Effects of 946-nm thermal shift and broadening on Nd^{3+}:YAG laser performance*

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(Received 30 April 2015; revised manuscript received 30 June 2015; published online 20 October 2015)

Spectroscopic properties of flashlamp pumped Nd^{3+}:YAG laser are studied as a function of temperature in a range from −30 °C to 60 °C. The spectral width and shift of quasi three-level 946.0-nm inter-Stark emission within the respective intermanifold transitions of $^4F_{3/2} \rightarrow {}^4I_{9/2}$ are investigated. The 946.0-nm line shifts toward the shorter wavelength and broadens. In addition, the threshold power and slope efficiency of the 946.0-nm laser line are quantified with temperature. The lower the temperature, the lower the threshold power is and the higher the slope efficiency of the 946.0-nm laser line is, thus the higher the laser output is. This phenomenon is attributed to the ion-phonon interaction and the thermal population in the ground state.

Keywords: 946-nm Nd:YAG laser, thermal broadening, thermal shift, flashlamp pump, slope efficiency, threshold power

PACS: 42.62.Fi **DOI:** 10.1088/1674-1056/24/12/124206

1. Introduction

During the last decade, solid state blue lasers at 473 nm have been very attractive because of their practical applications, such as high density data storage, color displays, Raman spectroscopy, underwater communication, high resolution printing, and medical diagnostics. One important way to produce blue lasers results from frequency doubling of the 946-nm wavelength in the Nd:YAG laser.[1–3] Since the 946-nm line has a quasi three-level nature, its lower laser state has a significant thermal population and therefore population inversion would emerge at strong pump intensities. As a result, additional heat is generated in the crystal.[3] As some critical parameters such as laser threshold, output power, internal loss, bandwidth and lineshift of the laser lines are dependent on temperature, the heat generated can seriously degrade the laser performance.[4–10] However, the modeling of high power solid state lasers requires precise investigation on temperature dependences of spectral linewidth and line broadening to ensure a good control of the effects of heat generated in the gain medium.[11]

Following the classical paper by McCumber and Sturge,[12] much research work has been carried out on thermally induced line broadening in trivalent rare earth ions doped in different crystal hosts.[5–16] Kushida[17] measured the linewidths and thermal shifts of several lines in Nd^{3+}:YAG crystal. Xing and Bergquist made considerable effort on the shifts of four-level system transition lines from Stark sublevels R_1 and R_2 in $^4F_{3/2}$ to Y_n (n is from 1 to 6) in the $^4I_{9/2}$ intermanifold level.[18] Similar work was also reported by Sato and Taira.[19] Temperature dependencies of stimulated emission cross section, linewidth, lineshift of twelve emission peaks of four-level system emission lines for Nd:YAG, Nd:YVO_4, and Nd:$GdVO_4$ were evaluated. To date only a little attention has been paid to the 946-nm wavelength induced by a flashlamp pumped Nd:YAG laser.

Dimov *et al.*, reported the first flashlamp pumped 946-nm Nd:YAG laser.[2] They investigated the temperature dependences of threshold power, slope efficiency, and unsaturated gain in a temperature range of 240 °C–300 °C. They also achieved a threshold power of about 62 J and a slope efficiency of 0.0014 at a reduced temperature of 248 °C. The same work was carried out by Barnes *et al.*[4] They studied the temperature dependences of the threshold and slope efficiency in the range from −5 °C to 16 °C. They also achieved a threshold power of 16 J and a slope efficiency of 0.0032 at 16 °C. The temperature dependence of flashlamp pumped Nd:YAG laser within the temperature range from −60 °C to 80 °C was introduced by Bass *et al.*[8] They claimed that in long-pulse four level operation at 1064 nm, the threshold power increases, the slope efficiency is unchanged, and a corresponding decrease in output energy occurs when temperature increases.

In the present paper, we report the effects of temperature on the shift, bandwidth, threshold power and slope efficiency of free running quasi-three-level laser transition at 946 nm induced by a flashlamp pumped Nd^{3+}:YAG laser.

