Temperature Dependence of 914 nm Stimulated Emission Cross Section of Diode End-pumped Nd:YVO₄

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Abstract

The thermal effect on stimulated emission cross section of 914 nm (R₂→Z₅) emission of ⁴F₃/₂→⁴I₉/₂ transition in Nd:YVO₄ was investigated. The gain medium temperature was stabilized via thermoelectric cooler which controlled in the range of -3 °C to 60 °C. The emission spectrum was fitted using Lorentzian function to reveal an accurate linewidth. The stimulated emission cross section was estimated using Füchtbauer–Ladenburg Equation. It is yield that the peak stimulated emission is inversely proportional to temperature with a slope of -1.39×10⁻²² cm² °C⁻¹. The less photon-phonon interactions in the crystal field at the lower temperature inducing narrow linewidth of transition line 914 nm at low temperature. Furthermore, less reabsorption effects at the terminal level allows the increases stimulated emission cross section in low temperature operation.

Keywords: 914 nm laser; stimulated emission cross section; Nd:YVO₄; temperature variation

1. Introduction

Neodymium Orthovanadate (Nd:YVO₄) laser crystal is one of the most commonly used laser gain medium due to its broad absorption cross section around 809 nm and high stimulated emission cross section for 1064 nm. Nd:YVO₄ laser crystal also can produce 914 nm and 1342 nm laser outputs as the result of quasi three level operation through ⁴F₃/₂→⁴I₉/₂ and four level laser at ⁴F₃/₂→⁴I₃/₂ intermanifold transition respectively. 914 nm is an attractive emission due to the second harmonic generation in blue region at 457 nm and the possibility of utilizing 914 nm laser as a pumping source for Yb-doped materials [1,2]. Blue lasers have wide applied in the field of data storage, display technology, biological and medical.

Stimulated emission cross section is an important parameter in determining threshold condition of a laser transition in continuous wave operation [3]. Furthermore, the peak stimulated emission cross section determines the maximum spatial amplification of emission intensity [4]. Since stimulated emission cross section is a function of temperature, Nd:YVO₄ laser crystal temperature plays an important role in determining laser parameters of 914 nm output. Previously, Yu et al. [1] maintained the cooling temperature of Nd:YVO₄ at 10 °C by rationalizing depopulation of higher Stark level of ground state at low temperature. While Chen
et al. [5] have reduced thermal lensing effect by using a copper micro-channel heatsink cooling at 13 °C. Similar work also reported by Blandin et al., [6] by sustaining the Nd:YVO₄ temperature at 20 °C. Therefore, variety of Nd:YVO₄ temperature used in previous studies and less attention were given to effects of temperature variation on 914 nm emission compared to 1064 nm emission of Nd:YVO₄.

However not many works have been published on variation of stimulated emission cross section of 914 nm transition line with respect to temperature. Hence In this letter, the relationship between stimulated emission cross section of 914 nm transition with temperature of thermoelectric cooler will be investigated.

2. Experimental setup

Figure 1 shows the experimental setup used to detect the spectroscopy properties of Nd:YVO₄ crystal. Laser diode at 808 nm with maximum output of 35 W was used as an end-pumping source. A gain medium is comprised of an uncoated a-cut, 1 at % Nd:YVO₄ laser crystal with dimension of 3x3x2 mm³. A small gain medium was particular selected to ensure that low temperature gradient induce in perpendicular directions with respect to pumping source propagation. The Nd:YVO₄ was mounted onto a copper holder and wrapping with 0.05 mm thermal interface material such as indium to have a good heat transfer from crystal to the holder. The whole ensemble system was cooled by Peltier plates which regulate the temperature of copper holder in the range of -3 to 60 °C. The pump beam was focused on the back surface of the crystal to minimize the thermal effects. The fluorescence radiation was collected with an Ophir Wavestar spectrum analyzer.

![Figure 1 Schematic of the experimental setup](image)

3. Experimental results and discussion

Figure 2 shows the example of fluorescence spectrum of ⁴F₉/₂→⁴I₉/₂ intermanifold transition at 25 °C. Five main peaks are detected including (1) 878 nm, (2) 881 nm, (3) 888 nm, (4) 892 nm and (5) 914 nm. Obviously the highest intensity in the fluorescence spectrum is 914 nm which is corresponding to π polarized of R₂→Z₅ inter-Stark transition of ⁴F₉/₂→⁴I₉/₂ transition. However, σ polarized c inter-Stark transition (915 nm) fluorescence was weakly present in the spectrum and leads to asymmetrical shape of fluorescence curve in Figure 2. In order to accurately measure the linewidth of the lineshape function at 914 nm, the Origin Labs software was utilized. The intensity data from each fluorescence spectrum were used to fit the Lorentzian lineshape function. Origin Labs software’s Multi-Peak Lorentzian Fit was utilized to separate the high intensity R₂→Z₅ emission (914 nm) and weak R₁→Z₅ emission (915 nm). The fitting was performed by fixing the peak wavelengths of both emission lines. The average peak of R₂→Z₅ transition wavelength was determined from fluorescence spectrums by repeating the measurement of fluorescence spectrum acquisition at 25 °C. Furthermore the position of the R₁→Z₅ transition peak wavelength was fixed with the knowledge of R₂ and R₁ stark levels of
$^4F_{3/2}$ are separated by the wavenumber of 18 cm$^{-1}$ [7]. Fig. 3 shows the multi curves Lorentzian fitting performed on fluorescence curve (5) of Figure 2.

