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Repetition-rate dependence of thermal loading in diode-end-pumped Q-switched lasers: influence of energy-transfer upconversion

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Abstract. The fractional thermal loading in diode-end-pumped Q-switched lasers was estimated from the theory of cavity stability. The experimental results show that the thermal loading depends on the pulse-repetition rate. This dependence is attributed to the effect of energy-transfer upconversion (ETU). A theoretical model including the ETU effect was developed to analyze the fractional thermal loading in end-pumped Q-switched lasers. The theoretical predictions were found to be in good agreement with the experimental data.

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Diode-end-pumped solid-state lasers have the main advantage of achieving high conversion efficiencies for fundamental mode operation. However, power scaling of these lasers is usually hindered by the thermal effect in the gain medium due to the small volume of the pumping profile. The thermally induced lensing behavior may cause the resonator to be unstable [1–3]. Moreover, the thermal loading may be so large that the laser crystal is fractured [4, 5]. Therefore, the thermal effect must be thoroughly understood and characterized for the optimization of the resonator design.

Recently, Hardman et al. [6] measured thermal lensing in end-pumped Nd:YLF crystals under lasing and nonlasing conditions. They found that the energy-transfer upconversion (ETU) process leads to a significant difference in thermal lensing between lasing and nonlasing conditions, with a much stronger lens power under nonlasing conditions. This result indicates may result in extra heat generation in Q-switched operation or operation as an amplifier.

In this work, we studied the thermal effects in diode-end-pumped Q-switched lasers. We first measured the fractional thermal loading in a diode-end-pumped Q-switched Nd:YAG laser from the theory of cavity stability. The fractional thermal loading represents the fraction of the absorbed pump power that is converted to heat during the laser process. The experimental results later described show that the thermal loading depends on the pulse-repetition rate and increases with decreasing pulse-repetition rates. To explain this dependence, we developed a theoretical model to analyze the thermal loading in an end-pumped Q-switched laser. We included the ETU effect in the rate equations to derive the dependence of thermal loading on the repetition rate. It was found that the experimental data could be explained very well with the developed model.

1 Experiment

To study the thermal effect, we set up a diode-end-pumped Q-switched laser, as shown in Fig. 1. The input mirror was a concave mirror with radius of curvature of 5 m, antireflection coated at 808 nm on the entrance face, high-reflectance coated at 1064 nm and high-transmittance coated at 808 nm on the other face. The output coupler was a plane mirror with 20% transmission at 1064 nm. The total cavity

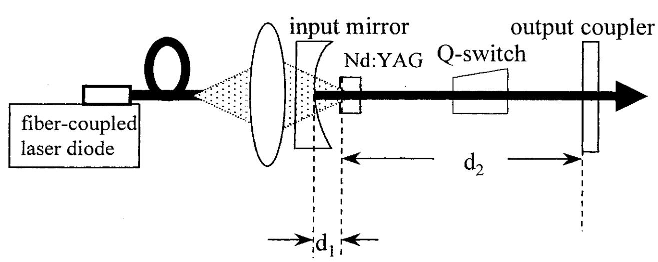

Fig. 1. Experimental setup for diode-end-pumped Q-switched Nd:YAG laser

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length was around 9.0 cm. The laser crystal was a 5-mm-diameter, 10-mm-long Nd:YAG rod with Nd^{3+} concentration of 1.0 at%. The laser crystal was wrapped with indium foil and was press-fitted into a water-cooled copper housing. The water temperature was held at 20 °C. The crystal of the acousto-optic (AO) Q-switcher was made of fused silica, and was driven at a 40.68 MHz center frequency with 3.0 W of rf power. The pumping source was a fiber-coupled diode laser that delivered a maximum output power of 30 W at the fiber-bundle end. The output beam from the fiber-bundle end was 0.8 mm in diameter and 0.18 in numerical aperture, and was focused into the laser crystal with a focusing lens of 0.5 magnification. The average spot size was about 0.26 mm.

