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Experimental Study on Temperature Dependence of Absorption and Emission Properties of Yb:YAG Crystal as a Disk Laser Medium

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Abstract**—**In this paper, the absorption and fluorescence emission spectra of Yb:$Y_3Al_5O_{12}$ (YAG)(25 at%) crystal as a disk laser medium are measured at high temperature (300-450K). The absorption and emission cross sections of Yb:YAG crystal are determined using Reciprocity method. Temperature dependence of 941nm absorption cross section and 1031nm emission cross section is extracted in the range of 300-450K. According to our experimental results, an exponential temperature dependence between 300K and 450K is acquired for the 1031nm peak emission cross section and also for 941nm peak absorption cross section of Yb:YAG crystal. These results could be used for simulation and design of high power highly doped Yb:YAG thin disk lasers.

Keywords**—**Yb:YAG crystal, Emission cross section, Absorption coefficient, Temperature dependence, Reciprocity method .

I. INTRODUCTION

IN recent years, Yb:YAG crystal has attracted much attention as an active medium for high power solid state lasers. Because of wide absorption area, optically pumped solid state lasers using Yb:YAG may 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 [1]. However, the emission and absorption cross sections of the laser depend on temperature so that these variations will affect the lasing performance and characteristics, such as threshold, output power, pulse width and etc [3].

Laura D. Deloach et al studied absorption and emission properties of Yb^{3+}-doped YAG crystals at room temperature [2]. Dong et al also studied the temperature dependence of the emission cross section of Yb:YAG below the room temperature [3]. However, the study on the variation of the emission cross section of Yb:YAG(25at%) above the room temperature is more favorable for high power laser designers.

In this work the emission cross section is evaluated using the method of Reciprocity. The experimental evidence for temperature dependence of 103l nm peak emission cross section and 941 nm peak absorption cross section of 25 at% Yb^{3+}-doped YAG crystal have been presented as well (between 300K and 450K).

Also we obtained an exponential temperature dependency for the emission and absorption cross sections of Yb:YAG crystal by fitting the experimental data.

II. OPTICAL AND PHYSICAL PROPERTIES OF YB: YAG CRYSTAL

Ytterbium Yb^{+3} ions are ideally suited for diode pumping since it has a very simple energy level scheme with desirable properties for a laser system. As shown in Fig. 1, there are only two energy level manifolds, the ground state $^2F_{7/2}$ and an exited state $^2F_{5/2}$, separated by approximately $10000 cm^{-1}$ [4]. The next higher level is in the 5d configuration which begins near $100000 cm^{-1}$. The crystal field splits the 4f manifolds by approximately 700 cm^{-1}, consequently Yb^{+3} lasers could be categorized as quasi-three level laser at room temperature [5].

The host YAG has high thermal conductivity, excellent physical and chemical properties and is mechanically robust and optically isotropic. So the Yb^{3+} ion doped YAG crystal is a desirable candidate for high efficiency and high-power applications [4].

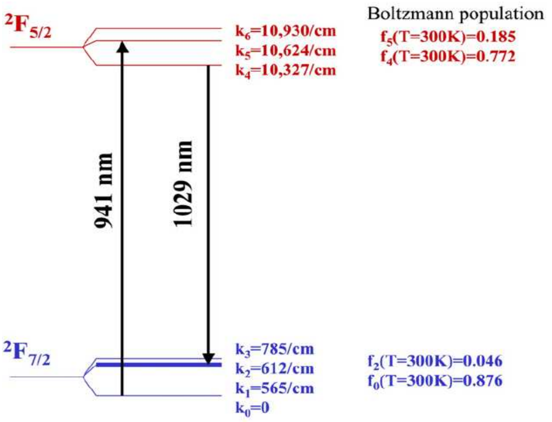

Fig. 1 Energy level scheme of Yb:YAG. f_i 's are the relative thermal occupancies and the k_i 's denote the wave number for different levels with regard to the ground level [6]

III. TEMPERATURE DEPENDENCE OF ABSORPTION AND EMISSION CROSS SECTION

A. Measurement of the Absorption Cross Section

According to Lambert-Beer law, when a light with entrance intensity of I_0 passes through an absorbent crystal with thickness of L, the transmitted intensity, I, is acquired as:

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$$I = I_{\circ} \exp(-\alpha L) \tag{1}$$

Changing Neperian logarithm into decimal form, the absorption coefficient could be expressed as follows:

$$\alpha(\nu) = 2.303 L^{-1} \log(I_{\circ} / I) \tag{2}$$

Comparing with the equation $\alpha(\nu) = N.d.\sigma_{abs}(\nu)$, the absorption cross section σ_{abs} results as:

$$\sigma_{abs}(\nu) = 2.303 (L.N.d)^{-1} \log(I_{\circ} / I) \tag{3}$$

L is the thickness of the sample (Yb:YAG crystal), d is the doping(25at%), N is the concentration of Yb^{3+} ions and equals to 1.36×10^{20} ions/cm^3 for 1at% [7,10].

