Millijoule pulse energy *Q*-switched short-length fiber laser

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We report on a Q-switched short-length fiber laser producing 100 W of average output power at 100 kHz repetition rate and pulse durations as short as 17 ns. Up to 2 mJ of energy and sub-10-ns pulse duration are extracted at lower repetition rates. This performance is obtained by employing a rod-type ytterbium-doped photonic crystal fiber with a 70 μm core as gain medium, allowing for very short pulse durations, high energy storage, and emission of a single-transverse-mode beam. © 2007 Optical Society of America

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Q-switched lasers producing energetic nanosecond pulses find widespread applications in industrial areas for marking, trimming, and machining, as well as in scientific fields such as frequency conversion even to the extreme ultraviolet.

The properties of beam confinement combined with excellent heat dissipation make double-clad ytterbium-doped fiber lasers superior to conventional bulk solid-state lasers with regard to high-power applications in continuous-wave as well as in Q-switched operation [1,2]. Due to their attributes fiber lasers possess a high spatial beam quality, do not suffer from thermal lensing, and have inherently fiber-coupled outputs. The generation of nanosecond pulses in a fiber can follow two approaches. The first is the amplification of a low-energy seed source with a defined and flexible pulse duration (even subnanosecond pulses are possible) and repetition rate. Pursuing this approach, megawatts of pulse peak power have been reported [3–6]. The second way is Q-switching a fiber laser, which has the advantage of direct and highly efficient generation of nanosecond pulses in a single stage with the desired parameters and without the need of a sophisticated pulse seed source, their optical isolation, pre-amplification, etc., resulting in a significant reduction of size and cost.

However, in conventional Q-switched fiber lasers the pulse duration is in the range of >100 ns [7]. The reason is the direct proportionality between the generated pulse duration and cavity length [8], which is typically in the range of several meters or even longer. Consequently, a reduction of pulse duration and hence an increase of pulse peak power can be achieved by using a rare-earth-doped fiber with a short absorption length. Recently a novel fiber design possessing a high gain together with a significantly reduced nonlinearity (large single-mode core and short fiber length) has been reported. This fiber is referred to as ytterbium-doped rod-type photonic crystal fiber (PCF) [9,10]. The large core ensures excellent energy storage capability, and the short cavity length leads to a short pulse duration in Q-switched operation. Hence, this fiber design is predestined as the gain medium for high-average-power and high-pulse-energy nanosecond fiber lasers [11].

In this contribution, we report on the efficient extraction of an average power of up to 100 W, a pulse energy of up to 2 mJ, and pulse durations down to 7.3 ns from a Q-switched fiber laser in single-transverse-mode beam quality. To our knowledge, the obtained peak power of 275 kW is the highest peak power ever reported for directly Q-switched high-power fiber lasers.

The experimental setup of the high-average-power and high-energy Q-switched fiber laser is shown in Fig. 1. The ytterbium-doped core of the 70 μm microstructured fiber is formed by 19 missing air holes, surrounded by four rings of air holes with a pitch of $\Lambda = 11.5$ μm, a relative hole size $d/\Lambda = 0.1$, and a calculated mode-field diameter of 58 μm. The pump core has a diameter of ~ 200 μm and, due to the air clad, a high numerical aperture (NA) of ~ 0.6. Figure 2 shows a cross section of the fiber. Because of the small ratio between pump and active core, the small signal pump light absorption is in the range of 30 dB/m; therefore, just 60 cm of fiber length is sufficient for efficient operation. The air-clad pump core is surrounded by an overall 1.7 mm thick fused silica outer cladding to provide enough stiffness for the weakly guided fundamental mode of the 70 μm core.

The laser cavity is formed by one highly reflective mirror, an air-cooled acousto-optical modulator (AOM) as Q-switching element, the rare-earth-doped fiber, and the 4% Fresnel reflection from the fiber end

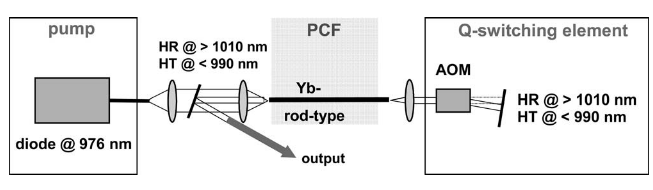

Fig. 1. Experimental setup of the Q-switched rod-type fiber. PCF, photonic crystal fiber. HR, highly reflective; HT, highly transmissive.

