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Received January 10, 2013; revised February 4, 2013; accepted February 4, 2013;
posted February 5, 2013 (Doc. ID 183285); published March 13, 2013

We demonstrated laser operation of a passively Q-switched diode-pumped Er:YAG solid-state laser emitting at 1645 or 1617 nm depending on the initial transmission of the Cr:ZnSe saturable absorber. The crystal emitted up to 10 W at 1645 nm and up to 8 W at 1617 nm in CW mode while pumped with 65 W of incident pump power at 1533 nm. In passive Q-switched mode with 40 W of incident power, a Cr:ZnSe saturable absorber with initial transmission of 85% led to 330 μJ pulse energy, 61 ns pulse duration at a repetition rate of 1460 Hz at 1645 nm. An 80% initial transmission Cr:ZnSe sample led to 510 μJ energy pulses, 41 ns pulse duration at a repetition rate of 820 Hz with a central wavelength change from 1645 to 1617 nm. This is the first reported passively Q-switched diode-pumped Er:YAG laser operating on the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition.

OCIS codes: 140.3580, 140.3540, 140.3500, 140.3070.

Direct resonant pumping of Er:YAG is a laser configuration studied for compact eye-safe emitters which applications require kilometer range propagation in the atmosphere, like active imaging or Lidar. The pump sources are either Er:Yb fiber lasers operating at 1532 nm [1] or laser diodes emitting at 1470 nm [2] and 1532 nm [3,4]. For several configurations, the laser emission naturally occurred at 1645 nm. Indeed, although the emission cross section is higher at 1617 nm, the needed population inversion for transparency at 1617 nm is 14% of the total population (at 300 K) whereas it is only 9% at 1645 nm [5]. Unfortunately, a methane absorption line exists at this wavelength in the atmosphere with a typical value of 0.1 km^{-1} [6]. One way to increase the range of the emitter is to use the 1617 nm emission line, which is free of absorption. The 1617 nm wavelength was observed in free running at temperature below 90 K [7], in high loss cavities [5] or with injection seeding [8] with a diffraction limited Er:Yb fiber laser as pump source. Recently, directly diode-pumped emitters achieved 8 W in CW mode with 100 W of incident pump power in a waveguided configuration [9], and 11.8 mJ pulses in actively Q-switched regime [10].

Successfull attempts of passive Q-switch (QS) has been recorded for the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition at 1.6 μm with erbium fiber laser as pump source [11,12] or Er:glass flashed pump systems with low repetition rate [13]. The fairly complexity of the pump setup used in these experiments reduces the benefit of the use of a saturable absorber as QS system. On our way to develop compact and simple sources for eye-safe applications [14], we investigated passively Q-switched diode-pumped Er:YAG cavities for laser operation at 1617 nm. For Er:YAG, such configuration has been demonstrated at 2.9 μm [15] with 3 μJ of pulse energy.

In this Letter, we demonstrate for the first time a direct diode-pumped Er:YAG solid-state laser passively Q-switched operating at 1645 or 1617 nm depending on the initial transmission of the Cr:ZnSe saturable absorber. For that, we used the potential of single crystal fibers (SCFs) for pump confinement and consequently for high inversion population ratio to favor the 1617 nm laser emission.

An Er:YAG Taranis module produced by Fibercryst, integrating a 750 μm diameter, 30 mm long Er:YAG crystal with a doping concentration of 0.5% is used as gain medium. The pump light is provided by a fiber-coupled laser diode from QPC with a 400 μm core diameter and an NA of 0.22, delivering up to 60 W at 1532 nm. Its spectrum is narrowed by an internal grating, down to 1 nm approximately. The beam is collimated by a 40 mm focal length doublet and then focused a few millimeters inside the Er:YAG crystal thanks to another 40 mm focal length doublet. With this setup, we estimate that the pump beam undergoes between two and three reflections in the SCF (Fig. 1), allowing a higher population inversion and a better spatial overlap between the pump and the laser signal than in standard rods. The Er:YAG was antireflection coated on both ends and actively cooled at 12°C.

A first cavity has been designed for CW operation (Fig. 2). It consists in one meniscus with a radius of curvature of 100 mm and dichroic coatings (high transmission at 1532 nm and high reflectivity at 1617–1645 nm), a highly reflective mirror with a radius of curvature of 400 mm, which collimates the laser beam, and a plano output coupler with a transmission of 20% at 1.6 μm. The 100 μm thick etalon, inserted inside the cavity on the collimated arm, acts as a wavelength selector between 1645 and 1617 nm. The optical length of the cavity is 350 mm.

