Q-switching of a mode-controlled, diode-side-pumped Nd^{3+}:$YLiF_4$ laser at 1053 nm with high efficiency and diffraction limited beam quality

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Abstract: In this work we present passively Q-switched operation of a Nd^{3+}:$YLiF_4$ slab laser that achieves 3.2 mJ per pulse and 500Hz rep rate with diffraction limited beam quality by mode-controlling in a simple, compact cavity.

OCIS codes: (140.3580) Lasers, solid state; (140.3530) Lasers, neodymium; (140.3480) Laser, diode-pumped;

1. Introduction

Q-switched, and diode pumped solid state lasers have become rugged and reliable devices in many applications such as industrial, medical, environmental and scientific because of several key advantages such as compactness, efficiency and long lifetime. Several pumping schemes are nowadays employed. Longitudinal pumping schemes show some restrictions with respect to power scaling of the TEM_{00} mode due to thermal effects caused by the high pump densities. This has initially led to a certain decrease in the usage of fluoride crystals such as $YLiF_4$ (YLF) due to their low fracture limit when compared to oxide crystals, in spite of their excellent thermo-optical and energy-storage characteristics. Proper thermal management has recently led to very high cw power and diffraction limited output in a longitudinally pumped Nd:YLF slab design [1]. Dergachev et al. have developed a side-pumped Nd:YLF laser design with a multipass slab technique and 806 nm diode bars to get uniformly distributed pump absorption inside the crystal [2]. They have been able to obtain as much as 20 W of TEM_{00} mode at the 1053 nm emission for 64 W of continuous wave (CW) pump power, resulting in 31% optical efficiency. At the higher gain 1047 nm emission line they achieved actively Q-switched operation with approximately 3.8 mJ at 500 Hz repetition rate in a 24 ns pulse for 40 W of pump power. Nd:YLF is an uniaxial crystal (and therefore naturally polarized) that has two principal lasing transitions at 1047 nm (π) and at 1053 nm (σ), corresponding to the polarizations parallel and perpendicular to the crystal c-axis, respectively. Although the 1053 nm transition has a 33% lower gain, it also has the advantage of a weaker thermal lens [3], with a dioptric power 2.3 times smaller than that for the 1047 mm transition. Additionally, the long upper laser level life time of 480 μs permits excellent energy storage characteristics and therefore efficient Q-switching.

The cavity design employed in our set-up uses the high inversion density located in a shallow region near the pumped surface and takes advantage of the 1053 nm transition in order to benefit from the weaker thermal lens. A similar configuration that also uses one total internal reflection at the pump face was proposed for the first time by Bernard et al. using a grazing incidence configuration [4] in a high gain crystal. This resonator was dubbed bounce resonator. Minassian et al. achieved 68% of optical-to-optical efficiency in multimode operation and 58% efficiency in fundamental mode using an asymmetric cavity geometry in a $Nd:YVO_4$ bounce resonator [5].

In this work we show efficient Q-switching of a diode-side-pumped Nd:YLF laser at 1053 nm and demonstrate diffraction limited beam quality by using a new concept of mode-controlling.

2. Laser setup

The home-grown Nd:YLF crystal was a-cut and had its c-axis orientated parallel to the diode polarization in order to access the higher absorption cross-section of the π polarization. The slabs dimensions were 14 x 13 x 3 mm^3 and the dopant concentration was 0.8 mol%. For the cw experiments we used a 20 W TM-polarized and fast-axis collimated diode bar whereas for the qcw (quasi-continuous) experiments we used a 44 W TM-polarized diode operating at 797 nm. The diode beam was focused into the crystal by a f = 2.5 cm spherical lens, resulting in a spot size of 4.2 mm x 97 mm in the horizontal and vertical directions, respectively.

For the cw experiments the crystal was side pumped with two different configurations. In the first experiment, a compact plano-convex cavity with a 30cm ROC high reflector mirror and a flat output coupler with 7% transmission were used in a single pass configuration (**Erro! Fonte de referência não encontrada.**a). This cavity was very compact with less than 11 cm overall length. Fundamental mode was achieved in a double pass configuration using an additional flat high reflector mirror (M3) and a 3m ROC folding mirror (**Erro! Fonte de referência não encontrada.**b). For the qcw, Q-switched experiments a Cr^{4+}:YAG saturable absorber of T = 70% initial transmission was added before the output coupler (**Erro! Fonte de referência não encontrada.**c) and a 10% transmission output coupler was employed.

