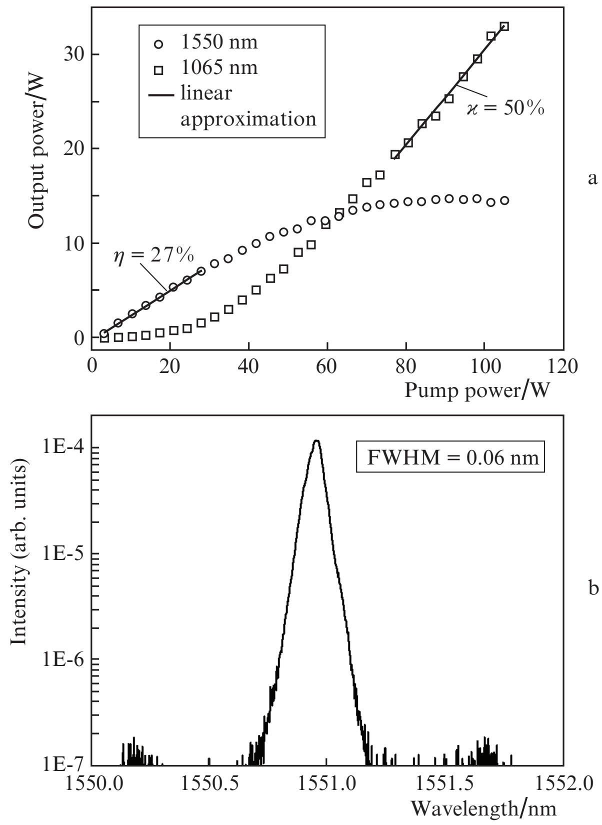

Figure 2. (a) Dependences of the output power at wavelengths of 1550 and 1065 nm for laser No. 3. (Fig. 1a) with single-mode pumping at λ_p = 1065 nm and (b) emission spectrum at λ_s = 1550 nm at an output power of 15 W. $\varkappa$ = 50% is the differential fraction of unabsorbed pump power in the signal saturation region.

3. Analysis of the results

The output power saturation was observed in each of the performed experiments. The saturation powers are considerably different and depend on the pump wavelength and the fibre parameters (Table 2).

We relate the limitation of the output laser power with the existence of a finite time for which an ion can receive energy, transfer a part of it to the environment in the form of electromagnetic radiation, and return to the unexcited state.

The scheme of energy transfer in the ytterbium–erbium system is presented in Fig. 3. The pump photon energy excites the ytterbium ion (transition $^2F_{7/2} \rightarrow {}^2F_{5/2}$), and then the excitation is transferred to the short-lived $^4I_{11/2}$ level of the erbium ion, from which nonradiative relaxation occurs to the metastable $^4I_{13/2}$ level.

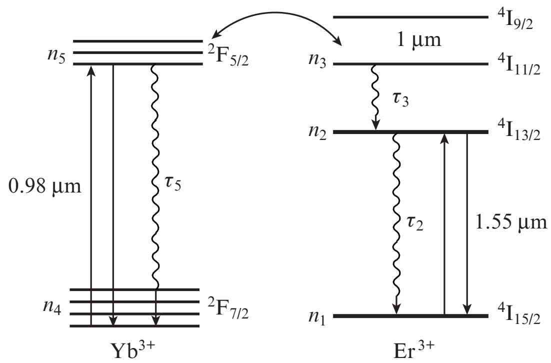

Figure 3. Energy level diagram of the Yb–Er laser medium.

Lasing in the active medium corresponding to the scheme given in Fig. 3 in the absence of parasitic losses, upconversion, and absorption from the excited state can be described by the following system of steady-state rate equations:

