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Temperature dependence of the 1.03 μm stimulated emission cross section of Cr:Yb:YAG crystal

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Abstract

The fluorescence emission spectra of Cr:Yb:YAG crystal are measured and the effective stimulated emission cross section of the crystal are obtained from −80 °C to +80 °C. A linear temperature dependence between −80 °C and +80 °C is reported for the 1.03 μm peak stimulated emission cross section of Cr:Yb:YAG crystal.

Keywords: Cr:Yb:YAG crystal; Fluorescence emission spectra; Stimulated emission cross section; Temperature dependence

1. Introduction

In recent years, ytterbium-doped crystal of yttrium aluminum garnet (Yb:YAG) have attracted much attention as promising active media for high average power solid state laser applications because of its reduced heat generation relative to Nd:YAG [1–3]. By using acoustic-optic modulator, Cr^{4+}:-doped garnets and semiconductor saturable absorber as active and passive Q-switches, respectively, the Q-switched Yb:YAG lasers have been demonstrated [4–8]. Moreover, By using Cr, Yb co-doped yttrium aluminum garnet (Cr,Yb:YAG) crystal, the self-Q-switched Cr,Yb:YAG laser has been achieved [9]. Generally speaking, optically pumped solid state lasers using Cr, Yb:YAG may have to operate over a wide range of temperatures. Optical elements in a typical laser resonator (e.g., mirrors, beam splitters, etc.) show no variation of optical properties over a wide range of temperatures. However, the stimulated emission cross-section of the laser transition will depend on temperature and the variation with temperature will affect the lasting performance characteristics, such as threshold, output power, pulse width etc. Laura D. Deloach studied the room temperature absorption and emission properties of Yb^{3+}-doped crystals [10]. Recently, Dong [11] studied the temperature dependence of the emission cross section and lifetime of the different Yb^{3+}-doped YAG crystal below room temperature. However, the study of variation of the stimulated emission cross-section of Yb-doped crystals with the above room temperatures of interest for practical applications has not been reported as far as we know. The present paper presents the experimental evidence for a linear temperature dependence of the 1.03 μm peak stimulated emission cross section of Cr:Yb:YAG crystal between −80 °C and +80 °C.

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2. Experimental

The effective stimulated emission cross-section of laser crystal Cr:Yb:YAG at different temperature can be calculated by recording the entire emission spectrum of the excited crystal and the measured emission lifetime of the crystal at different temperature. The emission spectra are measured at 950–1450 nm. The excitation source is a fiber-coupled diode laser operating at 943 nm and the temperature of diode laser is controlled by automatic temperature-controller. The size of Cr:Yb:YAG crystal with co-doped 0.025 at.% Cr and 10 at.% Yb is $5\,\text{mm} \times 5\,\text{mm} \times 0.5\,\text{mm}$, and located inside a temperature controller ($-80\,°\text{C} \sim +80\,°\text{C}$). Below room temperature, the temperature-controlled compressed helium cryostat is used to cool samples, while above room temperature, a heating ribbon is wrapped around the sample holder and the temperature is monitored by using a calibrated temperature sensor. The light of diode laser is focused to the Cr:Yb:YAG crystal surface ($5\,\text{mm} \times 0.5\,\text{mm}$) with the index gradient lens. The crystal thickness is only 0.5 mm so that it experiences minimal radiation trapping. The excitation signal is monitored during the experiment with a silicon (Si) detector. The emission fluorescence of the crystal is focused with a lens to Jarell-Ash monochromator. An indium gallium arsenide (InGaAs) detector located at the output slit of the 25 cm focal length monochromator is used to detect the fluorescence emission intensity. With 50-μm slits, the resolution of this detection system is about 0.4 nm.

The experimental arrangement for the emission lifetime measurement is very similar to the above setup for the emission spectrum measurement, except that the excitation source is a tunable optical parametric oscillator (Quanta Ray MOPO-SL, pulse width 5 ns) tuned to 943 nm. In addition, the detection wavelength of Jarell–Ash monochromator is fixed at 1.03 μm and a photo-multiplier tube is connected to the output slit of the monochromator to detect the intensity of the fluorescence emission. The decay curves of the fluorescence are recorded with a storage oscilloscope (TDS694C) and a computer-controlled data acquisition system.

