High-efficiency, Q-switched and diffraction-limited Nd:YLF side-pumped laser

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ABSTRACT

This work presents a mode-controlled quasi-CW resonator design based on an Nd:YLF crystal. Up to 47 % optical efficiency was obtained and, by passively Q-switching the laser, 209 kW of peak power at 1053 nm was obtained. The new resonator design is capable of delivering 2.3 mJ and 11 ns pulses in a very compact, simple and lightweight set-up.

Keywords: DPSSL, neodymium, 1053 nm, Q-switched, side-pumped, Nd:YLF, mode controlling.

1. INTRODUCTION

There exist a great number of processes and applications in industry, biomedicine, pure and applied sciences that rely on high power Q-switched lasers either for material processing or process analysis [1,2]. In the past years, several developments have been made in the laser design field of research, aiming to achieve compact, cost effective and electrically efficient laser systems at reduced cost that are capable of delivering high energy pulses of the order of ten nanoseconds. Other major goals of this field are power scalability of the resonator design, diffraction limited beam quality and high repetition rates. Several novel laser designs have been reported in the specialize literature claiming to have achieved one or more of these goals [3–5].

Lasers systems with high power and high energy may be supplied by traditional lamp pumped designs, however, they generally cannot deliver high repetition rates (> 30 Hz) nor good beam quality. Also, the efficiency of such a system is usually very low. Nevertheless, given their robust design, they are still in use in applications such as medical and dental [6,7]. On the other hand, conduction cooled, quasi-continuous (qcw) diodes are compact and efficient systems of up to 300 W output power per bar, capable of operating with duty cycles ranging from 2 to 20 % which allows for repetition rates of a few kHz, depending on the on-time of the diode.

Although a significant amount of novel crystalline laser materials with important features for the usage as gain media in Q-switched lasers can be found in the literature, the neodymium lithium yttrium tetra fluorite (Nd:YLF) has proven some excellent thermo-optical characteristics along with its high energy storage capability due to its long upper laser level lifetime. Its natural birefringence and combination of negative refractive index variation and positive laser facet bulging with temperature leads to a very weak thermal lens and no thermal birefringence, allowing for a very high quality laser output beam [8].

There are two main laser transitions in the Nd:YLF uniaxial crystal, 1047 nm and 1053 nm, corresponding to the polarization parallel (π) and perpendicular (σ) to the c-axis, respectively. The sigma (1053 nm) laser emission band presents lower laser gain, but the dioptric power of its thermal lens is a factor of 2.3 weaker than for the 1047 nm transition [9]; besides, this wavelength is also of great interest in laser fusion experiments [10].

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Active Q-switching of a diode-pumped laser produces very short jitter between the pulses, less than the pulse duration, as is required for many applications. This working regime is generally obtained by two different technologies: acoustic-optical Q-switching or electro-optical Q-switching. Very short pulses with duration comparable to passive Q-switching can only be obtained with electro-optic Q-switching that requires a high voltage, fast-switching power supply of increased complexity which is susceptible to electrical failure. On the other hand, saturable absorber Q-switching is passive and therefore much less complex but it is difficult to reduce its characteristic timing jitter that is typically of the order of hundreds of nanoseconds [11],[12].

The most well-known pumping scheme that employs diodes is the end-pumped resonator setup that, based on recent developments in high-power fiber-coupled diodes operating at 800 nm, has received a lot of attention. This configuration allows a very good overlap between the pump beam and the laser and outstanding optical-to-optical efficiency [13],[14]. Although the directional emission of the laser diode is favorable for tight focusing and spatially matching with the TEM_{00} resonator mode, thereby allowing for diffraction limited output, power scaling of the TEM_{00} mode is limited. The longitudinal set-up permits at the most two pump spots on either end of the gain crystal and the depth of focus of the pump beam is small given the diode's low beam quality and therefore, beam overlap with TEM_{00} is limited to a small length, calling for high pump absorption. Especially when using Nd:YLF the high pump densities inside the crystal combined with its low thermally induced stress fracture limit can cause easily catastrophic damage when compared to other crystals such as $Nd:GdVO_4$.

In the traditional power-scalable, side-pumped resonator design the pump power density is reduced by orders of magnitude however, this is achieved at the expense of beam quality and energy efficiency [15],[16]. At comparable output powers, the side-pumped setup has generally the advantage of reduced complexity and cost over the longitudinal set-up. There are only few power scalable configurations that allow good beam quality and high efficiency with side-pumping, most of these are complex zig-zag geometries or actively Q-switched master-oscillator-power-amplifier (MOPA) systems [17],[18].

