

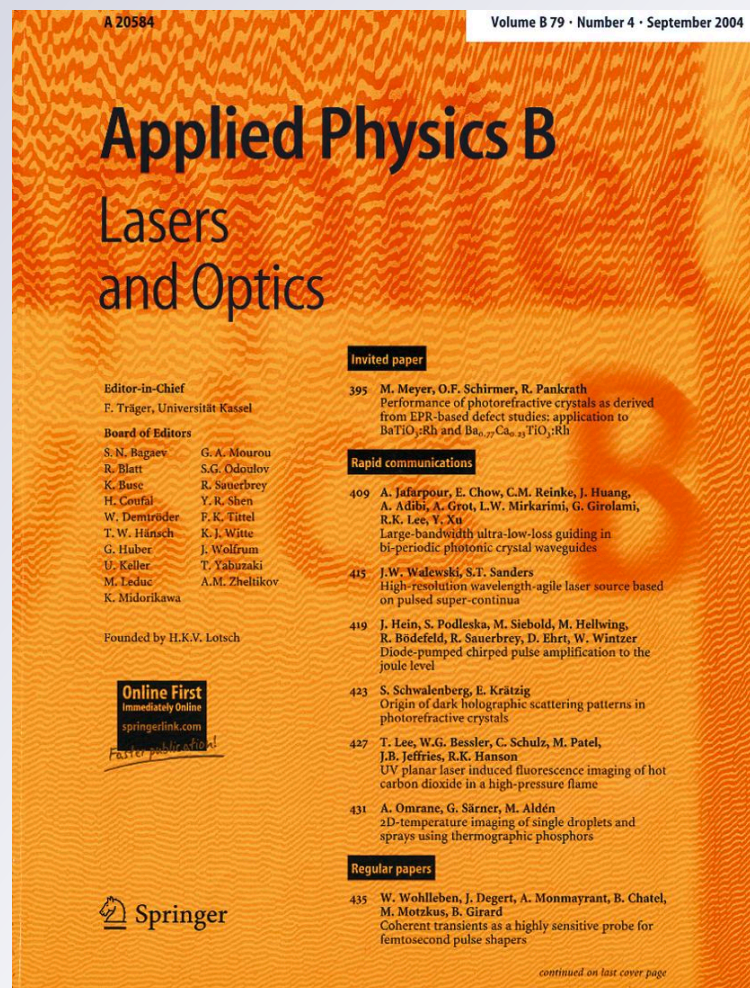
# Compact, diode-side-pumped and Q-switched Nd:YLiF<sub>4</sub> laser cavity operating at 1053 nm with diffraction limited beam quality

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**Applied Physics B**  
Lasers and Optics

ISSN 0946-2171  
Volume 106  
Number 4

Appl. Phys. B (2012) 106:877-880  
DOI 10.1007/s00340-011-4828-1



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# Compact, diode-side-pumped and Q-switched Nd:YLiF<sub>4</sub> laser cavity operating at 1053 nm with diffraction limited beam quality

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Received: 4 July 2011 / Revised version: 8 October 2011 / Published online: 7 December 2011  
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**Abstract** This work reports a diode-side-pumped and passively Q-switched Nd:YLiF<sub>4</sub> (YLF) laser operating at 1053 nm using a new laser resonator concept. Very stable pulses of 1 mJ energy with less than 10 ns pulse duration are obtained at 1 kHz repetition rate in a very simple, compact, and robust cavity that uses a double bounce configuration to achieve TEM<sub>00</sub> operation.

To obtain high power, short Q-switched pulses of the order of 10 ns, diffraction limited beam quality and high repetition rates is still a major goal in laser cavity design. A great number of industrial, environmental, and scientific applications would certainly benefit from a laser cavity design that provides these characteristics at reduced complexity and costs. Whilst high power is supplied by simple lamp pumped designs, they generally cannot deliver the high repetition rates (>30 Hz) and good beam quality. On the other hand, QCW diodes can operate with typical duty cycles of 5% which allow, in principal, repetition rates of several kHz. The directional emission of the laser diode allows for tight focusing and spatially matching with the TEM<sub>00</sub> resonator mode, thereby permitting for diffraction limited output. When diode-pumping is used in combination with active Q-switching, the timing jitter between pulses can be made less than the short pulse duration which is an essential advantage to many applications. Saturable absorber