B. Measurement of the Emission Cross Section

The Emission cross section is determined by using either Reciprocity method (R-M), or Füchtbauer-Ladenburg (F-L) formula. The obtained emission cross section using Reciprocity method requires absorption cross section and detailed knowledge of energy levels and degeneracies of the system. On the other hand, the input parameters for the F-L formula are the emission line shape function, the radiative lifetime and the refractive index. Theoretical details concerning determinations of the cross section are discussed in the following subsection [2].

1. Füchtbauer-Ladenburg Equation

The fundamental relationship between spontaneous and stimulated emission rates in the Füchtbauer-Ladenburg (F-L) equation allows a straightforward calculation of the emission cross section using input parameters such as emission spectra, radiative lifetime and refractive index. Thus relationship between spontaneous-emission distribution and emission cross section distribution $\sigma_{em}(\lambda)$ is [8], [11]:

$$\sigma_{em}(\lambda) = \frac{1}{8\pi} \frac{\lambda^5}{n^2 c \tau} \frac{I(\lambda)}{\int I(\lambda)\, \lambda \, d\lambda} \tag{4}$$

Where τ is the radiative lifetime of the upper laser level, c is the velocity of light in vacuum, and n is the refractive index at the emission wavelength, and $I(\lambda)$ is the emission spectral intensity of emission of the Yb^{3+} ions[8].

2. The Method of Reciprocity

The basis of Reciprocity may be described by the emission and absorption cross sections written in terms of the energy levels E_k and degeneracies d_k. The summation of the individual cross section between the i th lower and the j th upper energy level can be formulated to describe both absorption and emission cross section[2]:

$$\sigma_{em}(\nu) = \sum_{ij} d_j \frac{\exp(-E_j / kT)}{Z_u} \sigma_{ji}(\nu) d_i \tag{5}$$

$$\sigma_{abs}(\nu) = \sum_{ij} d_i \frac{\exp(-E_i / kT)}{Z_l} \sigma_{ij}(\nu) d_j \tag{6}$$

Where Z, the partition function, is defined as:

$$Z_k = \sum_k d_k \exp(-E_k / kT) \tag{7}$$

At high temperature, the partition functions are simply equal to the degeneracy of the two states [2]. In each case, the energies E and the partition functions Z are measured from the lowest crystal field level of the $^2F_{7/2}$, (l), and the $^2F_{5/2}$, (u), electronic states.

Considering reciprocity principle, $\sigma_{ij} = \sigma_{ji}$, and division of (5) by (6), we obtain an emission cross section in terms of the absorption cross section. It is also helpful to define an energy parameter, the zero-line energy, E_{ZL}, as the energy separation between the lowest components of the upper and lower crystal field states. Thus, a particular energy separation could be written as:

$$E_j - E_i = h\nu - E_{ZL} \tag{8}$$

Now, the emission cross section is readily formulated from the absorption cross section with energy level parameter, E_{ZL}, Z_l and Z_u as follows:

$$\sigma_{em}(\nu) = \sigma_{abs}(\nu) \frac{Z_l}{Z_u} \exp[(E_{ZL} - h\nu) / kT] \tag{9}$$

Where k, h and E_{ZL} represent Boltzmann constant, Plank constant and the zero line energy. For Yb:YAG crystal, $\lambda_{ZL} (= E_{ZL} / \nu)$ is about 968.3nm at room temperature [5]. Herein, we have used Reciprocity method to evaluate the emission cross section.

C. Experimental Setup

Experimental setup for measuring the optical absorption of the Yb:YAG crystal is shown in Fig. 2. We used a HR2000 spectrometer as the measuring instrument from Ocean Optics Company. The spectra resolution, the ratio of the signal to noise and the wavelength range of this spectrometer are 0.25nm, 1:250 and 200-1100nm respectively .In order to survey the temperature dependence of the absorption over a wide range of temperature from 300K to 450K by the step of 10°C, we placed a 1mm thickness, 25at.% Yb:YAG disk sample in an aluminum disk holder and put it inside a closed loop oven with thermal stability of $\pm 0.1\,^{\circ}C/\min$ in the light path of the spectrometer. A precise pivot has been designed for the sample holder so that enables us to remove or put the sample in the light path inside the oven easily without any changes in optical setup.

