Output Characteristic of a Flashlamp Pumped Nd:YAG Laser at 1,414 nm and 1,444 nm

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Stimulated emission cross section of 1,444 nm is known to be higher than that of 1,414 nm. After calculation of the effective stimulated emission cross section for 1,414 nm and 1,444 nm using the reported spectroscopic data of the stimulated emission cross section for 1,414 nm and 1,444 nm, the output characteristic of a flashlamp pumped Nd:YAG laser at 1,414 nm and 1,444 nm was investigated. The calculated effective stimulated emission cross section of 1,444 nm was almost twice higher than that of 1,414 nm. However, the threshold input energy of 1,414 nm was 2.3 J lower than that of 1,444 nm and the output energy of 1,414 nm was 57 % higher than that of 1,444 nm with electrical input energy of 47 J. Our experimental results were not in agreement with reported spectroscopic data on stimulated emission cross section for 1,414 nm and 1,444 nm.

Key words

Nd: YAG, Pulsed laser

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INTRODUCTION

Nd:YAG lasers have been investigated for more than 40 years and used in many application fields. Nd:YAG laser has four transition lines in the 1,400 nm region of spectrum.¹ Many authors reported that output characteristic of 1,444 nm in Nd:YAG.²⁻⁵ However, to our knowledge, have been only one report about lasing at 1,414 nm in Nd:YAG up to now.⁶ Lasers with wavelengths of 1,414 and 1,444 nm are useful for many technical applications, such as lidar, communications, surgery, dermatology and near infrared spectroscopy. The wavelength of 1,444 nm is in the eye-safe spectral region and has a very high water absorption coefficient compared to the wavelength of 1,064 nm. Therefore, the use of 1,444 nm wavelength has been sought after in a variety of surgical and dermatological applications.^{2-5,7} Human fatty tissue and water absorptions at 1,414 nm and 1,444 nm are much higher than those at 1,064 nm, 1,319 nm and 1,338 nm.⁸ Therefore, we anticipate that Nd:YAG lasers at 1,414 nm and 1,444 nm have a merit for clinical study of fat removal inside the human body. On the other hand, the fresh bread has a high absorption coefficient at the wavelength of 1,414 nm, which gives the information about the changes in the amylopectin of bread.⁹

The stimulated emission cross-sections at the spectrum region of 1,400 nm is considerably smaller than 1,064, 1,319 and 1,339 nm in Nd:YAG crystal. In spite of a low stimulated emission cross section at 1,444 nm, lasing with 100 W of average output power was demonstrated by Hodgson.² In this study, effective stimulated emission cross section for 1,414 and 1,444 nm were calculated and the output characteristics of a flashlamp pumped Nd:YAG laser at the 1,414 nm and 1,444 nm were investigated.

Fig. 1. Energy level diagrams of 1,400 nm region of spectrum in Nd:YAG crystal.

ANALYSIS

Fig. 1 shows the energy level diagrams for 1,400 nm region of spectrum in Nd:YAG. The stimulated emission cross sections at the 1,400 nm region of spectrum is considerably smaller than the spectrum region of 1,300 nm and the wavelength of 1,064 nm.^{1,4,10} In order to suppress laser oscillations at 1,064 nm and the 1,300 nm region of spectrum, the resonators should have very high losses. Table 1 shows the stimulated emission cross sections at the 1,400 nm region of spectrum. As shown, 1,427 nm has the lowest stimulated emission cross section, whereas 1,444 nm has the largest stimulated emission cross section. The transitions at 1,427, 1,431, and 1,444 nm share the same upper laser level R₁. On the other hand, the transition at 1,414 nm originates from another upper laser level R₂. Therefore, if use the output mirror that has same reflectivity at 1,400 nm region of spectrum, the oscillations at 1,427 and 1,437 nm cannot occur.