3. Experimental results

The ytterbium emission from Cr:Yb:YAG crystal is not polarization dependent, so the emission spectra obtained could be used to calculate the effective stimulated emission cross-section of an Yb^{3+} ion from the manifold ${}^2F_{5/2}$–${}^2F_{7/2}$ transition in Cr:Yb:YAG by applying the F–L formula [12]:

$$\sigma(\lambda) = \frac{1}{8\pi} \cdot \frac{\lambda^5 \eta}{n^2 c \tau} \cdot \frac{I(\lambda)}{\int I(\lambda)\lambda \mathrm{d}\lambda} \tag{1}$$

here λ is the wavelength, $\sigma(\lambda)$ is the effective stimulated emission cross-section at wavelength λ, η is the quantum efficiency (assumed to be close to 1 for Cr:Yb:YAG), n is the index of refraction of the material, c is the speed of light in vacuum, and τ is the fluorescent lifetime of the upper laser level, $I(\lambda)$ is the fluorescent intensity at wavelength λ.

In order to calculate the effective stimulated emission cross-section of crystal with Eq. (1), the fluorescent lifetime τ must be given. For Cr:Yb:YAG crystal at 1.03 μm, from the detected decay curve of the fluorescent intensity at 1.03 μm, the fluorescent lifetime can be obtained with a fit to Forster–Dexter model [13–15]. Fig. 1 is the detected decay curve of the fluorescent intensity at room temperature. A fit to Forster–Dexter model shows that the fluorescent lifetime is 590 μs. We measure the fluorescent lifetime of Cr:Yb:YAG crystal at different temperature (from $-80\,°\text{C}$ to $+80\,°\text{C}$). The results show that the fluorescent lifetime varies little with the temperature at the above temperature ranges. Therefore, we fix its value at 590 μs when evaluating Eq. (1). Similarly, for Cr:Yb:YAG crystal, the index of refraction of the material varies very little over the temperature ranges ($-80\,°\text{C} \sim +80\,°\text{C}$), so we use a constant value of 1.82 in the Eq. (1).

The fluorescence emission spectrum of Cr:Yb:YAG crystal at room temperature is shown in Fig. 2. According to the $I(\lambda)$ in Fig. 2 and the related parameters, the calculated effective stimulated emission cross sections by using Eq. (1) are given in Fig. 3. The figure shows that the peak value at 1.03 μm is $3.97 \times 10^{-20}\,\text{cm}^2$. Due to Cr-doping, the emission cross section $3.97 \times 10^{-20}\,\text{cm}^2$ of Cr,Yb:YAG crystal is higher than that of usual Yb:YAG crystal ($2.3 \times 10^{-20}\,\text{cm}^2$) [16]. In fact, the emission cross section of Cr,Yb:YAG crystal varies with Cr-doped concentration.

By adjusting the temperature controller system of Cr:Yb:YAG crystal, the fluorescence emission spectra

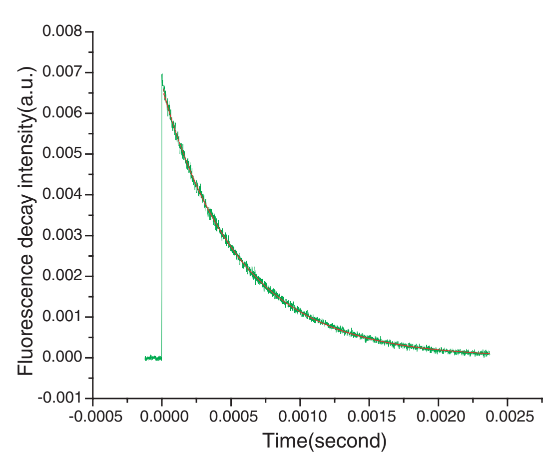

Fig. 1. Fluorescent decay curve of Cr:Yb:YAG crystal at room temperature.

