2460

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

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Abstract

Highly-efficient repetitive passive Q-switching of a cladding-pumped Er-Yb fiber laser has been demonstrated by employing an external cavity configuration containing a Co^{2+}:ZnS crystal as saturable absorber. Energies up to 60 μJ in pulses of duration as short as 3.5ns (FWHM), corresponding to a peak power >10kW, have been generated, and the maximum slope efficiency with respect to absorbed pump power was 13%. Using a bulk diffraction grating in Littrow configuration to provide wavelength selective feedback, the passively Q-switched fiber laser was tuned over 31nm from 1532nm to 1563nm. The prospects for further improvement in performance will be discussed.

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Over the last decade, progress in the development of efficient, diode-pumped, pulsed solid-state lasers operating in the eyesafe wavelength regime around 1.5μm has been dramatic, fuelled by the needs of variety of scientific, industrial and defense applications. For some of these applications (e.g. range finding and remote sensing) the requirement for short pulses (~few ns) has led to the development of compact Er-Yb-doped glass micro-lasers with active or passive Q-switching. By virtue of their very short cavity lengths (typically ~few mm), these lasers can generate pulses of duration <8ns and energy >3μJ[1]. An alternative method for producing pulsed output in the 1.5μm spectral range is to Q-switch an Er-Yb co-doped fiber laser. This approach has the potential attraction that output powers should be scalable to much higher levels without degradation in beam quality via the use of a double-clad fiber design and cladding-pumping[2]. Actively Q-switched single-clad Er and Er-Yb fiber lasers are well-established[3-7], and recently an actively Q-switched cladding-pumped Er-Yb fiber laser has also been demonstrated[8]. 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 using a liquefying gallium mirror[9], a semiconductor saturable absorber[10] or a Co^{2+}:ZnSe crystal as saturable absorber[11]. However, the last system has shown relatively poor performance with pulse durations >1μs and peak powers <1W.

In this Letter, we report a cladding-pumped passively-Q-switched Er-Yb co-doped fiber laser with a Co^{2+}:ZnS crystal as saturable absorber, which generates pulses of energy up to 60μJ and duration of 3.5ns (FWHM), corresponding to a peak power >10kW, 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 ~2m of Er-Yb doped double-clad fiber (EYDF) and an external cavity comprising a collimating lens (L_2) of 4.5mm focal length, a focusing lens (L_3) of focal length 8.6mm to focus the fiber output into a Co^{2+}:ZnS crystal, a second collimating lens (L_4) of focal length 15mm to re-collimate the beam, and finally, a diffraction grating, blazed at 1.55μm with 600 lines/mm, used in Littrow configuration to provide wavelength selective feedback. The intracavity focalization into the Co^{2+}:ZnS crystal was found necessary to increase sufficiently the fluence on the absorber well-above saturation. Both L_2 and L_3 focal lengths were chosen to roughly minimize the mode volume in the Co^{2+}:ZnS crystal in order to obtain a low threshold for passive Q-switching. The EYDF had a phospho-silicate core of 11μm diameter and 0.21 NA, and was surrounded by a pure silica inner-cladding of diameter 125μm. The outer-cladding was fabricated from a low refractive index (n=1.375) UV curable polymer resulting in a high NA (~0.49) for the inner-cladding. The EYDF was pumped by a beam-shaped diode-bar at 915nm with 8W of maximum power. The pump light was coupled into the fiber through a perpendicularly cleaved end-facet via an arrangement comprising two dichroic mirrors, with high reflectivity (~100%) at 915nm and high transmission (>95%) at 1.5-1.6μm, and a gradient-index lens (L_1) of 25mm focal length with anti-reflection coatings at the pump and lasing wavelengths. The diffraction grating and 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 (multimode) core is attractive since it allows greater energy storage than conventional single-mode core designs[12], but obviously has the disadvantage that the beam quality is degraded due to multimode lasing. To suppress lasing on higher-order modes, a short length (~400mm) of standard single-mode fiber with a core diameter of 8μm was spliced on to the EYDF end adjacent to the external cavity. This fiber is single-moded at 1550nm, and has a high-index coating that suppresses light in the cladding. Besides mode selection, additional advantages are that it reduces amplified spontaneous emission (ASE) 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. By bending the EYDF in a figure of 8 in order to improve the overlapping of the pump modes with the fiber core, the absorption efficiency of the launched pump power was 95%.

