Passively Q-switched 0.1 mJ Fiber Laser System at 1.53 µm

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We demonstrate a passively Q-switched fiber laser system generating pulses with as much as 0.1 mJ pulse energy at 1.53 µm and > 1 kHz repetition rate. This was achieved with a simple MOPA (master oscillator, power amplifier) scheme with a single pump source, realized with large mode area fiber and multiple reflections on a semiconductor saturable absorber mirror (SESAM).

Q-switched pulses with nanosecond durations in the 1.5 µm wavelength region are required for applications like range finding (at an eye-safe wavelength) and pumping of nonlinear devices such as OPOs [1]. Q-switched bulk lasers based on erbium-doped glasses can deliver several millijoules in this wavelength region [2], but have so far been limited in average power and repetition rate by thermal problems. Passively Q-switched microchip lasers [3,4] can generate single-frequency output but have so far not delivered more than ~12 µJ. Fiber laser systems based on single-mode erbium-doped fibers can be used as compact, simple and stable sources of Q-switched pulses with an excellent spatial mode profile and the potential for tunability over a wide wavelength range. Until recently, typical pulse energies from such systems, when actively Q-switched, were limited to about 10 µJ, while pulse energies from passively Q-switched single-mode erbium-doped fiber systems [5] stayed well below 1 µJ to our knowledge. (20 µJ pulses have been reported [6] for a system which contained a highly multimode fiber with a very large core; presumably poor transverse mode quality was obtained, although the authors did not comment on this.) Pulses of a few microjoules (or less) in a single transverse mode are sufficient for some applications, but more energy and peak power is needed for others, particularly for pumping of parametric nonlinear devices. Significant improvements in available pulse energies have recently been made by using fibers with large mode area. Single transverse mode operation can be maintained despite the large mode areas by using a low numerical aperture design. Using this concept, pulse energies of 180 µJ have been demonstrated [7]. The laser mode area in this fiber was 310 μm^2 as compared to the 30-50 μm^2 typical for conventional erbium-doped fibers. Even higher energies of up to 0.8 mJ have been obtained using advanced fiber designs which allow for further increased mode areas [8] without excessive sensitivity to bend losses. While these high pulse energies were all obtained with active Q-switching, we demonstrate a passively Q-switched fiber laser system in this paper.

Passive (as opposed to active) Q-switching eliminates the need for a modulator in the cavity and the corresponding drive electronics, making the whole system very compact and inexpensive. However, the available pulse energy is limited by the relatively small modulation depths of typical saturable absorbers. In this paper we demonstrate very high pulse energies despite these limitations.

The semiconductor saturable absorber mirror (SESAM) [9,10] used as Q-switch in all experiments contains a Bragg mirror, an absorber layer, a cap layer, all grown with MOCVD (metal organic chemical vapor deposition) on a GaAs substrate, and a dielectric antireflection coating. The Bragg mirror consists of 40 pairs of $In_{0.65}Ga_{0.35}As_{0.73}P_{0.27}$ / InP lattice-matched quarter-wave layers. The 520 nm thick absorber is made of $In_{0.58}Ga_{0.42}As_{0.9}P_{0.1}$ and covered with a 24 nm thick cap layer of InP to prevent a lifetime reduction by surface recombination of carriers. We measured a modulation depth of ΔR = 27%, a saturation fluence of $F_{sat} = 86\ \mu J/cm^2$, an absorber recovery time of 13 ns, and nonsaturable losses of 13%.

As a first step, we built a simple Q-switched oscillator (Fig. 1) using 60 cm of an erbium-doped fiber (containing 1500 ppm by weight of Er^{3+} ions) with a relatively large mode area of 300 μm^2. The fiber was pumped with a Ti:sapphire laser at 980 nm through a cleaved end, which acted as the output mirror with a 4% Fresnel reflection. The other end was angle polished to eliminate the influence of the Fresnel reflection. The light from this end was collimated with an f = 4.5 mm lens and directed to the SESAM under normal incidence. Residual pump light was removed with a dichroic filter of low loss at the lasing wavelength. The saturation fluence of the SESAM ($F_{sat} = 86\ \mu J/cm^2$) was suitable for working with a collimated beam, i. e. without special focussing optics at the SESAM. The exact value of the spot size on the SESAM was not critical because the fluence can be varied in the range ~3 F_{sat} to ~50 F_{sat} with little influence on the performance and with no risk of damage.

