1kHz repetition rate, mode-controlled, passively Q-switched Nd:YLF laser operating at 1053 nm

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ABSTRACT

This work presents a passively Q-switched and mode-controlled Nd:YLF laser that generates 150 kW of peak power at 1053 nm with 1kHz repetition rate. The new resonator design is capable of delivering 1.5 mJ and 10 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

The research and development of novel resonator schemes aiming to achieve power scalability, short Q-switched pulses of the order of 10 ns, diffraction limited beam quality and high repetition rates is still a major goal in the laser cavity design field. A great number of industrial, biomedical, environmental and scientific applications would benefit from a laser resonator design that provides these characteristics at reduced complexity and costs. Whilst high power is supplied by simple lamp pumped designs, they generally cannot deliver high repetition rates (> 30 Hz) nor good beam quality. On the other hand, compact quasi-continuous diodes can operate with duty cycles ranging from 2 to 20 % which allows, in theory, repetition rates up to few kHz, depending on the on-time of the diode.

Although nowadays there are several host materials available for neodymium doped gain media, the Nd:YLF (Nd:$YLiF_4$) has proven to have some excellent thermo-optical characteristics, along with its high energy storage capability. It also has natural birefringence that eliminates thermal depolarization of the laser. The combination of the negative variation of the refraction index with the temperature of the YLF with the crystals' positive thermal expansion coefficient leads to a very weak thermal lens, allowing high quality output beam [1].

The Nd:YLF is a uniaxial crystal that has two different main laser transitions at 1047 nm and 1053 nm, corresponding to the polarization parallel (π) and perpendicular (σ) to the c-axis, respectively. The 1053 nm emission band has lower laser gain, but its thermal lens' dioptric power is also a factor of 2.3 weaker than for the 1047 nm transition [2], besides, this wavelength is of great interest in laser fusion experiments [3].

Recent developments in high-power fiber-coupled diodes operating at about 800 nm and at 880 nm allowed researchers to develop new resonators with end-pumping configurations, operating in cw, quasi-cw and Q-switched regimes. Active Q-switched, diode-pumped lasers produce very short jitter between the pulses, less than the pulse duration as is required for many applications. However, very short pulses with duration comparable to passive Q-switching can only be obtained with electro-optic Q-switching that relies on high voltage power supplies, susceptible to electrical failure. The usage of a saturable absorber is less complex but, due to the intrinsic mechanisms of the absorber, typically results in pulse timing jitter of the order of hundreds of nanoseconds [4]

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Nowadays, several diode-pumping schemes are employed aiming different goals. A good overlap between the laser and the pump mode is achievable by using a diode-end-pumped configuration, which allows outstanding optical-to-optical energy efficiency [5]-[8]. 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. On the other hand, longitudinal pumping schemes show some restrictions with respect to power scaling of the TEM_{00} mode due to thermally induced stress fracture caused by the high pump densities. Although the Nd:YLF has lower thermally induced stress fracture limit, in comparison with Nd:YAG or Nd:YVO_4, very high cw power was obtained for a longitudinally pumped slab design with diffraction limited beam quality [9].

By designing a side-pumped resonator, the pump intensity may be reduced by orders of magnitude but, generally, at the expense of beam quality and energy efficiency. There are only few power scalable configurations that allow good beam quality and high efficiency with side-pumping, most of these are complex, involving zig-zag geometry [10], [11] or actively Q-switched MOPA (Master Oscillator Power Amplifier) systems [11], [12].

In this work we, present a resonator design that is very compact, lightweight and efficient, as required for applications such as on site LIDAR, or portable lasers for surgery, where size, weight, reliability and power are major factors. We demonstrate that for this laser cavity the TEM_{00} mode prevails for up to 21 W of pump power in cw operation and 34 W of peak pump power in Q-switched operation. The mode-controlling approach allows high pulse energies of the laser up to 1 kHz of repetition rate.