In this work a resonator design that is very compact, lightweight, efficient, power scalable and versatile, as required in a number of applications such as military and LIDAR, or portable lasers for surgery, where size, weight, reliability and power are major factors. We demonstrate that this laser setup presents very high optical-to-optical efficiency and allows Q-switched operation. The mode-controlling approach allows high pulse energies and repetition rates with good beam quality.

2. RESONATOR SET-UP

In this letter we present a laser design similar to the "bounce" resonator [19],[20]. A bounce resonator setup is based on a grazing incidence total internal reflection of the laser beam at the pump surface of the crystal. The Nd:YLF active medium has a lower absorption coefficient in comparison with $Nd:YVO_4$ or $Nd:GdVO_4$ and therefore the inverted region behind the crystals pump facet is much less shallow. For this reason grazing incidence is not required at the location of total internal reflection and larger angles may be used meanwhile maintaining good overlap with the inversion region.

In this setup, the active medium is cut and polished in a square shape and the laser beam enters the side surface at Brewster angle, therefore no coating is required. The simple but robust design permits a double bounce configuration, with two total internal reflections at the pumped surface, increasing the overlap between the lowest order mode and the region with the highest population inversion. This approach effectively decreases the gain available for higher order modes by correctly adjusting the beam diameter and separation of both beams. It has been demonstrated that in a double pass cavity design, the TEM_{00} mode is more efficient than higher order modes without the need for any other mode-selective techniques, depending only on the beam separation, pump power and beam waist [21]–[25]. For a given set of cavity mirrors and fixed distances among them, the waist of each transverse mode is fixed, such that only the distance D between both beams is variable, allowing for mode controlling of the beam quality in an easy manner. The absence of any additional mode-selective device in the resonator reduces losses for the TEM_{00} and creates a very efficient laser cavity.

Figure 1 shows a schematic setup of the laser design, where CL is a 25 mm cylindrical lens used to collimate the diode's fast axis and SL is a spherical lens with 25 mm focal distance. A half wave plate was employed to rotate the diode's polarization by 90 degrees in order to access the crystal's highly absorbing pi-polarization (parallel to the diodes TE direction). M1 is a plane output coupler with 40% transmission at 1053 nm and M3 is a flat high reflectivity (HR) mirror. M2 is a curved high reflective mirror with 3 m radius of curvature (ROC). The largest beam waist inside this resonator set-up is near the curved folding mirror M2. This fact is used to limit higher mode oscillation, which is a function of beam waist, placing M2 as close as possible to the crystal.

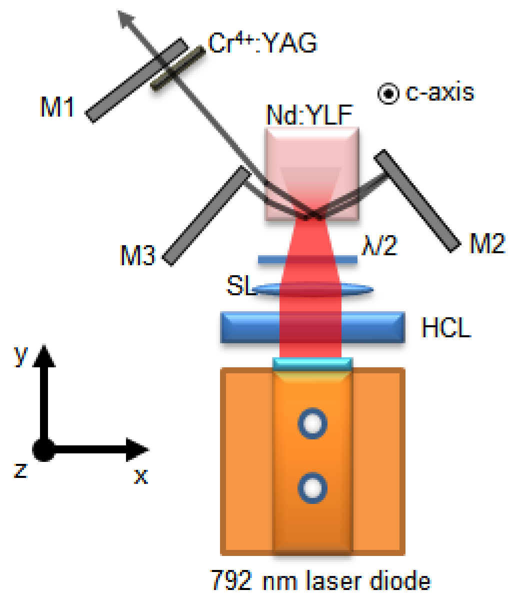

Figure 1. Schematic diagram of the diode pumped Nd:YLF mode-controlled laser resonator. M1 is a plane output coupler, M2 is a curved high HR mirror and M3 is a flat HR mirror. HCL is a horizontal cylindrical lens and SL is a spherical lens, λ/2 is a half-wave plate.

The active medium is a $YLiF_4$ slab with 1 mol% neodymium doping level at the yttrium site. The sample is 13x13x3 mm^3 in dimension and was a-cut with its c-axis orientated perpendicular to the crystal's largest surface. The crystal was placed on a copper bar without cooling for heat dissipation and mechanical support. The 40 W, TM-polarized and fast-axis collimated diode was focused into the crystal by a f = 25 mm spherical lens (SL) and a f = 25 mm horizontal cylindrical lens (HCL), resulting in a spot size of approximately 4 mm width and 0.1 height (horizontal and vertical directions in figure 1). After the focusing optics and Fresnel reflection at the uncoated pump facet, about 35.7 W of the pump power were effectively delivered to the crystal at 40 W of pump power. To avoid thermally induced stress fracture of the crystal, no more than 7 W of average pump power was delivered to the crystal.