This setup led to CW output powers up to 10 W at 1645 nm (Fig. 3). At 1617 nm, the cavity yielded 8 W of CW output power, reaching the state-of-the-art CW

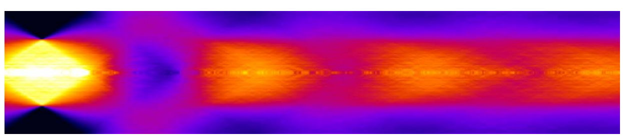

Fig. 1. (Color online) Pump profile inside a 30 × 0.75 mm undoped YAG SCF obtained by raytracing simulation (diameter slice along the crystal axis).

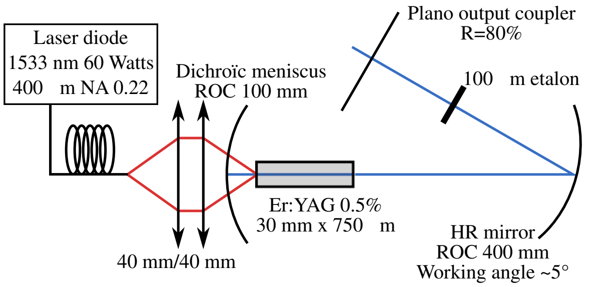

Fig. 2. (Color online) Experimental setup of the directly diode-pumped Er:YAG laser in CW regime.

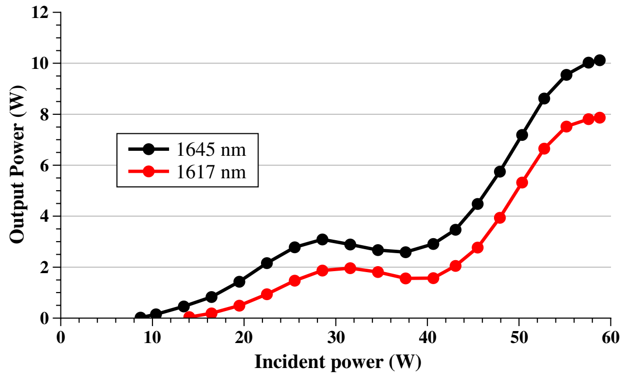

Fig. 3. (Color online) CW output power at 1617 and 1645 nm versus the incident pump power.

performance of [9] with a better efficiency (pump power reduced by 40%). The particular shape of the efficiency curve comes from the spectral shift of the laser diode despite the internal grating (same effect with lower wavelength shift already observed in [10]).

For compactness matters, a second cavity has been designed (Fig. 4) and only consists in two concave mirrors with a radius of curvature of 100 mm. Moreover, in view of a low consumption system, the maximum pump power was reduced to 40 W. The first one was highly reflective for 1617 and 1645 nm and transparent for 1532 nm. The second one was an output coupler with a transmission of 20% around 1.6 μm. The optical cavity length is 120 mm. The Cr:ZnSe saturable absorber is inserted just next to the output coupler to decrease the energy density as its damage threshold is lower (~2 J/cm^2) than the damage threshold of the Er:YAG coatings (~6 J/cm^2). No etalon has been inserted inside this cavity.

In CW regime, this laser cavity emits a power of 3.3 W at 1645 nm with a threshold pump power of 19 W (16% of

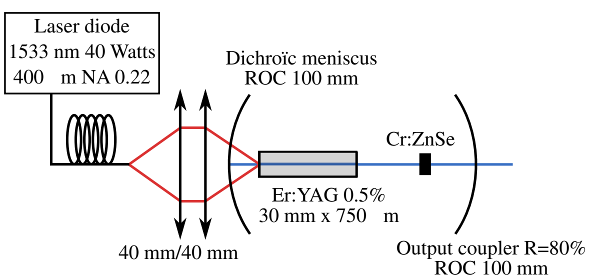

Fig. 4. (Color online) Experimental setup of the passively Q-switched directly diode-pumped Er:YAG laser.

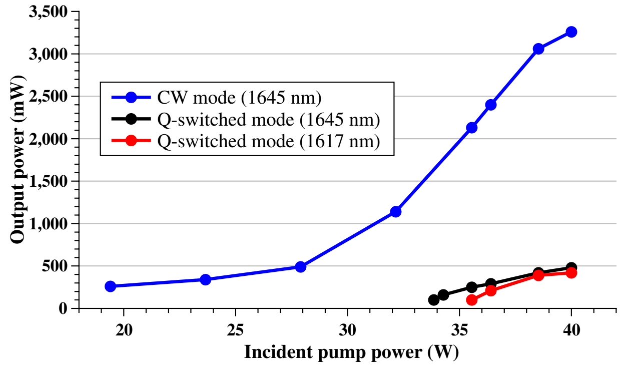

Fig. 5. (Color online) Output power of the laser cavity described in Fig. 4 in CW mode at 1645 nm and in passive Q-switched mode at 1645 and 1617 nm versus the incident pump power.

slope efficiency) (Fig. 5). The nonresonant pumping at low incident power caused by the pump spectral shift induces the particular shape of the efficiency curve.

