High average power Q-switched 1314 nm two-crystal Nd:YLF laser

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A 1314 nm two-crystal Nd:YLF laser was designed and operated in both CW and actively Q-switched modes. Maximum CW output of 26.5 W resulted from 125 W of combined incident pump power. Active Q-switching was obtained by inserting a Brewster-cut Acousto Optic Modulator. This setup delivered an average power of 18.6 W with a maximum of 5.6 mJ energy per pulse with a pulse duration of 36 ns at a pulse repetition frequency of 500 Hz.
OCIS Codes: 140.0140, 140.3070, 140.3480, 140.3530, 140.3540

High-power 1.3 μm lasers have a wide range of applications, which includes communications, remote sensing, timing systems, and display technology [1–4]. The 1.3 μm output can be Raman-shifted to the 1.5 μm region, which is useful for applications requiring eye-safe operation at high powers such as Lidar and free-space optical communication [1]. Furthermore, 1314.0 nm (specifically the 657.0 nm second harmonic) is required to probe the relevant transition for optical Calcium clocks [2]. Harmonic conversion of 1.3 μm can also be used for the generation of red and blue light which is used in display technologies [3,4].

The stronger 1.3 μm emission lines of Nd:YLF are at 1314 nm for the σ-polarization and 1321 nm for the π-polarization. Operating an end-pumped Nd:YLF laser at 1.3 μm is attractive because of the weak thermal lens when emitting on the σ-polarization [5,6]. This results in excellent beam quality over a wide range of output powers.

The upper-laser-level ($^4F_{3/2}$) lifetime of $\tau \sim 520$ μs for Nd:YLF is longer compared to ~ 250 μs for Nd:YAG and ~ 100 μs for $Nd:YVO_4$ [7,8]. The resulting high energy storage capability makes Nd:YLF suitable for generating high pulse energies during Q-switched operation [7–10]. The emission cross section (σ_{em}) at 1.3 μm for Nd:YLF is ~$2–2.5 \times 10^{-20}$ cm^2 (for both polarizations). This σ_{em} is about an order of magnitude less than for the strongest Nd:YLF emission lines at 1.0 μm and is also a factor of 3 less than that of Nd:YAG at 1.3 μm and an order of magnitude less than 1.3 μm σ_{em} for $Nd:YVO_4$ [8]. Because of this low σ_{em} for 1.3 μm Nd:YLF, power scaling such lasers is more difficult than for either 1.0 μm Nd:YLF or other Nd-doped media at 1.3 μm. The relatively longer upper-laser-level lifetime τ of Nd:YLF however partially compensates for this.

The σ_{em} and τ values of Nd:YLF necessitates a careful design of the pump beam radius in pulsed lasers where a trade-off has to be made between a reasonably low threshold and the risks of optical damage and thermal fracture [9]. Thermal effects are especially problematic under 1.3 μm operation (compared to 1.0 μm) due to the larger quantum defect. By using a relatively low Nd doping one can reduce upconversion and spread out the thermal load longitudinally in the crystal, which increases the thermal fracture pump limit [9,11,12]. Furthermore, Nd:YLF crystals grown by the Czochralski method have a longitudinal gradient in doping resulting from the physical crystal growth process. Pumping from the lower-doping side of the crystal further lowers the risk of thermal fracture [13].

We previously reported the highest 1.3 μm Continuous Wave (CW) output power from a diode-*end*-pumped Nd:YLF laser of 10.4 W and also the highest energy per pulse of 825 μJ for a *passively* Q-switched Nd:YLF 806 nm *end*-pumped setup [14]. Recent 1.3 μm Nd:YLF work by other groups based on *side*-pumped setups delivered CW powers of up to 14.9 W [15] and for *actively* Q-switched Nd:YLF pumped at 796 nm average powers of up to 12.3 W (from 180 W of pump power) with corresponding pulse energies of 3.8 mJ [16].

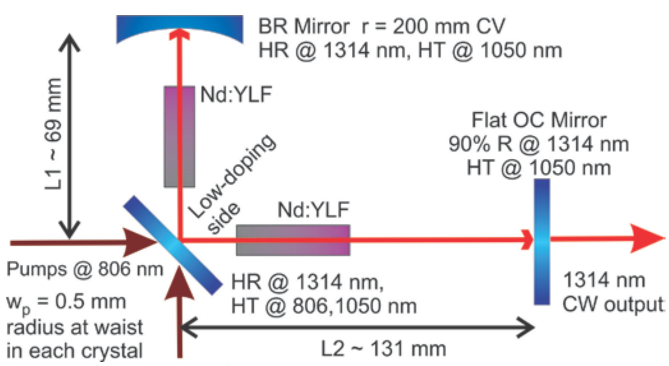

Fig. 1. (Color online) Experimental resonator layout for CW operation.