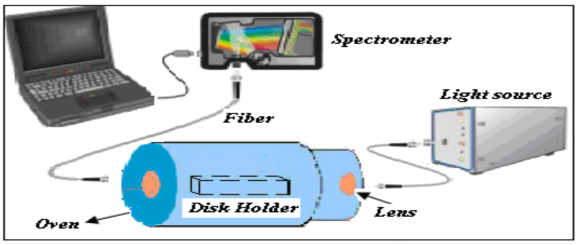

Fig. 2 Schematic view of the experimental setup for measuring the optical absorption of the disk crystal

D. Results and Discussion

Fig. 3 represents the absorption coefficient of Yb:YAG crystal sample at different temperature from 300K to 450K. The absorption coefficient of this crystal decreases from about 26cm^{-1} to about 19cm^{-1} as the temperature increases from room temperature to 450K.

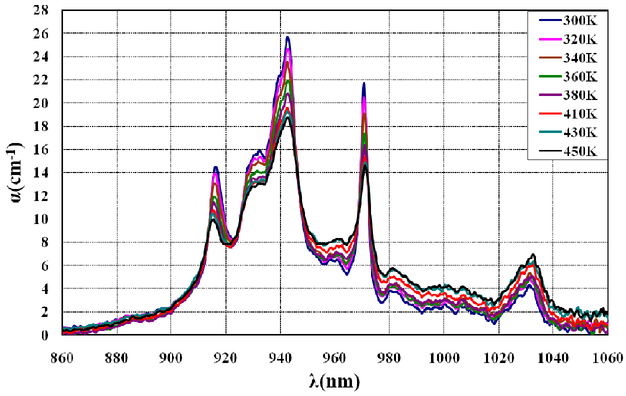

Fig. 3 Experimental measured absorption coefficient of 25at% Yb:YAG crystal in the range of 300-450K

As illustrated in Fig. 4, the absorption of Yb^{3+} in Yb:YAG crystal occurs in the wavelength range of 910-1040nm. There are four main absorption bands lied at 916, 941, 971, 1031nm attributed to the $^2F_{5/2} \rightarrow {}^2F_{7/2}$ transition of Yb^{3+} in YAG crystal. The strongest absorption peak occurs in 941nm, and the absorption Full-Width at Half-Maximum (FWHM) is about 19nm and the peak absorption cross section is 7.5×10^{-21}cm^2 at room temperature. A wide absorption band means that laser crystal can accommodate some thermal shift of the pump light wavelength, while the output power of the laser remains stable. Moreover, the large absorption cross section means that laser crystal is easy to realize laser diode pumping [7].

Fig. 4 clearly shows that, as the temperature increases from 300K to 450K, the maximal absorption cross section drops from 7.5×10^{-21} cm^2 to 5.49×10^{-21} cm^2, whereas the linewidth rises almost from 19nm to 24nm.

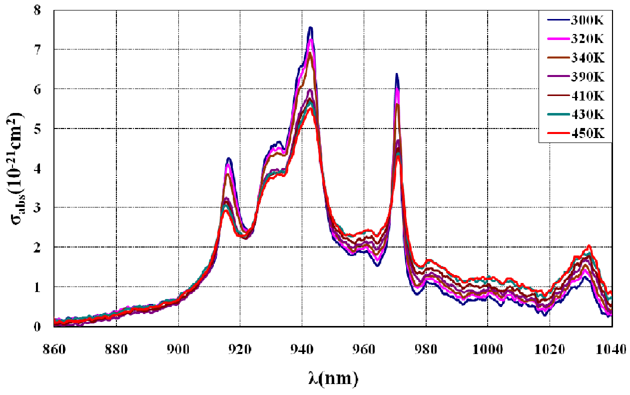

Fig. 4 Experimental measured absorption spectrum of 25at% Yb:YAG in the range of 300-450°K

The relationship between the calculated absorption cross section of the Yb:YAG crystal and the temperature at the wavelength 941nm is shown in Fig. 5. Fitting the experimental data with an exponential function, we obtained the temperature dependence of absorption cross section as:

$$\sigma_{abs}(\lambda = 941nm, T(K)) = (1.82 + 6.02\times \exp((273-T)/279)))\times 10^{-21}\ cm^2 \qquad (10)$$

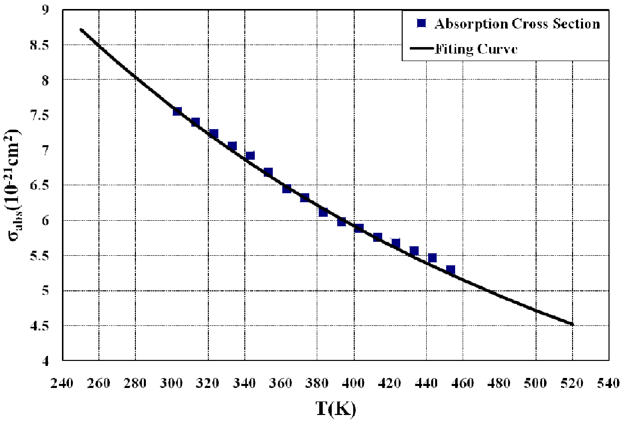

Fig. 5 Absorption cross section of 25at% Yb:YAG as a function of temperature

According to the measured absorption spectra, the emission cross section has been also calculated using Reciprocity method (Eq.9). At first, the values of the partition functions of the lower and upper energy levels should be evaluated using the equation 7 at different temperatures. Then the ratio of the partition functions, Z_l / Z_u, should be extracted. Some of these calculated values are listed in table 1.

