Influence of Energy-Transfer Upconversion on the Performance of High-Power Diode-End-Pumped CW Lasers

Y. F. Chen, *Associate Member, IEEE*, Y. P. Lan, and S. C. Wang, *Member, IEEE*

***Abstract*—The influence of energy-transfer upconversion (ETU) on the performance of diode-end-pumped lasers is studied by including ETU effects into the space-dependent rate equations. The dependence of ETU rates on the mode-to-pump size ratio and on the output mirror transmission is derived. Experiments for Nd : YAG and Nd : YVO_4 crystals are performed to validate the present model. It is found that the ETU process increases the sensitivity of the output power to the output mirror transmission but its influence on the output power is not significant for low output transmission.**

***Index Terms*—Diode-pumped, energy-transfer upconversion, Nd-doped crystal, rate equation.**

I. INTRODUCTION

DIODE-PUMPED solid-state lasers offer high efficiency, high reliability, compactness, and high beam quality, especially in an end-pumping configuration [1], [2]. Neodymium-doped (Nd-doped) crystals such as, Nd : YAG, Nd : YLF, and Nd : YVO_4, have been identified as promising materials for diode-pumped lasers. Researchers have worked to scale the output power of diode-end-pumped Nd-doped lasers to higher powers because of many potential applications [3], [4].

Several works [5]–[10] recently showed that energy-transfer upconversion (ETU) may be a detrimental effect in Nd-doped lasers, especially in high-gain small-signal amplifiers, Q-switched lasers, and CW lasers with higher output transmission. The ETU process involves two nearby ions in the metastable level $^4F_{3/2}$. One ion returns to the $^4I_{9/2}$, $^4I_{11/2}$, $^4I_{13/2}$, and $^4I_{15/2}$ levels and higher lying levels by transferring its energy to the other ion that is, in turn, brought into a higher excited state. Consequently, the ETU process results in the reduction of the inversion density, hence degrading the laser performance. So far, most studies on ETU effects concentrated on the measurement of upconversion rates and ETU induced heat generation [5]–[10]. The influence of ETU on end-pumped laser performance has not yet been considered.

In this work, we first used space-dependent rate equations to consider the influence of the ETU process on the performance of diode-end-pumped CW lasers. The analysis shows that ETU processes lead to an increase in threshold as well as the reduction of output power, especially at high-output mirror transmission. We carried out laser experiments for Nd : YAG and Nd : YVO_4 crystals to verify the accuracy of the theoretical model. It was found that the ETU process increases the sensitivity of the output power to the output mirror transmission but has a rather weak influence on the output power for low output transmission.

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II. THEORETICAL CONSIDERATIONS

We used a space-dependent rate-equation analysis to take into account the influence of ETU. Considering a single transverse mode and an ideal four-level laser, the rate equations can be written as [11], [12]

$$\frac{dN(x,\,y,\,z)}{dt} = Rr_p(x,\,y,\,z) - c\sigma N(x,\,y,\,z)\Phi\phi_o(x,\,y,\,z) - \frac{N(x,\,y,\,z)}{\tau} - \gamma N(x,\,y,\,z)^2 \qquad (1)$$

$$\frac{d\Phi}{dt} = c\sigma\Phi\int_{\text{rod}} N(x,\,y,\,z)\phi_o(x,\,y,\,z)\,dV - \frac{\Phi}{\tau_c} \qquad (2)$$

where N is the upper state population density, σ is the stimulated emission cross section, c is the speed of light in medium, Φ is the cavity photon number, τ is the upper state lifetime, γ is the upconversion rate, and

$$\tau_c = \frac{2l_{\text{eff}}}{c}\,\frac{1}{L + \ln[1/(1-T)]} \qquad (3)$$

is the photon lifetime, where $l_{\text{eff}} = l_{\text{cav}} + (n-1)l$ is the effective length of the resonator, l_{cav} is the length of the laser cavity, l is the crystal length, n is the index of refraction at the laser wavelength, L is the round-trip loss, and T is the output transmission. R is the pumping rate and is given by $R = P_{\text{abs}}h\nu_p$, where P_{abs} is the absorbed pump power and $h\nu_p$ is the pump photon energy. The main difference between our theoretical model and previous models [11], [12] is that we added the term $\gamma N(x,\,y,\,z)^2$ in (1) to take into account ETU effects. The functions $r_p(x,\,y,\,z)$ and $\phi_o(x,\,y,\,z)$ describe the spatial variation of the pump beam and fundamental laser cavity mode, respectively. These terms are normalized such that

$$\int_{\text{rod}} r_p(x,\,y,\,z)\,dV = \int_{\text{cavity}} \phi_o(x,\,y,\,z)\,dV = 1. \qquad (4)$$

With the same approach as in [11], the input–output characteristic for the steady-state condition is given by (5), shown at the bottom of the page. Here the relationship between the output power $P_{\rm out}$ and the cavity photon number Φ is given by

$$P_{\rm out} = \frac{c}{2l_{\rm eff}}\,\Phi h\nu_l\,\ln\left(\frac{1}{1-T}\right) \tag{6}$$

where $h\nu_l$ is the energy of the laser photon.