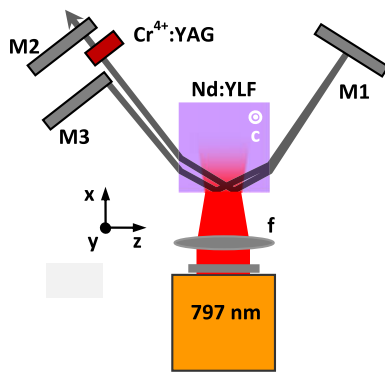
Q-switching is much less complex and less prone to electrical failure of the high voltage power supplies, but results in pulse timing jitter of the order of 100 ns because of the complex bleaching mechanisms inside the saturable absorber. Nevertheless, there exists at least one simple technique that permits to decrease the jitter of diode-pumped saturable absorber Q-switched lasers down to the order of the pulse duration [1].

Several diode-pumping schemes are nowadays employed. Good beam quality is achieved with a longitudinal pumping configuration that permits good overlap between the laser and the pump mode. On the other hand, longitudinal pumping schemes show some restrictions with respect to power scaling of the TEM<sub>00</sub> mode due to thermal effects caused by the high pump densities. This difficulty can be solved using a side pumped configuration, generally at the expense of beam quality. Only few power scalable configurations exist that permit good beam quality and high efficiency with side-pumping. Most of these are complex, actively Q-switched MOPA (Master Oscillator Power Amplifier) configurations [2, 3].

Nd:YLiF<sub>4</sub> (YLF) has excellent thermo-optical and energy-storage characteristics. It has natural birefringence that eliminates thermal depolarization and very weak thermal lensing due to a combination of negative temperature dependence of the refractive index and positive crystal expansion, which contributes to a high quality output beam [4]. Recently, very high CW power and diffraction limited output has been obtained in a longitudinally pumped slab design [5] despite the lower fracture limit of YLF when compared to YAG. Nd:YLF is an uniaxial crystal that has two principal lasing transitions at 1047 nm ( $\pi$ ) and at 1053 nm ( $\sigma$ ), corresponding to the polarizations parallel and perpendicular to the crystal c-axis, respectively. The 1053 nm transition is of great interest in laser fusion experiments [6]. Although the

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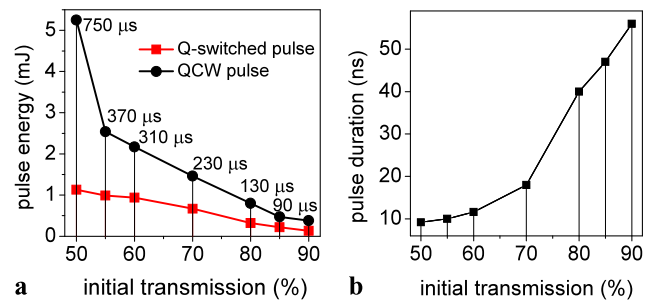
**Fig. 1** Passively Q-switched resonator. M1 is a folding mirror (ROC = 3 m), M2 is a flat output coupler with  $T = 40\%$  and M3 is a flat, high reflector;  $f$  is the spherical pump focusing lens. The total footprint of this cavity is 11 cm  $\times$  15 cm (W  $\times$  H)

1053 nm transition has a 33% lower gain, it also has the advantage of a weaker thermal lens with a dioptric power 2.3 times smaller than that for the 1047 nm transition [7].

The laser cavity reported here is very compact, lightweight and efficient as required for applications such as planetary exploration, where size, weight, reliability, and power are key factors.

The home-grown Nd:YLF crystal slab of approximately square dimension ( $14 \times 13 \times 3 \text{ mm}^3$ ) with dopant concentration of 0.8 mol% was a-cut with its  $c$ -axis oriented parallel to the diode polarization in order to access the higher absorption cross-section of the  $\pi$  polarization. The cavity configuration (Fig. 1) is similar to the bounce resonator [8, 9] but does not use grazing incidence at the location of total internal reflection because of the lower absorption coefficient of Nd:YLF when compared to Nd:YVO<sub>4</sub> or Nd:GdVO<sub>4</sub>. This is advantageous in terms of simplicity and robustness of the crystal, especially for high intensity Q-switched applications, because a simple square slab without coatings may be used with the laser beam entering the side face at Brewster angle.