2. RESONATOR SET-UP

The cavity design (Figure 1) is similar to the "bounce" resonator [9], [14] , where the intracavity laser beam reflects at the crystal's pump surface. However, it does not use grazing incidence at the location of total internal reflection due to the lower absorption coefficient of Nd:YLF, when compared to Nd:YVO_4 or Nd:$GdVO_4$. This configuration is simpler and robust because a square slab without coatings may be used with the laser beam entering the side face in Brewster angle. A double pass configuration with total internal reflection at the pumped surface was employed in order to increase the overlap between the lowest order mode and the pump inversion region. This effectively decreases the available inversion for higher order modes and produces pure TEM_{00} mode if the beam diameter and separation of both beams are correctly adjusted. 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 [15]-[17]. 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 [15] - [17].

Figure 1 shows a schematic diagram of the laser design, where M1 is a plane output coupler with 40% transmission at 1053 nm. M2 is a curved high reflective mirror with 3 m radius of curvature (ROC). M3 is a flat high reflectivity (HR) mirror. CL is a 25.4 mm cylindrical lens used to collimate the diode's fast axis and SL is a spherical lens with 25.5 mm focal distance. A half wave plate was employed to rotate the diode's polarization by 90 degrees to the same direction as the crystal's highly absorbing pi-polarization.

The active medium is a neodymium doped $YLiF_4$ slab with 0.8 mol% doping level at the yttrium site. The sample is 13x13x3 mm^2 in dimension and was a-cut with its c-axis orientated perpendicular to the crystal's largest surface. It was placed on a cooper 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 = 25.4 mm spherical lens (SL) and a f = 25.4 mm cylindrical lens (CL), resulting in a spot size of approximately 4 mm× 0.1 mm in the horizontal and vertical directions in figure 1, respectively. After the focusing optics and Fresnel reflection at the pump surface, about 34 W of the pump power were effectively delivered to the active media. To avoid thermally induced stress fracture of the crystal, no more than 7 W of average pump power was absorbed by the crystal.

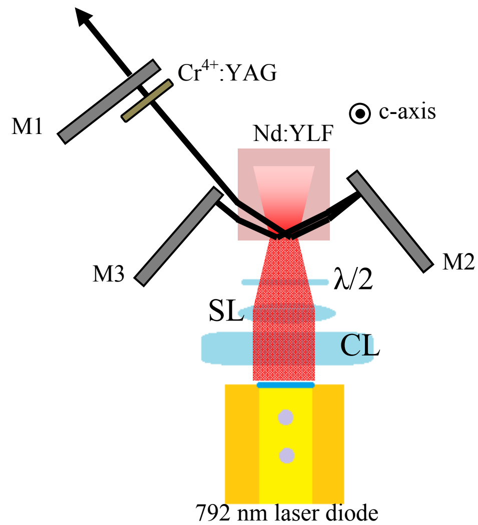

Figure 1. Schematic diagram of the diode pumped Nd:YLF mode-controlled laser resonator. M1 is a plane output coupler with 40% transmission at 1053 nm. M2 is a curved high HR mirror andM3 is a flat HR mirror. CL is a cylindrical lens and SL is a spherical lens. λ/2 is a half-wave plate.

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 quasi-cw operation by temperature tuning of the diode. At 27^{o} C the emission wavelength of the diode in qcw operation matches the absorption peak of the Nd:YLF 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.