It can be easily found that, if $\gamma = 0$, (5) becomes the conventional formula used in the foregoing investigation [11], [12] without ETU effects. In the limit of $P_{\rm out} \rightarrow 0$, from (5), the equation for the threshold pump power is given by

$$P_{\rm th} = \frac{I_{\rm sat}}{l_{\rm eff}}\,\frac{\nu_p}{\nu_l}\,\frac{\ln[1/(1-T)]+L}{2} \cdot \left(\int_{\rm rod} \frac{2\phi_o r_p}{1+\sqrt{1+\dfrac{4\gamma\tau^2 P_{\rm th} r_p}{h\nu_p}}}\,dV\right)^{-1}. \tag{7}$$

For more intuitive knowledge, we used the first-order approximation to develop (7) as

$$\begin{aligned} P_{\rm th} &\approx \frac{I_{\rm sat}}{l_{\rm eff}}\,\frac{\nu_p}{\nu_l}\,\frac{\ln[1/(1-T)]+L}{2}\,\frac{1}{\displaystyle\int_{\rm rod}\phi_o r_p\,dV} \cdot \left[1+\frac{\gamma\tau^2 P_{th}}{h\nu_p}\,\frac{\displaystyle\int_{\rm rod}\phi_o r_p^2\,dV}{\displaystyle\int_{\rm rod}\phi_o r_p\,dV}\right] \\ &= \frac{P_{\rm th}^o}{1-\beta} \end{aligned} \tag{8}$$

where

$$P_{\rm th}^o = \frac{\ln[1/(1-T)]+L}{2l_{\rm eff}}\,\frac{\nu_p}{\nu_l}\,I_{\rm sat}\,\frac{1}{\displaystyle\int_{\rm rod}\phi_o r_p\,dV} \tag{9}$$

and

$$\beta = \left(\frac{\gamma\tau^2 P_{th}^o}{h\nu_p}\right)\frac{\displaystyle\int_{\rm rod}\phi_o r_p^2\,dV}{\displaystyle\int_{\rm rod}\phi_o r_p\,dV}. \tag{10}$$

Here, $P_{\rm th}^o$ is the threshold pump power without ETU effects [12], [13]. Equation (8) indicates that ETU processes increase the threshold pump power by the factor $(1-\beta)^{-1}$. The parameter β is a measure of the magnitude of the effect of upconversion, being proportional to the term $\gamma\tau^2$. In addition, the influence of ETU depends on the threshold pump power $P_{\rm th}^o$ because the ETU rates are proportional to the square of the inversion density and the inversion density is clamped at the threshold value for CW lasers above threshold. In view of this dependence, if an output coupler of higher transmission is used, consequently increasing the threshold, then ETU may become an important factor.

With the distributions of $r_p(x,\,y,\,z)$ and $\phi_o(x,\,y,\,z)$, numerical analysis of (5) can be performed to yield a plot of power output versus absorbed pump power. In addition, the dependence of the β parameter on the spatial variation of both the pump beam and the cavity field can be explicitly expressed in (10). For a top-hat pump distribution and a $\rm TEM_{00}$ laser mode [14], [15], one obtains

$$\beta = \frac{\gamma\tau^2}{h\nu_p}\,\frac{I_{\rm sat}}{2}\,\frac{\nu_p}{\nu_l}\,\frac{\alpha}{1-\exp(-2\omega_p^2/\omega_o^2)} \cdot \frac{1-e^{-2\alpha l}}{(1-e^{-\alpha l})^2}\left[\frac{1}{\ln(1-T)}+L\right]. \tag{11}$$

Equation (11) clearly shows the dependence of β on the mode-to-pump size ratio. As mentioned above, β is a measure of the magnitude of the influence of ETU effects on laser performance. Therefore, it is of practical interest to find the relationship between β and the mode-to pump size ratio. From (11), it can be found that β rapidly increases as $(\omega_p/\omega_o)^2 \rightarrow 0$. On the other hand, if the ratio $(\omega_p/\omega_o)^2$ is slightly greater than unity, then β is nearly independent of the mode-to-pump size ratio. This independence comes from the fact that a larger pump spot size leads to a higher threshold, hence the inversion density above threshold being nearly unchanged. When scaling end-pumped lasers to higher power [14], the condition of $(\omega_p/\omega_o)^2 \leq 1$ usually needs to be satisfied in order to avoid the thermally induced diffraction loss. However, (11) indicates that it is generally no use to eliminate ETU effects in high-power end-pumped lasers by means of further expanding the pump spot size.