$$
\begin{aligned}
&0 = c(\rho_s^+ + \rho_s^-)(\sigma_{Er}^a n_1 - \sigma_{Er}^e n_2) - \frac{n_2}{\tau_2} + \frac{n_3}{\tau_3},\\
&0 = -\frac{n_3}{\tau_3} + C_{tr}(n_1 n_5 - n_3 n_4),\\
&0 = -\frac{n_5}{\tau_5} - C_{tr}(n_1 n_5 - n_3 n_4) + c\rho_p(\sigma_{Yb}^a n_4 - \sigma_{Yb}^e n_5),\\
&\frac{\partial \rho_s^+}{\partial z} = \rho_s^+(\sigma_{Er}^e n_2 - \sigma_{Er}^a n_1),\\
&\frac{\partial \rho_s^-}{\partial z} = -\rho_s^-(\sigma_{Er}^e n_2 - \sigma_{Er}^a n_1),\\
&\frac{\partial \rho_p}{\partial z} = \rho_p(\sigma_{Yb}^e n_5 - \sigma_{Yb}^a n_4),\\
&n_1 + n_2 + n_3 = n_{Er},\\
&n_4 + n_5 = n_{Yb}.
\end{aligned} \tag{1}
$$

Here, n_i and τ_i are the populations and lifetimes according to Fig. 3; n_{Er} and n_{Yb} are the concentrations of erbium and ytterbium ions in the fibre; ρ_s^+, ρ_s^-, and ρ_p are the photon flux densities (in $m^{-2}\,s^{-1}$) of the signal radiation at $\lambda_s = 1550$ nm propagating in the cavity in the direct and reverse directions and of the pump radiation; σ_{Er}^a, σ_{Er}^e, σ_{Yb}^a, and σ_{Yb}^e are the absorption and stimulated emission cross sections of the erbium and ytterbium working transitions; C_{tr} is the coefficient of energy transfer between the $^2F_{5/2}$ and $^4I_{11/2}$ levels; and c is the speed of light.

In the considered configuration, the excitation transfer rates for the $^2F_{7/2} \rightarrow {}^2F_{5/2}$ and $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transitions cannot be the limiting factors, because these transitions are induced and their rates increase with increasing radiation power. The limiting factors can be only the $^2F_{5/2} \rightarrow {}^4I_{11/2}$ and $^4I_{11/2} \rightarrow {}^4I_{13/2}$ transitions because their rates depend only on the inversion density in the medium, which cannot exceed a definite level.

Note also that the concentration ratios of the active ions in the medium are chosen so that the rates of excitation transfer between Yb and Er ions are very high [8]. Therefore, the bottleneck for pumping the working level is the $^4I_{11/2} \rightarrow {}^4I_{13/2}$ transition, and the saturation power P_{sat} can be represented as

$$P_{sat} = \frac{hc}{\lambda_s}\frac{N_3}{\tau_3}, \tag{2}$$

where h is the Planck constant and N_3 is the total number of Er ions with en excited electron at level 3. However, formula (2) contains the unknown population of the $^4I_{11/2}$ level in the process of lasing, which makes it difficult to estimate the saturation power.

We can assume that coefficient C_{tr} in system (1) at high rates of energy exchange between Yb and Er ions is $C_{tr} \rightarrow \infty$. Then, we can write the relation

$$\frac{n_5}{n_4} \approx \frac{n_3}{n_1}. \tag{3}$$

Note that, with increasing pump power, the populations of levels of ytterbium ions tend to values ensuring bleaching (saturation) of the corresponding transition, which are determined by the absorption and stimulated emission cross sections at this transition:

$$n_5 \approx \frac{\sigma_{Yb}^a}{\sigma_{Yb}^e} n_4. \tag{4}$$

In the process of lasing, the radiation power in the cavity is so high that the erbium transition is also almost saturated, and the populations of the corresponding levels are related as

$$n_2 \approx \frac{\sigma_{Er}^a}{\sigma_{Er}^e} n_1. \tag{5}$$

Using (3)–(5) and the expression for the total number of erbium ions at each point of the fibre ($n_{Er} = n_1 + n_2 + n_3$), we find

$$n_3 \approx n_{Er}\left[1 + \frac{\sigma_{Yb}^e}{\sigma_{Yb}^a}\left(1 + \frac{\sigma_{Er}^a}{\sigma_{Er}^e}\right)\right]^{-1}. \tag{6}$$

In the case of homogeneous doping, the total number of erbium ions in the fibre is

$$N_{Er} = \frac{\pi d^2}{4} L n_{Er}. \tag{7}$$

In the first approximation, lasing will occur with participation only of erbium ions positioned in the region of propagation of signal single-mode radiation, we have

$$N_3 = \frac{\pi d_m^2}{4} L n_3, \tag{8}$$

where d_m is the radiation mode diameter.

