Journal of Luminescence 133 (2013) 5–9

Contents lists available at SciVerse ScienceDirect

Journal of Luminescence

journal homepage: www.elsevier.com/locate/jlumin

Precise determination of minimum achievable temperature for solid-state optical refrigeration

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ARTICLE INFO

Available online 5 October 2011

Keywords:
Optical refrigeration
Laser cooling of solids
Cryogenic laser cooling
Yb:YLF
Anti-Stokes luminescence
Derivative spectroscopy

ABSTRACT

We measure the minimum achievable temperature (MAT) as a function of excitation wavelength in anti-Stokes fluorescence cooling of high purity Yb^{3+}-doped $LiYF_4$ (Yb:YLF) crystal. Such measurements were obtained by developing a sensitive noncontact thermometry that is based on a two-band differential luminescence spectroscopy using balanced photo-detectors. These measurements are in excellent agreement with the prediction of the laser cooling model and identify MAT of 110 K at 1020 nm, corresponding to E4–E5 Stark manifold transition in Yb:YLF crystal.

1. Introduction

The physical principle of optical refrigeration is based on a phonon-assisted anti-Stokes fluorescence. Spectrally narrow-band low-energy excitation photons produce energetically upshifted incoherent fluorescence emission, extracting heat away from the lattice in the process and resulting in cooling of the latter [1]. Optical refrigeration was first postulated by Pringsheim in 1929 [2], put on a solid thermodynamic footing by Landau in 1946 [3] and finally demonstrated in solids by Epstein and co-workers in 1995 [4]. First observation consisted of bulk cooling of an ytterbium-doped fluorozirconate glass (Yb:ZBLAN) by 0.3 K, starting from the room temperature. Cooling of this material system has progressed over the years and culminated with demonstration of cooling to 208 K by Thiede et al. in 2005 [5]. In parallel with these results, other trivalent ions of Tm and Er were cooled on various transitions and in a wide variety of hosts (see Refs. [6,7] for recent reviews of this field). Interesting applications of optical refrigeration have also been proposed, including solid-state cryogenic refrigerators [8,9,1] and radiationally-balanced lasers [10]. Advancing toward realization of the former, laser cooling to 155 K (from room temperature) was recently demonstrated [11], followed by cooling a semiconductor payload to 165 K [12], utilizing 5 mol% ytterbium doped yttrium lithium fluoride crystal (Yb:YLF). These bulk cooling results provided the proof-of-principle demonstration of operation of all solid-state optical refrigerator at temperatures below what conventional Peltier devices can achieve.

In this paper we discuss rate-equation based cooling efficiency model [13,6] along with the predictions of minimum achievable temperature (MAT) of 110 K at 1020 nm [11], corresponding to E4–E5 Stark manifold transition in Yb:YLF. In order to make these predictions, model is supplemented with experimentally determined quantities, details of which are discussed below. To verify these model predictions, we developed a highly sensitive differential spectroscopic technique that allows us to fully characterize cooling sample performance. Below we discuss several implementations and details of this technique along with recent results on Yb:YLF verifying MAT of 110 ± 5 K at 1020 nm, in excellent agreement with the model.

2. Model

The cooling efficiency is defined as the ratio of the cooling power (P_{cool}) to the absorbed laser power (P_{abs}), is given by [13]

$$\eta_c(\lambda,T)=\frac{P_{cool}}{P_{abs}}=p(\lambda,T)\frac{\lambda}{\lambda_f(T)}-1, \tag{1}$$

where $\lambda_f(T)$ is a temperature-dependent external mean fluorescence wavelength (i.e. including fluorescence trapping and reabsorption). The term $p(\lambda,T)$ is a probability of the conversion of a low-energy excitation photon into an escaped fluorescence photon:

$$p(\lambda,T)=\eta_{ext}\frac{\alpha(\lambda,T)}{\alpha(\lambda,T)+\alpha_b}, \tag{2}$$

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0022-2313/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.jlumin.2011.09.045

where η_{ext} is the external quantum efficiency (EQE) defined as the fraction of excited ions that lead to a fluorescence photon exiting the host material; $\alpha(\lambda,T)$ is the resonant absorption of the ions while parasitic absorption on impurities is represented by the background absorption term α_b. In the sign convention adopted here, positive η_c corresponds to cooling. High η_{ext} ($>99\%$) is typical for metastable f–f transition in rare-earth ions doped in hosts with low phonon energy (such as fluorides). In addition, η_{ext} is largely temperature independent [14]. The remaining term on the right hand side of Eq. (2) represents the fraction of the absorbed photons by the rare-earth ions (e.g. $^2F_{7/2}$–$^2F_{5/2}$ transition in Yb^{3+}), and is termed absorption efficiency η_{abs}. The origin of background absorption α_b is due to the unwanted growth contamination (estimated to be much less than part per million), and is typically attributed to the presence of transition metals such as copper and iron, similar to glass hosts [15]. Following this assumption, α_b is also taken to be temperature independent, and broadband (i.e. independent of wavelength) within the spectral region of the cooling transition [15]. Thus, to obtain a quantitative analysis of the cooling efficiency, we perform independent experiments to evaluate the material-dependent constituents of Eq. (1), namely: η_{ext}, α_b, $\alpha(\lambda,T)$ and $\lambda_f(T)$.