It is worth mentioning that a similar β parameter was derived by Hardman *et al.* [10]. However, their β parameter was derived under nonlasing conditions, thus without including stimulated emission and the effect of spatial overlap between pump

$$P_{\rm abs} = \frac{I_{\rm sat}}{l_{\rm eff}}\,\frac{\nu_p}{\nu_l}\,\frac{\ln[1/(1-T)]+L}{2} \times \left\{\int_{\rm rod}\frac{2\phi_o r_p}{\left[1+\dfrac{2l_{\rm eff}P_{\rm out}\phi_o}{I_{\rm sat}\,\ln[1(1-T)]}\right]+\sqrt{\left[1+\dfrac{2l_{\rm eff}P_{\rm out}\phi_o}{I_{\rm sat}\,\ln[1/(1-T)]}\right]^2+\left(\dfrac{4\gamma\tau^2 P_{\rm abs} r_p}{h\nu_p}\right)}}\,dV\right\}^{-1} \tag{5}$$

and mode distribution. Their work focused on ETU induced heat generation under nonlasing conditions, while our work concentrates on the influence of ETU on laser performance.

III. Laser Experiment and Discussion

A concave-flat cavity was adopted to perform Nd : : YAG and Nd : YVO_4 laser experiments. The Nd concentrations of the Nd : YAG and Nd : YVO_4 crystals are 1.0 at.% and 0.3 at.%, respectively. The lengths of the Nd : YAG and Nd : YVO_4 crystals are 10 and 8 mm, respectively. The laser crystal was wrapped with indium foil and was press fitted into a water-cooled copper housing. The water temperature was held at 17 °C. The laser crystal was singly end-pumped by a fiber-coupled laser diode through a concave high-reflection mirror. The output coupler is a flat mirror and its reflectivity covered the range 50%–98%. By changing the resonator length and the radius of curvature of the input mirror, the waist at the input mirror could be varied approximately between 0.15–0.45 mm. The fibers were drawn into round bundles of 0.8 mm in diameter and a numerical aperture of 0.16. The focus pump-spot radius was around 0.24–0.25 mm.

It is important to note that an end-pump-induced thermal lens is not a perfect lens, but a lens with aberration. In our previous study [14], we found that, for mode-to-pump ratios greater than unity, the thermally induced diffraction loss is a rapidly increasing function of mode-to-pump ratio at a given pump power. In practice, the optimum mode-to-pump ratio is in the range of about 0.8–1.0 when the absorbed pump power is greater than 3 W. Under optimum pump conditions, the fiber-coupled diode-end-pumped Nd : : YAG and Nd : YVO_4 experiments were performed in the linear standing-wave cavity mentioned above. An aperture was inserted into the cavity to monitor the laser in the TEM_{00} mode.

Figs. 1 and 2 show the variations of the threshold pump power and the slope efficiency with the output mirror transmission, respectively. The theoretical results (solid lines) are calculated from (5) and (7) by using the following parameters: $I_{\rm sat} = 2.9$ kW/cm^2 [7], $\gamma = 2.8 \times 10^{-16}$ cm^3/s [5], $\alpha = 8$ cm^{-1}, $\omega_p = 0.25$ mm, $\omega_o = 0.20$ mm, $L = 0.01$, and $\tau = 250$ μs. For comparison, the calculation results without ETU effects are also shown in Figs. 1 and 2. The value of L is obtained by adjusting the theoretical results for best fit to the experimental slope efficiency in the region of $T \to 0$. It can be seen that the theoretical results including ETU effects agree very well with experimental data. As expected, ETU effects enhance the threshold pump power and reduce the output power more significantly at higher output mirror transmissions.