Here we demonstrate high-power 1314 nm operation of a diode end-pumped Nd:YLF laser in both CW and actively Q-switched modes.

The resonator used for CW operation at 1314 nm is shown in Fig. 1. It consists of an r = 200 mm concave Back Reflector (BR) and a flat 10% transmission Output Coupler (OC). The resonator was folded with a flat mirror (HR @ 1314 nm, HT @ 806, 1050 nm) to pump both crystals. Operation was forced onto the 1.3 μm emission line by specifying both the input and output couplers to be highly transmissive at ~1 μm. Mode-matching at full pump power was achieved by adjusting the positions of the OC and BR.

The Nd:YLF laser crystals were obtained through a collaboration with VLOC, who estimated the doping gradient of a specially manufactured boule and maintained the crystal orientation information during the manufacturing process. The two crystals used were a-cut rods with 6 mm diameter and 45 mm length and each had a linear doping gradient along the rod from 0.30% to 0.52%. Each crystal was mounted in a water-cooled copper block with its c-axis horizontal and placed next to the resonator folding mirror. The laser crystals were end-pumped from the low-doping (0.30%) side using fiber-coupled diode laser modules (Jenoptik JOLD-75-CPXF-2P, 0.4 mm 0.22 NA fibre, ~ 808 nm) with the pump powers each limited to ~ 62.5 W (125 W total) to avoid thermal fracture. The laser diodes were also temperature-controlled to 27°C to provide a pump wavelength of 805.5 nm (at full pump power), ensuring an absorption efficiency of ~ 91.5% in this setup. The pump beam was focused to a waist radius of ~ 500 μm in the center of the gain medium with a roughly top-hat shaped energy distribution at that position. This waist radius was determined through a gain optimization method similar to the one described in [9] since both the pump and laser beam radii have a strong influence on the gain as well as on the thermal load.

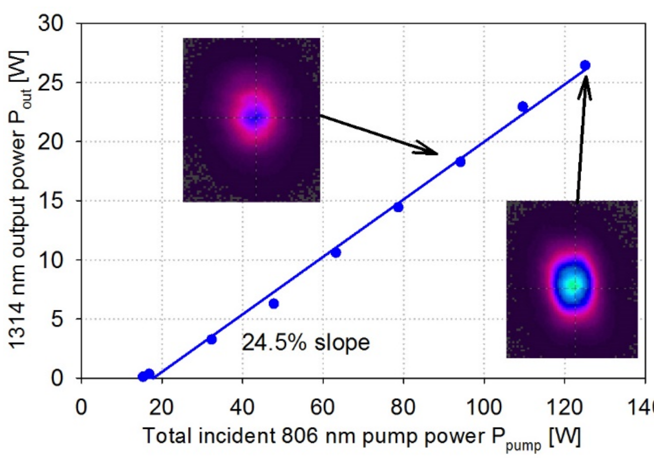

Fig. 2. (Color online) Incident 806 nm optical-to-optical Slope Efficiency together with beam profiles of the 1314 nm CW laser.

The CW incident optical-to-optical slope efficiency of the oscillator is shown in Fig. 2. The most efficient CW operation as well as highest output power was achieved with a 10% OC with a resulting incident optical-to-optical slope efficiency of 25%. This laser had an incident pump power threshold of 15.3 W and a maximum power output of 26.5 W, which is 2.5 times higher than what was recently reported by our group [14]. Wavelength measurements showed oscillation only at 1314 nm on the σ-polarization due to the oscillator being unstable for the stronger negative thermal lenses associated with the π-polarization [5,6]. The beam mostly had a symmetrical Gaussian profile but at the maximum pump power it became slightly elliptical with a horizontal radius ~ 20% smaller than the vertical. This is due to the YLF's astigmatic thermal lensing [17]. The beam was measured by the ISO11146 method (knife-edge) to have an M^2 value of 2.0 (horizontal) and 2.6 (vertical).

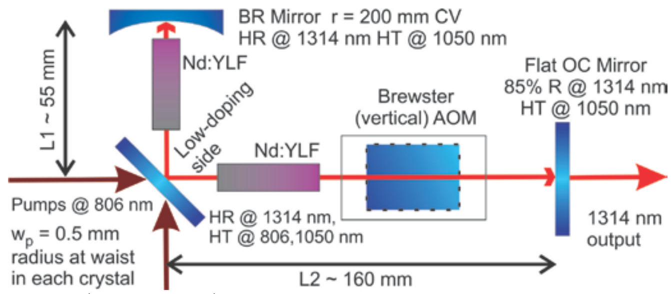

Fig. 3. (Color online) Experimental resonator layout for actively Q-switched (with AOM) operation.