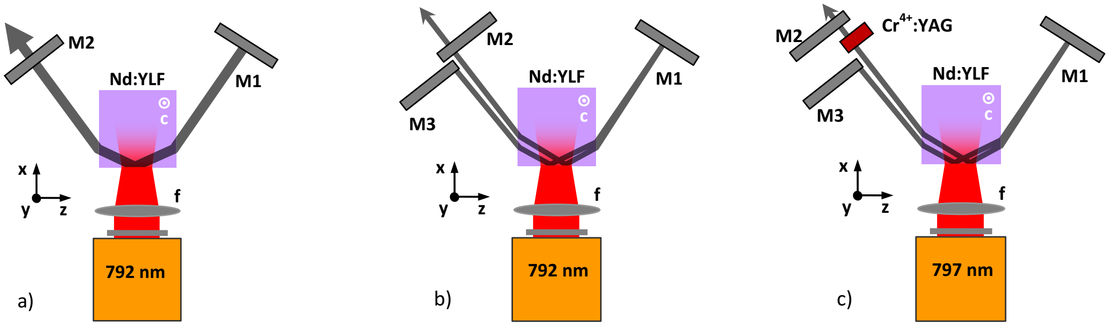

Fig. 1: Cavity configurations: Single bounce resonator (a); double bounce resonator (b) and passively Q-switched resonator (c). M2 is a flat T = 10% output coupler, M1 a curved folding mirror (ROC=3m) and M3 is a flat, high reflector; f is the pump focusing lens.

The transverse-mode behaviour in the side-pumped bounce- resonator was analyzed and simulated with a MATLAB program. The equation for the onset of higher order mode oscillation can be calculated using the theory of Kubodera et al. [6]. In the case of our specific resonator design an analytical relation was obtained for the threshold pump powers $P_{th,00}$ and $P_{th,10}$ of the TEM_{00} and TEM_{10} mode, respectively:

$$\frac{P_{th,00}}{P_{th,10}}=\frac{\int s_1 r dV}{\int s_0 r dV}=1+\frac{\alpha^2 w_x{}^2}{4}-\frac{\alpha\ w_x}{\sqrt{2\pi}}\exp\left(-\frac{\alpha^2 w_x{}^2}{8}\right)\left(1-erf\left[\frac{\alpha\cdot w_x}{2\sqrt{2}}\right]\right)^{-1} \qquad (1)$$

where s_0 and s_1 are the normalized distribution functions of the photon density of the TEM_{00} and next higher order mode, respectively, and r is the distribution function of the normalized pumping rate. S_0 is the total photon number in the TEM_{00} mode normalized to the saturation flux, $I_S=(\sigma_e \tau_f)^{-1}$, c is the speed of light, σ_e the emission cross section, τ_f the fluorescence lifetime, erf is the error function, α is the absorption coefficient of the crystal, w_x is the mode's beam radius along the pump direction and dV integrates over the pumped volume of the crystal.

3. Results

The single bounce resonator generated in cw operation a multi-mode output with a maximum of 9.5 W for a pump power of 21 W, resulting in 45% optical-to-optical efficiency and 49% slope efficiency (Fig. 2a).

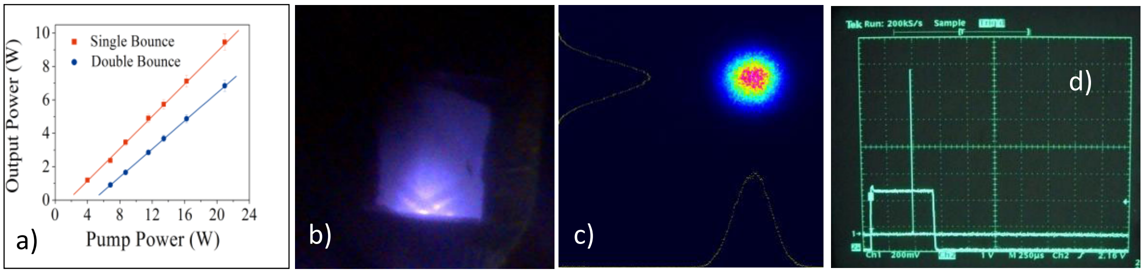

Fig. 2: a) output power versus diode pump power for single and double bounce configurations; b) two TEM_{00} beams undergoing total internal reflection at the pump face of the Nd:YLF slab in the double bounce configuration; c) diffraction limited output of the double bounce resonator; d) oscilloscope trace of diode pump pulse and Q-switched pulse at 1053 nm.