2. Theory

2.1. Thermal shift and broadening of the spectral lines

A well-known equation for the temperature dependence of the ith energy level width is given by:[6,13,14]

$$\Delta E_i(\mathrm{cm}^{-1}) = \Delta E_i^{\mathrm{strain}} + \Delta E_i^{\mathrm{D}} + \Delta E_i^{\mathrm{M}} + \Delta E_i^{\mathrm{R}}, \qquad (1)$$

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where the terms on the right-hand side of the equation represent the broadenings due to the crystal strain inhomogeneity ($\Delta E_i^{\text{strain}}$), direct one-phonon process (ΔE_i^{D}) between the i-th energy level and other nearby levels (j), multi-phonon emission process (ΔE_i^{M}) which occurs between two levels whose energy difference is greater than the greatest energy of the available phonons, and is shown to be essentially temperature independent, and the Raman phonon scattering process (ΔE_i^{R}) which is temperature-dependent and related to phonon scattering by the impurity ions.

2.2. Temperature dependence of free running lasers

The performance of free running or long pulse of the Nd^{3+}:YAG laser, can be evaluated based on the laser output energy as described as follows:[8]

$$E_{\text{out}} = \eta_{\text{s}} \left(E_{\text{in}} - E_{\text{th}}(T) \right), \tag{2}$$

where η_{s} is the slope efficiency, E_{in} is the input energy, and $E_{\text{th}}(T)$ is the threshold energy. The threshold energy is given by

$$E_{\text{th}}\,(\text{T}) = \frac{V h \nu_{\text{p}}}{2\sigma\,(T)\,\eta_{\text{pe}}} \left(-\ln R + L \right), \tag{3}$$

where V is the laser volume, R is the reflectivity of the resonator output coupler, L is the intracavity nonproductive loss, σ is the stimulated emission cross section, η_{pe} is the efficiency with which pump photons at frequency ν_{p} are absorbed into the upper laser. The stimulated emission cross section of crystal and therefore the threshold energy are temperature dependent.[11]

Differentiating Eqs. (2) and (3) with respect to temperature yields

$$\frac{\mathrm{d}E_{\text{out}}}{\mathrm{d}T} = \eta_{\text{s}} \left(-\frac{\mathrm{d}E_{\text{th}}}{\mathrm{d}T} \right), \tag{4}$$

$$\frac{1}{E_{\text{th}}} \frac{\mathrm{d}E_{\text{th}}}{\mathrm{d}T} = \left(-\frac{1}{\sigma} \frac{\mathrm{d}\sigma}{\mathrm{d}T} \right). \tag{5}$$

Equation (4) shows that the output energy of the laser is proportional to the slope efficiency and the mines change of threshold energy. Equation (5) explained that the threshold energy increases as the temperature increases if $\mathrm{d}\sigma/\mathrm{d}T$ is negative. In this case, the input energy remains constant at each temperature.

2.3. Experimental setup

The schematic diagram of the experimental setup is shown in Fig. 1. The system is comprised of two parts. The first part was to energize a laser crystal and stabilize the stimulating emission of fluorescence radiation. The second part was for the measurement equipment containing a spectrometer.

A commercial laser rod Nd:YAG laser crystal was utilized as a gain medium. The doping level of the laser rod was 1 at.% with 4 mm in diameter and 70 mm in length. The laser rod was enclosed in a ceramic reflector. The laser rod was placed parallelly to a linear flashlamp filled xenon gas at 450 Torr (1 Torr = 1.33322×10^2 Pa). The flashlamp was pumped by a homemade power supply.[20] The driver was triggered by a simmer mode technique. A capacitor bank with a capacitance of 150 μF was charged from zero volt up to a maximum voltage of 1200 V, thus the input energy was varied between 0 J to 100 J.