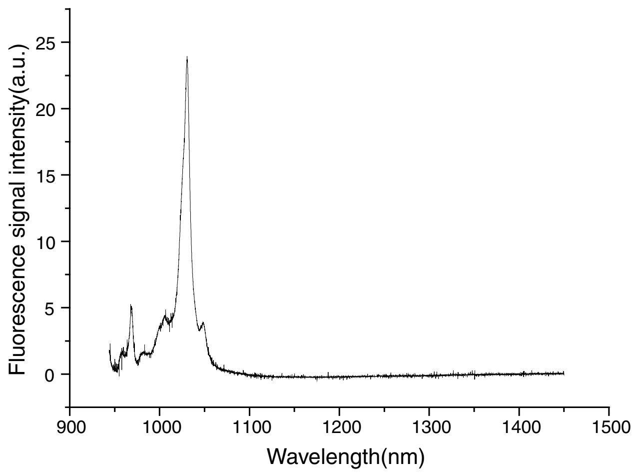

Fig. 2. Fluorescent emission spectrum of Cr:Yb:YAG crystal at room temperature.

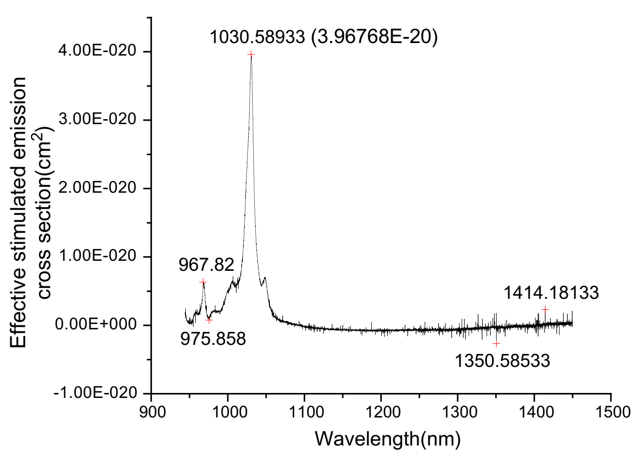

Fig. 3. Effective stimulated emission cross section of Cr:Yb:YAG crystal at room temperature.

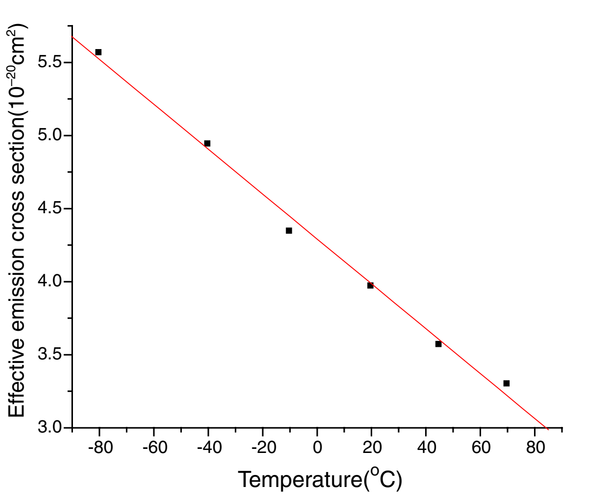

Fig. 4. Effective stimulated emission cross section versus temperature.

at various temperature (−80 °C ~ +80 °C) can be measured. Using Eq. (1), we can calculate the effective stimulated emission cross section of Cr:Yb:YAG crystal at 1.03 μm over various temperature ranges. Fig. 4 shows the effective stimulated emission cross section of Cr:Yb:YAG crystal at 1.03 μm as a function of temperature. The points are the calculated values and the line is a linear fit. The figure shows that the effective stimulated emission cross section of Cr:Yb:YAG crystal at 1.03 μm varies linearly with temperature with a negative slope of $1.536 \times 10^{-22}\,\mathrm{cm}^2/°\mathrm{C}$. If T stands for temperature in °C, the the effective stimulated emission cross section σ (cm^2) can be expressed:

$$\sigma = (4.25\text{–}1.536 \times 10^{-2} T) \times 10^{-20} \tag{2}$$

4. Conclusion

The fluorescent emission spectra and radiative lifetime of Cr:Yb:YAG crystal from −80 °C to +80 °C are measured and the peak stimulated emission cross section at 1.03 μm for different temperature are calculated. A linear temperature dependence between −80 °C and +80 °C is given for the peak stimulated emission cross section of Cr^{4+} ions and Yb^{3+} ions co-doped YAG crystal.

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