Impact of energy-transfer-upconversion on performance in quasi-three-level solid-state lasers

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Energy-transfer-upconversion (ETU) has a detrimental impact on performance in a number of different solid-state lasers [1]. ETU manifests itself as a reduction in the effective upper laser level lifetime leading reduced energy storage and increased thermal loading, and hence can be particularly problematic when attempting to scale to high average power or operate in Q-switched mode. In some situations ETU can be so severe that a very large fraction of the absorbed pump light is converted to heat and thermally-induced damage results, or it may prevent the build-up of a large enough population inversion for threshold to be reached. The requirement for a larger fraction of the active ions to be excited in a quasi-three-level laser can further exacerbate these issues. Thus, an accurate knowledge of the upconversion parameter and the impact of ETU on laser performance are crucial for power scaling of solid-state lasers and for efficient operation in Q-switched mode. In the past, modelling the influence of ETU on laser performance has required numerical simulations [1]. In this paper, we present a simplified analytical approach and derive an approximate expression for threshold in an end-pumped quasi-three-level laser taking into account ETU. The predictions of our model have been compared with experimental results for an in-band pumped quasi-three-level Er:YAG laser at 1645 nm confirming its validity. The resulting expression for threshold pump power is

$$P_{th}\,(\text{with ETU}) = P_{th}\,(\text{without ETU})\left(1+\frac{L_T + 2\eta_{LP}\, f_1 \sigma N_t l_R}{F_{ETU}}\right) \tag{1}$$

where $F_{ETU} = 4\sigma(f_1 + f_2)\eta_{LP} / W_{up}\tau\,\alpha_p$, f_1 and f_2 are the Boltzmann factors of the upper and lower Stark levels for the laser transition, W_{up} is the upconversion parameter, $L_T = -\log_e(1-L_R)-\log_e(1-T)$ is the resonator loss parameter, T is the transmission of the output coupler, L_R is the round-trip resonator loss (excluding the output coupler transmission), σ is the emission cross-section, τ is the fluorescence lifetime of the upper laser level, η_{LP} is the spatial overlap factor for the laser mode with the pumped region, α_p is the absorption coefficient, N_t is rare-earth ion doping concentration and l_R is the length of the laser rod. F_{ETU} can be thought of as a figure-of-merit for the impact of ETU on performance. It can be seen that a large value for F_{ETU} compared to the resonator loss and re-absorption loss will mean that ETU has only a small effect on performance. In Q-switched mode of operation, the value for L_R should include the loss under low cavity Q conditions to gauge the impact of ETU on performance. From (1) it can be seen that the effect of ETU on performance will be more severe in a laser with high resonator loss and/or high reabsorption loss (i.e. more pronounced three-level character). This can be mitigated by using low rare earth ion doping levels to reduce W_{up} and α_p at the expense of using a longer crystal for efficient pump absorption. Thus, the expression for threshold given above provides us with a useful guide as to how best to minimise the impact of ETU on performance for a particular laser system.

Fig 1 shows the measured threshold pump power for in-band pumped Er:YAG lasers operating at 1645 nm with different Er concentrations. The graph shows that the calculated threshold pump power and its behaviour are in very good agreement with the experimental results for moderate concentration levels. Further details of the threshold analysis and laser performance will be discussed.

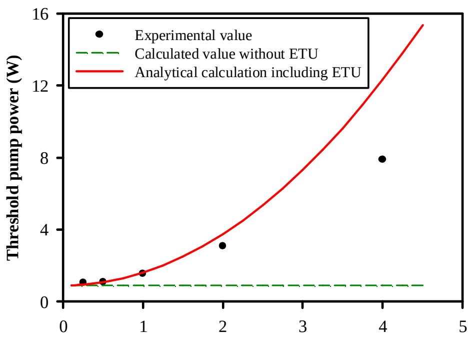

Fig. 1 Experimental and calculated threshold pump power as a function of a doping concentration.

References

[1] M. Pollnau, P. J. Hardman, M. A. Kern, W. A. Clarkson and D. C. Hanna, “Upconversion-induced heat generation and thermal lensing in Nd:YLF and Nd:YAG,” Phys. Rev. B, **58**, 16070-16092 (1998).