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Abstract

A recent publication (Wang *et al* 2013 *Laser Phys. Lett.* **10** 115804) described an actively Q-switched and diode-pumped Er:YAG (yttrium aluminum garnet) laser source. The novelty of that letter lies in the use of a very bright and spectrally narrowed fiber-coupled laser diode as a pump, thus leading to very good performance in continuous wave mode. In Q-switch operation, the output energy reported is surprisingly high (6.6 mJ) for this kind of setup with a low pump power (only 10 W) and with small beam diameter (250 μm). In this letter, we demonstrate that the output energy exceeds the maximum extractable energy of the gain medium.

Keywords: Q-switch, oscillator, Er:YAG

(Some figures may appear in colour only in the online journal)

1. Introduction

Er:YAG crystal is often used as a quasi-three-level gain medium for emission at 1617 or 1645 nm. It is well suited for eye-safe laser emission in a transmission window of the atmosphere and for applications like LiDAR, telemetry and active imaging. Er:YAG can be resonantly pumped by an Er:Yb fiber laser at 1533 nm [2], or by a laser diode at 1470 nm [3] or 1533 nm [4], generally in a longitudinal configuration. The optical-to-optical efficiency of the diode-pumped Er:YAG laser is generally far below the efficiency obtained with a fiber laser as the pump source. This is due to the limited overlap between the pump beam and the laser beam, the overlap being particularly important for efficient quasi-three-level lasers.

Recent progress for laser diodes in terms of brightness and spectral purity may increase the laser efficiency and then reduce the pump power that is needed to address applications. The letter [1] is one recent example showing what can be achieved with a very bright and spectrally narrowed laser diode. The author used a 0.5% Er:YAG, like many other publications [5–7]. The letter reported efficient laser operation at a low pump power level: only 10 W, typically 3–5 times lower than for previously published papers. In order to achieve laser operation at such a low pump power level, the pump beam has been tightly focused (250 μm in diameter). Consequently, the number of excited ions is limited by the small pump volume. The energy in Q-switched operation should be reduced compared to that for similar Er:YAG crystals pumped at higher power levels. However, despite the small pump power and the small pump volume, the energy reported in Q-switched operation (6.6 mJ) [1] is in the same range as the ones obtained in other setups using higher pump power.

In this letter, we propose a critical analysis of this performance. We present a numerical model giving a rough evaluation of the maximum stored energy through the evaluation of the number of excited erbium ions inside the gain medium. We applied this model to various Er:YAG laser systems reported, including that of the letter [1].

2. Estimation of the maximum number of excited ions

We consider the pump volume V as a cylinder whose diameter is the pump spot diameter and which has length equal to the crystal's length. Assuming that the medium is pumped at a very high power level such that absorption saturation occurs over the volume V, the population density in the upper level n_1 reaches its maximum value in V. Hence, the maximum number of excited ions $N_1^{\max}$ is given by

$$N_1^{\max} = V n_{\mathrm{Er:YAG}} \beta_{\max}.$$

$n_{\mathrm{Er:YAG}}$ is the density of erbium ions (per unit volume). $\beta_{\max}$ is the maximum of the ratio of $n_1/n_{\mathrm{Er:YAG}}$, n_1 being the density of atoms in the upper state level. It is worth noting that the real value of N_1 is generally much lower than $N_1^{\max}$ because the pump power is limited and because it is progressively absorbed going along the gain medium (in the case of longitudinal pumping).

The density of erbium ions $n_{\mathrm{Er:YAG}}$ depends on the YAG density d_{YAG}, the number of yttrium ions N in one garnet unit (3 for the $Y_3Al_5O_{12}$ matrix) which are replaced by erbium ions, the atomic mass of YAG m_{YAG} and the doping ratio R in at.%:

$$n_{\mathrm{Er:YAG}} = \frac{N d_{\mathrm{YAG}}}{m_{\mathrm{YAG}}} R.$$

For the numerical applications, the following values will be adopted:

$$d_{\mathrm{YAG}} = 4.55 \times 10^6 \text{ g m}^{-3}$$
$$m_{\mathrm{YAG}} = 9.93 \times 10^{-22} \text{ g}.$$

For a 0.5% doped Er:YAG crystal, $n_{\mathrm{Er:YAG}}$ is equal to 6.87×10^{25} m^{-3}.

$\beta_{\max}$ can be calculated by solving the rate equation for the upper level in the steady state:

$$\frac{\mathrm{d}n_1}{\mathrm{d}t} = \sigma_{\mathrm{al}} I_1 n_0 + \sigma_{\mathrm{ap}} I_{\mathrm{p}} n_0 - \sigma_{\mathrm{el}} I_1 n_1 - \sigma_{\mathrm{ep}} I_{\mathrm{p}} n_1 - A n_1$$

where A is the upper state lifetime, I_1 the laser intensity, I_{p} the pump intensity, n_0 and n_1 the population densities of the ground state and upper state respectively, and σ_{**} the absorption/emission cross-section of the laser/pump.