Taking into account (6)–(8), we can write the saturation power in the form

$$P_{sat} = \frac{hc}{\lambda_s} \frac{N_{Er}}{\tau_3} \frac{d_m^2}{d^2} \left[1 + \frac{\sigma_{Yb}^e}{\sigma_{Yb}^a} \left(1 + \frac{\sigma_{Er}^a}{\sigma_{Er}^e} \right) \right]^{-1}. \quad (9)$$

To provide signal gain in the case of an amplifier, the system should satisfy the relation

$$n_2 > \frac{\sigma_{Er}^a}{\sigma_{Er}^e} n_1. \quad (10)$$

In this case,

$$P_{sat} < \frac{hc}{\lambda_s} \frac{N_{Er}}{\tau_3} \frac{d_m^2}{d^2} \left[1 + \frac{\sigma_{Yb}^e}{\sigma_{Yb}^a} \left(1 + \frac{\sigma_{Er}^a}{\sigma_{Er}^e} \right) \right]^{-1}. \quad (11)$$

An important factor influencing the saturation power is the pump wavelength, which affects the coefficient

$$\sum = \left[1 + \frac{\sigma_{Yb}^e}{\sigma_{Yb}^a} \left(1 + \frac{\sigma_{Er}^a}{\sigma_{Er}^e} \right) \right]^{-1}.$$

For diode pumping at $\lambda_p = 965$ nm, $\Sigma \approx 0.44$, while for pumping at $\lambda_p = 1070$ nm this coefficient is only 0.005. Thus, a change in the pump wavelength can lead to a change in the saturation power by several orders of magnitude (Fig. 4).

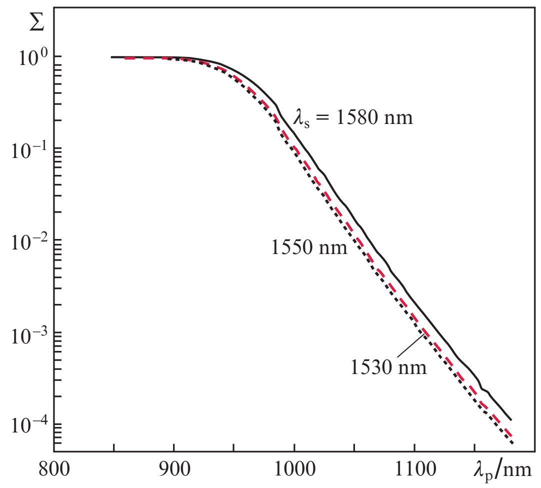

Figure 4. Dependences of coefficient Σ on the pump radiation wavelength λ_p.

The obtained expression determines the theoretical limit of the power of ytterbium – erbium fibre lasers of a given geometry. According to formulas (9) and (11),

$$P_{sat} < \frac{hc}{\lambda_s} \frac{N_{Er}}{\tau_3}. \quad (12)$$

The saturation power will tend to the theoretical limit (12) in the case of short-wavelength pumping near $\lambda_p = 900$ nm (Fig. 4), but the factor limiting the output laser power in this case can be parasitic lasing of Yb ions.

For a more rigorous mathematical description of the obtained results, we simulated operation of a fibre laser using rate equations (1) and the parameters presented below (r_{out} is the output grating reflection coefficient).

λ_s/nm 1550
λ_p/nm 1065
d_m/μm. 12
n_{Er}/ppm 300
n_{Yb}/ppm 10000
r_{out} (%) 10
τ_2/ms 10
τ_3/μs. 1
τ_5/ms 1.4
σ_{Yb}^e/pm^2. . . . . .0.13
σ_{Yb}^a/pm^2. . . . .1.6×10^{-3}
σ_{Er}^e/pm^2 . . . . .0.22
σ_{Er}^a/pm^2 . . . . .0.18

We compared the saturation powers determined by the following three methods.

1. By computer simulation based on system of rate equations (1).

2. By formula (2), in which concentration N_3 was calculated by integrating n_3 taken from the simulation results over the entire volume.

3. By formula (9).

The saturation powers determined by methods 1 and 2 coincided with each other and turned out to be lower than the power calculated by formula (9) by less than 5%. This difference is related, first of all, to the assumption that the medium is saturated for the signal radiation (5), and decreases with increasing output grating reflection coefficient in simulation. Nevertheless, the results of this comparison prove the validity of the assumptions used for deriving formula (9).