In this cavity, the smallest beam waist is near the plane output coupler, therefore the Cr^{4+}:YAG saturable absorber was kept as close as possible to this mirror during the Q-switching experiments, allowing for fast saturation.

The diode is set to operate at 797 nm in continuous operation. By using a thermoelectric device, we were able to tune the laser's emission to 792 nm in qcw operation by temperature tuning of the diode to 27^{o} C. The efficiency of this mode-controlled laser relies on a stable absorption distribution of the pump photons at the pump surface. As opposed to an end-pumped configuration, where the laser and the pump are collinear, in this side-pumped design any change in the effective absorption will result in a poorer overlap between the laser and the pump or in multi-mode operation. Since the spectral bandwidth of the absorption of the neodymium ion is very narrow, any small shift at the pump wavelength will result in significant fluctuations of the output power. Therefore the pump diode that is temperature tuned to the absorption peak of the crystal must remain at constant and stable temperature (less than 0.3 degrees Celsius of fluctuation) during the whole duration of the experiment or otherwise significant fluctuation are observed at the output power of the laser.

3. EXPERIMENTS

In previous works we demonstrated that this laser setup shows power scalability of the TEM_{00} mode, good optical-to-optical efficiency in quasi-continuous operation, high Q-switched pulse energy and kHz-level repetition rates [21–25]. The 1 mol% neodymium doping of the Nd:YLF slab used in this work is higher than the concentration used in the previous works. The higher doping concentration resulted in a peak absorption coefficient of about 6 cm^{-1} at 792 nm (Figure 2), decreasing the pump penetration depth and increasing the gain mainly by an increase in overlap with the resonator mode. As will be shown below, pure TEM_{00} laser mode was obtained at higher pump levels when compared to our previous work.

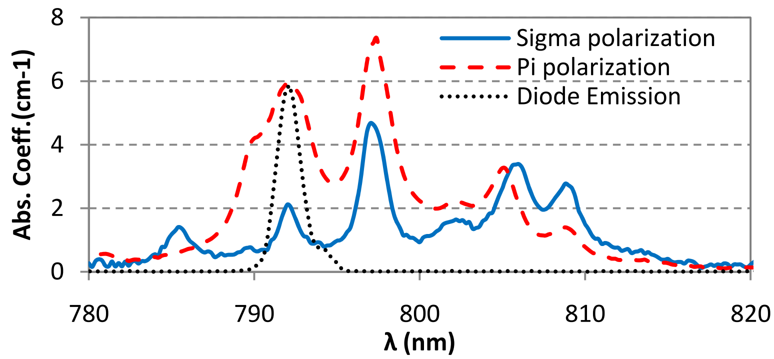

Figure 2: (color online) Absorption coefficient of the crystal employed in this work as a function of the wavelength for both π and σ polarization.

The resonator was first characterized in terms of its performance during long pulse qcw excitation. The average duration of the qcw pulses emitted at 1053 nm was 0.85 ms. At the maximum pump power of 35.7 W absorbed by the crystal, 16.7 W of output power were measured in TEM_{00} mode corresponding to 61% of slope efficiency and 47% optical-to-optical efficiency. To the best of our knowledge, this is the highest efficacy ever reported for a side-pumped Nd:YLF laser. By using an output coupler optimized for qcw operation with less transmission even higher efficiencies might be obtained. The M^2 of this laser is 1.31 and a picture of the TEM_{00} intensity distribution is shown in Figure 4. The threshold of the laser is 8.9 W.