Co^{2+}:ZnS was chosen as the saturable absorber because it has a long metastable lifetime (≈200μs) and a high ground state absorption (GSA) cross-section (~9×10^{-19}cm^2), and hence it has a very low saturation fluence[13] (0.145J/cm^2 at 1.53μm). In addition, it has very low non-saturable losses (<0.1cm^{-1}) compared to other saturable absorber Q-switches, and its absorption spectrum covers a broad wavelength range (1200nm – 1900nm), making it a suitable candidate for tunable Er^{3+} lasers systems operating in the 1.5-1.6μm spectral region. The Co^{2+}:ZnS crystal used in our experiments was 1mm thick and had uncoated facets. The small signal transmission at 1.534μm was only 9.5% and hence CW lasing is suppressed even with the high gain value obtained with the EYDF amplifying medium.

Under the above operating conditions, we found that the threshold for passive Q-switching was ~600mW of absorbed pump power. The average output power and pulse repetition rate as function of absorbed pump power is shown in Fig.2. The average slope efficiency was ~13% with respect to the absorbed pump power. From Fig.2 it can be seen that the pulse repetition rate increases linearly with the absorbed pump power, starting from 600Hz at threshold and increasing to 6kHz at the highest pump power (2.75W 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 lower than for typical passively Q-switched bulk lasers[14].

One interesting feature of the laser was that the Q-switched pulse duration (~3.5-5ns) was much shorter than the cavity round-trip time (~25ns) and did not vary significantly with pump power. A typical Q-switched pulse (see inset of Fig.3) comprises a main pulse with much lower power satellite pulses before and after the main pulse. Similar short generated pulse has already been observed in an actively Q-switched Er-doped fiber laser and the proposed explanation was the conjunction of the Q-switched operation with self-mode-locking due to self-phase modulation[15,16]. The pulse energy was measured directly using a calibrated detector in order to avoid including contributions due to ASE, which can arise when determining the pulse energy via a measurement of the average power and dividing by the pulse repetition frequency. At the maximum pump power, the pulse energy was found to be ~60μJ, with 75% contained within the main pulse, and corresponds to a peak power of more than 10kW. This is by far the highest peak power ever reported to date for any Q-switched Er^{3+} fiber laser. A further interesting feature of the Q-switched behavior was that the pulse energy did not vary significantly with pump power and was >50μJ over the full range of pump power used (i.e 500-2750mW). A consequence of the generated giant pulse propagating along the fiber is the presence of stimulated Brillouin scattering (SBS) which can occur because of the high peak power. The spectrum of the laser is shown in Fig. 4. It was composed of 5 sharp lines with a 0.2Å width (FWHM), spreading over 4Å and separated by 0.8Å. SBS can clearly be identified since this spacing value exactly matches with the Brillouin shifting in silica around 1550nm and this structure can only be seen when a giant pulse is propagating along the fiber. The diffraction grating also allowed tuning of the output laser signal from 1532nm and 1563nm. 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 keeping all the other optical components in place. Under these operating conditions the CW slope efficiency was measured to be 15 %, and hence only 2% higher than for the passively-Q-switched laser. The low value for the CW slope efficiency can be easily explained by the extra resonator losses in the external cavity 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 butted to one end of the fiber and by a perpendicularly-cleaved fiber end facet, we obtained a maximum slope efficiency with respect to absorbed pump power of 46 %. Thus, by improving the design of the external cavity and using lower loss components, and 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 passively Q-switched fiber laser with high peak power pulses and a broad tunability. This system gives a simple way to obtain more than 10kW 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 (PPLN OPO) devices pumped by such pulsed fiber sources and emitting in a broad range can also be imagined and could be suitable for many practical applications[17].