With the decrease of temperature, positive (in the cooling region) cooling efficiency decreases due to diminishing resonant absorption α and red-shifting of λ_f, until it switches sign, corresponding to overall heating. The temperature corresponding to this cooling-to-heating transition is the minimum achievable temperature (MAT) for a given excitation wavelength. A global MAT is defined as the minimum temperature T_{min} for which $\eta_c(\lambda,T_{min})=0$, or $min(\mathrm{MAT}(\lambda))$. Spectrum of $\mathrm{MAT}(\lambda)$ thus uniquely characterizes laser cooling performance of a given material and hence is of great interest to access experimentally. The following sections detail the experimental procedures that allow us to accurately measure MAT spectrum as well as the four input parameters needed to evaluate the cooling efficiency of Eq. (1).

3. Experimental results and discussion

Before we discuss direct measurements of $\mathrm{MAT}(\lambda)$, we point out that predictive capabilities of the cooling efficiency model (Eq. (1)) can be gained only if its individual components are well characterized, namely: η_{ext}, α_b, $\alpha(\lambda,T)$ and $\lambda_f(T)$.

3.1. Spectroscopic data for Yb:YLF

We conduct our studies on high purity Czochralski-grown 5 mol% doped Yb:YLF crystal [16] of dimensions $3\times3\times9\ \mathrm{mm}^3$, used previously for bulk cryocooling results [11]. Polarized and unpolarized instrument-response-corrected fluorescence spectra of the crystal are obtained versus temperature from 100 K to 300 K (in 10 K increments), inside of a liquid-Nitrogen cryostat. Fig. 1(a) shows temperature dependent fluorescence spectra, as normalized by integrated value at 100 K. Reciprocity analysis [17] is then performed to calculate $\alpha(\lambda,T)$ (Fig. 1(b)). Effects of reabsorption become significant, especially at low temperatures. For modeling of the cooling efficiency, we reproduce the exact geometry of the cooling experiments, namely with the excitation beam aligned through the center axis along the largest dimension $L=9$ mm of the crystal. Mean fluorescence wavelength $\lambda_f(T)$ is calculated by taking a first moment of the unpolarized fluorescence spectra (Fig. 1(c)), exhibiting approximately linear dependence where a fit to $\lambda_f(T)=mT+b$, with $m=-0.031\pm0.001$ nm/K and $b=1008.9\pm0.1$ nm, was obtained.

As was mentioned in previous section, external quantum efficiency η_{ext} is typically independent of temperature [14]. Similarly, the background absorption coefficient α_b is also assumed to be nearly independent of temperature. Therefore, these two quantities are only determined in experiments conducted at room temperature. The validity of these assumptions however will be tested by the outcome of the experiments reported below.

A high purity Czochralski-grown 5% doped Yb:YLF crystal of dimensions $3\times3\times9\ \mathrm{mm}^3$ is situated in ambient air on thin microscope coverslips (to minimize conductive load) and is excited in $E||c$ orientation via a tunable CW Ti:Sapphire laser (950–1080 nm, 1.3–1.8 W). Subsequent temperature change is monitored using a calibrated bolometric thermal camera. Recall that $\eta_c=P_{cool}/P_{abs}$ with $P_{cool}\cong C\Delta T$ and $P_{abs}=P_0[1-\exp(-\alpha(\lambda)L)]$, where C is thermal-load dependent constant, ΔT is the laser-induced temperature change and P_0 is the incident power on the crystal. The measured quantity $\Delta T/P_{abs}$ is thus proportional to the

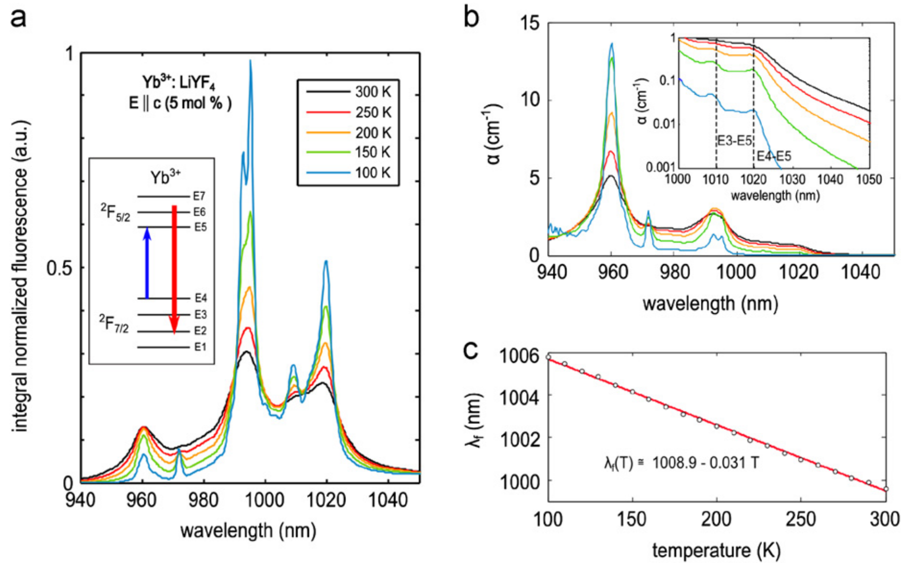

Fig. 1. (a) Temperature-dependent fluorescence spectra of Yb^{3+}:$LiYF_4$ crystal in $E||c$ orientation (inset shows Stark manifolds of Yb^{3+} $^2F_{5/2}$–$^2F_{7/2}$ transition) normalized by integrated value at 100 K; (b) temperature-dependent absorption spectra of a Yb:YLF (5 mol%) crystal with same color coding as panel a and also for $E||c$ orientation; inset shows anti-Stokes absorption (cooling) tail on a semi-logarithmic scale, with resonant features corresponding to E3–E5 and E4–E5 Stark manifold transitions; (c) temperature dependence of the mean fluorescence wavelength $\lambda_f(T)$ along with an approximate linear fit in the temperature range of 100–300 K (see text for more details).