Compact diode-pumped passively Q-switched tunable Er–Yb double-clad fiber laser


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Efficient repetitive passive Qswitching of a cladding-pumped Er–Yb fiber laser has been demonstrated by use of an external-cavity configuration containing a Co2+ :ZnS crystal as a saturable absorber. Energies of as much as 60 μJ in pulses of durations as short as 3.5 ns (FWHM), corresponding to a peak power of >10 kW, have been generated, and the maximum slope efficiency with respect to the absorbed pump power was 13%. Using a bulk diffraction grating in the Littrow configuration to provide wavelength-selective feedback, we tuned the passively Q-switched fiber laser over 31 nm from 1532 to 1563 nm. The prospects for further improvement in performance are discussed. © 2002 Optical Society of America

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Over the past decade, progress in the development of efficient diode-pumped, pulsed solid-state lasers operating in the eye-safe wavelength regime near 1.5 μm has been dramatic, fueled by the needs of a variety of scientific, industrial, and defense applications. For some of these applications (e.g., range finding and remote sensing) the requirement for short pulses (a few nanoseconds) has led to the development of compact Er–Yb-doped glass microLasers with active or passive Q switching. By virtue of their very short cavity lengths (typically a few millimeters), these lasers can generate pulses of <8-ns duration and >3-μJ energy. An alternative method for producing pulsed output in the 1.5-μm spectral range is to Q switch an Er–Yb-codoped fiber laser. This approach has the potential attraction that output powers should be scalable to much higher levels without degradation in beam quality by the use of a double-clad fiber design and cladding-pumping. Actively Q-switched single-clad Er and Er–Yb fiber lasers are well established, and recently an actively Q-switched cladding-pumped Er–Yb fiber laser was demonstrated. To simplify the resonator design and eliminate the need for external Q-switching electronics, passive Q switching of single-clad Er-doped fiber lasers has also been attempted with a liquefying gallium mirror, a semiconductor saturable absorber, and a Co2+ :ZnSe crystal as the saturable absorber. However, the last-named system has shown relatively poor performance, with pulse durations of >1 μs and peak powers of <1 W.

In this Letter we report a cladding-pumped passively Q-switched Er–Yb-codoped fiber laser with a Co2+ :ZnS crystal as a saturable absorber, which generates pulses of as much as 60 μJ of energy and a duration of 3.5 ns (FWHM), corresponding to a peak power of >10 kW, and with a maximum slope efficiency with respect to absorbed pump power of 13%. To the best of our knowledge these results show the highest peak power ever recorded in any passively or actively Q-switched Er fiber laser reported to date.

The fiber laser configuration used in our experiments (shown in Fig. 1) consists of ~2 m of Er–Yb-doped circular double-clad fiber (EYDF) and an external cavity that comprises a collimating lens (L2) of 4.5-mm focal length; a focusing lens (L3) of focal length 8.6 mm to focus the fiber output into a Co2+ :ZnS crystal; a second collimating lens (L4), of focal length 15 mm, to recollimate the beam; and finally, a diffraction grating, blazed at 1.55 μm with 600 lines/mm, used in the Littrow configuration to provide wavelength-selective feedback. Intracavity focalization into the Co2+ :ZnS crystal was found necessary for sufficiently increasing the fluence on the absorber well above saturation. The focal lengths of both L2 and L3 were chosen to roughly minimize the mode volume in the Co2+ :ZnS crystal to produce a low threshold for passive Q switching, and the crystal was oriented at a small angle with respect to the beam to prevent backreflection into the fiber. The EYDF, fabricated in house by the standard modified chemical-vapor deposition process, had a phosphosilicate core of 11-μm diameter, with Er2+ and Yb3+ concentrations of 132,000 and 6400 parts in 106.

Fig. 1. Schematic of the passively Q-switched fiber laser: SM, single mode.
respectively, and 0.21 N.A., and it was surrounded by a pure-silica inner cladding of 125-μm diameter. The outer cladding was fabricated from a low-refractive-index (n = 1.375) UV-curable polymer, resulting in a high N.A. (0.49) for the inner cladding. The EYDF was pumped by a beam-shaped diode bar at 915 nm with 8 W of maximum power. The pump light was coupled into the fiber through a perpendicularly cleaved end facet via an arrangement that comprised two dichroic mirrors, with high reflectivity (~100%) at 915 nm and high transmission (~95%) at 1.5–1.6 μm, and a gradient-index lens (L1) of 25-mm focal length with antireflection coatings at the pump and lasing wavelengths. The diffraction grating and a cleaved fiber end facet provided the feedback required for laser oscillation, with the end facet serving as the output coupler. The use of a large-diameter (multi-mode) core is attractive because it allows for greater energy storage than conventional single-mode core designs,12 but it obviously has the disadvantage that beam quality is degraded as a result of multimode lasing. To suppress lasing on higher-order modes, a short length (~400 mm) of standard single-mode fiber with a core diameter of 8 μm was spliced onto the EYDF end adjacent to the external cavity. This fiber is single mode at 1550 nm and has a high-index coating that suppresses light in the cladding. Besides providing for mode selection, its additional advantages are that it reduces amplified spontaneous emission, a few milliwatts in our case, and prevents unabsorbed pump light from damaging the saturable absorber. The end facet of the single-mode fiber was angle cleaved at ~15° to suppress parasitic lasing between the fiber end facets. When the EYDF was bent into a figure-8 shape (radius of curvature ~2 cm) to improve the overlap of the pump modes with the fiber core, the absorption efficiency of the launched pump power was 95%.