3. EXPERIMENTS

3.1 cw operation

In this part of the experiment we empirically determined the maximum pump power at which the TEM_{00} mode prevails over higher order modes, as a function of the separation between the beams at the total internal reflection surface. A resonator with fixed arms was designed. M1 and M3 (figure 1) were placed 10.5 cm and 10 cm away from the crystal's facet, respectively. The transmission of the output coupler M1 was 7% in this experiment. The curved high reflective mirror with 3 m ROC (M2 figure 1) was placed 5 cm away from the slab's surface. The distance between both beams at the position of the total internal reflection was calculated and changed in steps of approximately 0.1 mm from 0.5 mm to 2.5 mm. At each position the input power was increased until the next higher order mode shows up on the CCD camera that is positioned behind the folding mirror. When turning up the pump power the first mode that starts to oscillate is the TEM_{00}, followed by higher modes, as has been shown in [16]. The results of the transition from TEM_{00} to multimode as a function of pump power and beam separation are shown in figure 3. The pump power at which the transition between fundamental mode and the multimode occurs is not fixed and may vary slightly on repetitive measurements as represented by the error bars in figure 3 (standard deviation).

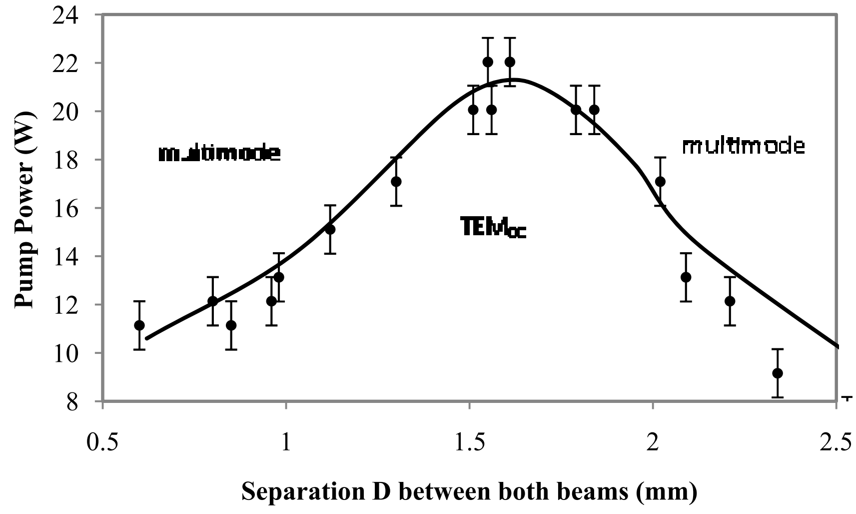

Figure 3: Experimental threshold for higher order modes as a function of pump power and separation between the two beams. The error bars represent the standard deviation of the measurement and the solid line represents a theoretical model from [17].

Figure 3 shows that the separation between both beams inside the crystal for which pure TEM_{00} mode is obtained is not critical and ranges approximately from 1.0 mm to 2.0 mm, depending on pump power. These findings are applicable for a Nd:YLF laser doped with 0.8 mol%, pumped at 792 nm and with a curved high reflective folding-mirror of 3 m ROC (M2 in figure 1) placed 5 cm away from the slab surface. For different configurations, the maximum pump power at which the TEM_{00} mode prevails may vary. The solid line represents the theoretical model for this resonator from [17]. It is important to mention that not necessarily the next higher order mode that appears on the CCD as the pump power is increased is a TEM_{10} mode but sometimes a TEM_{30} appears first.

3.2 QCW-operation

In the bounce resonator used in our experiment, the largest beam waist is near the folding mirror M2 (figure 1), therefore, to increase even more the laser beam area of the TEM_{00} mode inside the crystal and limit higher mode oscillation, the M2 mirror was shifted to a position as close as possible to the crystal. In this experiment we used a 40 % transmission output coupler that is not optimized for quasi-cw, but for Q-switched laser operation. By building this asymmetrical resonator (figure 1) we were able to obtain stable and efficient TEM_{00} mode oscillation (figure 4) at higher pump power levels than in figure 3, as will be explained below.