**Figure 2** Fluorescence spectrum of $^4F_{3/2} \rightarrow ^4I_{9/2}$ transition at 25°C

![Fluorescence spectrum of $^4F_{3/2} \rightarrow ^4I_{9/2}$ transition at 25°C](image)

**Figure 3** Multi-Peak Lorentzian Fit performed on fluorescence curve (5) of Figure 2

![Multi-Peak Lorentzian Fit performed on fluorescence curve (5) of Figure 2](image)

The stimulated emission cross section of intermanifold transition of $R_2 \rightarrow Z_5$ was calculated based on Füchtbauer–Ladenburg Equation which expressed as [4, 8]

$$\sigma_p(J \rightarrow K) = \frac{1}{8\pi} \frac{\lambda^4 \eta \beta_{J \rightarrow K}}{n^2 c \tau} g(v_o) \tag{1}$$

where $\lambda$ is the wavelength, $\eta$ is the quantum efficiency, $\beta_{J \rightarrow K}$ is the branching ratio for transition from upper manifold $J$ to the lower manifold $K$, $n$ is the refractive index, $c$ is the speed of light in vacuum, $\tau$ is the radiative lifetime of upper manifold and $g(v_o)$ is peak lineshape function value.

Since almost all the excited neodymium ions fall to $^4F_{3/2}$ metastable state, $\eta$ can be assumed to be unity. The lineshape of $R_2 \rightarrow Z_5$ transition is obtained from the fitted Lorentzian function (Figure 3) where the $g(v_o)$ can be expressed as

$$g(v_o) = \frac{2}{\pi \Delta v} \tag{2}$$

where $\Delta v$ is the FWHM linewidth.

By substituting Eq. (2) into Eq. (1) which expressed as

$$\sigma_p(R_2 \rightarrow Z_5) = \frac{\lambda_p^4}{4\pi^2 n^2 c \Delta v} A(R_2 \rightarrow Z_5) \tag{3}$$

Where $\lambda_p$ is the peak wavelength of $R_2 \rightarrow Z_5$ transition, $\Delta v$ is the FWHM linewidth in cm$^{-1}$ unit and the radiative probability of $R_2 \rightarrow Z_5$ transition, $A(R_2 \rightarrow Z_5)$, can be expressed as
where $\Delta$ is the energy difference between $R_1$ and $R_2$ from the manifold of $^4F_{3/2}$, $k$ is the Boltzmann constant, $T$ is the absolute temperature, $\beta(R_2 \rightarrow Z_5)$ is the branching ratio of the inter-Stark transition, $\beta(^4F_{3/2} \rightarrow ^4I_{9/2})$ is the branching ratio of the intermanifold transition and $\tau(^4F_{3/2})$ is the radiative lifetime of $^4F_{3/2}$ manifold.

The $\Delta v = 35.21 \text{ cm}^{-1}$ at 25 °C which was determined from the 914 nm fitted curve of Figure 3. While $c$ was determined by dividing the area under $R_2 \rightarrow Z_5$ transition curve (Figure 3) by total area of $^4F_{3/2} \rightarrow ^4I_{9/2}$ transitions in Figure 2, which is 16.53 %. Meanwhile $\beta(^4F_{3/2} \rightarrow ^4I_{9/2})$ is taken to be 38.14 % [9]. It is assumed that $\tau(^4F_{3/2})$ is unchanged during the whole set of experiment, which is 100 µs [10]. By substituting $\beta(R_2 \rightarrow Z_5)$, $\beta(^4F_{3/2} \rightarrow ^4I_{9/2})$ and $\tau(^4F_{3/2})$ into Eq. (4), $A(R_2 \rightarrow Z_5)$ is acquired at 25 °C. Subsequently, $\sigma_p(R_2 \rightarrow Z_5)$ is determined by substituting $A(R_2 \rightarrow Z_5)$ and $\Delta v$ into Eq. (3). It is found that the peak stimulated emission for 914 nm transition of Nd:YVO$_4$ at 25 °C is 5.12×10$^{-20}$ cm$^2$. This value is in good agreement with previous researcher [11].

The peak stimulated emission cross section of transition line 914 nm as a function of temperature is presented in Figure 4. The peak stimulated emission cross section decreases with a negative slope of 1.39×10$^{-22}$ cm$^2$°C$^{-1}$. This is corresponding to 16.19 % decrease in stimulated emission cross section of 60 °C compared to value at -3 °C. Obviously stimulated emission cross section of 914 nm transition line is inversely proportional to the temperature. In other word fluorescence linewidth is proportional to temperature. As the temperature of the crystal is increased, the greater frequencies of crystal lattice vibrations or the Phonons. The phonon-photon interactions during end pumping processes are responsible to broaden the linewidth of the fluorescence spectrum [12]. Furthermore negative effects such as reabsorption loss at the terminal level and thermal lensing also reduced when operating Nd:YVO$_4$ at low temperature.

![Figure 4](image)

The stimulated emission cross section against temperature

4. Equations

Stimulation emission cross section of 914 nm emission was investigated with respect to variation in Nd:YVO$_4$ crystal temperature. The lower the temperature of the crystal the higher the value of stimulated emission cross section. Less photon-phonon interactions and reabsorption effect are responsible for increment in the stimulated cross section of 914 nm at low temperature.
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6. References


