Slope Efficiency of a Pulsed 2.8-μm Er^{3+}:$LiYF_4$ Laser

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Abstract

A 40 % slope efficiency from a pulsed Er^{3+}:$LiYF_4$ is demonstrated under cw Ti:sapphire pumping. This value clearly exceeds the Stokes limit of 35 % due to energy recycling from lower to upper laser level. With reduction of the pump-pulse duration a decrease of the slope efficiency and an increase of the threshold is experimentally observed and confirmed by a computer simulation. An approximate function following an exponential law can be used to describe the dependence of the slope efficiency on the pump-pulse duration.

Key Words

Infrared and far-infrared lasers, Rare earth and transition metal solid state laser, Laser theory

Introduction

In recent years there has been 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, highly precise cutting and ablation of biological tissue with minimal thermal damage to adjacent tissue can be performed. Long pulses (300 μs) applied in aqueous media, e.g. in orthopedic surgery, lead to an optimum in ablation efficiency [1]. Pulses can be generated either by pulsed modulation of the cw output or by pulsed excitation of the laser.

However, pulsed excitation of an Erbium 3-μm laser affects the efficiency of the laser output. In this contribution the dependence of the slope efficiency of an Er^{3+}:$LiYF_4$ crystal (15 at. % with respect to Y^{3+} site, 4.5 mm length) at 2.8 μm on pump-pulse duration is investigated. The dopant concentration of 15 at. % in $LiYF_4$ is proven to be optimal for 3-μm emission [2].

Experimental

The laser crystal was excited with an Ar^+-laser-pumped Ti:sapphire laser at 973 nm by direct pumping into the $^4I_{11/2}$ upper laser level. The 970-nm pump band has been shown to be more efficient than other pump wavelengths used for this laser transition [3]. The pump beam (TEM_{00} mode) controlled with a CCD camera was chopped with frequency 16.7 Hz and duty cycle 33 %, which provides an excitation time of 20 ms. The pump beam was focused onto the crystal front face with a lens of focal length $f = 65$ mm. The pump-beam waist at the crystal front surface was approximately 40 μm. More than 99 % of the pump power are absorbed within the crystal of length 4.5 mm. The $LiYF_4$ crystal was mounted on a water-cooled copper block and was placed close to the input mirror of a nearly hemiconcentric resonator. Both mirrors, the plane input and the concave (75-mm radius) output mirror had a non-optimized transmission of 1.2 % at 2.81 μm. The 2.81-μm laser radiation was measured to be transmitted in equal parts on both sides of the resonator. This is verified

by placing identical beam splitters on each side outside of the resonator, pumping through one of them, and measuring simultaneously the output powers reflected by the beam splitters.

Results and Discussion

The output power as function of the input pump power is shown in Fig. 1. A slope efficiency with respect to absorbed pump power of 40 % is obtained, to our knowledge the highest value so far for any 3 μm-Er^{3+} laser. Thus the slope efficiency clearly exceeds the Stokes limit of

$$\eta_{st} = \lambda_{pump} / \lambda_{laser} = 35 \% \quad .$$

This results from energy recycling into the upper laser level via interionic upconversion ($^4I_{13/2}$, $^4I_{13/2}$ —> $^4I_{15/2}$, $^4I_{9/2}$) [3,4,5]. The laser threshold was 13 mW (slope threshold 60 mW). A maximum output power of 77 mW was reached with an input power of 250 mW which was limited by the available pump laser.
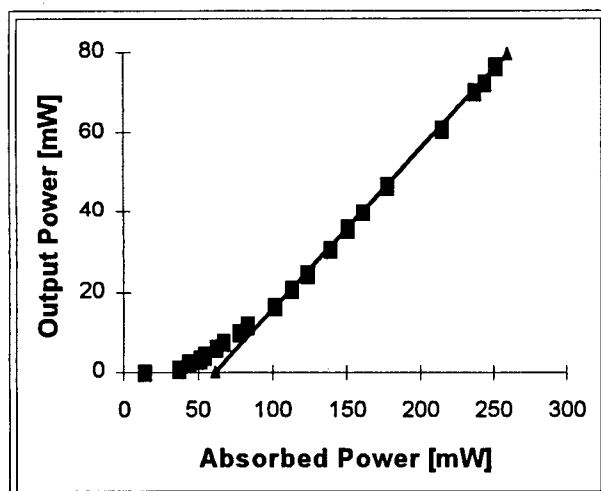