A double pass configuration with two total internal reflections at the pumped facet was employed, increasing the overlap between the lowest order mode and the pump inversion. This effectively decreases the available inversion for higher order modes and produces a pure TEM<sub>00</sub> mode if the beam diameter and separation of both beams are correctly adjusted. A theoretical and experimental analysis of this new cavity concept for the case of CW operation can be found in [10] and shows that in this cavity the TEM<sub>00</sub> mode prevails and is more efficient than higher order modes without the need for any other mode-selective techniques. The separation between both beams inside the crystal for which pure TEM<sub>00</sub> mode as well as the highest power are obtained is not critical and ranges approximately from 1.6 mm to 2.0 mm, depending on pump power. For smaller or larger separations



**Fig. 2** (a) Q-switched pulse energy at 1053 nm as a function of the initial transmission of the saturable absorber (squares) and energy of the QCW pulse at 1053 nm (dots). The insets show the duration of the pump pulse necessary to achieve one single Q-switched pulse at a fixed absorber transmission. (b) Pulse duration as a function of absorber transmission

between both beams inside the crystal, a less efficient TEM<sub>20</sub> could be observed.

In this work, we show experimentally, that TEM<sub>00</sub> mode can be maintained in this novel cavity for much higher pump power than in the CW case [11]. We used a 34 W, TM-polarized and fast-axis collimated diode operating at 797 nm that was focused into the crystal by a  $f = 2.5$  cm spherical lens, resulting in a spot size of approximately 4 mm  $\times$  0.1 mm in the horizontal ( $z$ ) and vertical directions ( $y$ ) in Fig. 1, respectively. Fundamental mode oscillation was extracted with a TEM<sub>00</sub> mode beam of 0.8 mm radius inside the crystal by using a folding mirror with 3 m radius of curvature, a plane end mirror and a plane output coupler with 40% transmission. We also tested other output couplers of 20% and 10% transmission that resulted in 28% and 50% less pulse energy, respectively. Cr<sup>4+</sup>:YAG was used as a saturable absorber with the initial transmission ranging from 50% to 90%. The pump pulse duration was adjusted as a function of the absorber's transmission in order to achieve one single Q-switched pulse at 1053 nm per pump pulse. This reduces greatly the amplitude fluctuations of the Q-switched pulses.

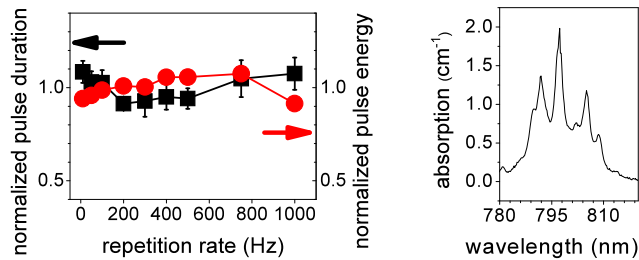
The pump pulse duration was varied from 90  $\mu$ s to 750  $\mu$ s to achieve Q-switching with absorbers ranging from 90% to 50% transmission, respectively, as shown in Fig. 2. The pulse energy for the Q-switched laser decreases linearly with increasing Cr:YAG initial transmission as expected.

The highest output power of 1.13 mJ with 9.2 ns pulse duration, corresponding to 123 kW peak output power, was achieved with 50% transmission but was inefficient needing a long pump pulse duration of 750  $\mu$ s. A good compromise was obtained for a pump pulse duration of 310  $\mu$ s that resulted in 1.00 mJ of output power and 10.0 ns pulse duration using an absorber with 60% transmission. The average ratio between the Q-switched pulse energy and the QCW pulse energy at 1053 nm without an absorber was 33%, as shown in Fig. 2a. We verified that no amplified spontaneous emission or parasitic lasing occurred between the parallel facets

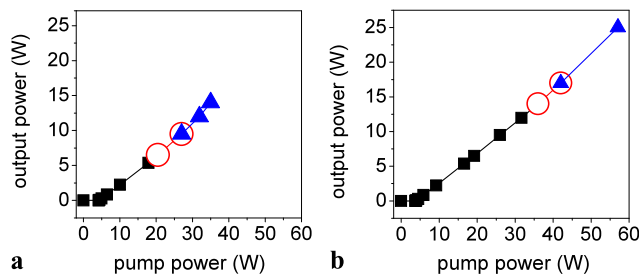
of the square Nd:YLF slab. The power stability over 30 minutes, after a few minutes of warm up time, was better than  $\pm 0.9\%$ . The timing jitter of the Q-switched pulse with respect to the pump pulse was approximately 1% of the pump pulse duration. Pump pulse jitter is negligible and of the order of 10 ps.

