Actively Q-switched 1.6-mJ tapered double-clad ytterbium-doped fiber laser

Juho Kerttula,[1,*] Valery Filippov,[1] Yuri Chamorovskii,[2] Konstantin Golant,[2] and Oleg G. Okhotnikov,[1]

[1]*Optoelectronics Research Centre, Tampere University of Technology, P.O. Box 692, 33101 Tampere, Finland*
[2]*Institute of Radio and Electronics of the Russian Academy of Sciences, Mokhovaya 11, bld.7, 125009 Moscow, Russia*
**juho.kerttula@tut.fi*

Abstract: We have demonstrated an actively Q-switched tapered double-clad fiber laser capable of single-shot generation of 1.6-mJ, 64-ns pulses. The active medium based on tapered double-clad fiber is shown to exhibit a reduced level of amplified spontaneous emission which allows for high-energy pulse extraction at extremely low repetition rates.

OCIS codes: (060.2280) Fiber design and fabrication; (060.2320) Fiber optics amplifiers and oscillators; (060.3510) Lasers, fiber

References and links

1. O. Schmidt, J. Rothhardt, F. Röser, S. Linke, T. Schreiber, K. Rademaker, J. Limpert, S. Ermeneux, P. Yvernault, F. Salin, and A. Tünnermann, "Millijoule pulse energy Q-switched short-length fiber laser," Opt. Lett. **32**(11), 1551–1553 (2007).
2. F. Di Teodoro, and C. Brooks, "Multi-MW peak power, single transverse mode operation of a 100 micron core diameter, Yb-doped photonic crystal rod amplifier", Fiber Lasers IV: Technology, Systems, and Applications, Proc. of SPIE **vol. 6453**, 645318, (2007).
3. L. Michaille, D. M. Taylor, C. R. Bennett, T. J. Shepherd, and B. G. Ward, "Characteristics of a Q-switched multicore photonic crystal fiber laser with a very large mode field area," Opt. Lett. **33**(1), 71–73 (2008).
4. J. A. Alvarez-Chavez, H. L. Offerhaus, J. Nilsson, P. W. Turner, W. A. Clarkson, and D. J. Richardson, "High-energy, high-power ytterbium-doped Q-switched fiber laser," Opt. Lett. **25**(1), 37–39 (2000).
5. C.C., "*Renaud,* H.L. *Offerhaus,* J.A. *Alvarez-Chavez,* J. *Nilsson,* W.A. *Clarkson,* P.W. *Turner,* D.J. *Richardson and* A.B. *Grudinin,* "Characteristics of Q-switched cladding-pumped ytterbium-doped fiber lasers with different high-energy fiber designs," IEEE J. Quantum Electron. **37**(2), 199–206 (2001).
6. J. A. Alvarez-Chavez, A. B. Grudinin, J. Nilsson, P. W. Turner, and W. A. Clarkson, "Mode selection in high power cladding pumped fiber lasers with tapered section", *Conf. Lasers and Electro-Optics, OSA Technical Digest*, pp. 247 - 248, 1999.
7. V. Filippov, Y. Chamorovskii, J. Kerttula, A. Kholodkov, and O. G. Okhotnikov, "Single-mode 212 W tapered fiber laser pumped by a low-brightness source," Opt. Lett. **33**(13), 1416–1418 (2008).
8. V. Filippov, Y. Chamorovskii, J. Kerttula, A. Kholodkov, and O. G. Okhotnikov, "600 W power scalable single transverse mode tapered double-clad fiber laser," Opt. Express **17**(3), 1203–1214 (2009).
9. V. Filippov, Y. Chamorovskii, J. Kerttula, K. Golant, and O. G. Okhotnikov, "750 W double-clad ytterbium tapered fiber laser with nearly theoretical limited efficiency," Fiber Lasers VII: Technology, Systems and Applications, Proc. of SPIE **vol. 7580**, 758017 (2010).
10. V. Filippov, Y. Chamorovskii, J. Kerttula, K. Golant, M. Pessa, and O. G. Okhotnikov, "Double clad tapered fiber for high power applications," Opt. Express **16**(3), 1929–1944 (2008), http://www.opticsinfobase.org/abstract.cfm?URI=oe-16-3-1929.
11. K. M. Golant, "Surface plasma chemical vapor deposition: 20 years of application in glass synthesis for lightguides (a review)", XXI International Congress on Glass, Strasbourg, Proc. on CD ROM,paper L13 (2007).

