# Suppressing effect of the laser extraction on heat generation in Nd:YAG

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The suppressing effect of the laser extraction on heat generation in Nd:YAG was investigated. The extraction efficiency could be deduced from the slope efficiency, and heat generation in Nd:YAG could be obtained with the heat model developed, which was verified by the previous experiment. The essential reasons were given to explain the change trend of heat generation under the condition of laser extraction.

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Heat generation in laser materials seriously deteriorates the output laser beam quality and the efficiency of laser operation due to a temperature- and stress-dependent variation of the index of refraction. The accurate prediction of the amount of heat generation in laser media is particularly important in the design of the high-power solid-state laser systems, and quantifying heat generation in laser media under the condition of laser extraction is fundamental for the further research on the thermal effects, such as thermal lensing and thermal stress-induced birefringence[1,2].

Many works have focused on heat generation in the diode-pumped rare-earth-doped gain media. A widely used method of quantifying heat generation is to use the fractional thermal loading[3−5], $\eta_{\mathrm{h}}$, the ratio of heat generated in laser media to the absorbed energy. In general, the calorimetric, interferometric, and thermocouple methods[3,6] are proposed to measure heat generation in the laser medium without laser extraction. More recently, the thermally induced depolarization of the second-harmonic output[4] and the critical quenching pump power[5] are used to quantify heat generation in the laser media under the condition of laser extraction.

It has been experimentally reported that heat generation in Nd:YAG is significantly decreased under the condition of laser extraction[7]. Taking into account the suppressing effect of laser extraction on the non-radiation relaxation[8], we developed the heat generation model in the Nd:YAG lasers. According to this model, the change trend of heat generation in Nd:YAG under the condition of laser extraction was well explained.

Firstly, a new heat generation model in Nd:YAG was developed based on Brown's work[8]. According to the definition of the fractional thermal loading, $\eta_{\mathrm{h}}$ was expressed as

$$\begin{aligned}\eta_{\mathrm{h}} = {} & 1 - \eta_{\mathrm{p}}\eta_{\mathrm{f-withlaser}}\eta_{\mathrm{b}}\eta_{\mathrm{average}} \\ & -\eta_{\mathrm{p}}\eta_{\mathrm{f-nolaser}}(1-\eta_{\mathrm{b}})\eta_{\mathrm{average}} - \eta_{\mathrm{p}}\eta_{\mathrm{b}}\eta_{\mathrm{l}}\eta_{\mathrm{S}}, \qquad (1)\end{aligned}$$

where $\eta_{\mathrm{p}}$, the pumping quantum efficiency, is the probability of that the Nd ion absorbing a pump photon will eventually relax to the ${}^4F_{3/2}$ state; $\eta_{\mathrm{b}}$ is the beam overlap efficiency, which can be calculated by an overlap integral between the pump and resonator mode distributions; $\eta_{\mathrm{l}}$, the extraction efficiency, is defined as the fraction of total upper state ${}^4F_{3/2}$ ions that relax to the terminal state via stimulated emission; $\eta_{\mathrm{S}}$ is the Stokes factor that presents the ratio of the photon energy emitted at the laser transition to the energy of a pump photon, i.e., $\eta_{\mathrm{S}} = \lambda_{\mathrm{P}}/\lambda_{\mathrm{l}}$, where $\lambda_{\mathrm{P}}$ and $\lambda_{\mathrm{l}}$ is the wavelength of the pump transition and the laser wavelength, respectively; $\eta_{\mathrm{average}}$ is the ratio of the average energy of the photon emitted at the fluorescence radiation to the energy of a pump photon, i.e., $\eta_{\mathrm{average}} = \lambda_{\mathrm{P}}/\lambda_{\mathrm{average}}$, where $\lambda_{\mathrm{average}}$ is the average wavelength of the fluorescence radiation, which can be calculated from the branching ratios for fluorescence; $\eta_{\mathrm{f-withlaser}}$ is the fluorescence radiation efficiency defined as the fraction of total upper state ${}^4F_{3/2}$ ions that relax to ${}^4I_J$ via fluorescence radiation under the condition of laser extraction, and $\eta_{\mathrm{f-nolaser}}$ is the fluorescence radiation efficiency without laser extraction.

In general, the variables, such as $\eta_{\mathrm{p}}$, $\eta_{\mathrm{b}}$, $\eta_{\mathrm{S}}$, and $\eta_{\mathrm{average}}$, are constants for a certain laser. Now we will discuss how to obtain the values of $\eta_{\mathrm{f-withlaser}}$, $\eta_{\mathrm{f-nolaser}}$, and $\eta_{\mathrm{l}}$. The non-radiation efficiency, $\eta_{\mathrm{non}}$, is defined as the probability of that the fraction of total upper state ${}^4F_{3/2}$ ions relax via the non-radiation relaxations, such as concentration quenching and upconversion process, etc.. Basing on Brown's results[8], we can obtain the fluorescence radiation efficiency, the extraction efficiency, and the non-radiation efficiency as