Without any laser operation in the steady state and under continuous wave pumping, we have

$$\frac{n_1}{n_0} = \frac{\sigma_{\mathrm{ap}} I_{\mathrm{P}}}{A + \sigma_{\mathrm{ep}} I_{\mathrm{P}}}.$$

As we want an estimate of the maximum population in the upper state, we can assume a very high pumping level, meaning that I_{p} tends toward infinity. We can then write

$$\frac{n_1}{n_0} = \frac{\sigma_{\mathrm{ap}}}{\sigma_{\mathrm{ep}}}.$$

This leads to a maximum population inversion factor of

$$\beta_{\max} = \frac{n_1}{n_{\mathrm{Er:YAG}}} = \frac{n_1}{n_1 + n_0} = \frac{1}{1 + n_0/n_1} = \frac{1}{1 + \sigma_{\mathrm{ep}}/\sigma_{\mathrm{ap}}}.$$

The numerical applications give

$$\beta_{\max,1533\text{ nm}} = 0.57.$$

3. Estimation of the maximum extractable energy at the laser wavelength

Assuming that all the atoms in the upper state level are transformed into laser photons by stimulated emission, a rough approximation of the maximum pulse energy could be calculated as $E_{\max} = hc/\lambda \cdot N_1^{\max}$.

However, after a Q-switched pulse there is no more gain inside the crystal, meaning that the energetic state of the crystal is at the transparency threshold. Hence, for a three-level laser system, a noticeable amount of the stored energy is actually used to reach this transparency.

To evaluate the minimum population inversion for transparency $\beta_{\min}$, we use the laser gain cross-section (this evaluation has already been done in [8]):

$$\sigma_{\mathrm{gl}} = \sigma_{\mathrm{el}} \frac{n_1}{n_{\mathrm{Er:YAG}}} - \sigma_{\mathrm{al}} \frac{n_0}{n_{\mathrm{Er:YAG}}}.$$

With a laser gain cross-section equal to 0, we obtain

$$g = \sigma_{\mathrm{el}} n_1 - \sigma_{\mathrm{al}} (n_{\mathrm{Er:YAG}} - n_1) = 0$$
$$n_1 = \frac{\sigma_{\mathrm{ap}}}{\sigma_{\mathrm{al}} + \sigma_{\mathrm{el}}} n_{\mathrm{Er:YAG}}$$
$$\beta_{\min} = \frac{1}{1 + \sigma_{\mathrm{el}}/\sigma_{\mathrm{al}}}.$$

For the transition ${}^4I_{13/2} \rightarrow {}^4I_{15/2}$ at 1645 nm,

$$\beta_{\min} = 0.09.$$

The maximum extractable energy is limited by two factors: the stimulated emission at the pump wavelength (responsible for $\beta_{\max} < 1$) and the absorption at the laser wavelength (responsible for $\beta_{\min} > 0$). Hence, the energy extractable from the crystal is given by

$$E_{\mathrm{extractable}} = \frac{V h c n_{\mathrm{Er:YAG}}}{\lambda} (\beta_{\max} - \beta_{\min}).$$

4. Numerical applications for *Q*-switched Er:YAG lasers

The maximum extractable energy is calculated for different setups of the Er:YAG laser reported in the literature. Table 1 compares these values with experimental values obtained in Q-switched operation. These results are obtained with Er:YAG crystals of doping concentration between 0.25% and 0.5%. In order to reach a minimum population inversion along the crystal for good efficiency, the pump spot diameter should decrease when the launched power decreases, but this is achieved at the expense of the stored energy.

In all cases, except that of [1], the experimental energy is significantly lower than the maximum extractable energy (between 10% and 40%, depending on the configuration). In the case of [1] we believe that the measurement of the output energy was incorrect, either due to a continuous wave background or due to some secondary pulses.

Table 1. Comparison of maximum extractable energy and experimental energy in Q-switched operation for different Er:YAG lasers.

Publication	Launched power	Pump spot diameter (μm)	Doping ratio (at.%)	Crystal's length (mm)	Extractable energy (mJ)	Experimental energy in Q-switched operation (mJ)	Ratio (%)
[1]	10 W	250	0.5	40	5.87	6.6	**112**
[2]	45 W (fiber laser)	1700	0.25	29	262	30.5	11.6
[9]	50 W	600	0.5	60	67.6	8.2	2.1
[10]	16 W (fiber laser)	500	0.25	40	15.7	5.8	36.9
[11]	310 mJ	1000	0.25	130	204	24	11.8
[12]	117 mJ (Er:glass laser)	400	0.5	25	12.5	1.6	12.8
[13]	17 W (fiber laser)	400	0.5	29	14.5	4	27.6
[14]	30 W	800	0.25	30	30.1	12	39.9
[15]	20 W	800	0.25	30	30.1	7	23.3

5. Conclusion

Using a simple calculation for the maximum energy extractable from an Er:YAG laser, we demonstrate that the output energy reported in [1] is certainly overestimated. Parasitic laser emission should certainly occur between Q-switched pulses leading to an average power much higher than the one coming from the pulses only.

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