Based on the experimental data and formula (9), we estimated the $^4I_{11/2}$ level lifetime (Table 3). One can see that the saturation powers for the optical schemes of lasers with different amounts (concentrations) of erbium ions and different pump wavelengths are considerably different, but the reconstructed lifetimes τ_3 are, as expected, approximately identical.

Table 3. Experimental and theoretical results.

Scheme number	$(d_m^2 N_{Er}/d^2) \times 10^{-16}$	$\Sigma \times 10^3$	P_{sat}/W (experiment)	τ_3/μs (according to formulas (9), (11))
1	0.53	4	1.7	0.68
2	0.8	4	2.5	0.69
3	3.5	5	15	0.61
4	7.0	5	> 27	< 0.68

The lifetimes of the $^4I_{11/2}$ level of the Er ion are considerably different in different glass matrices. Work [6] gives $\tau_3 <$ 3 μs for erbium-doped phosphate glasses, while the authors of [7] used for calculations $\tau_3 = 0.1$ μs, but they did not write for which matrix this lifetime was used. In the case of the phosphosilicate matrix, this time is ~0.6 μs [8], which well agrees with the obtained results (Table 3), although phosphosilicate matrices in [8] and in this paper may be different.

Thus, the measurement of the saturation power can be used to determine the characteristics of ytterbium – erbium fibre laser systems. In particular, as is described above, it is possible to estimate the $^4I_{11/2}$ level lifetime for different types of glasses. On the other hand, using the measured saturation power at known length and geometry of the fibre, as well as at known cross sections and lifetimes of the nonradiative $^4I_{11/2}$ level of erbium ions, one can estimate the number of erbium ions in the active fibre and, hence, their concentration.

For such measurements, it is recommended to use the optical scheme with a low saturation power, which allows one to avoid fibre heating, which can considerably change the absorption and stimulated emission cross sections, and to avoid other limiting factors. The saturation power can be decreased by using a longer-wavelength pumping and a shorter active fibre length.

4. Conclusions

To our best knowledge, the output power saturation in Yb–Er fibre lasers was observed in the present work for the first time. This effect is related to limitation of the rate of energy transfer from the $^4I_{11/2}$ to the $^4I_{13/2}$ level of erbium ions and can be the main reason for limitation of the output power for some laser systems using short active fibres or long-wavelength pumping.

We have derived formula (9) for estimating the saturation power, which can be used for developing Yb–Er fibre lasers, and analysed the main factors affecting the saturation power. Using formula (9) and based on the experimental data, we estimated the lifetime (~0.6 μs) of the nonradiative $^4I_{11/2}$ level of erbium ions in phosphosilicate active fibres. The correctness of the assumptions used when deriving this formula was evaluated by comparing the saturation power determined using this formula and the values obtained as a result of simulation of rate equations.

We also proposed a new method for measuring the active medium parameters (lifetimes of levels and concentrations of active ions) based on measuring the saturation power.

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References

1. Briese C. et al. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci*., **40**, 119 (2013).
2. Surin A.A., Larin S.V., Borisenko T.E., Prusakov K.Yu., Strimanov Yu.S. *Quantum Electron*., **46** (12), 1097 (2016) [*Kvantovaya Elektron*., **46** (12), 1097 (2016)].
3. Puju P.V., Zelenova M.V., Tyrtyshnyy V.A. *Proc. 17th Internat. Conf. 'Laser Optics'* (WeS1A-21, 2016).
4. Singh S.P., Singh N. *Progr. Electromagnet. Res*., **73**, 249 (2007).
5. Surin A.A., Molkov A.A., Borisenko T.E., Prusakov K.Yu. *Quantum Electron*., **48** (12), 1095 (2018) [*Kvantovaya Elektron*., **48** (12), 1095 (2018)].
6. Quimby R.S. *Appl. Opt*., **30** (18), 2546 (1991).
7. Yahel E., Hardy A. *J. Lightwave Technol*., **21** (9), 2044 (2003).
8. Melkumov M.A. et al. *Inorgan. Mater*., **46** (3), 299 (2010).