Similar plots of the variation of the threshold and the output power with the output mirror transmission in Nd : YVO_4 crystals are shown in Figs. 3 and 4. The theoretical results are calculated by using the following parameters: $I_{\rm sat} = 2.2$ kW/cm^2, $\gamma = 1.5 \times 10^{-15}$ cm^3/s [16], $\alpha = 8$ cm^{-1}, $\omega_p = 0.24$ mm, $\omega_o = 0.20$ mm, $L = 0.015$, and $\tau = 100$ μs. Here again the present results including ETU effects agree closely with experimental data. The good agreement between experimental data and theoretical predictions confirms the present analysis. To investigate the influence of pump size, we expanded the pump

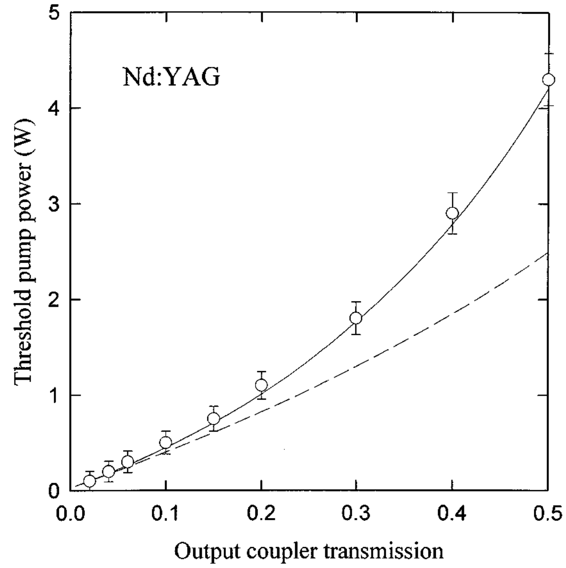

Fig. 1. A plot of the variation of the threshold pump power with the output mirror transmission in Nd : : YAG under the condition of $\omega_p = 0.25$ mm and $\omega_o = 0.20$ mm: experimental results (symbols) and theoretical results with ETU effects (solid line) and without ETU effects (dashed line).

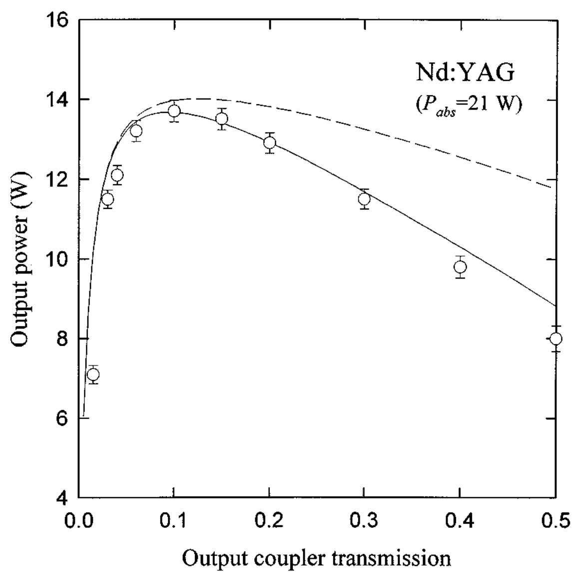

Fig. 2. A plot of the variation of the output power with the output mirror transmission in Nd : : YAG under the condition of $\omega_p = 0.25$ mm and $\omega_o = 0.20$ mm: experimental results (symbols) and theoretical results with ETU effects (solid line) and without ETU effects (dashed line).

spot size to $\omega_p = 0.34$ mm. The cavity mode size was changed to $\omega_o = 0.26$ mm for optimum mode-to-pump size ratio [14]. Fig. 5 shows the experimental and theoretical results for output power as a function of the output mirror transmission when $\omega_p = 0.34$ mm and $\omega_o = 0.26$ mm. Compared with Fig. 4, it can be seen that the influence of ETU was essentially not reduced by means of expanding the pump spot size.

Finally, it is worth while noting that the ETU effect increases the sensitivity of the output power to the output mirror transmission, as seen in Figs. 2, 3, and 5. Even so, Figs. 2, 3, and 5 also indicate that the influence of ETU on the output power is not significant for output transmissions lower than 20%. The experimental and theoretical results show that the