$$\eta_{\mathrm{f}} = \frac{1}{F(\rho)+1+\xi}, \qquad (2)$$

when $\xi = 0$, $\eta_{\mathrm{f}} = \eta_{\mathrm{f-nolaser}}$, and $\xi \neq 0$, $\eta_{\mathrm{f}} = \eta_{\mathrm{f-withlaser}}$

$$\eta_{\mathrm{l}} = \frac{\xi}{F(\rho)+1+\xi}, \qquad (3)$$

$$\eta_{\mathrm{non}} = \frac{F(\rho)}{F(\rho)+1+\xi}, \qquad (4)$$

where $\xi = \varphi/\varphi_{\mathrm{S}}$ is the ratio of the photon density to the saturation density, $\rho$ is the $\mathrm{Nd}^{3+}$ concentration (at.-%). From Eq. (2), for $\xi = 0$, $F(\rho) =$

$(1-\eta_{\mathrm{f-nolaser}})/\eta_{\mathrm{f-nolaser}}$. Lupei *et al.*[9] has worked on the emission dynamics of the $^4F_{3/2}$ level of $\mathrm{Nd}^{3+}$ in YAG. According to their results, the fluorescence radiation efficiency without laser extraction takes the form as

$$\eta_{\mathrm{f-nolaser}} = 0.98\exp(-20C_{\mathrm{a}}), \tag{5}$$

where $C_{\mathrm{a}}$ is the relative acceptor concentration, i.e., $C_{\mathrm{a}} = \rho/(100-\rho)$. Equation (5) is valid for low concentration Nd:YAG at weak pump intensity. However, the changing trend of $\eta_{\mathrm{f-nolaser}}$ with $C_{\mathrm{a}}$ given by Eq. (5) is the same with high concentration Nd:YAG at strong pump intensity. Moreover, there is still lack of thorough research of emission dynamics of the $^4F_{3/2}$ level of $\mathrm{Nd}^{3+}$ in YAG. Therefore, Eq. (5) is used and the function $F(\rho)$ is

$$F(\rho) = 1.02\exp(20C_{\mathrm{a}}) - 1. \tag{6}$$

With knowing the values of $F(\rho)$ and $\eta_{\mathrm{l}}$, the value of $\xi$ can be calculated from Eq. (3), and then, the value of $\eta_{\mathrm{f-wihlaser}}$ can be obtained from Eq. (2). Finally, the fractional thermal loading in Nd:YAG under the condition of laser extraction can be calculated from Eq. (1). However, the extraction efficiency cannot be experimentally measured directly. To deduce the extraction efficiency, we build the relationship between the slope efficiency and the extraction efficiency. When the absorbed pump power is far above the threshold, i.e., $P_{\mathrm{ab}} \gg P_{\mathrm{th}}$, the relationship takes the form

$$\eta_{\mathrm{l}} = \frac{\sigma_{\mathrm{s}}}{\eta_{\mathrm{P}}\eta_{\mathrm{b}}\eta_{\mathrm{S}}}, \tag{7}$$

where $\sigma_{\mathrm{s}}$ is the slope efficiency of the output power versus the absorbed pump power curve.

As an example, we deduce the fractional thermal loading in our reported Nd:YAG laser with the slope efficiency of 0.598[10]. Because the pump and cavity modes have a high spatial overlap, the beam overlap efficiency can be assumed to be unity, i.e., $\eta_{\mathrm{b}} = 1$. $\eta_{\mathrm{p}}$ is 0.9 for the 1.0 at.-% Nd:YAG[3]. Because the Nd:YAG laser is pumped at 808 nm and oscillates at 1064 nm, $\eta_{\mathrm{S}}$ is 0.76. Based on Eq. (7), $\eta_{\mathrm{l}}$ is calculated to be 0.87, for $\sigma_{\mathrm{s}} = 0.598$. The calculated $F(\rho)$ for the 1.0 at.-% Nd:YAG is 0.248, and then, from Eq. (3), $\xi$ is calculated to be 8.35. Finally, from Eq. (2) $\eta_{\mathrm{f-withlaser}}$ and $\eta_{\mathrm{f-nolaser}}$ can be calculated to be 0.104 and 0.801, respectively. In addition, according to the calculated average fluorescence wavelength of 1.038 $\mu$m, $\eta_{\mathrm{average}}$ is 0.778. Thus, from Eq. (1), the fractional thermal loading in the Nd:YAG under the condition of laser extraction can be deduced to be 0.33, which is lower than the experimental result of 0.37—0.47[3] without laser extraction.

With the developed heat model in this work, it is convenient to investigate the relationship between heat generation in Nd:YAG and laser extraction. Figure 1 clearly shows the suppressing effect of laser extraction on heat generation in Nd:YAG, which agrees well with the experimental results[7]. However, the change trend of heat generation cannot be explained by Ref. [8]. In fact, because the laser wavelength of 1064 nm is longer than the average fluorescence wavelength of 1038 nm, the quantum defect between lasing photon and pumping photon is not less but more than that between fluorescing photon and pumping photon. And just for this reason, based on the Fan's theoretical model[3], heat generation with laser extraction is more than that without laser extraction, which is contrary to the reported experimental data. The suppressing effect of laser extraction on heat generation in Nd:YAG with the reason that the non-radiation relaxation is suppressed with laser extraction is shown in Fig. 2.