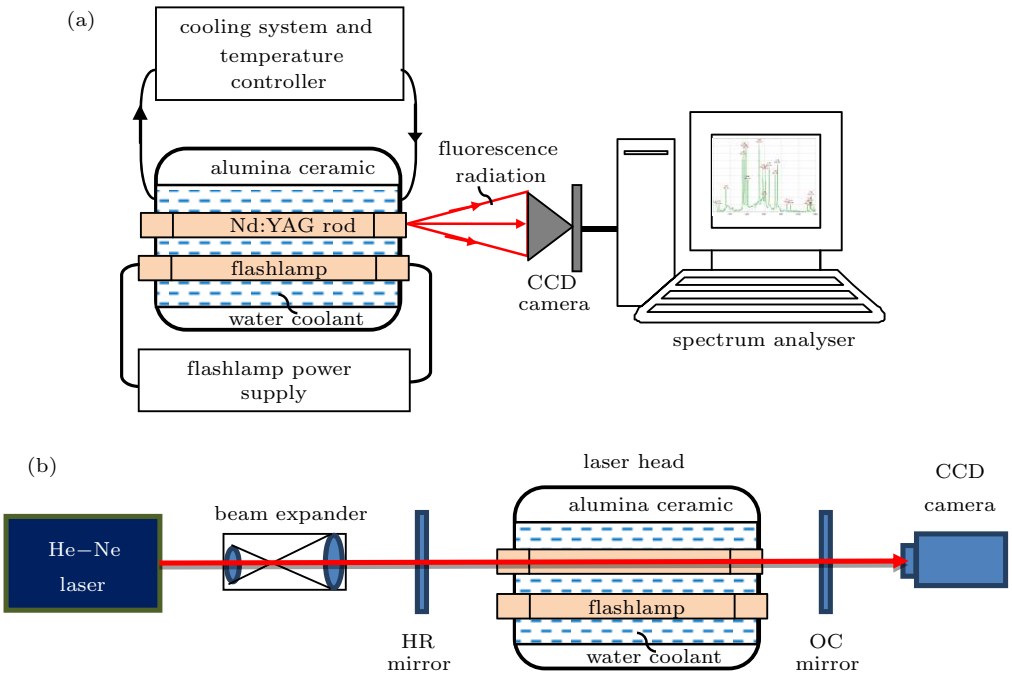


Fig. 1. (color online) (a) Schematic diagram of the spectrum analyser of a laser rod and (b) thermal focal length experimental set up.

The Nd^{3+}:YAG crystal together with the flashlamp were flooded with a coolant comprised of the mixture of 60% ethylene glycol and 40% distilled water. Such a particular coolant covers the temperature range from −30 °C to 60 °C. The actual temperature of the chamber was measured via a thermocouple attached to the cavity. The flashlamp was further enclosed with a samarium flow tube to absorb ultra-violet (UV) light radiation and to keep the flow rate under a steady state condition. The fluorescence radiation after pumping was emitted at one end of the laser rod. The light was detected by a CCD camera placed at 20 cm away from the source in both fluorescence and laser detection. The emission spectrum was analyzed via a Wavestar version 1.05 software. The resolution of this detection system was 0.5 nm so it could resolve most of the transition lines. The optical resonator was composed of two mirrors which were placed around the gain medium. The mirrors are designed with precise coating at 946.0 nm to provide feedback of the light in the resonator. In the present work, the output coupler was a flat mirror whereas the rear mirror was a concave mirror with 5-m radius of curvature and each of the two mirrors has a thickness of 5 mm and a diameter of 25.4 mm. The output mirror with precise coating at 946 nm with a reflectivity of 97% and high transmitting at 1064 nm was used to generate 946-nm laser transition.

Finally the focal length of the thermal lens was measured by scanning a commercial He–Ne laser beam through the laser rod while the laser was pumped by flaslamp. Then the length from the position of the smallest diameter of the He–Ne laser beam to the center of the laser crystal was measured.

3. Results and discussion

Figure 2 shows the normalized intensities of sublevel transitions from $^4F_{3/2}$ to $^4I_{9/2}$ emitted from Nd^{+3}:YAG crystal at room temperature. Lineshift and linewidth of the major quasi three-level transition at 946.0 nm is determined by each of the recorded spectra at different temperatures in the range of −30 °C to 60 °C.