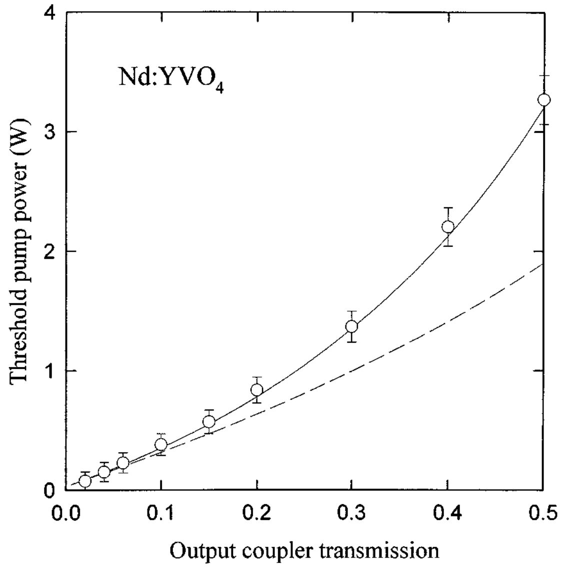

Fig. 3. A plot of the variation of the threshold pump power with the output mirror transmission in Nd : YVO_4 under the condition of $\omega_p = 0.24$ mm and $\omega_o = 0.20$ mm: experimental results (symbols) and theoretical results with ETU effects (solid line) and without ETU effects (dashed line).

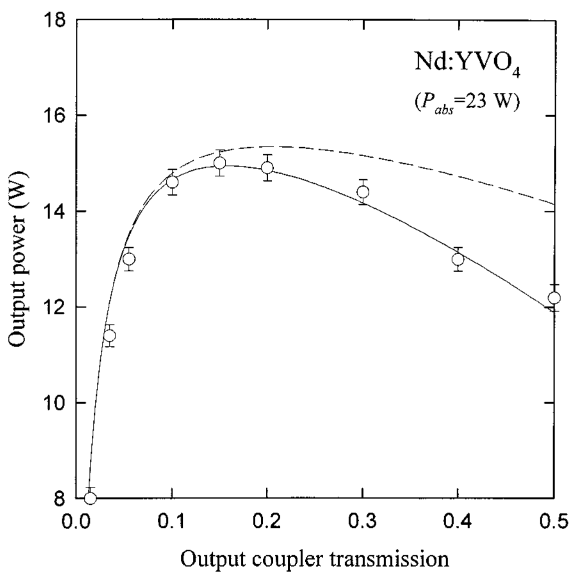

Fig. 4. A plot of the variation of the output power with the output mirror transmission in Nd : YVO_4 under the condition of $\omega_p = 0.24$ mm and $\omega_o = 0.20$ mm: experimental results (symbols) and theoretical results with ETU effects (solid line) and without ETU effects (dashed line).

optimum output transmission initially increases with increasing the absorbed pump power but its increase becomes rather slow for absorbed pump powers higher than 10 W. The optimum output transmissions are found to be around 10% and 15% for Nd : YAG and Nd : YVO_4 lasers in high-power operation, respectively. Therefore, the influence of ETU on the output power is not significant when the transmission is optimum.

IV. Conclusions

We have included ETU effects into the space-dependent rate-equation analysis to investigate the influence of ETU on

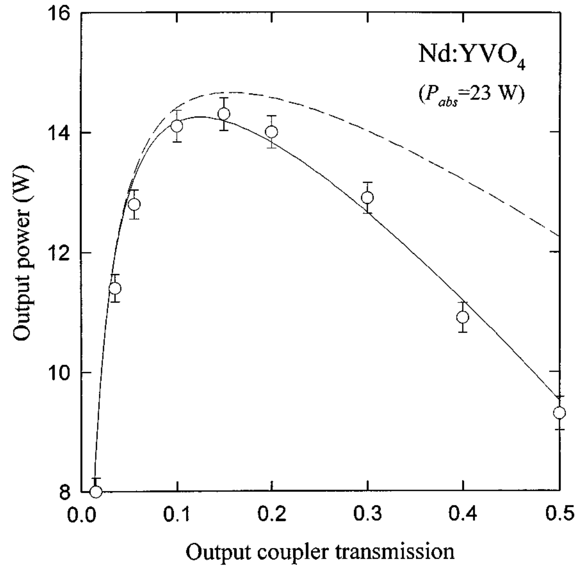

Fig. 5. A plot of the variation of the output power with the output mirror transmission in Nd : YVO_4 under the condition of $\omega_p = 0.34$ mm and $\omega_o = 0.26$ mm: experimental results (symbols) and theoretical results with ETU effects (solid line) and without ETU effects (dashed line).

scaling diode-end-pumped lasers to higher power. Experiments with Nd : YAG and Nd : YVO_4 crystals were performed to confirm the accuracy of the theoretical model. The good agreement between experimental data and theoretical predictions confirms the present analysis and validates our space-dependent rate-equation model. It is found that ETU effects increase the sensitivity of the output power to the output transmission. However, the ETU process has a rather weak influence on the output power for low transmission of the output coupler.

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