The output beam was separated from the pump beam with a dichroic mirror. The obtained pulse energy was 4.9 µJ at 1.53 µm, with a duration of about 65 ns. These parameters were independent of the pump power, even for operation close to threshold; only the repetition rate increased with pump power, reaching the maximum value of 26 kHz (0.13 W average power) for the maximum incident pump power of 2.1 W. The relatively high doping concentration of the fiber somewhat compromised the power efficiency of the system, however it allowed the use of a shorter fiber and thus to obtain shorter pulses and reduce the influence of fiber nonlinearities.

In order to increase the pulse energy, we then increased the overall effective modulation depth by using multiple bounces on the SESAM. Two bounces were achieved by reflecting the beam off the SESAM under a slight angle and then using a highly reflecting mirror under normal incidence; this yielded 9.6 µJ pulses with 27 ns duration. (Note that the effective modulation depth is doubled although the light hits the same spot on the SESAM twice within much less than the recovery time.) Using two highly reflecting mirrors, we made configurations with four bounces (15 µJ, 20 ns) and six bounces (17 µJ, 14 ns). The peak power of the 17 µJ pulse was just over 1 kW. The pulses had a clean temporal shape, and the typical spectral bandwidth was about 0.1 nm.

We obtained a significant further increase of pulse energy with a MOPA (master oscillator, power amplifier) configuration (Fig. 2). We used the same oscillator as before (with up to 6†bounces on the SESAM), but pumped it through an amplifier section, made of 78 cm of the same erbium-doped fiber. The pump was now launched into an angle polished end of the amplifier fiber. The other end of the amplifier fiber was cleaved and aligned opposite the input end of the oscillator fiber with an air gap of a few microns between the ends. The alignment was done under the microscope of a manual fusion splicer and optimized for maximum average system output power. The Fresnel reflections together with the air gap formed a Fabry-Perot interferometer, acting as a mirror with up to ~16% reflection at the laser wavelength. The reflectivity into the oscillator could be modified by adjusting the air gap. The loss of pump light (which propagates in several transverse modes) at the air gap was significant; we estimated it to be around 60 % by measuring the throughput at a detuned pump wavelength with small absorption of the erbium dopant. A more stable and practical solution with lower loss to the pump light would be to use a UV-written fiber grating. This could be made from an undoped fiber of similar mode size, spliced between amplifier and oscillator fiber.

In the MOPA configuration used, the oscillator is pumped with the residual pump light from the amplifier so that no additional pump source is required. The lower pump power to the oscillator, compared to the configuration without the amplifier fiber, decreases the repetition rate; this is favourable for high output pulse energies as it allows the amplifier to operate with higher inversion and thus higher gain. Moreover the pump transmission of the amplifier fiber drops very significantly (by a few dB) after extraction of energy by a pulse, so that the oscillator does not generate a pulse before the inversion in the amplifier is large. This was particularly evident in our experiments because the residual pump power from the amplifier in the fully inverted state was not much higher than the threshold power of the oscillator.

The amplifier length of 78 cm was chosen so that the residual pump power was sufficient to pump the oscillator. Also the maximum amplifier single-pass gain (before amplification of a pulse) must be restricted to about 20 dB, because at higher gains significant power is lost by amplified spontaneous emission (ASE).

With four bounces on the SESAM in the oscillator, the MOPA configuration typically generated pulses with around 76 µJ energy and a clean temporal shape (Fig. 3, solid curve). We always used the full available pump power of ~2 W incident on the launching objective. (The high threshold power of the oscillator did not allow pulsed operation with less than ~1.5 W pump power.) The average output power was ~190 mW. The pulse duration was 54 ns – consistently longer than from the oscillator alone (20 ns). The suspected reason for this increase of pulse duration is that some spurious weak reflections from within the amplifier or possibly from its input end prematurely triggered the oscillator, altering its performance characteristics.