Due to the quantum defect, a part of the energy absorbed by the active ion of laser crystal is lost. It is transformed into heat by interaction with phonons in the upper or lower-laser levels. Fractional thermal loading is defined as a fraction of the absorbed power, which is transformed into heat.¹¹ Fractional thermal loading at R₁ is 50% higher than R₂ of ⁴F_{3/2} manifold in a 1.04 at. % Nd:YAG crystal at the pumping wavelength 808 nm.^{12,13} According to Boltzmann distribution the rise of temperature in laser material leads to increasing of population density in the upper energy level of each manifold. If there is insufficient elimination of heat in laser crystal, it will affect the gain at each lasing wavelength.¹⁴ H. M. Kretschmann reported existence excited state absorption (ESA) in the 1,400 nm spectral region⁴ whereas, S. Kuck reported that ESA at 1,400 nm region could not be found.¹⁵ Therefore, we do not have confidence about the ESA in this study. At room temperature the level of ⁴F_{3/2} is split into Stark levels referred to as R₁ and R₂ which Stark levels are always in thermal equilibrium by phonon interaction.

Table 1. Stimulated emission cross section of Nd:YAG at 1,400 nm region of spectrum^{1,10}

Transition	Wavelength (nm)	Stimulated emission cross section (10 ⁻²⁰ cm ²)
R ₂ of ⁴ F _{3/2} → X ₆ of ⁴ I _{13/2}	1,414	3.3 ¹ , 2 ⁹
R ₁ of ⁴ F _{3/2} → X ₅ of ⁴ I _{13/2}	1,427	0.8 ⁹
R ₁ of ⁴ F _{3/2} → X ₆ of ⁴ I _{13/2}	1,432	2.3 ¹ , 1.3 ⁹
R ₁ of ⁴ F _{3/2} → X ₇ of ⁴ I _{13/2}	1,444	3.4 ¹ , 2.8 ⁹

Total population density of the ${}^4F_{3/2}$ manifold, $n({}^4F_{3/2})$, is equal to sum of the $n(R_1) + n(R_2)$. The rate equation for the population density of ${}^4F_{3/2}$ is¹⁶

$$\frac{dn}{dt} = W(n_0 - n) - \frac{n_1}{\tau_1} - \frac{n_2}{\tau_2} - (\sigma_1 n_1 + \sigma_2 n_2) \frac{c\rho}{h\nu} \quad (1)$$

where W is the pumping rate into upper level, n_0 is the density of active atoms, $\tau_{1,2}$ are the upper level life times, c is the velocity of light, ρ is the energy density inside the resonator.

In thermal equilibrium, $n({}^4F_{3/2})$ and $n(R_1)$ and $n(R_2)$ are related by the Boltzmann distribution¹⁷

$$n(R_1) = \left(\frac{1}{1 + e^{-\Delta E/kT}} \right) n({}^4F_{3/2}) \quad (2)$$

$$n(R_2) = \left(\frac{e^{-\Delta E/kT}}{1 + e^{-\Delta E/kT}} \right) n({}^4F_{3/2}) \quad (3)$$

where ΔE ($=84 \text{ cm}^{-1}$) is the difference in energy between Stark levels R_1 and R_2 , k is Boltzmann's constant, and T is the absolute temperature. At room temperature ($\approx 300 \text{ K}$) only 40% of the ${}^4F_{3/2}$ population is at level R_2 and the remaining 60% are at the lower sublevel R_1 . If the laser transition takes place from only one Stark level is an upper laser level of R_1 then in the electrons in the other Stark level of R_2 is replenished from the laser level of R_1 by thermal transition.¹⁸ It is well known that this transfer can be taken into account by using the effective cross section of the laser line.¹⁶ According to the Boltzmann distribution,

$$\frac{n_2}{n_1} = \exp(-\Delta E/kT) = B \quad (4)$$

Because of both transition have the Lorentzian line profile, the effective stimulated emission cross section can be described¹⁶

$$\sigma_i = \frac{(\delta\nu_i/2)^2}{\Delta\nu^2 + (\delta\nu_i/2)^2} \sigma_{i0} = f_i \sigma_{i0} \quad i=1 \text{ for } 1,444 \text{ nm, } 2 \text{ for } 1,414 \text{ nm} \quad (5)$$

where,

	$\delta\nu_1 \text{ (cm}^{-1}\text{)}$	$\delta\nu_2 \text{ (cm}^{-1}\text{)}$	$\nu_1 \text{ (cm}^{-1}\text{)}$	$\nu_2 \text{ (cm}^{-1}\text{)}$	$\Delta\nu_1 = \nu_2 - \nu_1 \text{ (cm}^{-1}\text{)}$
Ref 1	10	15	6,923	7,073	150
Ref 10	9	8.5	6,929	7,070	141