The oscillator in our setup was subsequently slightly modified for active Q-switched operation. An Acousto Optic Modulator (AOM) (a Brewster-cut Gooch & Housego, Model QS027-10M(BR)-NL6) was inserted in the cavity between the 2nd Nd:YLF crystal and output coupler (Fig. 3). The flat OC's transmission was increased to 15% to limit the intra-cavity peak power which in turn allowed us to operate at a low Pulse Repetition Frequency (PRF). The positions of the BR and OC were also slightly adjusted to mode-match the pump and laser modes within the Nd:YLF crystals.

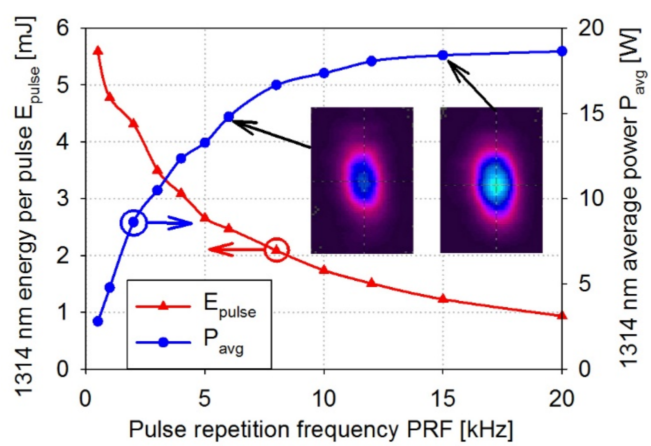

Fig. 4. (Color online) Actively Q-switched behavior at full pump power of 125W: Energy per pulse (left axis) and average output power (right axis), as a function of the pulse repetition frequency.

A maximum average output power of 18.6 W was achieved at an incident pump power of 125 W and a PRF of 20 kHz (Fig. 4). The Energy per pulse E_{pulse} increased from 0.93 mJ at a PRF of 20 kHz to 5.59 mJ at 0.5 kHz. Pulse duration at Full Width at Half Maximum (FWHM) decreased from 218 ns at a PRF of 20 kHz to 36 ns for 0.5 kHz (Fig. 5). The highest peak output power was 155 kW at a PRF of 0.5 kHz. A slight elliptical beam profile was observed due to astigmatic thermal lensing [17]. The decrease in the maximum output power from that of the CW setup is attributed to the increase of OC losses as well as a slight change in the mode-matching which resulted from the additional optical element in the resonator.

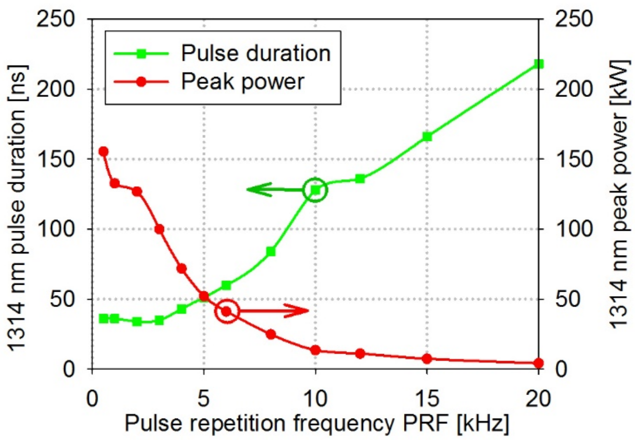

Fig. 5. (Color online) Actively Q-switched behavior at full pump power of 125W: Pulse duration (left axis) and Peak power (right axis), as a function of the pulse repetition frequency.

This is, to the best of our knowledge, the first demonstration of an actively Q-switched *end*-pumped Nd:YLF laser at 1314 nm. The resulting energy per pulse and average power is also higher than previously reported for other diode *side*-pumped actively Q-switched 1.3 μm Nd:YLF lasers [16].

Subsequently an attempt was made to increase the total pump power to 140 W. This resulted in one of the crystals fracturing at a PRF of 12.5 kHz, when decreasing it from 20 kHz. We therefore operated the laser just below the crystal damage threshold, since the increase in pump power resulted in a higher heat load (due to upconversion), which increased the stress inside the Nd:YLF above the fracture limit [9].

In conclusion, high average power 1314 nm oscillation of an end-pumped Nd:YLF laser has been demonstrated for CW operation delivering up to 26.5 W of output power. Active Q-switching of the laser using a Brewster-cut AOM resulted in pulsed operation with 5.59 mJ energy per pulse, pulse duration of 36 ns and an average power of 18.6 W. These results are, to the best of our knowledge, the highest reported values to date for diode-*end*-pumped 1.3 μm Nd lasers.

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