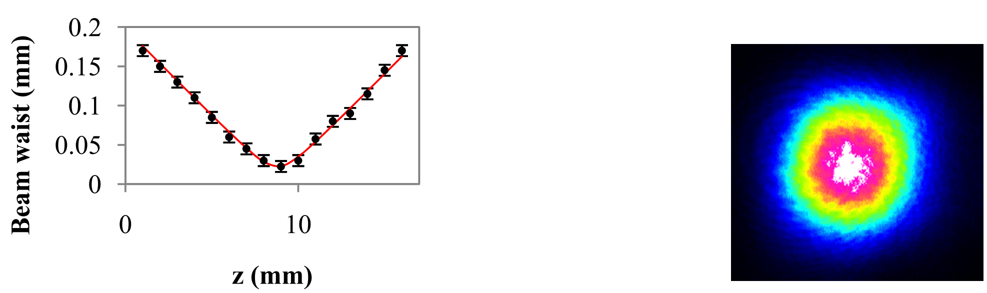

Figure 4. a) Beam quality measurement of the horizontal direction measured with the "knife edge" technique (dots) and adjusted model (solid line). We obtained $M^2 = 1.41$ in the horizontal (worse) direction. b) picture of the beam intensity distribution (Thorlabs CCD camera,model DCU223M) during qcw operation.

With this cavity, we obtained 9.6 W of multimode peak power (TEM_{10}) for 34 W of pump power for a separation of 1.6 mm between both beams, resulting in an optical-to-optical efficiency of 28.3 % and slope efficiency of 40.4 % (shown in figure 5). The pump pulse duration was 0.88 ms during this experiment.

A small realignment of the cavity permitted to introduce sufficient loss for the TEM_{10} mode in order for the TEM_{00} mode to prevail. Stable TEM_{00} beam quality (circles, dashed line) was obtained with 9.0 W of peak power can be obtained for 34 W of pump power resulting in an optical-to-optical efficiency of 26.4 % and a slope efficiency of 47.2 %. With the new TEM_{00} alignment the threshold pump power increased from 9.3 W to 14.7 W. By using an output coupler optimized for qcw operation, higher efficiencies should be obtained [15], [16] .

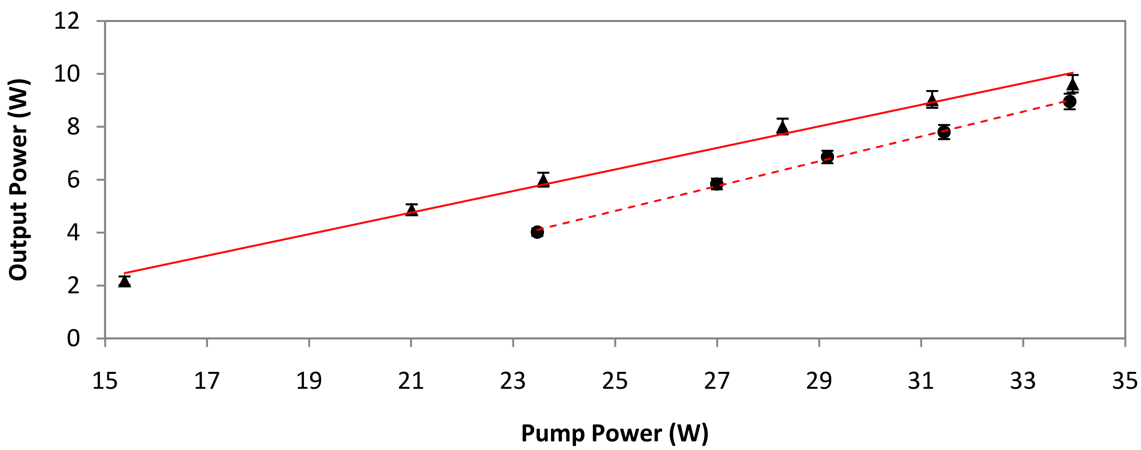

Figure 5. Peak output power as a function of the pump power for TEM_{10} (triangles, solid line) and for the fundamental mode (circle, dashed line).