#129597 - $15.00 USD Received 4 Jun 2010; revised 28 Jul 2010; accepted 29 Jul 2010; published 16 Aug 2010

12. S. Maryashin, A. Unt, and V. P. Gapontsev, “10-mJ pulse energy and 200 W average power Yb-doped fiber laser” Fiber Laser III: Technology, Systems and Applications, Proc. of SPIE **vol. 6102**, 6102O–1 (2006).
13. *Rare-earth-doped fiber lasers and amplifiers* Second edition, Michel J. F. Digonnet, ed., (Marcel Dekker, Inc., 2001).
14. J. R. Marciante, and J. D. Zuegel, “High-gain, polarization-preserving, Yb-doped fiber amplifier for low-duty-cycle pulse amplification,” Appl. Opt. **45**(26), 6798–6804 (2006), http://www.opticsinfobase.org/ao/abstract.cfm?URI=ao-45-26-6798.
15. J. Nilsson, R. Paschotta, J. E. Caplen, and D. C. Hanna, “Yb($^{3+}$)-ring-doped fiber for high-energy pulse amplification,” Opt. Lett. **22**(14), 1092–1094 (1997), http://www.opticsinfobase.org/ol/abstract.cfm?URI=ol-22-14-1092.
16. M. E. Fermann, “Single-mode excitation of multimode fibers with ultrashort pulses,” Opt. Lett. **23**(1), 52–54 (1998), http://www.opticsinfobase.org/ol/abstract.cfm?URI=ol-23-1-52.
17. K. Shiraki, M. Ohashi, and M. Tateda, “Suppression of stimulated Brillouin scattering in a fiber by changing the core radius,” Electron. Lett. **31**(8), 668–669 (1995).
18. A. Liu, “Suppressing stimulated Brillouin scattering in fiber amplifiers using nonuniform fiber and temperature gradient,” Opt. Express **15**(3), 977–984 (2007), http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-15-3-977.

1. Introduction

Gain media based on double-clad fiber (DCF) offer a technological platform for high brightness, highly efficient laser sources. Operating such a laser in the pulsed regime, and particularly in an actively Q-switched state, is beneficial for a wide range of applications, such as marking, machining, and range finding. Currently, there are two main approaches for high-energy Q-switching: utilization of short, rod-type photonic crystal fibers (PCF) with one or multiple cores [1–3] or the use of large mode area (LMA) double-clad fibers [4,5]. Either LMA fibers with a low numerical aperture (NA) or multimode fibers with a short tapered section are the main approaches used so far to achieve high-brightness lasing with large mode volume [5,6].

The fundamental mechanism limiting the pulse energy especially at repetition rates below 1 kHz is the high level of amplified spontaneous emission (ASE) accumulated during the long time slot between the pulses. ASE prevents efficient energy storage in the fiber cavity and becomes progressively stronger with decreasing repetition rate. A practical solution to this problem would allow for multi-mJ pulses with sub-100-ns duration at low duty cycles needed for industrial and LIDAR applications. Actively Q-switched fiber lasers reported to date are either long-cavity lasers producing pulse widths in the range from 100 ns to few μs with duty cycles of 10^{-4} – 10^{-3} [4], or alternatively lasers using short rod-like fibers with few-ns pulses and duty cycles of the order of 10^{-5} [1].

Recently we have proposed tapered double-clad fiber (T-DCF) as a promising gain medium for high-power lasers and amplifiers [7–10]. The advantages of the T-DCF approach in the actively Q-switched scheme are demonstrated in this study by generation of 1.6-mJ, 64-ns pulses at very low repetition rates, up to single-shot operation.