Figure 1. Output versus input power of a pulsed Er^{3+}:LiYF$_4$ laser under quasi-cw Ti:sapphire laser excitation (20-ms pump pulses). A maximum slope efficiency of 40 % has been experimentally demonstrated. Threshold of the laser is 13 mW and slope threshold is 60 mW (triangle).

In a second experiment which was performed with the same experimental setup the dependence of both, slope efficiency and slope threshold on pump-pulse duration was investigated (c.f. Figs.2 and 3). Therefore the pump pulse duration was reduced from 10 ms down to 1.68 ms by varying the duty cycle (between 33 %

and 5.6 %) of the chopper with fixed frequency (33.3 Hz). The experimental results (squares) showing the resulting consequences on slope efficiency are presented in Fig. 2.
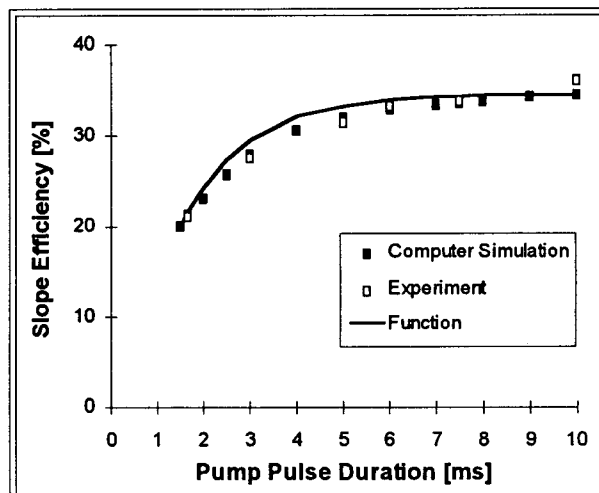

Figure 2. Dependence of the slope efficiency on pump-pulse duration is shown. Data from the experiment and from the computer simulation are approximated by a function which depends on the storage time of the upper laser level.

The slope efficiency drops from 36 % (10 ms pump-pulse duration) to 21 % (1.67 ms pump-pulse duration). In Fig.3 the slope threshold $P_{slope,thr}$, defined as the zero point of the progression line of the linear input-output slope, is presented as a function of pump-pulse duration. The slope threshold has been increased from 60 mW (10 ms pump-pulse duration) to 90 mW (1.67 ms pump-pulse duration).