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

Maintaining the laser oscillating in pure TEM_{00} mode at even higher pump levels is also possible by decreasing the size of the inverted area inside the active media [15]. This could be achieved either by pumping at a higher absorption peak of the Nd:YLF, for instance at 797 nm, or by increasing the doping concentration in the host. This is feasible for qcw operation only where the heat-load inside the crystal is smaller as during continuous operation and therefore crystal fracture can be avoided even for very high pump power densities, as shown in ref. [16], [18].

The optical efficiency of this laser, or any bounce laser, relies on a good absorption of the pump photons at the pump surface. 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 at the output power because, as opposed to an end-pumped configuration, where the laser and the pump are collinear, in a side-pumped design any decrease in the effective absorption will result in a poorer overlap between the laser and the pump. Therefore the pump diode must be temperature tuned to the highest absorption peak of the crystal and remain at constant and stable temperature (less than 0.3 degrees Celsius of fluctuation) during the whole duration of the experiment otherwise significant fluctuation may be observed at the output power of the laser.

3.3 Q-switching

It is well known that during Q-switching the first pulse has generally a much 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 repetition rate is given by the power supply and not by the complex bleaching mechanism of the saturable absorber, the repetition rate shows practically no jitter.

By inserting a saturable absorber with 50% initial transmission close to the output coupler, where the beam has the smaller radius, and correctly adjusting the beam separation inside the active gain medium, we were able to obtain a single Q-switched pulse. The absorber required a 455 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. We obtained 1.5 mJ pulse energy and pulse durations of 10 ns (FWHM), corresponding to a peak power of 150 kW (figure 6).

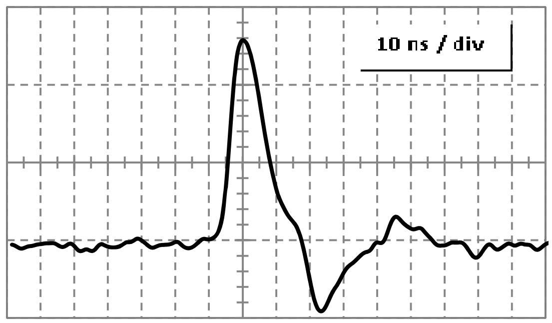

Figure 6. Temporal pulse profile for a saturable absorber with 50% initial transmission.

The complex bleaching mechanism of the saturable absorber requires high intensity to saturate, therefore when a Cr:YAG crystal with low initial transmission was used, only the TEM_{00} mode, which has the highest intensity, was obtained during Q-switch operation. Additionally, no multimode operation was observed at all even outside the separation interval for fundamental-mode operation in figure 3.

To avoid catastrophic thermally induced stress fracture, the average pump power was kept below 7 W. Therefore, with the 50% initial transmission absorber, the maximum frequency obtained for this configuration was about 480 Hz. To increase the repetition rate at the same duty cycle, it was necessary to replace the absorber with one of higher initial transmission, in order to decrease the pump pulse duration. The saturable absorber was replaced with one of 70 % initial transmission reducing the pump pulse duration to about 200 µs and increasing the repetition rate to 1kHz. Although this setup reduces the pulse energy, we were able to extract up to 1.1 mJ and 14 ns of pulse duration, corresponding to 79 kW peak power.

The maximum repetition rate permitted for our resonator depends mostly on the thermally induced fracture of the Nd:YLF slab, therefore, higher repetitions rate with this same pulse energy would be possible by designing a better heat exchanger for the slab.

4. CONCLUSIONS

In conclusion, we have demonstrated a robust, compact and lightweight resonator design capable of delivering up to 1.5 mJ and 10 ns which represents over 150 kW of peak power at 1053 nm, by employing a simple passive Q-switch. We have demonstrated high repetition rate, up to 1 kHz, with pulse energy over 1.1 mJ. The pulse-to-pulse energy is very stable and reproducible, as it is the pulse frequency. In principle, up to a few kHz would be possible, while maintaining the pulse energy, by improving the cooling system.

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.

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