The measured  $M^2$  beam quality of the Q-switched laser was always less than 1.45 in the worse (horizontal) direction, even for the highest repetition rate of 1000 Hz confirming that the laser remained always in TEM<sub>00</sub> mode. The same occurred without a Q-switcher and the TEM<sub>00</sub> operation was observed in the QCW mode. Pulse duration and energy as a function of repetition rate were measured up to 1 kHz and less than 10% variation of both parameters was detected as shown in Fig. 3.

In CW operation fundamental mode was maintained up to a maximum pump power of 21 W at 792 nm, whereas in the Q-switched and QCW regime, we achieved still fundamental mode with 34 W at 797 nm [11]. This behavior is due to the higher absorption cross-section of Nd:YLF along the pi-polarization at 797 nm with respect to 792 nm, as shown in Fig. 4. In most end- or side-pumped lasers, a higher absorption cross-section normally has the opposite effect or very little effect, as shown theoretically and experimentally in [12]: Increasing absorption normally causes earlier onset of higher order modes as a function of pump power or does



**Fig. 3** Left: Normalized pulse duration (rectangles) and pulse energy (circles) as a function of repetition rate. Normalization is with respect to average pulse duration of 10 ns and pulse energy of 0.99 mJ. Right: Absorption coefficient as a function of wavelength for the pi-polarization in YLiF<sub>4</sub> doped with 1 mol% neodymium



**Fig. 4** Input-output behavior in CW operation when pumped at 792 nm (a) and at 797 nm (b). The squares correspond to pure TEM<sub>00</sub> operation. Open circles are for operation of TEM<sub>10</sub> and TEM<sub>00</sub> together; triangles for additional operation of the TEM<sub>20</sub> mode

not change significantly the onset of higher order modes. This is quite different in bounce lasers as has been shown in [11]. The explanation is as follows: At the location on the pump facet where total internal reflection occurs, the center of the TEM<sub>00</sub> mode (and therefore peak intensity) is exposed. Higher order modes have less intensity at mode-center and, therefore, are less capable of exploiting higher absorption.

To demonstrate this, we simulated our laser cavity using a commercial program (LASCAD) to calculate the beam waist inside the crystal. With the help of a MATLAB program code based on the rate equations and the spatial distribution functions of the pump- and laser-beam, we calculated input-output characteristics and higher order mode thresholds to investigate the multitransverse-mode behavior as a function of pump power [12].

As can be seen in Fig. 4, when pumping the lower absorption cross-section at 792 nm, a higher order mode starts oscillating already at 21 W of pump power, whereas for 797 nm pumping a much higher pump power of 36 W may be supplied without onset of higher order modes. For the simulation, we used additional parameters given in [7, 11].

Recently, a passively Q-switched Nd:YLF laser operating at 1053 nm has been reported that uses a special, small radius rod-design as a mode selecting aperture [13]. Resonators using aperture-limiting are very sensitive to fluctuations of pump power and mechanical disturbances and therefore not adequate for applications where stability is a major issue [14]. Additionally, in cw operation, they only work efficiently for a small range of thermal lenses and therefore at a specific pump power. In contrast, the mode controlling technique used in our resonator does not use aperture controlling and is therefore very stable (0.9% overall energy fluctuations), not sensitive to minor mechanical disturbances and not limited by thermal lensing as can be seen by the absence of a roll-over effect in Fig. 4.

In conclusion, this work presents a new cavity design for passively Q-switched Nd:YLF lasers emitting more than 100 kW peak power with up to 1 kHz at 1053 nm. The compact and robust cavity achieves TEM<sub>00</sub> mode by means of a new technique based on two bounces inside the crystal. Very stable operation with less than 0.9% overall energy fluctuations could be maintained during a test period of 30 minutes.

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