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Figure captions :

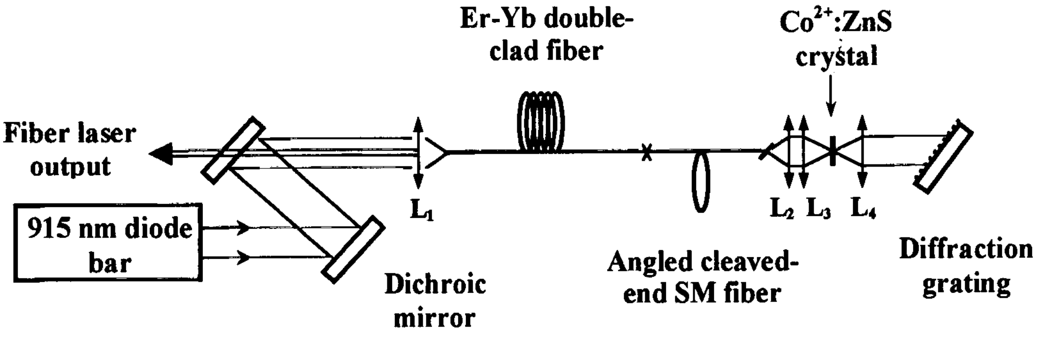
Fig. 1 : Experimental set-up of the passively Q-switched fiber laser.

Fig. 2 : Average output power (square) and pulse repetition rate (triangle) versus the absorbed pump power.

Fig. 3 : Typical Q-switch pulse train and its corresponding temporal pulse shape (inset).

Fig. 4 : Output spectrum of the laser on a linear scale. The resolution is 0.002 nm.

Figures



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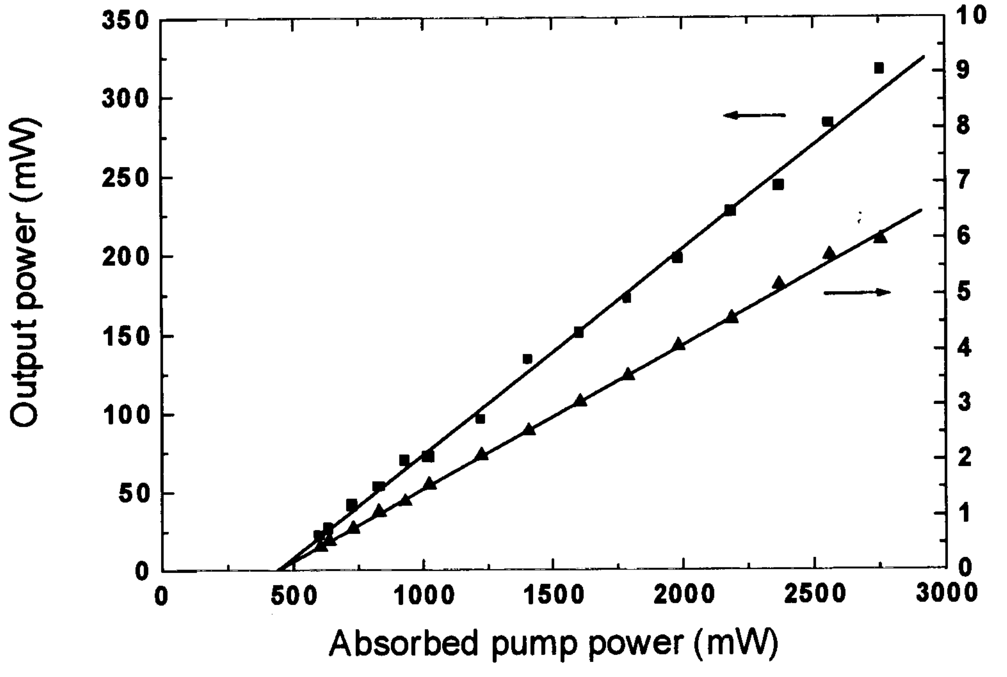

