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 of pulse energy at 1.53 μm and a >1-kHz repetition rate. These results were achieved with a simple master oscillator–power amplifier scheme with a single pump source, realized with large-mode-area fiber and multiple reflections upon a semiconductor saturable-absorber mirror.

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Q-switched pulses with nanosecond durations in the 1.5-μm wavelength region are required for applications such as range finding (at an eye-safe wavelength) and pumping of nonlinear devices such as optical parametric oscillators.[1] Q-switched bulk lasers based on erbium-doped glasses can deliver several millijoules of energy in this wavelength region[2] but so far have been limited in average power and repetition rate by thermal problems. Passively Q-switched microchip lasers[3,4] can generate single-frequency output but so far have 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 excellent spatial mode profiles and the potential for tunability over a wide wavelength range. Until recently, typical pulse energies from such systems, when they were actively Q switched, were limited to ~10 μJ, whereas 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 that contained a highly multimode fiber with a 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 are needed for others, particularly for pumping of parametric nonlinear devices. Significant improvements in available pulse energies were recently made by use of fibers with large mode areas. Single-transverse-mode operation can be maintained despite the large mode areas by use of a low-numerical-aperture design. With this concept, pulse energies of 180 μJ have been demonstrated.[7] The laser mode area in this fiber was 310 μm^2, compared with the 30–50 μm^2 typical for conventional erbium-doped fibers. Even higher energies, of as much as 0.8 mJ, have been obtained with advanced fiber designs that allow for further increased mode areas[8] without excessive sensitivity to bend losses. Whereas these high pulse energies were all obtained with active Q switching, in this Letter we demonstrate a passively Q-switched fiber laser system.

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 compact and inexpensive. However, the available pulse energy is limited by the relatively small modulation depths of typical saturable absorbers. Here we demonstrate high pulse energies despite these limitations.

The semiconductor saturable-absorber mirror[9,10] (SESAM) used as the Q switch in all experiments contains a Bragg mirror, an absorber layer, and a cap layer, all grown with metal-organic chemical-vapor deposition upon an InP 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 is covered with a 24-nm-thick cap layer of InP to prevent lifetime reduction by surface recombination of carriers. We measured a modulation depth of $\Delta R = 27\%$, 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 parts in 10^6 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 4% Fresnel reflection. The other end was angle polished to eliminate the influence of the Fresnel reflection. The light from this end was collimated

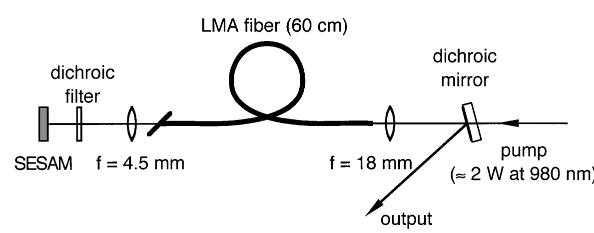

Fig. 1. Setup of a simple Q-switched oscillator, made from a large-mode-area (LMA) fiber and a SESAM. The left fiber end is angle polished, whereas the cleaved right end acts as the output coupler.

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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 focusing optics at the SESAM. The exact value of the spot size on the SESAM was not critical because the fluence could be varied in the range ~3–~50 F_{sat} with little influence on the performance and with no risk of damage.

The output beam was separated from the pump beam by a dichroic mirror. The obtained pulse energy was 4.9 μJ at 1.53 μm, with a duration of ~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 us to use a shorter fiber and thus to obtain shorter pulses and reduce the influence of fiber nonlinearities.

To increase the pulse energy we then increased the overall effective modulation depth by using multiple bounces on the SESAM. We achieved two bounces by reflecting the beam off the SESAM at 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 just slightly exceeded 1 kW. The pulses had a clean temporal shape, and the typical spectral bandwidth was ~0.1 nm.

We obtained a significant further increase of pulse energy with a master oscillator–power amplifier (MOPA) configuration (Fig. 2). We used the same oscillator as before (with from one to six bounces on the SESAM) but pumped it through an amplifier section made from 78 cm of the same erbium-doped fiber. The pump was then 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 micrometers 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 as much as ~16% reflection at the laser wavelength. The reflectivity into the oscillator could be modified by adjustment of 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 near 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 grating 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 no additional pump source is required. The lower pump power to the oscillator, compared with that for the configuration without the amplifier fiber, decreases the repetition rate; this is favorable 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 decibels) after extraction of energy by a pulse, so the oscillator does not generate a pulse before the inversion in the amplifier is large. This effect 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 such 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 ~20 dB, because at higher gains significant power is lost by amplified spontaneous emission.

With four bounces on the SESAM in the oscillator, the MOPA configuration typically generated pulses with ~76 μJ of energy and a clean temporal shape (Fig. 3, solid curve). We always used the full available pump power of ~2 W that was incident upon the launching objective. (The high threshold power of the oscillator did not permit pulsed operation with less than ~1.5 W of pump power.) The average

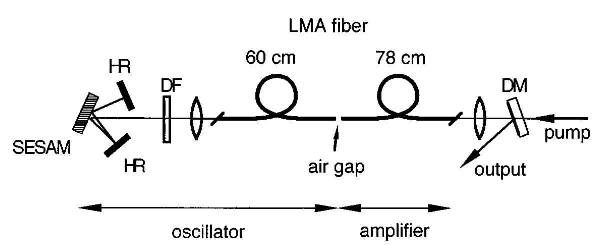

Fig. 2. Setup of the MOPA configuration, with four bounces per round trip on the SESAM: HR's, highly reflecting mirrors; DM, dichroic mirror; DF, dichroic filter; LMA, large mode area.

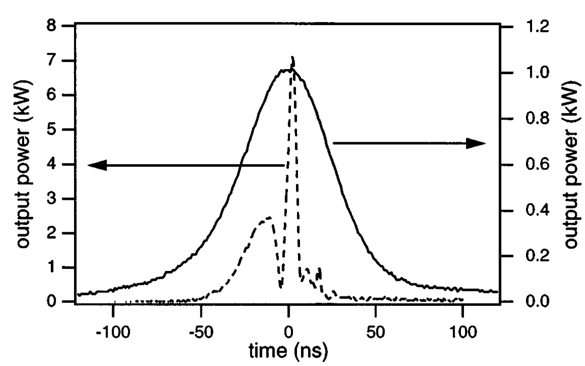

Fig. 3. Temporal pulse shapes obtained with MOPA configurations. Dashed curve, six bounces on the SESAM, 112-μJ pulse energy, with distortions that are due to stimulated Brillouin scattering. Solid curve, four bounces on the SESAM, 76-μJ pulse energy.

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 in 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 ~0.11 mJ. The high peak powers of more than 1 kW were now sufficient to trigger strong stimulated Brillouin scattering, which 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.

We could obtain pulse energies as high as 0.14 mJ by adjusting the air gap so 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, whereas they merely 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's stability should be much better with a diode laser as the 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 areas and semiconductor saturable-absorber mirrors. We anticipate that even higher pulse energies of 0.3 mJ or more should be obtainable by use of a somewhat more efficient fiber with an even larger mode area and replacement of the air gap with a fiber grating that could also be used to control the output wavelength and laser bandwidth.

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