Effective values of upper level lifetime and stimulated emission cross section are

$$\frac{1}{\tau} = \frac{1/\tau_1 + B/\tau_2}{1 + B} \quad (6)$$

$$\sigma = \frac{\sigma_{10}f_1 + B\sigma_{20}f_2}{1 + B} \quad (7)$$

If the laser oscillate with $\nu = \nu_1$, Eq.(7) reads

$$\sigma_a = \left[\sigma_{10} + \frac{(\delta\nu_2/2)^2}{[-(\Delta\nu)^2 + (\delta\nu_2/2)^2]} B\sigma_{20} \right] / (1 + B) \quad (8)$$

when $\nu = \nu_2$

$$\sigma_b = \left[\sigma_{10} \frac{(\delta\nu_1/2)^2}{\Delta\nu^2 + (\delta\nu_1/2)^2} + B\sigma_{20} \right] / (1 + B) \quad (9)$$

When increased the temperature from 300 K to 323 K, the calculated results of σ_a and σ_b were tabulated in Table 2.

Using the spectroscopic data of σ_{10} and σ_{20} in Ref 1 and 10, the effective stimulated emission cross section of 1,414 nm and 1,444 nm were calculated and tabulated in Table 3.

As can see Table 3, the effective stimulated emission

Table 3. Calculated effective stimulated emission cross section of 1,414 nm and 1,444 nm

Wavelength	Temperature	Ref 1	Ref 10
1,414 nm	300 K	1.324×10^{-20}	0.803×10^{-20}
	317 K	1.341×10^{-20}	0.813×10^{-20}
	323 K	1.347×10^{-20}	0.817×10^{-20}
1,444 nm	300 K	2.041×10^{-20}	1.679×10^{-20}
	317 K	2.024×10^{-20}	1.665×10^{-20}
	323 K	2.018×10^{-20}	1.660×10^{-20}

Table 2. Calculated results of σ_a and σ_b

	300 K	317 K	323 K
$\sigma_{a\text{-ref1}}$	$0.599\delta_{10} + 9.989 \cdot 10^{-4}\delta_{20}$	$0.594\delta_{10} + 0.001\delta_{20}$	$0.593\delta_{10} + 0.001\delta_{20}$
$\sigma_{a\text{-ref10}}$	$0.599\delta_{10} + 3.636 \cdot 10^{-4}\delta_{20}$	$0.594\delta_{10} + 3.683 \cdot 10^{-4}\delta_{20}$	$0.593\delta_{10} + 3.699 \cdot 10^{-4}\delta_{20}$
$\sigma_{b\text{-ref1}}$	$6.653 \cdot 10^{-4}\delta_{10} + 0.401\delta_{20}$	$6.595 \cdot 10^{-4}\delta_{10} + 0.406\delta_{20}$	$6.576 \cdot 10^{-4}\delta_{10} + 0.407\delta_{20}$
$\sigma_{b\text{-ref10}}$	$6.099 \cdot 10^{-4}\delta_{10} + 0.401\delta_{20}$	$6.046 \cdot 10^{-4}\delta_{10} + 0.406\delta_{20}$	$6.029 \cdot 10^{-4}\delta_{10} + 0.407\delta_{20}$

cross section of 1,444 nm is almost twice higher than 1,414 nm as increase temperature from 300 K to 323 K. As increased the temperature from 300 K to 323 K, the effective stimulated emission cross section of 1,414 nm was about 1.7% increased whereas it was about 1.1% decreased for 1,444 nm.

Heating and cooling of a Nd:YAG crystal, which results from the thermal loading by pumping process and heat remove by cooling water, lead to a radial temperature distribution in the Nd:YAG rod. Fig. 2 shows radial temperature distributions within a Nd:YAG as a function of radius of Nd:YAG at three cooling water temperature. Temperature distributions in a Nd:YAG can be calculated using the method described in reference.¹⁸ Because of cooling water temperature was rapidly increased from 23°C to 40°C at maximum input electrical input power of 1.88 kW, we calculated the radial temperature distributions up to 40°C. Stimulated emission cross section directly relate on laser output energy. Therefore, if the reported spectroscopy data of stimulated emission cross section of 1,414 and 1,444 nm is reliable, the output energy of 1,444 nm should be higher than 1,414 nm although temperature of Nd:YAG is increased through pumping process. Since the variation of stimulated emission cross sections as increased temperature is minimal, nearly constant output energy of 1,414 and 1,444 nm can be expect.