Table 1 is an outlook of Q-switched regime performance at 40 W of pump power. Two Cr:ZnSe saturable absorbers from Altechna with different initial transmissions are inserted inside the laser cavity. The average power drops down from 3200 mW to around 450 mW (Fig. 5). A saturable absorber with 85% of initial transmission leads to an emitted wavelength of 1645 nm. But a darker sample (80% of initial transmission) leads to a wavelength change from 1645 to 1617 nm. This sudden shift has already been observed in [11], and comes from the high losses introduced inside the cavity. In addition, the slightly higher Cr:ZnSe absorption at 1645 nm compared to 1617 nm contributes to the wavelength selection. This wavelength shift happens whatever the incident pump power.

Pulse duration has been recorded at 61 ns at 1645 nm and 41 ns at 1617 nm (Fig. 6) and is insensitive to the

Table 1. Output Performance in Q-Switched Regime for Two Different Initial Transmissions (T_{init}) of Saturable Absorber at 40 W of Pump Power

T_{init} (%)	Rep. Rate (Hz)	Duration (ns)	Wavelength (nm)	Energy (μJ)
85	1460	61	1645	329
80	820	41	1617	512

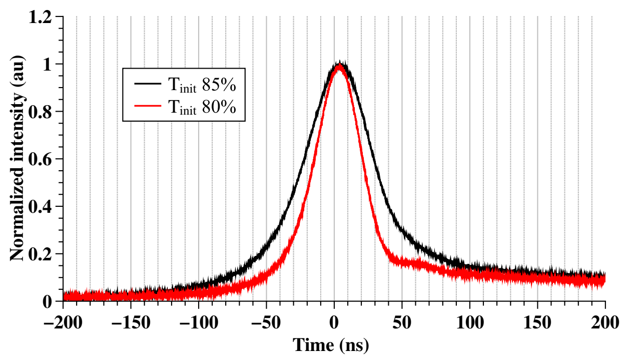

Fig. 6. (Color online) Normalized pulse shapes at full pump power (40 W).

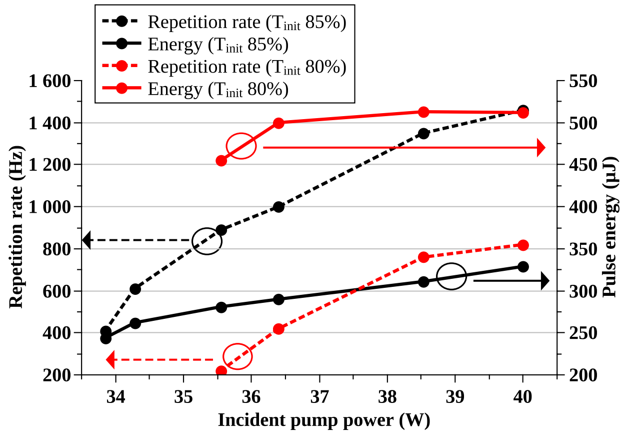

Fig. 7. (Color online) Pulse energy (plain) and repetition rate (dashed) versus the incident pump power for 85% (black) and 80% (red) of Cr:ZnSe initial transmission.

pump power, as the cavity losses and the gain before pulses are independent from the pump power in passive Q-switched lasers. These pulse durations are not the lowest recorded for Q-switched Er:YAG but still belong to low range pulse durations for this type of experiment.

The output M^2 is equal to 1.6 in CW or Q-switched regime at 40 W of pump power. We did not observed spatial beam filtering from CW to QS, mainly because of the very low Cr:ZnSe saturation intensity value of 14 kW/cm^2 [16].

In our experiments, repetition rates go from 400 to 1460 Hz and from 220 to 820 Hz depending on the saturable absorber's transmission, while pulse energies go from 240 to 330 µJ and from 455 to 510 µJ (Fig. 7).

In conclusion, we reported the first results in Q-switched operation at 1617 and 1645 nm of a directly diode-pumped Er:YAG cavity yielding 329 µJ at 1645 nm and more than 500 µJ at 1617 nm. The SCF geometry allowed a pump confinement to raise the population inversion to favor the emission of the 1617 nm line from the cavity. This work is a first step to add mobility and compactness to laser sources for range detection and Lidar, avoiding the use of water-cooled acousto-optic modulator for active QS operation and fiber laser as a pump source.

This work has been funded by the Direction Générale de l'Armement (112906173).

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