

Highly efficient Q-switched Yb:YAG channel waveguide laser with 5.6 W of average output power

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In this Letter, we present high-power continuous wave (CW) and Q-switched femtosecond laser-written Yb:YAG channel waveguide lasers. In Q-switched operation, obtained by a semiconductor saturable absorber mirror (SESAM), as well as in CW operation, the laser generates average output powers of more than 5.6 W and reaches slope efficiencies above 74%. The Q-switched laser operated at a maximum repetition rate of 5.4 MHz with a minimum pulse duration of 11 ns, and with a maximum pulse energy of 1 μ J. This laser has almost an order of magnitude higher average output power than previously reported Q-switched channel waveguide lasers.

OCIS codes: (140.3540) Lasers, Q-switched; (140.3615) Lasers, ytterbium; (230.7380) Waveguides, channeled.

Dielectric channel waveguide (WG) lasers are among the most promising technologies for compact and reliable laser sources, that combine multiwatt power levels with a high level of integration [1]. Major breakthroughs were achieved thanks to much progress in waveguide fabrication methods such as ion-exchange [2], liquid-phase epitaxy [3], and femtosecond-laser (fs-laser) inscription [4–6]. In continuous wave (CW) operation, power levels of up to 5.1 W and slope efficiencies up to 73% were reported for fs-laser-inscribed channel waveguide lasers [5]. Several Q-switched and CW modelocked dielectric channel waveguide lasers were demonstrated, and pulse durations down to 285 fs were realized [7,8]. Q-switched operation was demonstrated with average output power levels of up to 680 mW [9].

In this Letter, we demonstrate that the combination of femtosecond laser-written crystalline channel waveguides with semiconductor saturable absorber mirrors (SESAMs) enables the realization of a high-power Q-switched channel WG laser.

We present the first Q-switched channel WG lasers with multiwatt average output power, achieving pulse energies of up to 1 μ J.

The waveguiding microstructures were inscribed into a 7% Yb³⁺-doped Y₃Al₅O₁₂ (Yb:YAG) crystal with a fs-laser. They consist of two parallel tracks, which are inscribed by a linear translation of the sample perpendicular to the incident fs-laser beam. These tracks exhibit distances between 22 and 30 μ m. Owing to a stress-induced refractive index change, the waveguiding region is in the center between the tracks. Such waveguides are often referred to as type II waveguides [4,5]. Here, we superimposed the linear translation with a velocity of 25 μ m/s of the sample with a sine oscillation with an oscillation amplitude of 2 to 4 μ m and an oscillation frequency of 70 Hz; the fs-laser writing scheme can be seen in Fig. 1.

With this writing scheme a larger refractive index change and a better confinement of the laser mode can be achieved [5]. We modified our previous WG writing scheme [5,6,10] by inserting a pinhole with 600 μ m diameter into the beam path of the fs-laser to improve the beam quality by mode cleaning. Because of the large distance between the pinhole and the aspheric focusing lens ($f = 3.1$ mm, NA = 0.68) used for the laser inscription, only the 0th order of the resulting diffraction pattern is transmitted through the aperture of this lens. The position of the pinhole was adjusted so that the aperture of the lens was filled. For the experiments, we used WGs with lengths of 10.4 mm. We experimentally confirmed that due to the modified writing parameters the losses of the waveguides are decreased from 1.2 to 0.5 dB/cm, which were estimated with a transmission measurement at 633 nm.

The setup for the laser experiments is depicted in Fig. 2. The experiments shown here were performed with a WG with a track distance of 26 μ m and a superimposed oscillation amplitude of 2 μ m. The Yb:YAG WG was pumped with an optically pumped semiconductor laser (OPS), also referred to as vertical external cavity surface emitting laser (VECSEL) or semiconductor disk laser [11], delivering up to 9 W of power at

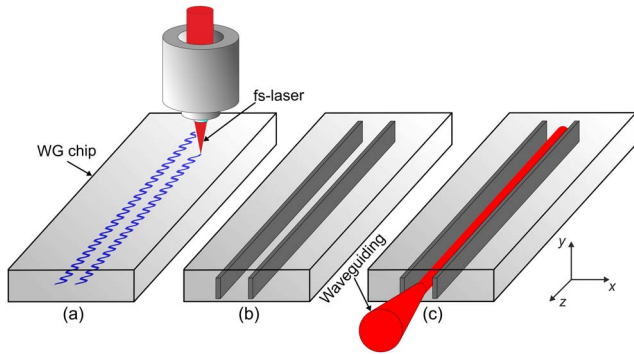


Fig. 1. Schematic of the fs-laser writing mechanism. (a) fs-laser sinusoidal translation (along x axis) superimposed to the linear translation (along z axis); (b) pair of inscribed tracks (material modification in those parts); (c) resulting waveguiding in between the tracks.