Co2+:ZnS was chosen as the saturable absorber because it has a long metastable lifetime (~200 μs) and a high ground-state absorption cross section (~9 × 10⁻¹⁹ cm²), and hence it has a very low saturation fluence (0.1451 J/cm²) at 1.53 μm). In addition, it has very low nonsaturable losses (<0.1 cm⁻¹) compared with other saturable absorber Q switches, and its absorption spectrum covers a broad wavelength range (1200–1900 nm), making it a suitable candidate for use in tunable Er³⁺ lasers systems operating in the 1.5–1.6-μm spectral region. The Co2+:ZnS crystal used in our experiments was 1 mm thick and had uncoated facets. The small-signal transmission at 1.534 μm was only 9.5%; hence cw lasing was suppressed, even with the high gain value obtained with the EYDF amplifying medium.

Under the operating conditions described above, we found that the threshold for passive Q switching was ~600 mW of absorbed pump power. The average output power and the pulse repetition rate are shown in Fig. 2 as functions of absorbed pump power. The average slope efficiency was ~13% with respect to the absorbed pump power, starting from 600 Hz at threshold and increasing to 6 kHz at the highest pump power (2.75 W absorbed). The pulse train was characterized by relatively stable peak-to-peak intensities (see Fig. 3), and the average pulse-to-pulse temporal jitter recorded over 64 pulses was typically less than ±4%, which is less than for typical passively Q-switched bulk lasers.14

One interesting feature of the laser was that the Q-switched pulse duration (approximately 3.5–5 ns) was much shorter than the cavity round-trip time (~25 ns) and did not vary significantly with pump power. A typical Q-switched pulse (Fig. 3, inset) comprises a main pulse and much lower-power satellite pulses before and after the main pulse. Similarly short pulses were observed previously in Q-switched Er-doped fiber lasers, and various explanations for this behavior, such as the conjunction of Q-switched operation with self-mode locking owing to self-phase modulation,15,16 and the effect of stimulated Brillouin scattering,17,18 have been proposed. Further research to determine the origin of the short-pulse generation for our passively Q-switched fiber laser is in progress. The pulse energy was measured directly with a calibrated detector to avoid including the effects of amplified spontaneous emission, which can arise when one is determining pulse energy by measurement of the average power and dividing by the pulse repetition frequency. At the maximum pump power, the pulse energy was found to be ~60 μJ, with 75% contained within the main pulse, and corresponds to a peak power of more than 10 kW. This is to our
knowledge by far the highest peak power reported for any Q-switched Er\(^{3+}\) fiber laser oscillator. A further interesting feature of the Q-switched behavior was that the pulse energy did not vary significantly with pump power and was >50 μJ over the full range of pump power used (i.e., 500–2750 mW). A consequence of the generated giant pulse propagating along the fiber is the presence of stimulated Brillouin scattering, which can occur because of the high peak power. The spectrum of the laser is shown in Fig. 4. It was composed of five sharp lines of 0.02-nm width (FWHM), spreading over 0.4 nm and separated by 0.08 nm. Stimulated Brillouin scattering can clearly be identified because this spacing value exactly matches the Brillouin shift in silica near 1550 nm, and this structure can be seen only when a giant pulse is propagating along the fiber. The presence of the diffraction grating also permitted tuning of the output laser signal from 1532 and 1563 nm. Moreover, because of the grating, the output power was 95% vertically polarized.

For comparison, the cw laser performance was also evaluated with the Co\(^2+\):ZnS crystal removed from the external cavity while all the other optical components were maintained in place. Under these operating conditions the cw slope efficiency was measured to be 15%, hence only 2% higher than for the passively Q-switched laser. The low value for the cw slope efficiency can easily be explained by the extra resonator losses in the external cavity that are due to the grating, the collimating and focusing lenses, and also the single-mode fiber. It is worth noting that, when the same fiber was employed in a simpler cavity configuration, where feedback for laser oscillation was provided by a high-reflectivity mirror buttressed to one end of the fiber and by a perpendicularly cleaved fiber end facet, we obtained a maximum slope efficiency of 46% with respect to the absorbed pump power. Thus, by improving the design of the external cavity and using lower-loss components, and by modifying the design of the EYDF, it should be possible to construct a passively Q-switched EYDF laser with much higher efficiency.

In conclusion, we have demonstrated a novel diode-pumped passive Q-switched fiber laser with high-peak-power pulses and broad tunability. This system gives a simple way to obtain more than 10 kW of peak power in a nanosecond pulse, and we believe that, in combination with additional fiber amplifiers, it could offer a route to a compact and reliable tunable millijoule laser. Compact periodically poled LiNbO\(_3\) optical parametric oscillator devices pumped by such pulsed fiber sources and emitting in a broad range can also be imaged and could be suitable for many practical applications.\(^\text{19}\)

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