The thermal lens of a laser crystal always affects the stability of a resonator, only sometimes it is crucial to alignment pump power. For a laser, pumped by a fiber-coupled diode, the focal length of the thermal lens, f_{th}, is given by [4, 7]:

$$\frac{1}{f_{\mathrm{th}}} = \frac{\xi P_{\mathrm{abs}}}{2\pi K_{\mathrm{c}} \omega_{\mathrm{p}}^2} \times \left[\mathrm{d}n_{\mathrm{o}}/\mathrm{d}T + (n_{\mathrm{o}} - 1)(1+\nu)\alpha_{\mathrm{T}} + n_{\mathrm{o}}^3 \alpha_{\mathrm{T}} C_{\mathrm{r}} \right], \tag{1}$$

where ξ is the fractional thermal loading, P_{abs} is the absorbed pump power, K_{c} is the thermal conductivity, n_{o} is the refractive index of the laser crystal, $\mathrm{d}n_{\mathrm{o}}/\mathrm{d}T$ is the thermal-optic coefficients of n_{o}, ν is Poisson's ratio, α_{T} is the thermal expansion coefficient, C_{r} is the photo-elastic coefficient, and ω_{p} is the averaged pump size in the active medium.

For the present cavity with a fixed cavity length, there exists a critical pump power at which thermally induced lensing will cause the laser cavity to be unstable. From the standard ABCD matrix approach, the critical thermal lens corresponding to the critical pump power is given by [8]

$$\left(\frac{1}{f_{\mathrm{th}}}\right)_{\mathrm{critical}} = \frac{1}{d_2^*} - \frac{1}{\varrho_1 - d_1}, \tag{2}$$

$$d_2^* = d_2 + l(1/n_{\mathrm{o}} - 1) + l_{\mathrm{Q}}(1/n_{\mathrm{Q}} - 1), \tag{3}$$

where ϱ_1 is the radius of curvature of the input mirror, d_1 and d_2 are the distances between the mirrors and the incident end of the laser crystal, n_{o} and n_{Q} are, respectively, the refractive indices of the laser crystal and the Q-switch crystal for the output laser beam, and l and l_{Q} are, respectively, the lengths of the laser crystal and the Q-switch crystal. The derivation of (2) was based on the fact that the effective thermal lens in end-pumped lasers is close to the surface of the pumping end.

From (1) and (2), the critical pump power, P_{critical}, is given by

$$\xi P_{\mathrm{critical}} = \left[\frac{1}{d_2^*} - \frac{1}{\varrho_1 - d_1}\right] \times \frac{2\pi K_{\mathrm{c}} \omega_{\mathrm{p}}^2}{\left[\mathrm{d}n_{\mathrm{o}}/\mathrm{d}T + (n_{\mathrm{o}} - 1)(1+\nu)\alpha_{\mathrm{T}} + n_{\mathrm{o}}^3 \alpha_{\mathrm{T}} C_{\mathrm{r}} \right]}. \tag{4}$$

With this fact, we measured the critical power for different pulse repetition-rates, as shown in Fig. 2. The arrows shown in Fig. 2 represent the positions of the critical pump powers. It can be found that the critical pump power depends on the pulse-repetition rate, f, and decreases with decreasing f. The right-hand side of (5) is nearly constant for a fixed cavity length. Therefore, it can be concluded that the fractional thermal loading, ξ, increases with decreasing the pulse-repetition rate. As discussed below, the dependence of the thermal loading on the repetition rate may arise from the effect of energy-transfer upconversion (ETU).