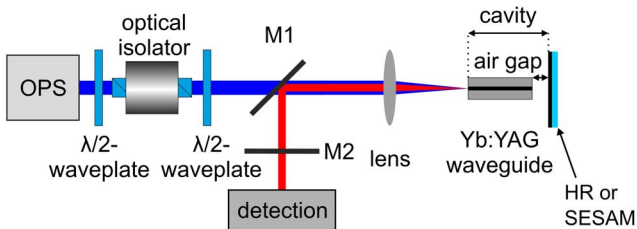


Fig. 2. Experimental setup of the CW and Q -switched waveguide laser. OPS laser at 969 nm as pump source; mirror M1, highly transparent (HT) at 969 nm, HR at 1030 nm; mirror M2, transparent at 1030 nm, HR at 969 nm.

969 nm with an $M^2 < 2$. The slightly elliptical collimated pump beam is focused onto the waveguide facet using a lens with a focal length of 30 mm. This results in a pump spot diameter of $23 \mu\text{m} \times 19 \mu\text{m}$. The waveguide mode field diameter is approximately $18 \mu\text{m} \times 22 \mu\text{m}$ at 969 nm. We estimated the coupling efficiency η_c by calculating the overlap integral [12] of waveguide and pump mode to be $\eta_c = 97\%$.

The laser cavity length is determined mainly by the length of the waveguide chip. The WG chip is pumped through the uncoated front facet, which also serves as an output coupler for the WG cavity. The second cavity end mirror is either a highly reflective (HR) mirror for CW operation or a SESAM [13] for Q -switched operation, placed close to the end facet of the WG. Owing to the Fresnel reflection of the front facet of 8.4% at 1030 nm, the cavity exhibits a resulting total output coupling of 91.6%. The laser light is separated from the pump light by a dichroic mirror M1, which is placed in front of the waveguide. An additional dichroic mirror (M2) is placed in front of the characterization setup to filter residual pump light reflected at the front facet of the crystal.

The SESAM is mounted on a Peltier cooled holder for temperature control. During the entire experiment the temperature of the SESAM is set to 17°C. However, no significant change on the pulsed laser operation has been observed by varying the SESAM temperature between 15°C and 35°C. The SESAM has a saturation fluence of $57 \mu\text{J}/\text{cm}^2$, a modulation depth of 0.7%, and nonsaturable losses of 0.2%, when characterized

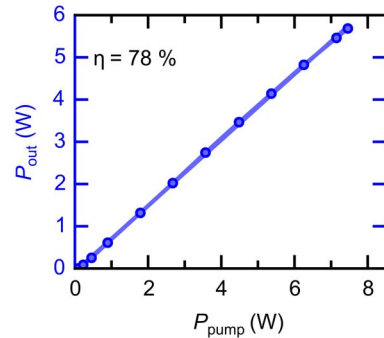


Fig. 3. Output power versus pump power for the CW laser configuration showing a slope efficiency of 78%.

with picosecond pulses at a wavelength of 1030 nm [14]. The recombination time of this SESAM was not measured but is expected to be < 100 ps, which is orders of magnitude shorter than the achieved pulse duration. Therefore, carrier recombination will occur during the presence of the pulse, whereas the states are immediately refilled leading to the bleaching of the absorber. No index matching fluid was applied between the SESAM and waveguide end facet. Hence, a tiny airgap is left, which can be adjusted by a piezoelectric ring actuator mounted on a mirror mount. During the entire experiment the air gap is kept between 10 and 100 μm .

The pump power is measured after the mirror M1 in front of the focusing lens. In the following, we refer to the pump power as the measured pump power corrected by the transmission of the focusing lens (97.5%) and the Fresnel reflection of the waveguide's end facet (8.4%), and assume the incoupling efficiency to be unity. It should be noted that this assumption leads to a minor underestimation of the actual efficiencies. The laser average output power is measured after the mirrors M1 and M2 and corrected by their transmission properties. For the characterization of the Q -switched operation a fraction of the laser beam is sent to an InGaAs-based high-speed photodetector with 45 GHz bandwidth (1014 Newport), connected to an oscilloscope or an RF spectrum analyzer. Another fraction is sent to an optical spectrum analyzer (Yokogawa AQ6370C) for wavelength characterization.

For CW operation the HR mirror is mounted on the piezo controlled mount, as described above. For this configuration lasing starts at 89 mW of pump power. We achieved a high maximum output power of 5.7 W at a pump power of 7.5 W. The slope efficiency amounts to 78% (Fig. 3). These results outperform earlier high power Yb:YAG waveguide lasers [5] and show that the writing parameters were improved considerably.

For Q -switched operation the HR mirror is replaced by the SESAM. In this case, Q -switching starts from the laser threshold at a pump power of 102 mW. During the entire experiment no Q -switched modelocking was observed. A maximum of 5.6 W average output power at the pump power of 7.7 W was achieved. The low modulation depth and nonsaturable losses of the SESAM allow for the high-power multiwatt Q -switched pulsed operation with only slightly reduced slope efficiency of 74% [Fig. 4(a)].