EXPERIMENT AND RESULTS

The experimental setup is shown in Fig. 3. A Nd:YAG rod (VLOC, dopant 1.1%) with length of 130 mm and diameter of 6 mm was used. A concave mirror had a radius of curvature of -3 m which was utilized as the total

Fig. 2. Radial temperature distributions within a Nd:YAG crystal as a function of radius of Nd:YAG at three cooling water temperature.

mirror (HR in Fig. 3) and a flat mirror was utilized as the partial mirror (OC in Fig. 3). Both the Nd:YAG and the Kr-flashlamp of 700 torr were placed in a ceramic reflector. The output energy was measured with a pyroelectric energy meter and the output spectrum was measured with a spectrometer (BTB-1100, B&W tek). The reflectivity of HR is less than 32% in 1,050-1,116 nm region (specially, 22% < 1,064 nm) and is less than 630% in 1,318-1,340 nm region, whereas it is 99.5% at 1,414 nm, 99.7% at 1,427 nm, 99.6% at 1,431 nm, and 99.7% at 1,444 nm, respectively. In order to obtain the 1,414 nm and 1,444 nm wavelengths, we used two OC. The OC-1 has a reflectivity less than 32% in 1,050-1,116 nm region (specially, 22% < 1,064 nm) and less than 77% in 1,318-1,340 nm region, whereas it has a reflectivity of 88.3%, 87%, 89.4%, and 92.2% at 1,414, 1,427, 1,431, and 1,444 nm, respectively. The OC-2 has a reflectivity less than 32% in 1,050-1,116 nm region (specially, 22% < 1,064 nm) and less than 77% in 1,318-1,340 nm region, whereas it has a reflectivity of 92.0%, 90.2%, 88.4%, and 86.7% at 1,414, 1,427, 1,431, and 1,444 nm, respectively. As shown in Fig. 4, we successfully obtain the single wavelength of 1,414 nm and 1,444 nm by utilizing these resonator mirrors. In spite of resonator mirrors have less than 22% at 1,064 nm, 1,064 nm was still found. Due to the spherical aberration of the thermal lens, the multimode 1,414 and 1,444 nm beam cannot reach the gain near the surface of the rod.² Therefore, the 45° incidence mirror was utilized as a spectral filter which was adopted in front of the partial reflector. A beam splitter was utilized for measuring the spectrum which has an average reflectivity less than 1% at 1,400 nm region. The pulse width of the current (FWHM) through the flashlamp was 120 μ s at the maximum electrical input energy of 47 J. The repetition rate was fixed at 40 Hz through the experiment.

Fig. 5 shows the output energy of 1,414 nm and 1,444 nm as a function of electrical input energy. Due to the exclusion of measurement error from misalignment, the alignment was repeatedly checked to obtain reliable

Fig. 3. Experimental setup of the pulsed Nd:YAG laser.

Fig. 4. Measured spectrums of single wavelength of 1,414 nm and 1,444 nm.

Fig. 5. Output energy of 1,414 nm and 1,444 nm as a function of electrical input energy.

results. As shown in Fig. 5, the required threshold energy of 1,444 nm is 2.3 J higher than 1,414 nm and output energy of 1,414 nm is 57% higher than 1,444 nm at electrical input energy of 47 J. Electro-optical conversion efficiencies of 1,414 nm and 1,444 nm were 0.79% and 0.51%, respectively. Low threshold input energy and high output energy of 1,414 nm means that the gain of 1,414 nm is higher than 1,444 nm. Therefore, the reported spectroscopic data of stimulated emission cross sections of 1,414 and 1,444 nm were not coincide of our results. To reduce the thermal loading from the pumping process, we diminish the pumping repetition rate from 10 Hz to 0.1 Hz. Increased mode volume due to reduced thermal lensing effect of Nd:YAG crystals at these operation condition, the output energy at each wavelength was increased. However, the output energy of 1,414 nm is still

higher than 1,444 nm.