2. Experimental setup and results

The experimental setup of the Q-switched fiber laser used in this study is schematically shown in Fig. 1. The active fiber was end-pumped by a fiber-coupled diode bar at 915 nm through the wide fiber end via a collimating/focusing lens pair and a 1-μm dichroic splitter. The laser cavity is terminated by Fresnel reflection from the wide fiber end and a broadband (BB) high-reflection (HR) mirror at the narrow end of the fiber, which was angle-cleaved (AC) to suppress spurious lasing. Active Q-switching was achieved by an acousto-optic modulator (AOM) placed between the narrow fiber end and the HR mirror that reflected the 1st diffraction order back to the cavity. A 1-μm edge filter was placed between the fiber and the AOM to filter out unabsorbed pump, reducing thermal load on the modulator. Laser radiation monitored from the wide end of the fiber was analyzed using a pyroelectric energy sensor (up to 25 kHz, 500 ns), a fast photodetector, and a thermal power meter.

The composition of the T-DCF used in this experiment was similar to composition which we have exploited earlier for the design of the CW high power Yb fiber laser [7–10]. The T-DCF was drawn from a preform fabricated by the SPCVD method [11]. The preform consists

#129597 - $15.00 USD Received 4 Jun 2010; revised 28 Jul 2010; accepted 29 Jul 2010; published 16 Aug 2010

of an Yb-doped aluminosilicate core, a pure-silica inner cladding, and a fluorine-doped silica outer cladding. Yb ion concentration corresponds to an in-core absorption of 1000 dB/m at 975 nm wavelength. Fiber core and cladding have numerical apertures of 0.11 and 0.22, respectively.

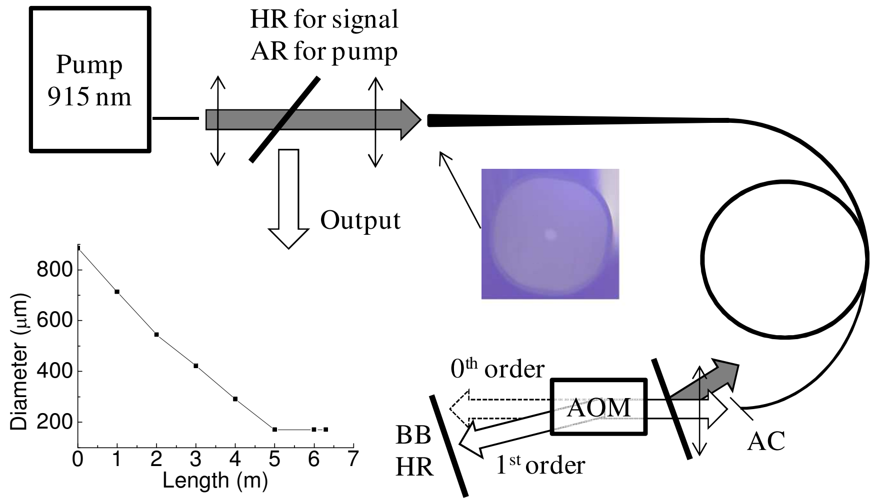


Fig. 1. Schematic of the Q-switched laser setup, a micrograph of the wide fiber end, and the longitudinal profile of the T-DCF.

The longitudinal profile of the active T-DCF with total length of 6.3 m is shown as an inset in Fig. 1. The cladding diameter of the slightly non-circular T-DCF varied from 880 μm to 940 μm at the wide end. The tapering ratio of the T-DCF is 5.5 with the core/cladding diameter ratio kept at 1:10, i.e. the core diameter was 83 μm and 15 μm at the wide and narrow ends of the taper, respectively. The double-clad pump absorption has been measured for radiation launched into the T-DCF from the narrow side to avoid pump power loss via vignetting [8]. The measured pump absorption was 10.1 dB (1.6 dB/m) at 915 nm. The T-DCF was coiled with 35 cm diameter and placed on a water-cooled aluminium plate. The T-DCF was first characterized in quasi-CW regime (high duty cycle) up to 6 W average power at 1070 nm. The measured slope efficiency with respect to launched pump was 43%, limited by coupling loss and the diffraction efficiency of the AOM.