In the double bounce resonator we achieved 6.9 W output power for 21 W of input pump power, which results in 33% optical-to-optical efficiency and 42% slope efficiency, and an excellent beam quality of M^2 of 1.16 x 1.05 in the horizontal and vertical directions, respectively (Fig. 2a,b,c).

For Q-switching, pump pulse duration of approximately 550 μs and a peak power of 44 W were used. TEM_{00} mode operation was maintained during Q-switched operation and a maximum of 3.2 mJ was measured for a 12 ns pulse duration which results in a pulse peak power of 267 kW (Fig. 2d). The pulse duration broadened by about 2 ns for the highest rep rate employed in our experiment of 500 Hz (limited by the diode driver). In order to achieve a single clean pulse at the 500 Hz rep rate, the saturable absorber was cooled by means of a specially designed heat sink. The timing jitter of the Q-switched pulse with respect to the pump pulse is approximately 100 ns whereas the jitter between subsequent pulses is limited only by the diode drivers electronics. Even shorter pulses were achieved using saturable absorbers with lower initial transmission but resulted in coating damage.

In the double bounce cavity, maximum output power is achieved for separations between both beams ranging from 1.3 mm to 2 mm inside the crystal. Outside this range, a less efficient, low-order multi-mode operation was observed. This shows that the second pass through the crystal needs to occur at a specific separation from the first beam, which is large enough to increase the overall width of both beams together to a point where there is not enough gain left farther inside the crystal for the next higher mode to oscillate. On the other hand, if the separation is too large, sufficient gain remains between both beams permitting the next higher order mode to oscillate.

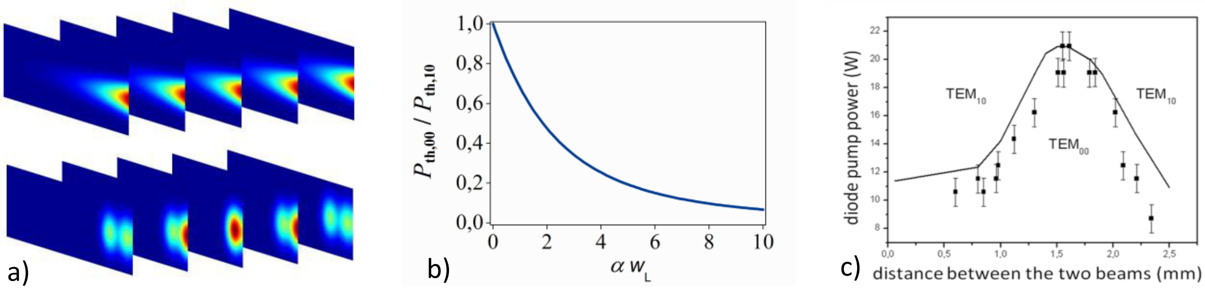

Fig. 3: a) Five cross sections of the diode-side pumped region of the crystal: above) normalized pump distribution; below) effective absorption at pump face shown for two parallel TEM_{00} modes undergoing total internal reflection. b) Threshold pump power of the TEM_{00} mode divided by the threshold pump power of the TEM_{10} mode for different products of absorption coefficient times laser beam radius. c) Beam quality as a function of pump power and intracavity beam separation. solid line: simulation; dots: measurements with CCD.

In order to apply equation (1), an important and necessary condition is that the TEM_{00} mode oscillates before all other modes even in the absence of more losses for higher order modes. Fig 3a shows the simulation of the pump distribution and the effective absorption of the two laser beams at the crystal facet. Fig 3b demonstrates that the threshold pump power for the higher order mode is always above the threshold power for the fundamental mode in the case of the side pumped bounce oscillator. Fig 3c shows the good agreement between the simulation and the results obtained in our experiment: Fundamental mode could be maintained up to 21 W of cw operation for a separation of 1.7 mm between the two bounce beams inside the crystal.

4. References

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