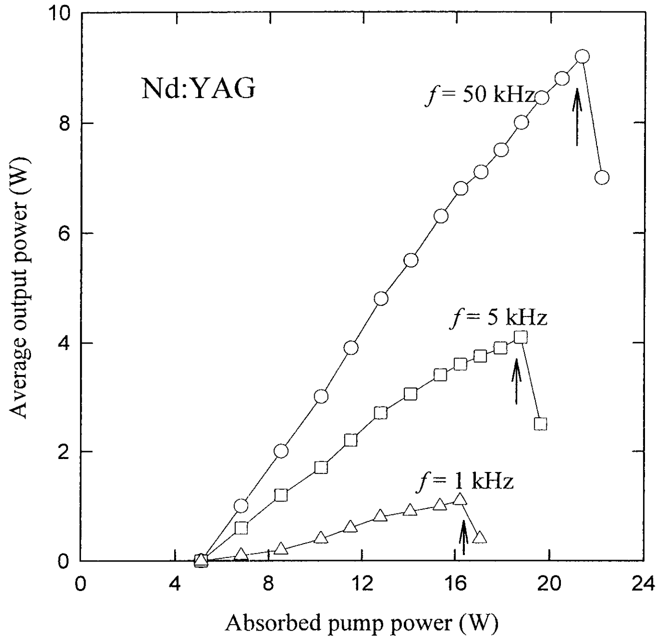

Fig. 2. Experimentally measured variation of the average output power as a function of the absorbed pump power for different pulse-repetition rates; the *arrows* indicating the critical pump power

2 Modeling and discussion

The ETU process involves two nearby ions in the upper laser level $^4F_{3/2}$ [9–11]. One ion returns to the lower level $^4I_{9/2}$, $^4I_{11/2}$, or $^4I_{13/2}$ and transfers its energy to the other excited ion which is thereby raised to a higher excited state from which the excited ion relaxes down to the level $^4F_{3/2}$ mostly via multi-phonon emission. Consequently, ETU processes not only reduce the population inversion but also increase the thermal loading in the laser material.

Since the Q-switched laser output pulses are much shorter than both spontaneous lifetime and the pump period (time between output pulses), spontaneous relaxation and pumping can be safely neglected during the development of the output pulse. Therefore, the rapidly Q-switched problem for a four-level laser reduces to the simultaneous solution of two coupled differential equations for the photon density ϕ and the population inversion density n [12]:

$$\frac{\mathrm{d}\phi}{\mathrm{d}t} = \frac{2\sigma n l \phi}{t_{\mathrm{r}}} - \frac{\phi}{t_{\mathrm{c}}} \tag{5}$$

and

$$\frac{dn}{dt} = -\sigma c \phi n \,. \tag{6}$$

σ is the emission cross section, l is the crystal length, c is the speed of light, and t_r is the roundtrip transit time in the laser resonator of length l'. The quantity t_c is the photon decay time defined by

$$t_c = \frac{t_r}{[\ln(1/R) + L]} \,, \tag{7}$$

where R is the output mirror reflectivity, and L is the roundtrip dissipated optical loss. With (5) and (6), the relationship between the initial inversion density, n_{max}, and the final inversion densities, n_f, is given by the usual transcendental equation:

$$n_{max} - n_f = n_t \ln \frac{n_{max}}{n_f} \,, \tag{8}$$

where the inversion density at threshold, n_t, is given by

$$n_t = \frac{1}{2\sigma l}\left[\ln\left(\frac{1}{R}\right) + L\right] . \tag{9}$$

To take ETU effects into account, the rate equation for population inversion density during the low-Q segment of the cycle is given by [13]:

$$\frac{dn}{dt} = R_p - \frac{n}{\tau} - \gamma n^2 \,, \tag{10}$$

where the average pump intensity, R_p, is expressed as

$$R_p = \frac{P_{abs}}{h\nu_p} \frac{1}{\pi \omega_p^2 l} \,, \tag{11}$$

and ν_p is the pump frequency, τ is the emission lifetime, and γ is the upconversion rate. Here we neglect the self-quenching effect, i.e. the cross relaxation, which could be significant at a high doping level [11]. Since the laser medium studied here was 1.0 at% Nd:YAG crystal, the cross relaxation is negligible. The solution of (10) is given by

