Cladding pumped Q-switched fiber laser using a tapered fiber saturable absorber

Sean W. Moore*, Daniel B. S. Soh, Scott E. Bisson, Brian D. Patterson, and Wen L. Hsu
Sandia National Laboratories, 7011 East Ave. Livermore, CA 94550, USA
*seanmoor@sandia.gov

Abstract: We report a passively Q-switched all-fiber laser using a large mode area Yb$^{3+}$-doped fiber cladding-pumped at 915 nm and an unpumped single-mode Yb$^{3+}$-doped saturable absorber fiber. 60 µJ 80 ns pulses at 1030 nm are reported.

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Passively Q-switched fiber lasers are attractive for many applications owing to their small form factor, excellent beam quality, and high efficiency. Previous efforts using Cr$^{3+}$:YAG as a saturable absorber (SA) have generated 25 µJ, 2.5 ns pulses, but require the use of free-space optics to couple into and out of fiber [1]. Bulk SA’s can be removed by using unpumped rare-earth doped fibers as the saturable absorbing elements. Passive Q-switching using Yb$^{3+}$-doped gain fiber and Sm$^{3+}$-doped fiber as the SA element has produced 19 µJ 650 ns pulses [2]. Similarly, an Er$^{3+}$-doped fiber laser using unpumped Er$^{3+}$-doped fiber as the SA and a Yb$^{3+}$-doped fiber laser using unpumped Yb$^{3+}$-doped fiber as the saturating element have produced 8 µJ 80 ns and 2.8 µJ 280 ns pulses, respectively [3,4]. However, the unfavorably low absorption and slow switching time of rare-earth doped SA fibers in the commonly used ASE bands of Yb$^{3+}$ and Er$^{3+}$ reduce the available unsaturated gain in the pumped fiber, leading to longer, less energetic pulses. We have effectively achieved faster switching times by coupling the ASE from a pumped large mode area (LMA) Yb$^{3+}$-doped fiber to an unpumped, single-mode Yb$^{3+}$-doped SA fiber with a low loss tapered fiber mode field adaptor. The high intensity of ASE in the single-mode SA fiber bleaches the absorption before the onset of gain depletion in the LMA gain fiber, resulting in short, energetic pulses.

![Figure 1. Schematic of experimental set-up](CF1E.4.pdf)

A schematic of the experimental set-up for the passively Q-switched system using tapered mode field adaptors is shown in Fig. 1. A LMA Yb$^{3+}$-doped fiber is end-pumped by four QCW 50 Hz, 100 µs 30 W IPG PDL-30 915 nm fiber-coupled pumps spliced to a fused fiber bundle. The end of LMA fiber opposite the pump side is down tapered to produce single mode operation in the tapered section and to reduce the mode field diameter (MFD) of the fundamental LP$_{01}$. Pulse energy, pulse width, and spectra were measured as shown in Figure 1.

Two Yb$^{3+}$ LMA gain fibers were employed to demonstrate passive Q-switching using single-mode SA fibers. The first was 39 cm of 20 µm core/125 µm clad 0.08 NA double clad fiber (nLight Yb1200 20/125) down tapered by a 0.461:1 ratio on one end for single mode operation in the tapered region. The estimated mode field diameter in the tapered region is 12 µm. The tapered section was fusion spliced to one end of a passive 6 µm core single mode fiber (ThorLabs 1060XP) down tapered by a 0.424:1 ratio to increase the mode field diameter to 12 µm. The composite taper was then spliced to 44 cm of single-mode SA fiber. Pumping the flat-cleaved end of the LMA gain fiber with 100 µs 50 Hz 915 nm 45 W QCW pulses (21 W absorbed) produced 60 µJ 81 ns pulses at 1030 nm with near diffraction-limited beam quality (M$^2$<1.15). The pulse temporal profile for a typical 60 µJ pulse is shown in Figure 2a. During oscillation and energy build-up of the pulse before the onset of Q-switching, 1030 nm light entering the LMA fiber from the tapered region should be preferentially launched into the LP$_{01}$ mode. However, fiber imperfections, external stresses, and environmental perturbations often cause the fundamental mode to partially scatter into higher order modes. The tapered single mode section does not support higher order modes and scatters any power in these modes into the cladding, resulting in additional losses in the tapered region. The
most energetic pulses with the shortest pulse widths (60 µJ, 81 ns) were achieved when the 20 µm core LMA Yb\textsuperscript{3+} fiber was configured in a straight line. Conversely, when the LMA gain fiber was bent to form a S-shape, the pulse energy dropped by a factor of 2-3 and the pulse width doubled, although there were several specific S-shaped configurations where the pulse energy and pulse width were nearly the same of those achieved using a straight-line configuration. This implies that mode scrambling in the LMA gain fiber is sensitive to fiber positioning, length, strain, and environmental factors and is generally not reproducible from one fiber to the next, although configurations of high performance can be found for any one fiber.

To minimize excess loss from higher order modes through the tapered region the multi-mode LMA Yb\textsuperscript{3+} fiber was replaced with 1.20 m of single-mode 14 µm core/125 µm clad Yb\textsuperscript{3+} fiber (NKT Photonics DC-135/14-PM-YB) with a 15 µm MFD. One end was spliced to a short section of nominally single-mode 10/125 passive fiber with a ~ 12 µm MFD. The other end of the passive fiber was spliced to a passive single-mode 6/125 fiber (ThorLabs 1060XP) down tapered by a 0.424:1 ratio to match to the MFD of the 10/125 passive fiber. The estimated splice loss between the 14/125 gain fiber and 10/125 passive fiber is ~13%. The total splice loss through the composite tapered section could not be accurately determined since the inner cladding of the gain fiber was micro-structured to guide the pump light and prevented separation of the core and cladding light. Pumping the flat-cleaved end of the gain fiber with 100 µs 50 Hz 915 nm 19 W QCW pulses (9 W absorbed) produced 25 µJ 90 ns pulses at 1030 nm as shown in Figure 2b. The pulse energy and pulse width changed by less than 10% when the fiber was positioned in different configurations, indicating that the all single-mode fiber cavity eliminated pulse instability as expected. The lower energy relative to that achieved with the 20/125 micron Yb\textsuperscript{3+} fiber is consistent with the lower pump absorption before the onset of Q-switching (9 W vs. 21 W)

In summary, we have demonstrated passive Q-switching in an all fiber oscillator using two LMA Yb\textsuperscript{3+}-doped fibers and an unpumped single-mode Yb\textsuperscript{3+} fiber as a saturable absorber. The larger core 20/125 Yb\textsuperscript{3+}-doped fiber produced 60 µJ 81 ns pulses at 1030 nm, but was sensitive to positioning of the gain fiber due to spatial mode mixing in the multi-mode region of the fiber. Similarly, 25 µJ 90 ns pulses were achieved with a single-mode 14 µm core Yb\textsuperscript{3+}-doped fiber. However, in this instance the all single-mode architecture prevented spatial mode mixing and allowed for excellent pulse stability. Increasing the lengths of the single-mode gain and SA fibers should improve pulse energy and decrease the pulse width.

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