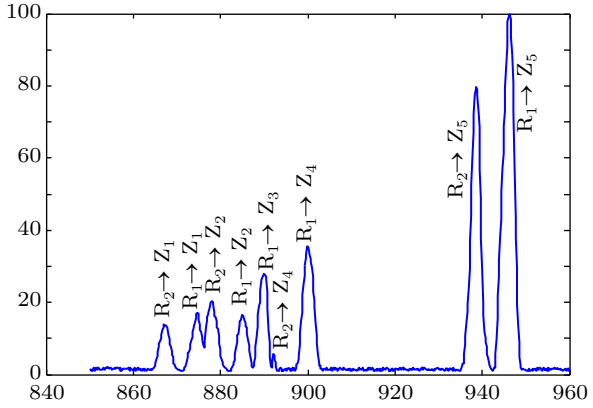


Fig. 2. (color online) Normalized fluorescent emission spectrum for $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition of Nd^{+3}:YAG.

The temperature dependences of lineshift and linewidth of the transition line at 946 nm are shown in Fig. 3. The experimental results show that the position and linewidth of the quasi three-level emission line at 946 nm are apparently temperature dependent. The 946-nm line in intermanifold $^4F_{3/2}$ to $^4I_{9/2}$ shifts to a shorter wavelength and broadens. Figure 3 shows that the main emission line of the quasi three-level shifts from 945.91 nm at −30 °C to 946.15 nm at 60 °C. As the temperature increases, the linewidth is increased by 0.74 nm in the temperature range of −30 °C to 60 °C.

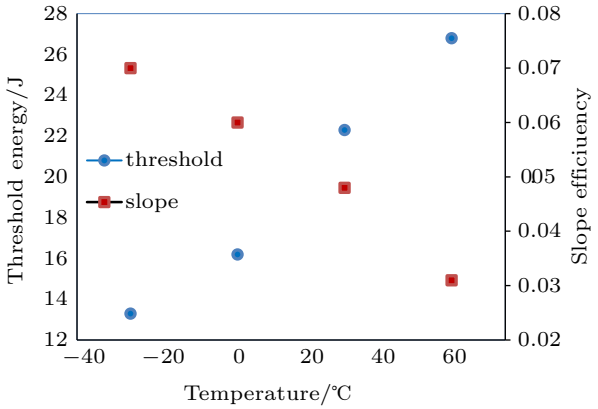


Fig. 3. (color online) Lineshift and linewidth of the 946-nm emission peak as a function of temperature.

Figure 4 shows the variations of output energy of long pulse 946-nm laser transition with electrical energy at four different temperatures of −30, 0, 30, and 60 °C. The higher the temperature, the lower the laser output energy is. It can be seen that the active medium temperature reducing from 60 °C to −30 °C leads to a threefold increase in output power at a fixed electrical energy of 68 J. The resulting data of Fig. 4 presents linear fitting, thus obtaining threshold and slope efficiency as a function of temperature and the results are shown in Fig. 5.

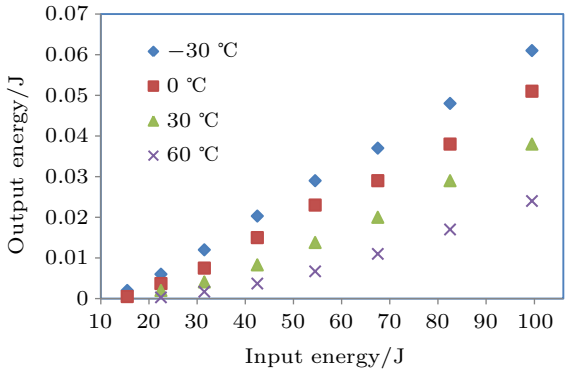


Fig. 4. (color online) Laser output energies from the 946-nm laser versus electrical pump energy for various temperatures.

Figure 5 confirms that the threshold and slope efficiency are dependent on temperature. As the temperature of the laser medium decreases, the threshold energy of the 946-nm laser line decreases. Besides, the decreasing of temperature leads to an increase of the slope efficiency. The experimental results

agree well with the theoretical results. Thermal changes of threshold and slope efficiency are 16%/°C and −0.04%/°C in the temperature range between −30 °C and 60 °C, respectively.

