Luminescence quenching in rare-earth-ion-doped Al_2O_3 lasers and its influence on relaxation oscillation frequency

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Abstract: The impact of luminescence quenching on rare-earth-ion doped lasers is investigated, and we show that the expression for the relaxation oscillation frequency needs to be modified to take the quenching properly into account.
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1. Introduction

Luminescence quenching in rare-earth-ion-doped optical materials is a well-established phenomenon [1-4]. The quenching is due to, e.g., the presence of ion pairs of clusters, impurities, or host material defects, and quenched ions exhibit a decay time on the order of a few μs [2] or even as short as 50 ns [3]. In most cases, this effect causes a loss of population inversion and can dramatically deteriorate the performance of optical devices, such as amplifiers and lasers.

In this paper, we investigate the effect of quenching on the laser characteristics, specifically on the relaxation oscillation frequency. As an example, we operate an Al_2O_3:Yb^{3+} distributed feedback (DFB) laser, but results can be applied to other rare-earth-ion-doped lasers as well.

2. Model

Al_2O_3:Yb^{3+} constitutes a two-multiplet-level system. Laser action occurs among the first excited state, pumped at rate R and with population N_1, and the ground state, with population N_0. The dynamic behavior of Yb ions is described by the following rate equation,

$$\frac{dN_1}{dt} = R - \varphi_L\left(\sigma_{emL}N_1 - \sigma_{absL}N_0\right) - \frac{f_q^* N_1}{\tau_{1q}} - \frac{\left(1-f_q^*\right)N_1}{\tau_1}, \qquad (1)$$

where φ_L is the photon flux of the laser field, σ_{absL} and σ_{emL} are the absorption and emission cross-sections, respectively, at the laser wavelength, and f_q^* represents the fraction of ions in the first excited state that are quenched. The quenched ions have a fast decay time τ_{1q}, on the order of a few μs for Yb^{3+}, while the non-quenched ions have a long luminescence lifetime τ_1 which ranges from hundreds of μs up to a few ms [4]. The dynamic of the laser is described by the following rate equation,

$$\frac{d\varphi_L}{dt} = \varphi_L\left[\frac{c}{n}\left(\sigma_{emL}N_1 - \sigma_{absL}N_0\right) - \frac{1}{\tau_c}\right], \qquad (2)$$

where c is the speed of light, n is the refractive index of the laser medium, and τ_c is the cavity lifetime. Together with the condition $N_0+N_1= N_d$ (total ion concentration), Eqs. (1) and (2) are solved under steady-state conditions, yielding

$$N_1^{ss} = \frac{n/(c\tau_C) + \sigma_{absL}N_d}{\sigma_{absL} + \sigma_{emL}}, \qquad (3)$$

$$\varphi_L^{ss} = \frac{c\tau_C}{n}\left(R - R_{Th}\right), \qquad (4)$$

where $R_{Th} = N_1^{ss}/\tau_w$ is the threshold pumping rate and

$$\tau_w = \left(\frac{f_q^*}{\tau_{1q}} + \frac{1 - f_q^*}{\tau_1} \right)^{-1} \tag{5}$$

has the meaning of an effective lifetime, obtained combining the lifetimes of active and quenched ions and weighted on the f_q^* value. The linearized transient behavior calculations yield

$$\varphi_L(t) = \varphi_L^{ss} + Ae^{-\gamma_{sp} t} \cos\left(\omega_{sp}^{'} t\right), \tag{6}$$

$$\gamma_{sp} = \frac{1}{2} \frac{1}{\tau_w} \left[1 + \left(1 + \frac{c\tau_c}{n} N_d \sigma_{absL} \right) \left(\frac{R}{R_{Th}} - 1 \right) \right], \tag{7}$$

and $\omega_{sp}^{'} = \sqrt{\omega_{sp}^2 - \gamma_{sp}^2} \approx \omega_{sp}$ (valid for strong-spiking lasers, where $\omega_{sp} >> \gamma_{sp}$). The oscillation frequency is

$$\omega_{sp}^2 = \frac{1}{\tau_c} \frac{1}{\tau_w} \left(\frac{R}{R_{Th}} - 1 \right) \left(1 + \sigma_{absL} N_d \frac{c\tau_c}{n} \right), \tag{8}$$

which is directly comparable with Eq. (10) of Ref. [5]. From this comparison we observe that the lifetime of the upper laser level τ_1 is replaced by the effective lifetime τ_w in the $1/\tau_w$ and R_{Th} terms.

3. Relaxation oscillation frequency measurements

Measurements of the relaxation oscillation frequency were performed on an Al_2O_3:Yb^{3+} DFB laser, with Yb concentration of 5.8×10^{20} cm^{-3}. Fabrication details and laser characteristics are described elsewhere [6]. Relaxation oscillations were induced by modulating the pump laser intensity by means of a square-pulse generator. Figure 1 shows a plot of the square of the measured relaxation oscillation frequency as a function of the pump ratio R/R_{Th}. As expected, ω_{sp}^2 is linear with the pump ratio and from the y-axis intercept we can calculate the value of τ_w, provided that all the other parameters are known. Given τ_c = 0.81 ns, $\sigma_{absL} = 0.29 \times 10^{-21}$ cm^2, and n= 1.6, we obtain τ_w= 29.6 ± 4.6 µs. The effective lifetime τ_w is much smaller than the intrinsic lifetime τ_1 of 740 µs (measured separately), highlighting the dramatic effect of the quenching process on the Yb-ion system and on the laser behavior. Although we estimated f_q^* to be only approximately 15%, τ_w is a factor of 25 shorter than τ_1, because of the dominating effect of τ_{1q} on τ_w, see Eq. (5). This finding has important implications in case one wants to use the relaxation oscillations to calculate the losses, as done for instance in [7]. τ_w needs to be used in place of τ_1, otherwise errors occur that would result in unrealistic predictions when used to calculate a practical laser performance.

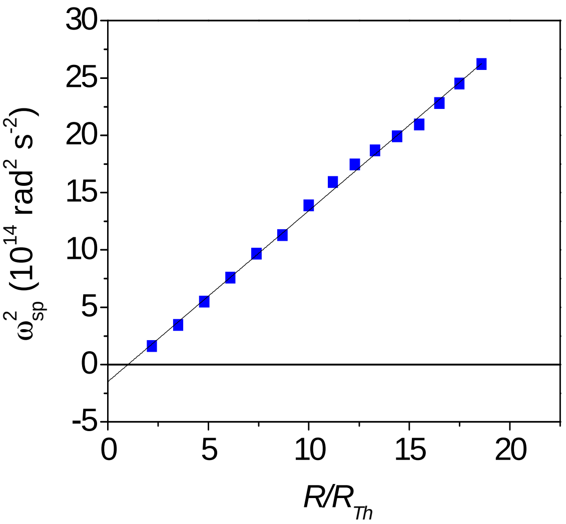

Fig. 1. Relaxation oscillation frequency squared as function of pump ratio, for a DFB laser with an Yb^{3+} concentration of 5.8×10^{20} cm^{-3}.

4. Summary

The impact of luminescence quenching on $Al_2O_3:Yb^{3+}$ lasers, specifically on the relaxation oscillation frequency, has been investigated. It has been shown that the quenching effect on the effective lifetime must be taken into account when using the relaxation oscillation frequency data to determine other laser parameters.

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5. References

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