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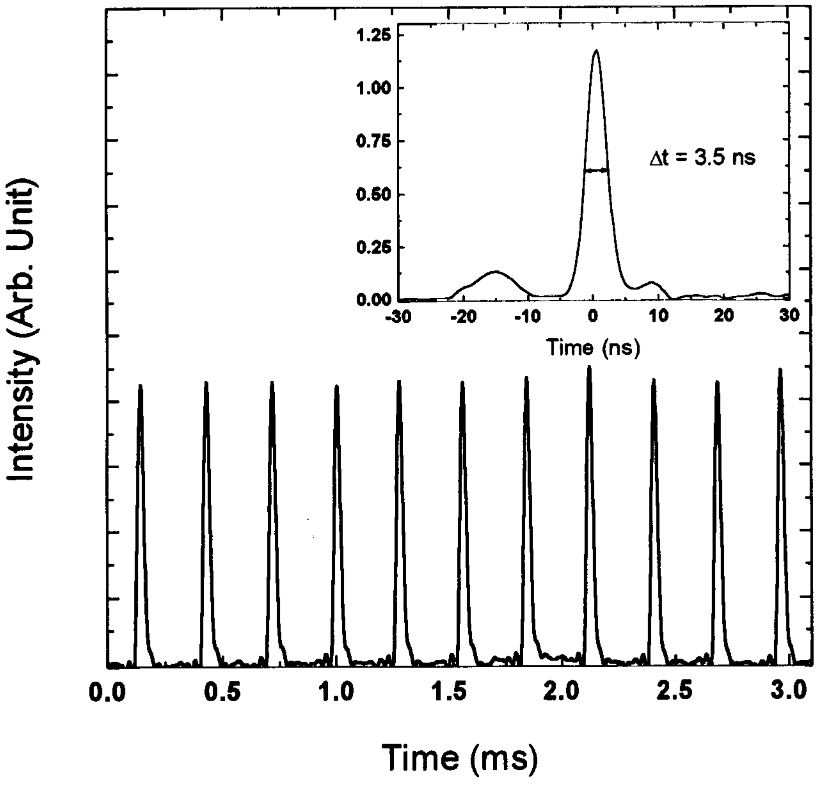

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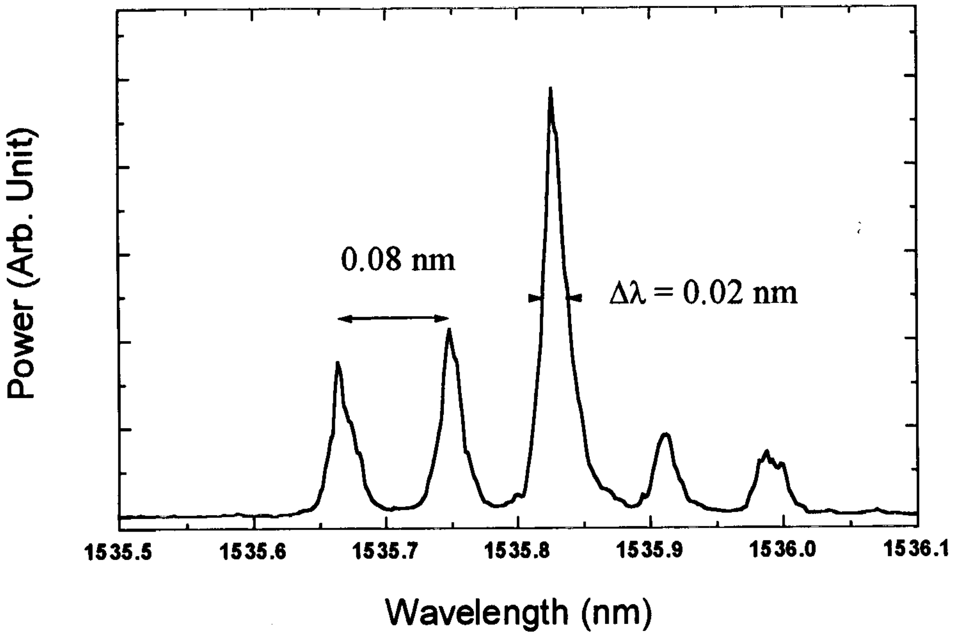

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