$$n = \frac{1}{B}\left[A \frac{(1 + Bn_f + A) + (1 + Bn_f - A)\exp(-At/\tau)}{(1 + Bn_f + A) - (1 + Bn_f - A)\exp(-At/\tau)} - 1\right] , \tag{12}$$

$$A = \sqrt{1 + 4\tau^2 \gamma R_p} \,, \tag{13}$$

$$B = 2\tau\gamma \,, \tag{14}$$

where $t = 0$ in (12) corresponds to the time when the laser giant pulse occurred. For Q-switching at a repetition rate f, we require that

$$n_{max} = \frac{1}{B}\left[A \frac{(1 + Bn_f + A) + (1 + Bn_f - A)\exp\left(-\frac{A}{\tau f}\right)}{(1 + Bn_f + A) - (1 + Bn_f - A)\exp\left(-\frac{A}{\tau f}\right)} - 1\right] \tag{15}$$

to have the inversion return to its original value after each Q-switching cycle. The value of n_f and n_{max} are determined from solving the simultaneous (8) and (15). Without ETU effects, i.e. $\gamma = 0$, the solution of the population density in (15) is simplified as

$$n^o_{max} = R_p\tau - (R_p\tau - n_f)\exp\left(-\frac{1}{\tau f}\right) . \tag{16}$$

This result is the same as the previous analysis of Chesler et al. [13]. With (15) and (16), the fractional reduction of the inversion density due to ETU is then given by

$$F_{ETU}(f, P_{abs}) = \frac{n^o_{max} - n_{max}}{n^o_{max}} \,. \tag{17}$$

The parameter F_{ETU} is a function of the absorbed pump power and the pulse-repetition rate, being a measure of the magnitude of the effect of upconversion. Since F_{ETU} represents the fraction of the ions in the metastable level $^4F_{3/2}$ via ETU process, the fraction of excited Nd^{3+} ions via the fluorescence process is given by $1 - F_{ETU}$.

With (8), (15), and (17), the parameter F_{ETU} can be numerically calculated. Figure 3 shows the dependence of F_{ETU} on the frequency-repetition rate, f, for several absorbed pump powers. The parameters used in the calculation are as follows: $\tau = 250\,\mu s$ [14], $l = 10$ mm, $\omega_p = 260\,\mu m$, $\alpha = 7\,cm^{-1}$, and $\gamma = 0.5 \times 10^{-16}\,cm^3/s$ [11]. It can be found that the fraction of excited Nd^{3+} ions involving the ETU processes, F_{ETU}, substantially increases with decreasing the repetition rate in the range of 1–10 kHz. For a fixed pump power, F_{ETU} is nearly constant as the repetition rate below 1 kHz, because the spontaneous emission leads to the saturation of the inversion density. In addition, the ETU effect is also more significant for higher pump power. Therefore, the influence of ETU is greatly crucial at high pump powers and low frequency-repetition rates in the Q-switched operation.

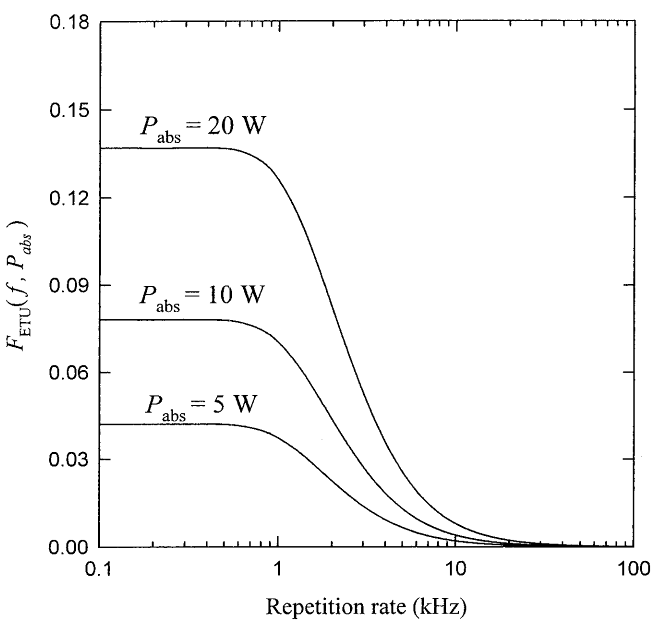

Fig. 3. A plot of the dependence of F_{ETU} on the frequency-repetition rate for several absorbed pump powers