TABLE.I
THE RATIO OF THE PARTITION FUNCTIONS AT DIFFERENT TEMPERATURE

Temperature (K)	Z_l	Z_u	Z_l / Z_u
300	1.1431	1.4715	0.7768
320	1.1722	1.5161	0.7732
350	1.2188	1.5796	0.7716
380	1.2678	1.6391	0.7735
400	1.3015	1.6766	0.7762
410	1.3185	1.6948	0.7780
430	1.3527	1.7298	0.7820
440	1.3700	1.7467	0.7843
450	1.3873	1.7632	0.7868
460	1.4045	1.7794	0.7893

The emission cross section of Yb:YAG(%25) crystal at different temperature is depicted in Fig. 6. There are several emission bands in the wavelength range of 930-1040nm of the spectra. One could easily see that four peaks appear at the wavelength of 941, 971, 1015, 1031nm attributed to the transitions between the lowest energy level of excited state $^2F_{5/2}$ and the ground state level $^2F_{7/2}$. In the Yb:YAG crystal, the peak at 1031nm is the strongest emission peak and the corresponding emission cross section is about 2.01×10^{-20} cm^2

at room temperature. This value drops to 1.22×10^{-20} cm^2 as the temperature rises to 450K.

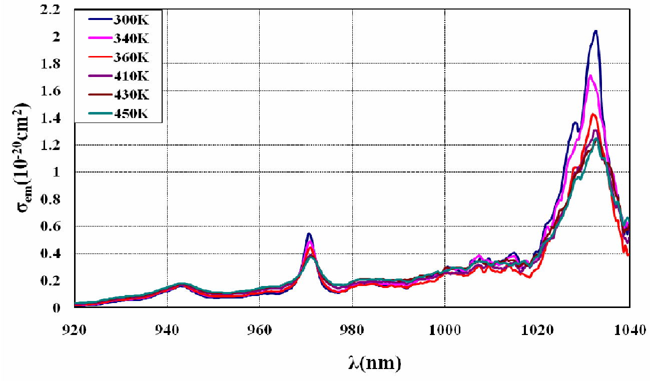

Fig. 6 Experimental measured emission spectrum of 25at% Yb:YAG at different temperature from 300-450K

The temperature dependence of the emission cross section of the Yb:YAG crystal at the wavelength 1031nm is shown in Fig. 7. Fitting the experimental data with an exponential function, we obtained the temperature dependence of emission cross section as:

$$\sigma_{em}(\lambda = 1031nm, T(K)) = (0.44 + 9.50\times \exp(-T/165))\times10^{-20}\ cm^2 \qquad (11)$$

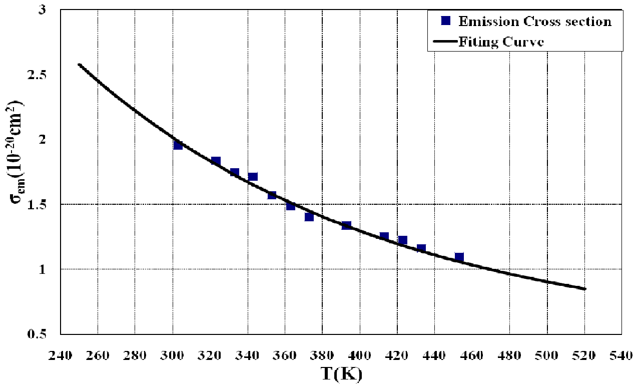

Fig. 7 Emission cross section of 25at% Yb:YAG as a function of temperature

IV. CONCLUSION

The obtained results show that spectroscopic properties of Yb:YAG crystal at high temperatures (300-450K) differ from the room-temperature properties so that the absorption and emission cross sections are strongly affected by temperature. According to our experimental results, an exponential temperature dependency between 300K and 450K is observed for the peak absorption and emission cross section of Yb:YAG crystal. In disk laser configuration, different layers of the crystal have various temperatures based on the cooling and pumping mechanism and geometry. So, In order to have a more realistic and precise estimation of laser parameters in the simulation procedure, one should consider these obtained temperature dependency.

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