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SCIENCE DIRECT

Journal of Luminescence 114 (2005) 43–52

JOURNAL OF LUMINESCENCE

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Upconversion from the $^4I_{13/2}$ and $^4I_{11/2}$ levels in Er:YAG

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Received 2 March 2004; received in revised form 1 November 2004; accepted 15 November 2004
Available online 4 January 2005

Abstract

The efficiency of erbium three-micron laser (laser transition $^4I_{11/2} \rightarrow {}^4I_{13/2}$) depends essentially on the ratio of the parameters of active energy transfer upconversion (ETU) from the laser levels. The parameters of both ETU processes can be obtained from the analysis of the shape of the kinetics of the $^4I_{11/2}$ level in concentrated Er:YAG crystals, under short pulse pumping. Mathematical modeling is used to evaluate the sensitivity of the method and to estimate the errors which can be introduced by the inhomogeneous pumping and accidental impurities. It was found that the ratio of the parameters corresponding to the ETU from the laser levels is less sensitive to the pumping inhomogeneities than that corresponding to the lower laser level. A reduction of this ratio with increasing erbium concentration is observed.

PACS: 42.70.−a; 42.70.Hj; 78.55.−m

Keywords: Upconversion; Energy transfer; Rare earth; Er:YAG

1. Introduction

The interest for 3-μm erbium lasers is generated by the applications in medicine and biology, based on the very strong absorption of biological tissues in this spectral region.

For the 3-μm erbium lasers, the lifetime of the initial laser level ($^4I_{11/2}$) is shorter than the lifetime of the terminal one ($^4I_{31/2}$). In spite of this limitation, efficient long pulse or cw operation was obtained at room temperature at high erbium concentrations [1–8]. The absence of self-saturation at high erbium concentrations was explained by the active energy transfer upconversion (ETU) from the terminal laser level [9,10]. However, besides upconversion from $^4I_{13/2}$ level, the energy level scheme of Er^{3+} (see Fig. 1) favors a large variety of other energy transfer processes, such as ETU from $^4I_{11/2}$ [11], cross-relaxation from $^4S_{3/2}$ [12,13] and cross-relaxation from $^4I_{9/2}$ [14,15].

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doi:10.1016/j.jlumin.2004.11.009

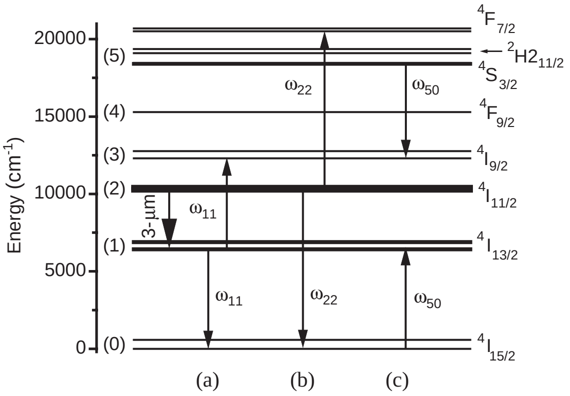

Fig. 1. Energy level scheme of Er^{3+} in YAG with the energy transfer processes considered: (a) upconversion from $^4I_{13/2}$; (b) upconversion from $^4I_{11/2}$ and (c) cross-relaxation from $^4S_{3/2}$.

As a result of these energy transfer processes, the population inversion for high erbium concentrations and high pump levels depends no more on the lifetimes of the laser levels, but on the ratio of the ETU parameters (more precisely, on the square root of this ratio) [16–18].

Various methods have been used to measure the ETU parameters. A first attempt to determine the ETU parameter corresponding to $^4I_{13/2}$ has been made using the time delay of the onset of stimulated emission for a 35-at% Er:YAG rod [9]. Other methods are based on the analysis of the shape of the luminescence decay of the "donor" or "acceptor" levels for short [19–26] or rectangular pulse [14,27] excitation or on the frequency analysis of the response of erbium-doped crystals excited with a sinusoidally modulated laser beam [28–30].

The ETU parameters in Er:YAG were measured in Refs. [19–21,25,26]. Zhekov et al. [19] have estimated the ETU parameters from both $^4I_{13/2}$ and $^4I_{11/2}$ levels from the analysis of the non-exponentiality of the decay of the $^4I_{11/2}$ level in an Er(10 at%):YAG sample excited in the $^4F_{9/2}$ state (in red) with a pulsed dye laser. Shi et al. [20] have examined the kinetics of both $^4I_{11/2}$ and $^4I_{13/2}$ levels excited with the second harmonic of a pulsed Nd:YAG laser for three concentrations of erbium in YAG: 16.7, 33.3 and 50 at%. Georgescu et al. [21] measured the concentration dependence of the ETU parameter corresponding to $^4I_{13/2}$ level for erbium concentrations between 7 and 100 at%. They found a quadratic concentration dependence of ETU parameter for erbium concentrations up to ~70 at%. The information was inferred from the non-exponentiality of the decay of the $^4I_{11/2}$ level induced by the upconversion from $^4I_{13/2}$ level.

The data from the literature concerning ETU parameters corresponding to the $^4I_{13/2}$ and $^4I_{11/2}$ levels in Er:YAG crystals are very spread, probably due to the experimental difficulties such as inhomogeneous pumping, accidental impurities in the sample, nonlinearity of the detector's response, and so on. Recently, Iparraguirre et al. [32] investigated the effect of excitation inhomogeneities on the temporal behavior of the population of excited levels in the presence of a cooperative upconversion process. Considering a Gaussian laser beam for excitation and a thick sample, they found a simple method to correct the value of the ETU parameter extracted from the experiment.

Because the efficiency of the erbium three micron laser depends essentially on the ratio of the ETU parameters [18,33], we shall focus our attention on the determination of this ratio in Er:YAG crystals and on the determination of its concentration dependence. Using a simplified rate equation model, very convenient for concentrated Er:YAG, we fit the experimental decays of the $^4I_{11/2}$ level in Er:YAG for several erbium concentrations and for various pump intensities. The same rate equation model is used to evaluate the sensitivity of the method and to simulate various types of pump inhomogeneities in order to estimate the possible errors produced in the determination of the ETU parameters. Also, we examine the effect of the accidental impurities present in the Er:YAG crystals on the kinetics of the $^4I_{11/2}$ level.

2. Experiment

The luminescence of Er:YAG crystals was excited at room temperature with the second harmonic of a Q-switched Nd:YAG laser and gathered into a GDM 1000 monochromator equipped with an S-1 photomultiplier in the photon counting configuration. The fluorescence