From the known Stark-level splitting [14], the possible ETU processes in Nd:YAG ${}^4F_{3/2} \rightarrow {}^2K_{15/2} + {}^2D_{3/2}$, ${}^4F_{3/2} \rightarrow {}^4G_{9/2} + {}^4G_{11/2}$, and ${}^4F_{3/2} \rightarrow {}^4G_{7/2} + {}^2K_{13/2} + {}^2G_{7/2}$ which arise from the down-conversion transitions ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$, ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$, and ${}^4F_{3/2} \rightarrow {}^4I_{13/2}$, respectively. The heat generated from ETU processes is due to the multiphonon relaxation from the excited level back to the upper laser level. Since the energy of the multiphonon relaxation is equal to the energy of the correlated down-conversion transitions, all the possible ETU processes emitted the same heat that is equivalent to the energy of an absorbed pump photon. On the other hand, the fraction $1 - F_{\mathrm{ETU}}$ of excited Nd^{3+} ions that decay via the fluorescence process results in the thermal loading equal to the quantum defect. Hence the fractional thermal loading can be expressed as [6]:

$$\xi(f, P_{\mathrm{abs}}) = F_{\mathrm{ETU}}(f, P_{\mathrm{abs}}) + [1 - F_{\mathrm{ETU}}(f, P_{\mathrm{abs}})]\left(1 - \frac{\lambda_{\mathrm{p}}}{\lambda_{\mathrm{f}}}\right), \tag{18}$$

where λ_{p} is the pumping wavelength and the average fluorescence wavelength λ_{f} is given by $\int \lambda f(\lambda)\,\mathrm{d}\lambda \,/ \int f(\lambda)\,\mathrm{d}\lambda$, where $f(\lambda)$ is the relative fluorescence spectrum. With the fluorescence spectra, λ_{f} was found to be 1038 nm for Nd:YAG.

From the results in Fig. 3 and (18), the dependence of the thermal loading on the pulse repetition rate was calculated and shown in Fig. 4. It can be seen that the fractional thermal loading is more significant at low repetition rates and at high pump powers because of ETU effects.

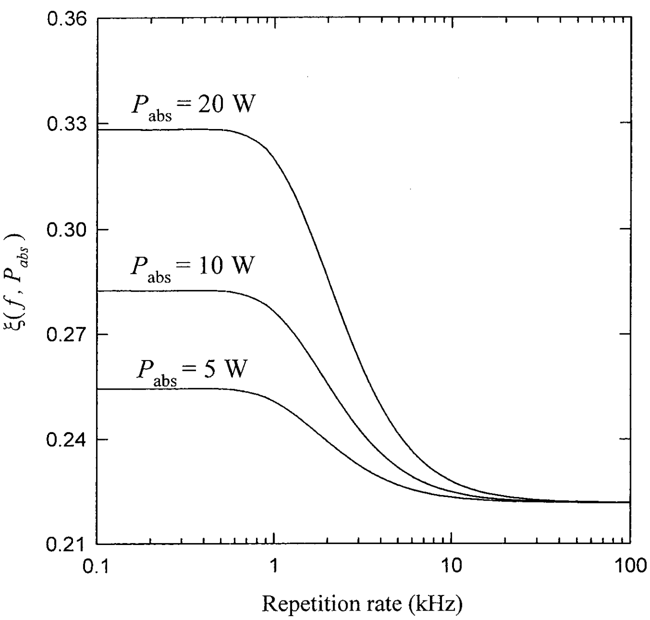

Fig. 4. The dependence of the fractional thermal loading on the pulse-repetition rate for several absorbed pump powers

