Heat Generation and Thermal Lensing in 2.8- μm $\text{Er}^{3+}:\text{LiYF}_4$ Lasers

Markus Pollnau *

Schatzkammer 10 B, D-21465 Reinbek, Germany

*Present Address: Department of Chemistry and Biochemistry, University of Bern

Freiestrasse 3, CH-3012 Bern, Switzerland

Tel. +41-31-631 42 53, Fax +41-31-631 43 99, email pollnau@iac.unibe.ch

For several years there has been an increased interest in lasers emitting at 3 μm mainly because of their potential applications in laser surgery. Due to the high absorption of 3- μm radiation in water, high-quality cutting or ablation is demonstrated in biological tissue using erbium-doped solid-state lasers. Recently, a cw output power of 1.1 W at this wavelength has been demonstrated in $\text{Er}:\text{YLF}$ ($\text{Er}^{3+}:\text{LiYF}_4$) under diode pumping at 970 nm [1]. However, efforts to scale diode-end-pumped 3- μm $\text{Er}:\text{YLF}$ lasers to higher powers, which would be required for many surgical applications, have been hindered by rod fracture.

To understand the mechanisms responsible for the increased risk of rod fracture in a 3- μm $\text{Er}:\text{YLF}$ laser, the heat generation, temperature profiles, and thermal-lensing behavior in this system under strong excitation were investigated in a finite-element calculation. It is shown that the underlying population mechanisms lead to a significantly increased heat dissipation in 3- μm $\text{Er}:\text{YLF}$ lasers pumped at 970 nm, compared to, e.g., 1- μm $\text{Nd}:\text{YLF}$ lasers pumped at 800 nm. The increased heat input in $\text{Er}:\text{YLF}$, in combination with the unfavorable temperature dependence of thermal and thermo-optical parameters [2], results in significantly higher temperature and larger temperature gradients, increased thermal lensing with consequent degradation in beam quality and increasing resonator losses, as well as increased stress and strain. Ultimately, with sufficient heat load, rod fracture occurs in a high-power diode-end-pumped system.

The finite-element calculation was performed for both lasing (round-trip loss 1%) and non-lasing conditions. A crystal with the optimum erbium concentration for 3- μm lasing of 15 at.% [1] was assumed. The calculation considered the relevant processes including interionic upconversion from the two laser levels. The parameters of upconversion from the $^4\text{I}_{13/2}$ lower laser level, $W_{11} = 4.8 \times 10^{-17} \text{ cm}^3/\text{s}$, and from the $^4\text{I}_{11/2}$ upper laser level, $W_{22} = 3.3 \times 10^{-17} \text{ cm}^3/\text{s}$, were derived from the measured data of [3]. The rate equations and the other calculation parameters were partly taken from [4]. The pump-waist radius was assumed to be 250 μm , with a pump-beam-quality factor of $M^2 = 70$ for both axes. It was assumed that 91% of the pump power at 967 nm was absorbed within the crystal of 6-mm length.

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At an incident power of 10 W, the fraction of the absorbed pump power of 9.1 W that is converted to heat in Er:YLF is 41% under lasing and 73% under non-lasing conditions (Fig. 1, left-hand side), compared to 25% and 54%, respectively, in Nd:YLF under comparable pump conditions. Considering the temperature dependence of the heat conductivity [2], this significantly increases the temperature in Er:YLF. Under lasing as well as non-lasing conditions, the heat load in Er:YLF is mainly due to the multiphonon relaxations following the upconversion and cross-relaxation processes from the laser levels and from the $^4S_{3/2}$ level, respectively.

Calculation of thermal lens powers considered the temperature dependencies of the thermo-optical parameters in YLF [2]. The results showed a significant difference in the thermal lens power under lasing and non-lasing conditions (Fig. 1, right-hand side). At an incident power of 10 W, the focal length in π -polarization (2.81- μm laser line) is $\sim$ factor-of-four shorter under non-lasing compared to lasing conditions. This demonstrates that increasing thermal lens power and, consequently, decreasing beam quality, increasing resonator losses, and resonator instabilities lead to additional heat dissipation and may significantly worsen the risk of rod fracture.

The above results suggest that erbium-doped fiber lasers which are much less affected by thermal problems will possibly have a higher potential of scaling the output power at 3 μm to more than 1 W [5].

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Fig. 1. Generated heat (left-hand side) and dioptric power of the thermal lens along the crystal a -axis in σ - (open symbols) and π - (solid symbols) polarization (right-hand side), both versus incident pump power, under lasing and non-lasing conditions.