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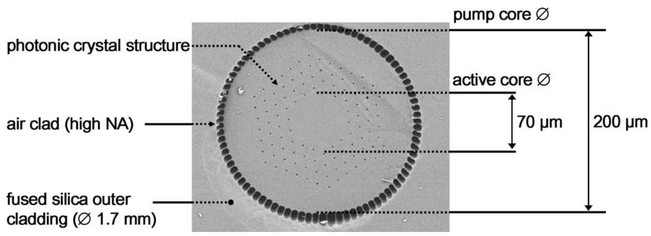

Fig. 2. Cross section of the 70 μm core rod-type fiber.

facet. The other fiber end facet is angled polished to avoid, even at the highest pump power levels, spurious lasing in the low Q-state of the cavity. Potential soiling of the photonic crystal structure during the wet polishing process is prevented by collapsing the capillaries by CO_2-laser beam exposure. The fiber laser is pumped by a fiber-coupled pump diode laser emitting at a wavelength of 976 nm out of a 400 μm core (NA=0.22).

Continuous-wave high-power extraction from this rod-type fiber laser has been already reported [11]. 320 W of single-transverse-mode output power has been obtained from a fiber just 60 cm long with a slope efficiency of about 80%, which confirms the low-loss propagation and the high potential of that fiber design.

Once the AOM is integrated into the cavity, Q-switched operation is easily achieved by aligning the setup to the first diffraction order of the AOM. Figure 3 shows the output characteristics in Q-switched operation at 100 kHz repetition rate. At the highest available pump power of 190 W an average output power of 100 W is obtained, corresponding to a pulse energy of 1 mJ. The maximum output in Fig. 3 also shows the emitted pulse duration as a function of output power, revealing the expected inverse proportionality to the extracted pulse energy. At 1 mJ of pulse energy the pulse duration is as short as 17 ns. Because there is no wavelength selection inside the cavity, the laser spectrum is located around the gain peak at ~1030 nm with an emission bandwidth of up to 10 nm. To make this laser suitable for frequency conversion an implementation of intracavity wavelength-selective elements (e.g., a diffraction grating) could significantly narrow the bandwidth.

The employed rod-type fiber with the 70 μm ytterbium-doped core can guide few transverse modes. However, an optimization of cavity alignment to maximum output power is sufficient to excite the fundamental mode only because the fundamental mode experiences the highest net gain. The M^2 value is characterized using a Spiricon M200 beam analyzer to be 1.35 independent of the output power. An average slope efficiency of ~55% is measured. One reason for the reduction in comparison with the continuous-wave operation is the limited diffraction efficiency of the AOM. Furthermore the rise time of the AOM from low Q-state to high Q-state is in the range of 100 ns, which is significantly longer than the pulse buildup time. In fact, the first giant pulse is built up in a lossy state of cavity and before the AOM has completely switched to the high Q-state. However, due to the high inversion level and therefore the high single-pass gain of a rod-type fiber most of these losses are compensated, leading to short pulse emission with durations in the range of the cavity round-trip time, which is approximately 7 ns.

Because of the nonperfect extraction efficiency at this power level, a reduction of laser efficiency due to an enormous temperature increase of the air-cooled fiber has been observed. Therefore, the rod-type PCF has been water cooled. The fiber is immersed in longitudinally flowing water to ensure sufficient heat dissipation and efficient operation.

To investigate the extractable pulse energy the average output power has been set to 10 W at 100 kHz. The result of successive reduction of repetition rate down to 1 kHz repetition rate at constant pump power is shown in Fig. 4. Down to 10 kHz the average power stays nearly constant; below 10 kHz a decrease is noticed. It has to be mentioned that the amount of amplified spontaneous emission (ASE) in the output is negligible up to a pulse energy of 1 mJ. However, all pulse energies mentioned herein are values corrected according to the following procedure. As an example, at 1 kHz the average output power is still as high as 2.25 W. Subtracting the ASE power in the low Q-state, which is considered a worst case estimation, of 250 mW results in a corrected

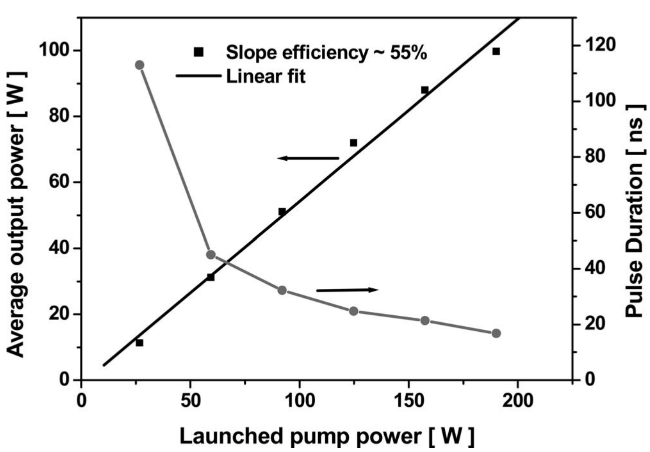

Fig. 3. Output power and pulse duration as a function of launched pump power at 100 kHz pulse repetition rate.