From (4) and (18), the critical pump power for the cavity shown in Fig. 1 can be determined as a function of the repetition rate by solving the following equation:

$$\xi(f, P_{\mathrm{critical}})P_{\mathrm{critical}} = \left[\frac{1}{d_2^*} - \frac{1}{\varrho_1 - d_1}\right] \times \frac{2\pi K_{\mathrm{c}}\omega_{\mathrm{p}}^2}{[\mathrm{d}n_{\mathrm{o}}/\mathrm{d}T + (n_{\mathrm{o}} - 1)(1+\nu)\alpha_{\mathrm{T}} + n_{\mathrm{o}}^3\alpha_{\mathrm{T}}C_{\mathrm{r}}]}. \tag{19}$$

Figure 5 shows the calculation results for the critical pump power as a function of the repetition rate. The values of the parameters used for calculation are $n_{\mathrm{o}} = 1.82$, $\alpha = 7$ /cm, $K_{\mathrm{c}} = 0.13$ W/K cm, $\alpha_{\mathrm{a}} = 7.8 \times 10^{-6}$ /K, $\mathrm{d}n_{\mathrm{o}}/\mathrm{d}T = 7.3 \times 10^{-6}$ /K, $\nu = 0.28$, $C_{\mathrm{r}} = 0.017$, $d_1 = 0.2$ cm, and $d_2^* = 8$ cm. For comparison, the experimental data were also plotted in the same figure. It is seen that the experimental results can be well described by the model by including the ETU effect. The good agreement obtained between experimental data and theoretical calculation confirms our physical analysis.

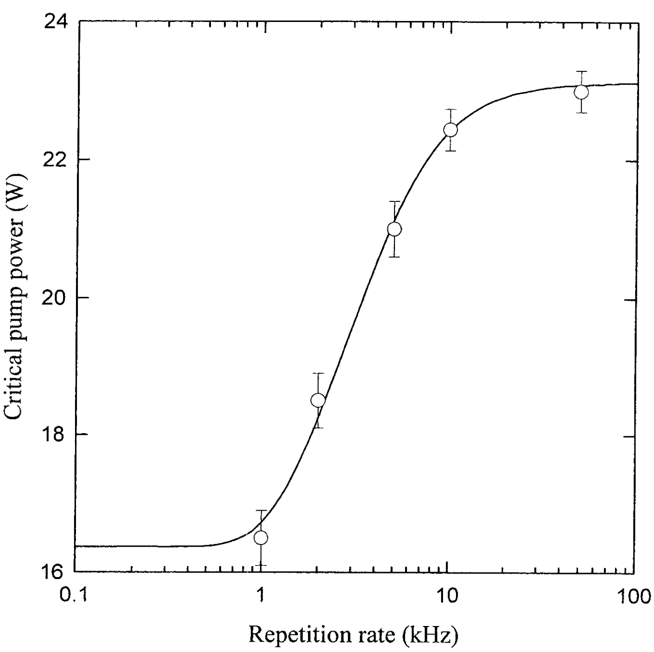

Fig. 5. A plot of the critical pump power as a function of the repetition rate. *Solid line*: calculation results; *symbols*: experimental data

Finally, it is worthwhile noting that (2) was derived from the ABCD matrix approach. Therefore, results are only valid for TEM_{00} modes. With a change in pump power, the value of the thermal lens changes and so should the laser mode size inside the gain medium. This changes the overlap of pump and laser mode and possibly the transvers mode distribution.

3 Conclusion

We have investigated the thermal loading in the diode-end-pumped Q-switched Nd:YAG laser. Experimental results show that the fractional thermal loading significantly increases with decreasing the pulse repetition rate in the range of 1–10 kHz. The enhancement of the fractional thermal loading at low repetition rate arises from ETU effect. We have developed a theoretical model by taking into account ETU effect in analysis. Experimental results have shown a fairly good agreement with the theoretical predictions. We believe that the present model can provide a useful guideline to the design of high-power diode-end-pumped Q-switched lasers.

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