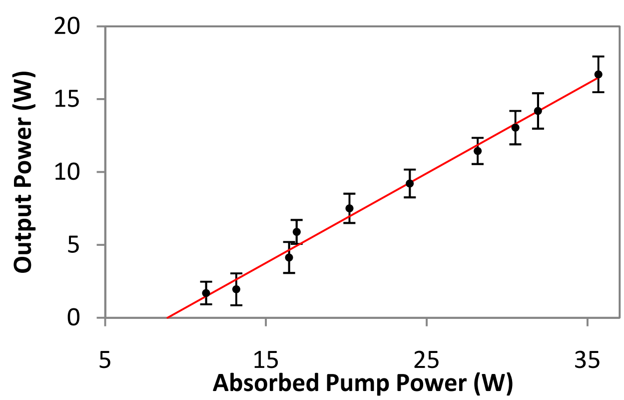

Figure 3. qcw output power as a function of the pump power

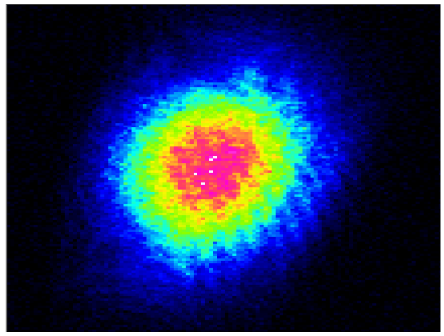

Figure 4. Picture of the beam intensity distribution made using a Thorlabs CCD camera, model DCU223M during qcw operation. The M^2 of this laser is 1.31.

It is well known that during Q-switching the first pulse has generally a higher energy than the subsequent pulses. This is not restricted to passive Q-switching but also happens with active Q-switching where most modern devices contain a first-pulse suppression mechanism in order to avoid destruction of the optics inside the resonator. It is therefore of interest to use qcw – operation for efficient, high-pulse-energy Q-switching with a short pump pulse duration, just long enough to permit only one single short pulse per pump pulse. In this manner only a series of first-pulses will emerge from the laser at the qcw repetition rate with pulse energies that are 10 % to 40 % higher than during long pump pulses. Additionally, since the long term repetition rate is given by the power supply and not by the complex bleaching mechanism of the saturable absorber, the long term repetition rate shows negligible jitter. Short term, pulse–to-pulse (standard deviation) jitter was roughly 100 ns with this set-up.

By inserting a saturable absorber with 50% initial transmission close to the 40% transmission output coupler and correctly adjusting the beam separation inside the active gain medium, a single Q-switched pulse per pump pulse was obtained. The absorber required a 450 µs long pump pulse duration, which is close to the spontaneous fluorescence life time of the $^4F_{3/2}$ energy level and therefore, the maximum population inversion was achieved. A pulse energy of 2.3 mJ and pulse durations of 11 ns (FWHM) were obtained, corresponding to a peak power of 209 kW (figure 6). The energy absorbed was 15 mJ, which corresponds to 15% optical-to-optical conversion efficiency. No multimode operation was observed at all pump powers and beam separations, even outside the separation interval for cw fundamental-mode operation [25].

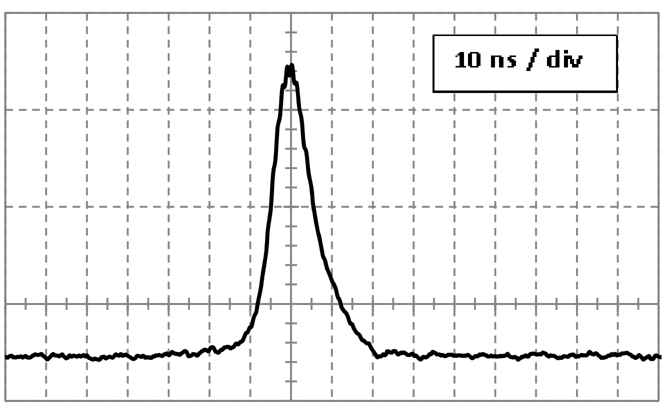

Figure 6. Temporal pulse profile for a saturable absorber with 50% initial transmission.

After a few minutes of warm up time, the laser produced a very stable output, with overall fluctuation lower than the detector fluctuation (Coherent PS19), which represents less than 2%, over a period of 4 hours of free running.

4. CONCLUSIONS

Up to 47% optical-to-optical conversion efficiency was obtained from a mode-controlled cavity emitting at 1053 nm which is, to the best of our knowledge, the highest efficiency ever reported for a side-pumped Nd:YLF laser. We obtained up to 16.7 W of qcw peak output power at 1053 nm by diode pumping with 35.7 W at 792 nm. Fundamental mode oscillation was extracted by using a three-mirror cavity comprised by a folding mirror of 3 m radius of curvature, a plane HR end mirror and a plane output coupler with 40% transmission. We also report on passively Q-switched pulses of 2.3 mJ at 116 Hz repetition rate and 11 ns pulse duration with this same cavity set-up.

This is a versatile, and simple design that is very efficient and stable showing less than 2 % of overall power fluctuation during a 4 h free running test.

5. ACKNOWLEDGES

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