Effects of temperature and input energy on quasi-three-level emission cross section of Nd^{3+}:YAG pumped by flashlamp*

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The influence of temperature and input energy on fluorescence emission cross section of Nd^{3+}:YAG crystal is studied. The stimulated emission cross sections of quasi-three-level systems are determined in a temperature range from −30 to 60 °C and an input energy range from 18 to 75 J. The cross section is found to decrease with the temperature and the input energy is increased. This is attributed to the thermal broadening mechanism of the emission line. This study is relevant for the development of laser design.

Keywords: emission cross section, Nd:YAG laser, flashlamp, fluorescence

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1. Introduction

During the last decade, wavelengths in the blue light region have attracted much attention because of their practical applications such as high density data storage, colour displays, Raman spectroscopy, underwater communication, high resolution printing, and medical diagnostics. One important way to produce blue lasers results from either the second harmonic generation of 946-nm and 938.5-nm wavelengths or the sum-frequency generation of 946-nm with 938.5-nm wavelengths in quasi-three-level Nd:YAG laser.[1,2]

However, in quasi-three-level lasers where lower laser states have significant thermal population, laser output suffers from significant re-absorption. This phenomenon increases the internal loss in the gain medium, and therefore population inversion would emerge at strong pump intensities. As a result, additional heat is generated on the crystal.[3]

As some parameters such as laser threshold, output power, internal loss, and linewidth of the laser line are dependent on temperature, heat generation can dramatically influence the laser performance.[4−6] Furthermore, in most high-power solid-state lasers, variation of emission cross section with temperature has a serious effect on the laser performance.

Spectroscopic properties and stimulated emission cross section of Nd:YAG crystals at room temperature have been studied extensively.[7−10] Similar studies have also been reported by Rapaport *et al.*,[6] who focused mainly on the major line of 1064-nm emission cross section and lifetime of the Nd^{3+}-doped YAG crystal in the temperature range from −70 to 70 °C.[5,6] Furthermore, Dong *et al.*[11] have investigated the absorption and emission spectra, stimulated emission cross section, and the radiative lifetime of Nd:YAG crystals doped at various atomic weight percents of Nd^{3+} (e.g., 1%, 2%, and 3%) within the temperature range between 70 and 300 K. In all previous papers, the Nd:YAG crystal was pumped by diode lasers.

However, the stimulated emission cross section of quasi-three-level lasers have seldom been studied as a function of temperature and input energy, using flashlamp as a pumping source. Thus, the present paper aims to investigate the effects of temperature and pumping energy on the stimulated emission cross section of quasi-three-level laser transitions from flashlamp-pumped Nd:YAG laser.

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2. Theory

Stimulated emission cross section (σ_e) is a crucial quantity to characterize an active medium and plays an important role for laser design and construction. The stimulated emission cross section for a specific transition between two states of an active ion can be measured using the spectral emission line and calculated via a Fuchtbauer–Ladenburg (F–L) formula. Since the $R_1 \to Z_5$ and $R_2 \to Z_5$ transition line shapes in Nd:YAG can be fitted by Lorentzian shape, the F–L formula is written as[13]

$$\sigma_p(R_i \to Z_5) = \frac{\lambda_p^2}{4\pi^2 n^2 c \Delta\nu} A(R_i \to Z_5), \quad i = 1, 2, \quad (1)$$

where λ_p, n, c, and $\Delta\nu$ are the wavelength of the peak emission line, refractive index, speed of light, and the full width at half maximum (FWHM), respectively. The radiative probability of the inter-Stark transition $R_i \to Z_5$ can be expressed as[14,15]

$$\begin{aligned} & A(R_i \to Z_5) \\ &= (1 + e^{-\Delta/kT}) \beta(R_i \to Z_5) \\ &\quad \times \beta({}^4F_{3/2} \to {}^4I_{9/2}) \tau^{-1}({}^4F_{3/2}), \quad i = 1, 2, \end{aligned} \quad (2)$$

where Δ is the difference in energy between the Stark levels R_1 and R_2 of the ${}^4F_{3/2}$ manifold, k is the Boltzmann constant, T is the absolute temperature, $\beta(R_i \to Z_5)$ represents the branching ratio for the corresponding inter-Stark transition, $\beta({}^4F_{3/2} \to {}^4I_{9/2})$ is the branching ratio for the respective inter-manifold transition, and τ is the fluorescence lifetime. The branching ratio for the inter-Stark transitions $\beta(R_1 \to Z_5)$ and $\beta(R_2 \to Z_5)$ are determined by comparing the luminescence density of this inter-Stark transitions with the total luminescence density for transitions that terminate at the Stark levels of ${}^4I_{9/2}$ manifold.[8]