The optical spectra of both operation modes look very similar, and they are centered at 1030 nm with a FWHM of ~ 0.5 nm. With increasing pump power the stability of the

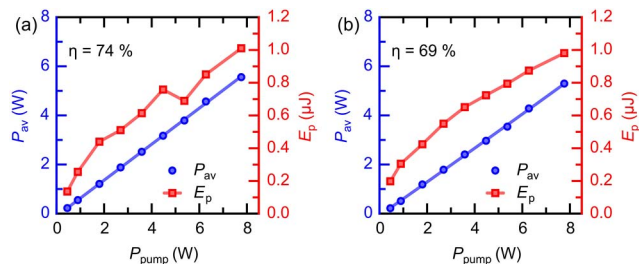


Fig. 4. Average output power and pulse energy versus pump power for the Q -switched laser configuration without (a) and with (b) aligning of the airgap distance between the SESAM and WG facet for highest pulse stability.

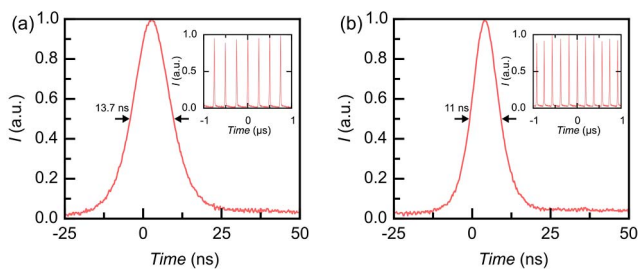


Fig. 5. Single Q -switched pulse and Q -switched pulse train (inset) at 2.4 W (a) and 5.3 W (b) of average output power for the stable Q -switching operation.

Q -switching decreases; this can be compensated for by fine-tuning the air gap between the SESAM and the waveguide chip, which due to the etalon effect can significantly change the coupling into the SESAM and thus its parameters [15]. By doing so, however, the slope efficiency drops by approximately 5% as depicted in Fig. 4(b). Also the maximum average output power drops to 5.3 W. In both cases the maximum average output power was limited only by the available pump power. The pulse energy versus pump power is depicted in Figs. 4(a) and 4(b) (red curves). With increasing pump power the pulse energy increases and approaches 1 μJ at the maximum average output power of 5.6 W. As shown in Figs. 4(a) and 4(b), for the stable Q -switching configuration [Fig. 4(b)] the dependence is approximately linear, while for the power-optimized (unstable) Q -switching configuration [Fig. 4(a)] the dependence is distorted. The dip of pulse energy at 5.4 W of pump power in Fig. 4(a) goes along with an abrupt increase of the repetition rate from 4.1 to 5.5 MHz.

Figure 5 shows the oscilloscope trace of a fully modulated single pulse and the pulse train (inset) of the Q -switched laser at 2.4 W (a) and 5.3 W (b) of average output power. The Q -switching in Fig. 5(a) is stable with a maximum pulse peak power fluctuation of 18% (evaluated in a time span of 10 μs corresponding to 40 pulses). The average pulse period was evaluated to be 263.2 ns with an rms timing jitter of 12.6 ns, corresponding to a pulse repetition rate of 3.81 ± 0.19 MHz.

The dependence of pulse duration and repetition rate on the pump power is depicted in Fig. 6. The pulse duration decreases from ~ 40 to 11 ns while the repetition rate increases from 1 to 5.4 MHz as the pump power is increased from 0.45 to 7.74 W.

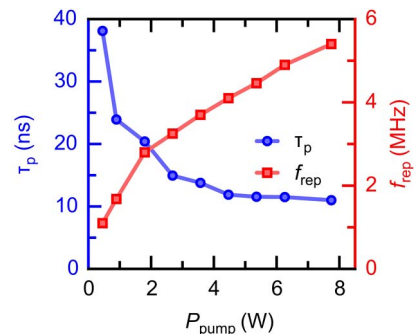


Fig. 6. Pulse duration and repetition rate versus pump power for the stable Q -switching configuration.

In conclusion, we demonstrate an fs-laser-written Yb:YAG channel waveguide laser with low losses of 0.5 dB/cm, high efficiency, and high output power. Using an HR mirror as a cavity end mirror, the CW laser has record high output power of 5.7 W and a slope efficiency of 78%. After exchanging the HR mirror by a SESAM, Q -switched output is observed at all power levels. Maximum average output power amounts to 5.6 W at a slope efficiency of 74%. The Q -switched pulses have pulse energies of up to 1 μJ at 11 ns pulse duration with a repetition rate of 5.4 MHz. These results are almost an order of magnitude higher in average output power than previously reported passively Q -switched channel waveguide lasers [1]. This demonstrates the potential of fs-laser-inscribed waveguide lasers for highly efficient short pulse generation, allowing for compact integrated pulsed optical devices.

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