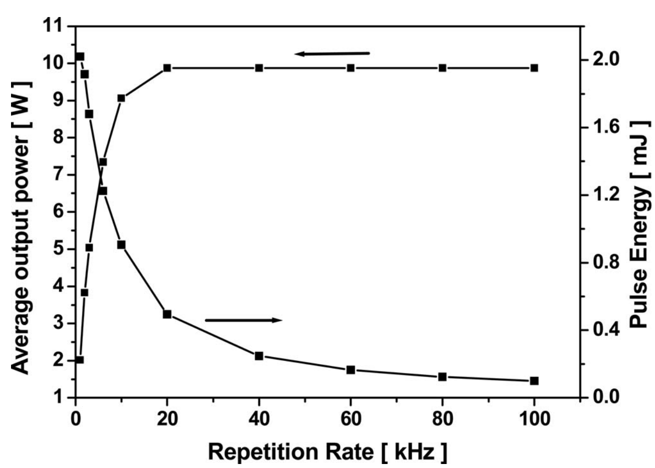

Fig. 4. Average output power and pulse energy as a function of pulse repetition rate.

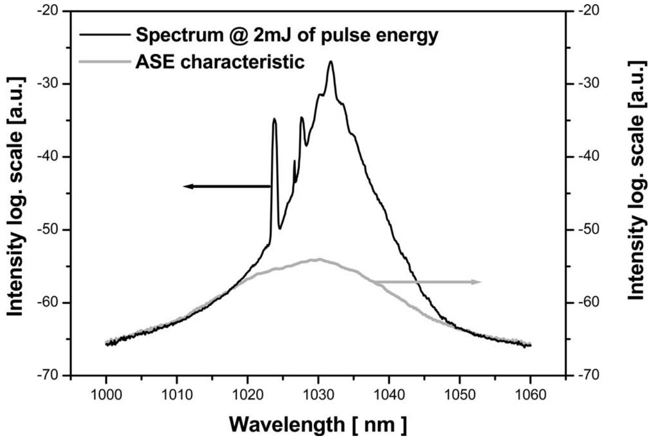

Fig. 5. Spectral characteristics at highest pulse energy and amplified spontaneous emission (ASE) characteristics in low Q-state at the same pump power level.

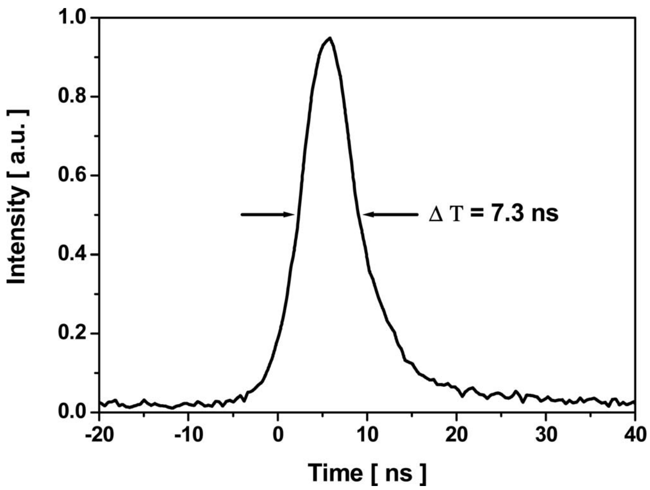

Fig. 6. Measured photodiode signal showing a pulse of 2 mJ energy.

pulse energy of 2 mJ. The spectral characteristics at this energy level are depicted in Fig. 5, illustrating the ASE distribution at this pump power level in the low Q-state and the emission spectrum in pulsed operation. Please note, due to different resolution and the scanning nature of the spectrum analyzer the two curves cannot be compared in terms of energy content. However, a significant change in spectral characteristics can be noticed. It should be mentioned that the on/off duty cycle of the AOM at 1 kHz was as low as 1/50. Changing this to any higher value did not result in a higher measured output power. Furthermore, due to the defined relation between pulse energy and pulse duration in a Q-switched laser the results obtained at low repetition rates can be directly compared with those at higher repetition rates. The measured pulse durations at certain energies at 100 kHz (where ASE is not a concern at all) agree very well with those measured at repetition rates below 10 kHz at the same pulse energy. The measured diode signal of the emitted pulses is shown in Fig. 6, revealing a pulse duration as short as 7.3 ns at this energy level. Even at the highest pulse energy no fiber facet damage has been observed. This is possible due to a special high-quality and scratch-free end facet preparation of the fiber.

In conclusion, we have demonstrated a simple and efficient Q-switched fiber laser delivering 100 W of average power at high repetition rates and up to 2 mJ of pulse energy at low repetition rates in a single-transverse-mode beam quality and linear polarization, with a measured degree of polarization of 86%. Due to the employed ytterbium-doped short-length photonic crystal fiber sub-10-ns pulses have been extracted. The high energy storage capability, high average power extraction, and excellent mode quality illustrate the potential for several applications and, furthermore, due to the low nonlinearity of the 70 μm core rod-type photonic crystal fiber the potential for the amplification of ultrashort laser pulses to very high peak powers.

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