However, in a wide range of temperature, the radiative lifetime of ${}^4F_{3/2}$ is independent of temperature. Therefore, the room-temperature radiative lifetime (e.g. 250 μs) is considered as a function of temperature. The branching ratio of the ${}^4F_{3/2} \to {}^4I_{9/2}$ transition has been found to be 28%, while 56% for the ${}^4F_{3/2} \to {}^4I_{11/2}$ transition.[6]

3. Experimental method

The schematic diagram of the experimental setup is shown in Fig. 1. The system comprises of two parts. The first part is energizing a laser crystal and stabilizing the stimulating emission of fluorescence radiation. The second part is the measurement equipment containing a spectrometer.

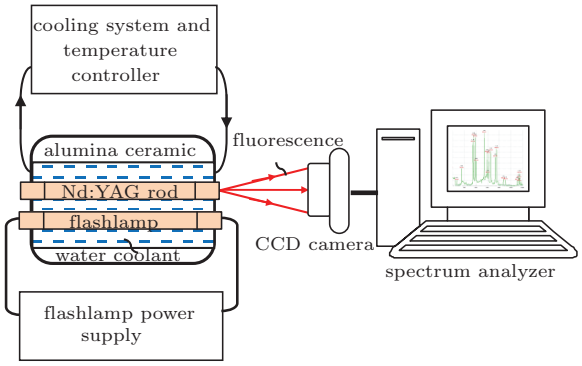


Fig. 1. (colour online) Schematic diagram of experimental setup.

A commercial laser rod Nd:YAG laser crystal is utilized as a gain medium. The doping level of the laser rod is 1% with a diameter of 4 mm and a length of 70 mm. The laser rod is enclosed in a ceramic reflector.

The laser rod is placed parallel to a linear flashlamp filled with xenon gas at 450 Torr. The flashlamp is pumped by a homemade power supply.[12] The driver is triggered by simmer mode technique. A capacitor bank with capacitance of 150 μF is charged by the maximal voltage of 1000 V so that the input energy is varied between 5 and 75 J.

The Nd:YAG crystal together with the flashlamp are flooded with a coolant comprised of the mixture of 60% ethylene glycol and 40% distilled water. Such particular coolant covers the temperature range from −30 to 60 °C. The flashlamp is further enclosed with a samarium flow tube to absorb ultraviolet (UV) light radiation, and to keep the flow rate in a steady-state condition.

The fluorescence radiation after pumping is emitted at one end of the laser rod. The light is detected by a CCD camera placed at 20 cm away from the source. The emission spectrum is analyzed via a Wavestar software (version 1.05). The resolution of this detection system is 0.5 nm so that it can resolve most of the transition lines generated from the pumping rod.

4. Results and discussion

The recorded fluorescent spectra of quasi-three-level laser induced from xenon flashlamp-pumped Nd:YAG laser is depicted in Fig. 2. Two strong peak signals are clearly seen at wavelengths of 938.5 and

946.0 nm along with many weaker peaks. The dependencies of these two peaks on the temperature and input energy are investigated. These two peaks are attributed to the transitions from Stark sublevels R_1 and R_2 in $^4F_{3/2}$ to Z_5 in $^4I_{9/2}$ inter-manifold level. The analysis of Fig. 2 indicates that the $^4F_{3/2}$ manifold of Nd^{3+}:YAG is split into the Stark components R_1 and R_2 by 84.3 cm^{-1}, $\beta(R_1 \rightarrow Z_5)$=0.316, and $\beta(R_2 \rightarrow Z_5)$=0.252. The inter-stark radiative probability can be calculated by substituting the values of branching ratios, radiative lifetime, and the values of Δ, k, and T into Eq. (2). Finally, the peak emission cross section for the inter-stark transitions at 938.5 and 946.0 nm are obtained using Eq. (1).