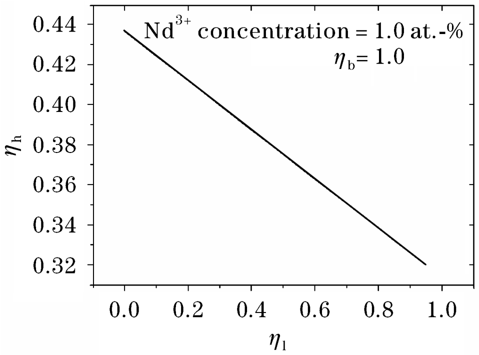

Fig. 1. Dependence of the fractional thermal loading $\eta_{\mathrm{h}}$ on the extraction efficiency $\eta_{\mathrm{l}}$.

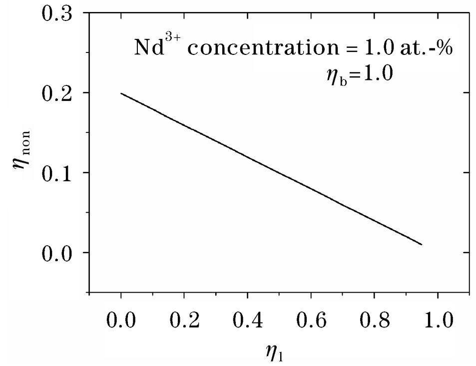

Fig. 2. Suppressing effect of laser extraction on the non-radiation transition process.

Furthermore, according to the developed heat model, we investigate the influence of the doping concentration on heat generation. It should be mentioned that, although the value of $\eta_{\mathrm{p}}$ is controversial for Nd lasers with 808 nm pumping, the Brown's assumption[8], $\eta_{\mathrm{p}} = 1 - 0.1\rho$, can be used to investigate how the heat generation will vary if a linear relationship between the pumping quantum efficiency and the $\mathrm{Nd}^{3+}$ concentration is assumed.

Figure 3 shows the dependence of the fractional thermal loading on the $\mathrm{Nd}^{3+}$ concentration, for $\eta_{\mathrm{b}} = 1$, and $\eta_l = 0.5$, 0.6 and 0.7, respectively. The fractional thermal loading increases as the $\mathrm{Nd}^{3+}$ concentration increases, which consists with Fan's experimental results[3].

The changing trend of the fractional thermal loading in Fig. 3 is because that the increase of the $\mathrm{Nd}^{3+}$ concentration results in a relatively low pumping quantum efficiency and a relatively high non-radiation efficiency as shown in Fig. 4, both of which will lead to more heat generation in laser medium.

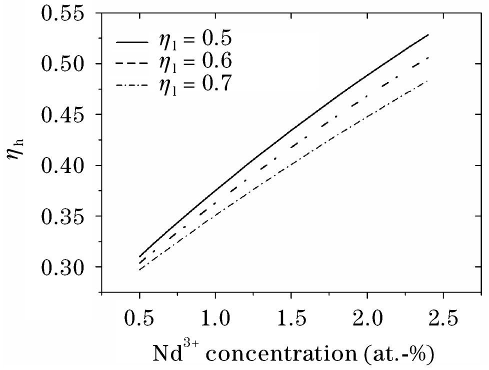

Fig. 3. Dependence of the fractional thermal loading $\eta_h$ on the $Nd^{3+}$ concentration.

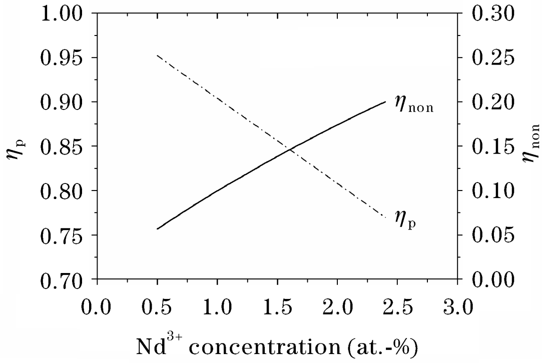

Fig. 4. Dependence of the pumping quantum efficiency $\eta_p$ and the non-radiation efficiency $\eta_{non}$ on the $Nd^{3+}$ concentration.

In conclusion, we investigate the suppressing effect of laser extraction on heat generation in Nd:YAG. The fractional thermal loading is used to quantify heat generation, which can be deduced from the developed heat model and the slope efficiency. The dependence of the fractional thermal loading on the $Nd^{3+}$ concentration is investigated, and the essential reasons for the change of heat generation are also discussed. Moreover, the developed model in this paper has been verified by the previous experimental reports.

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