With help of a computer simulation considering all relevant processes (ground-state absorption (GSA), excited-state absorption (ESA), interionic processes and their inverse processes, stimulated emission and the experimental data of crystal and resonator) time-resolved rate equations similar to those presented in Ref. [4] were solved in order to reproduce the experimentally obtained data (c.f. Fig.2 and Fig.3). With the experimentally obtained values for slope efficiency $\eta(10 \ ms) = 36$ % (c.f. Fig.2) and slope threshold $P_{slope,thr}(10 \ ms) = 60$ mW (c.f. Fig.1 and Fig.3) and values for the resonator losses of 0.8 % and the emission cross section of $\sigma_{em} = 1.5 \times 10^{-20}$ cm^2, the computer simulation gave good agreement with the experiment.
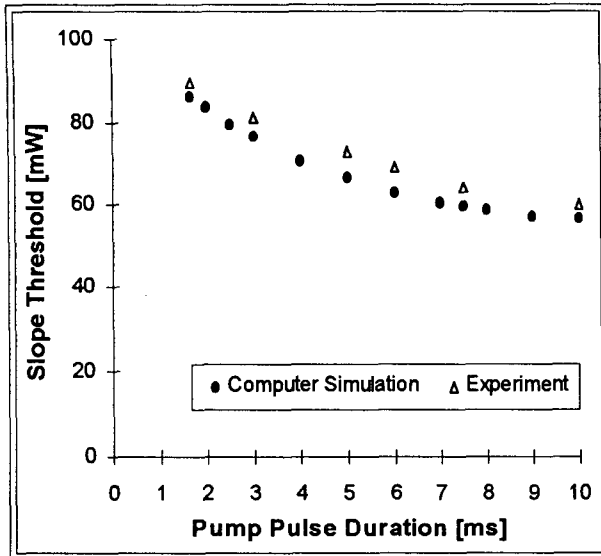
Figure 3. The slope threshold, defined as the zero point of the progression line of the linear input-output slope, is presented as a function of pump-pulse duration. The data experimentally obtained (triangles) are reproduced by the computer simulation (circles).

The dependence of the slope efficiency $\eta(T)$ on pump-pulse duration T (c.f. Fig. 2) can be approximated with a function that describes a decay - and a saturation process. Considering

- that the slope efficiency obtained under cw pumping represents an upper limit of the function and
- that threshold inversion is established with a delay of $(T_{delay} = E_{thr}/P_{in})$

the approximate function can be written as :

$$\eta_{slope}\,(T) = \eta_{slope}\,(cw) \left\{ 1 - \exp\left[-\frac{T - E_{thr}/P_{in}}{\tau_{store}} \right] \right\} \quad (1)$$

with a storage time, that is the effective lifetime of the upper laser level, defined as

$$\frac{1}{\tau_{store}} = \frac{1}{\tau_2} + N_2 W_{22} \quad (2)$$

With an intrinsic lifetime of the upper laser level $\tau_2 = 4$ ms , an upconversion parameter $W_{22} = 1.8 \times 10^{-17}$ cm^{3}s^{-1} [5], and an upper laser level

population $N_2 = 2.6 \times 10^{19}$ cm^{-3} (derived from simulation).

With values for slope efficiency in the case of cw excitation $\eta(cw) \cong \eta(10$ ms), threshold energy $E_{thr} = 60$ µJ and input power $P_{in} = 180$ mW (derived from experiment) a storage time of the upper laser level $\tau_{store} = 1.4$ ms is determined from formula (3).

Conclusion

In conclusion a slope efficiency of 40 % from an Er^{3+}(15 % at.):LiYF$_4$ 2.8 µm laser is demonstrated. This value clearly exceeds the Stokes limit of 35 % due to energy recycling from lower to upper laser level. A decrease of the slope efficiency and the increase of the slope threshold with reduction of the pump-pulse duration is experimentally observed and reproduced by a computer simulation. An approximate function following an exponential law can be used to describe the dependence of the slope efficiency on the pump-pulse duration.

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References

[1] M. Ith, H. Pratisto, H.J. Altermatt, M. Frenz, and H.P. Weber, Appl. Phys B **59**, 621 (1994).

[2] T. Jensen, A. Diening, and G. Huber, in Conference of Lasers and Electro-Optics, Vol. **15**, 1995 OSA Technical Digest Series (Optical Society of America, Washington DC, 1995), post-deadline paper CPD29.

[3] R. C. Stoneman and L. Esterowitz, Opt. Lett. **17**, 816 (1992).

[4] M. Pollnau, W. Lüthy, and H. P. Weber, Phys. Rev. A **49**, 3990 (1994).

[5] H. Chou and H.P. Jenssen, in Tunable Solid State Lasers, Vol. **5** of the OSA Proceeding Series, M.L. Shand and H.P. Jenssen, eds. (Optical Society of America, Washington, DC, 1989), pp. 167 - 174.