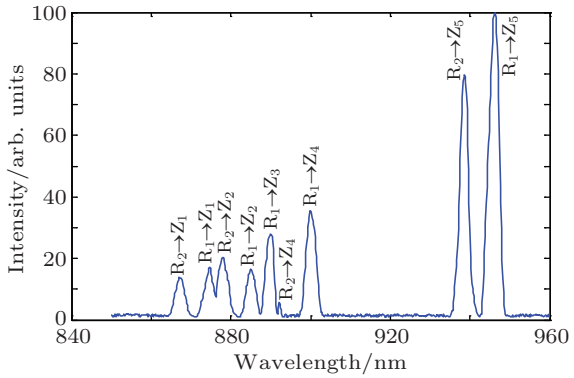


Fig. 2. (colour online) Normalized fluorescent emission spectra for $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition of Nd^{+3}:YAG.

The cross section of the two major lines from this quasi-three-level emission is estimated by measuring the linewidth as a function of temperature. The emission cross section at 938.5 and 946 nm are obtained at fixed electrical input energy, keeping the voltage constant (500 V). However, the stimulated emission cross section in the temperature range from −30 to 60 °C are measured and is shown in Fig. 3. The emission cross section decreases monotonically as the temperature increases from −30 to 60 °C. The slopes are found to be -3.1×10^{-21} and -3.4×10^{-21} cm^2/ °C for the 938.5-nm and 946-nm lines, respectively. This decrement is due to the thermal broadening of the observed lines.

Finally, we turn our attention to the input energy dependence of the fluorescence emission cross section. The emission cross section at 20 °C at varying input energies of 18–75 V is presented in Fig. 4. The input energy is varied by manipulating the capacitor voltage of the flashlamp driver. It can be seen from Fig. 4 that the stimulated emission cross section at 938.5 and 946 nm decrease continuously with increasing input energy. The slopes of the two lines are -4.4×10^{-21} and -6.8×10^{-21} cm^2/J, respectively.

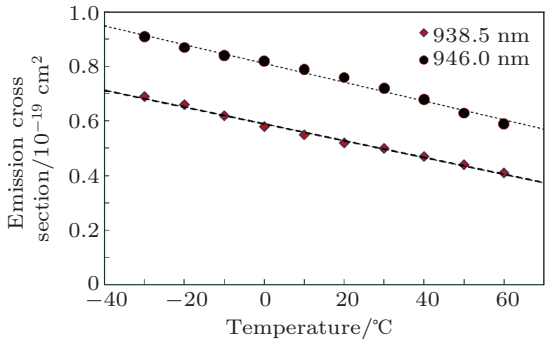


Fig. 3. (colour online) Peaks of stimulated emission cross section of Nd:YAG versus temperature at 938.5 and 946.0 nm.

Figures 3 and 4 indicate that the higher the temperature and pumping energy are, the lower the production of photon flux at 938.5 and 946 nm (quasi-three-level) lines is. This implies that thermal population at the ground level $^4I_{9/2}$ increases. Hence, more transition lines at 938.5 and 946 nm will be absorbed. As a result, less fluorescence radiation is emitted as these lines. In addition, effects of temperature and input energy on the emission cross section of 946-nm transition line is more dominant than that for 938.5-nm transition line.

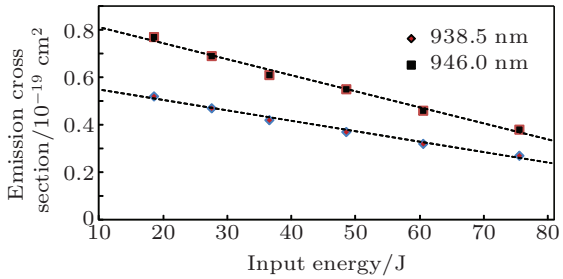


Fig. 4. (colour online) Input energy dependence of stimulated emission cross section.

5. Conclusion

The effects of temperature and input energy on the target of Nd:YAG rod pumped by flashlamp are investigated. The stimulated emission cross sections for 938.5-nm and 946-nm lines are quantified as a function of temperature and input energy. The linear dependence of temperature and input energy is observed. The inter-stark emission shows Lorentzian line shape, indicating the homogeneous broadening. These observations are new and may contribute to the design architecture of lasers.

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