CONCLUSIONS

We calculated the effective stimulated emission cross sections of 1,414 and 1,444 nm at temperature from 300 K to 323 K using the reported spectroscopic data. The calculated stimulated emission cross section of 1,444 nm is almost twice higher than 1,414 nm at these temperatures. Contrary to results of calculated effective stimulated emission cross sections, the output energy of 1,414 nm is 57% higher than 1,444 nm at electrical input energy of 47 J and threshold input energy of 1,414 nm is 2.3 J lower than 1,444 nm. This means that gain of 1,414 nm is higher than 1,444 nm. When single oscillated at each wavelength, electro-optical conversion efficiencies of 1,414 nm and 1,444 nm were 0.79% and 0.51%, respectively with electrical input energy of 47 J. Further investigation is needed to clear our results such as measuring the laser gain at two wavelengths and whether existence of other causes, such as ESA, for the increase the threshold energy and decrease output energy at 1,444 nm.

REFERENCES

1. Singh S, Smith RG, Van Uitert LG. Stimulated-emission cross section and fluorescent quantum efficiency of Nd³⁺ in yttrium aluminum garnet at room temperature. *Phys Rev B* 1974;10:2566-72.
2. Hodgson N, Nighan WL Jr, Golding DJ, Eisel D. Efficient 100-W Nd:YAG laser operating at a wavelength of 1.444 microm. *Opt Lett* 1994;19:1328-30.
3. Wong SK, Mathieu P, Pace P. Eye-safe Nd:YAG laser. *Appl Phys*

- Lett 1990;57:650-2.
4. Kretschmann HM, Heine F, Ostroumov VG, Huber G. High-power diode-pumped continuous-wave Nd(3+) lasers at wavelengths near 1.44 microm. *Opt Lett* 1997;22:466-8.
  5. Agnesi A, Dell'acqua S, Pennacchio C, Reali G, Gobbi PG. High-Repetition-Rate Q-Switched Diode-Pumped Nd:YAG Laser at 1.444 microm. *Appl Opt* 1998;37:3984-6.
  6. Marling J. 1.05-1.44 microm tunability and performance of the CW Nd3+:YAG Laser. *IEEE J Quantum Electronics* 1978;14:56-62.
  7. Perez-Maldonado A, Rünger TM, Krejci-Papa N. The 1,450-nm diode laser reduces sebum production in facial skin: a possible mode of action of its effectiveness for the treatment of acne vulgaris. *Lasers Surg Med* 2007;39:189-92.
  8. Altshuler GB, Anderson RR, Manstein D. Method and apparatus for the selective targeting of lipid-rich tissues. United States Patent Application Publication 2003;23:1-4.
  9. Osborne BG. NIR measurements of the development of crystallinity in the stored bread crumb. *Analisis* 1998;26:55-7.
  10. Powell RC. Physics of solid-state laser materials. New York: AIP Press/Springer; 1998.
  11. Lupei V, Lupei A. Emission quantum efficiency and heating effects in YAG:Nd3+ lasers. *Opt Eng* 1996;35:1252-7.
  12. Lupei V, Lupei A, Pavel N, Taira T, Shoji I, Ikesue A. Laser emission under resonant pump in the emitting level of concentrated Nd-YAG ceramics. *Appl Phys Lett* 2001;79:590-2.
  13. Lupei V, Aka G, Vivien D. Quasi-three-level 946 nm CW laser emission of Nd:YAG under direct pumping at 885 nm into the emitting level. *Opt Commun* 2002;204:399-405.
  14. Goldring S, Lavi R. Nd:YAG laser pumped 946 nm. *Opt Lett* 2008;33:669-71.
  15. Kuck S, Fornasiero L, Mix E, Huber G. Excited state absorption and stimulated emission of Nd3+ in crystals. Part I: Y3Al5O12, YAlO3, and Y2O3. *Appl Phys B* 1998;67:151-6.
  16. Fuhrmann K, Hodgson N, Hollinger F, Weber H. Effective cross section of the Nd:YAG 1.0641-microm laser transition. *J Appl Phys* 1987;62:4041-4.
  17. Krupke WF, Shinn MD, Marion JE, Caird JA, Stokowski SE. Spectroscopic, optical, and thermomechanical properties of neodymium- and chromium-doped gadolinium scandium gallium garnet. *J Opt Soc Am B* 1986;3:102-13.
  18. Koechner W. Solid-state laser engineering. Berlin, New York: Springer; 1999. p.48.