We then configured the oscillator for six bounces on the SESAM. The pulse energy was now increased to around 0.11 mJ. The high peak powers of more than 1 kW were now sufficient to trigger strong stimulated Brillouin scattering (SBS). This led to a complicated temporal shape of the pulses at these high energies (Fig. 3, dashed curve). The spectrum typically consisted of one or two peaks near 1.53 µm with a bandwidth of 0.2-0.3 nm.

Pulse energies as high as 0.14 mJ could be obtained by adjusting the air gap so that the oscillator just reached threshold; however, this regime (with lower repetition rate) was significantly less stable.

The pulse energy in the MOPA configuration fluctuated by a few percent, significantly more than from the oscillator alone. The main reason for this is believed to be that the fluctuations of pump power from the Ti:sapphire laser affect the gain in the amplifier fiber, while they would only cause fluctuations of the repetition rate in a passively Q-switched oscillator alone which always triggers a pulse when a certain stored energy is reached. The pulse energy stability should be much better with a diode laser as pump source.

In conclusion, we have demonstrated that very high pulse energies of 0.1 mJ in the 1.5 µm spectral region can be obtained from simple passively Q-switched fiber laser systems, involving fibers with large mode area and a semiconductor saturable absorber mirror. We anticipate that even higher pulse energies of 0.3 mJ or more should be obtainable by employing a somewhat more efficient fiber with even larger mode area and replacing the air gap by a fiber grating which could also be used to control the output wavelength and laser bandwidth.

References

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Figures

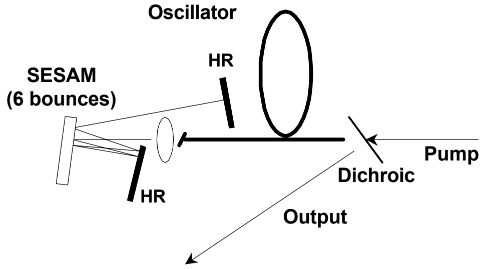

Fig. 1: Setup of simple Q-switched oscillator, made from large mode area (LMA) fiber and a semiconductor saturable absorber mirror (SESAM). The left fiber end is angle polished while the cleaved right end acts as the output coupler.

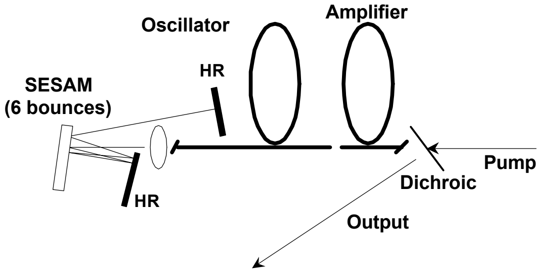

Fig. 2: Setup of MOPA configuration, with four bounces per roundtrip on the SESAM. HR = highly reflecting mirror, DM = dichroic mirror, DF = dichroic filter.

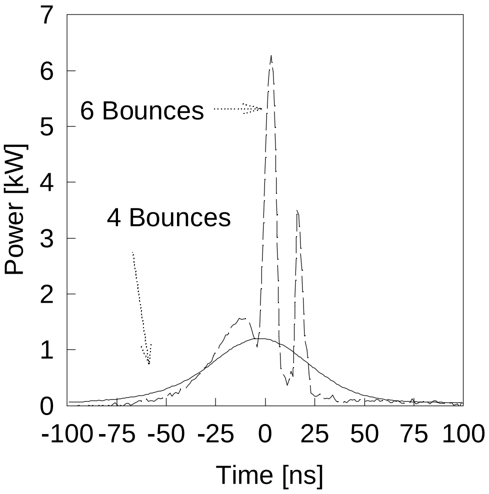

Fig. 3: Temporal pulse shapes obtained with MOPA configurations. Solid curve: six bounces on SESAM, 112 µJ pulse energy, with distortions due to SBS. Dashed curve: four bounces on SESAM, 76 µJ pulse energy.