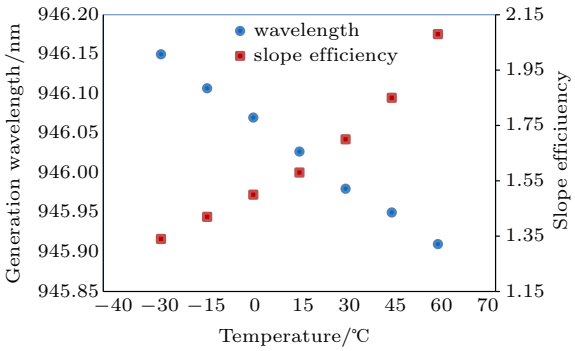


Fig. 5. (color online) Variations of threshold and slope efficiency of Nd:YAG at 946 nm with temperature.

In addition, the heat density in the laser rod pumped by a flashlamp is uniform, therefore the laser crystal is hot at the surface compared with on the beam axis. Owing to the thermal expansion of the material, the deformation of the crystal will cause a thermal lens effect. Figure 6 shows the variations of thermal focal lens with input energy at different temperatures. As the input energy increases, the thermal focal lens decreases. In addition, the decreasing of temperature results in the decrease of the thermal focal length. The experimental results show that for the high pumping energies of the flashlamp, variation of the focal lens does not exactly behave as the inverse of input energy.

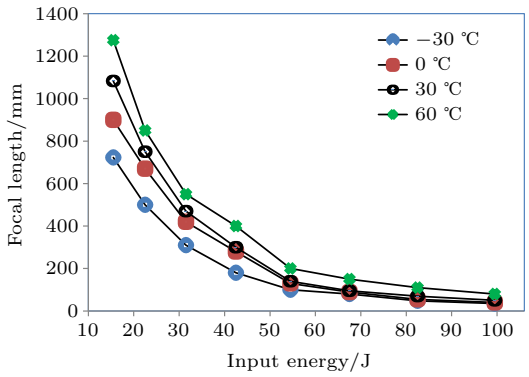


Fig. 6. (color online) Plots of thermal focal length versus input energy at different temperatures.

In fact the higher temperature causes the higher thermal vibration ions in the crystal. Then varying in the crystal field due to fluctuating in positions of active ions and the ligands of their surroundings bring about the local strain. When this strain is dynamically produced by the lattice vibrations, the interaction between the Nd^{3+} ions and the local crystalline field causes temperature dependent broadening of the ions. This phenomenon is the reason for the changing of emission linewidth of the spectrum. Besides the crystal field being weakened by lattice thermal expansion, the phonon transition has its effects on the energy of the electron-phonon system and modulation of Coulomb interaction between electrons and spin-orbital coupling, which have their contributions to the spectral thermal line shift.

Increasing the temperature of the cooling system leads to the increase of thermal population at the ground level of $^4I_{9/2}$. Therefore, more reabsorption at the 946-nm laser transition line occurs and as a result the photon flux of quasi three-level transition emitted at 946 nm decreases. Since the optical mirrors of the laser cavity are precisely coated at 946 nm, broadening and lineshift of the 946-nm laser line strictly affect the laser output energy.

4. Conclusions

The influence of temperature on fluorescence emission characteristics of flashlamp pumped Nd^{3+}:YAG laser is quantitatively studied. The spectral width and shift of the quasi three-level 946.0-nm transition line are investigated in a range from −30 °C to 60 °C. The 946.0-nm emission line shifts toward the shorter wavelength and broadens by increasing the temperature and as a result, the output performance of the laser is degraded. Furthermore the threshold power and slope efficiency of the 946.0-nm laser line are found to be proportional to temperature. The threshold and slope efficiency change by 16%/°C and −0.04%/°C as the temperature increases from −30 °C to 60 °C, respectively. In addition, by increasing the input energy the thermal focal length decreases and the lower the temperature, the shorter the thermal focal length of the Nd^{3+}:YAG rod is. This phenomenon is attributed to the ion phonon interaction and the thermal population in the ground state. The knowledge of this information is important for the laser design.

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