#129597 - $15.00 USD Received 4 Jun 2010; revised 28 Jul 2010; accepted 29 Jul 2010; published 16 Aug 2010

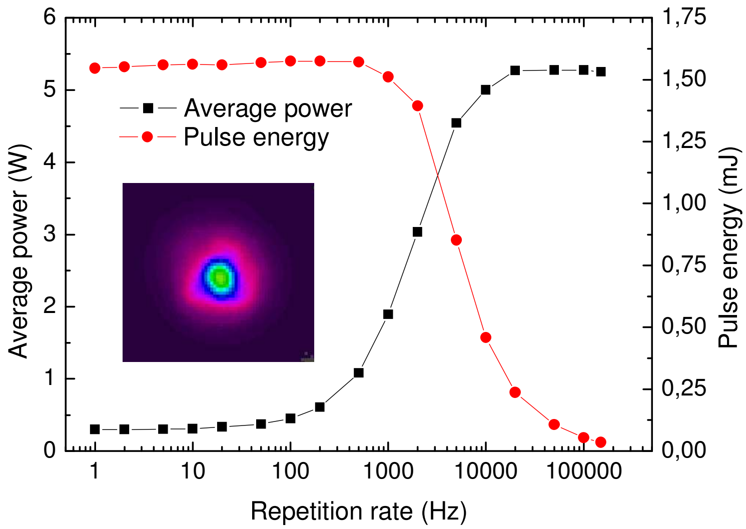


Fig. 2. Pulse energy and average power (including ASE) versus repetition rate at a constant pump power. The output beam profile with $M^2 = 2.7$ is shown as an inset.

In the Q-switched regime, the laser was operated at various repetition rates and pump powers. Figure 2 shows the pulse energy and average power as a function of repetition rate in the range of 1 Hz – 150 kHz. The ASE fraction of the total output power was below 9% at 1 kHz.

Figure 3 shows the pulse energy and peak power as a function of absorbed pump power at a constant repetition rate of 5 Hz. Figures 2 and 3 show that the pulse energy decreases with increasing repetition rate due to the decrease in the energy storage for small pulse periods and increases with pump power limited by the onset of stimulated Brillouin scattering (SBS). The average power increases with both pump power and repetition rate, as expected from general theory of Q-switched lasers. The pulse width decreases with increasing pump power and increases with the repetition rate. These effects can be attributed to incomplete inversion between pulses. Indeed, low pump power and/or short low-Q time reduce the energy storage in the fiber resulting in low gain and longer pulse build-up time.

#129597 - $15.00 USD Received 4 Jun 2010; revised 28 Jul 2010; accepted 29 Jul 2010; published 16 Aug 2010

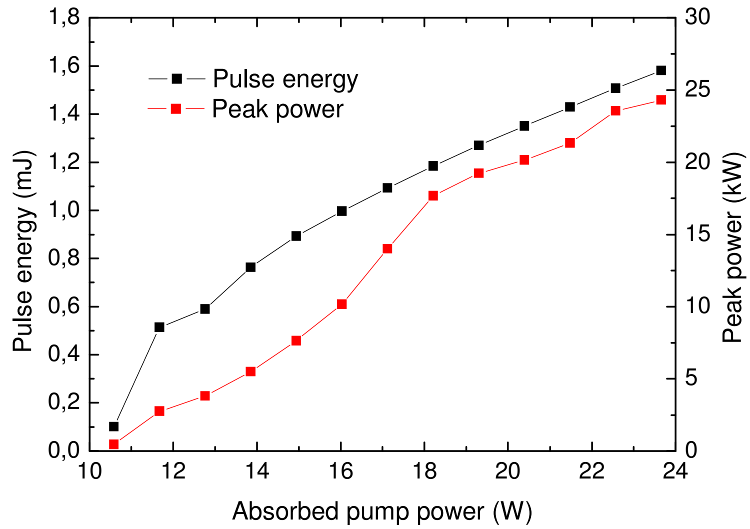
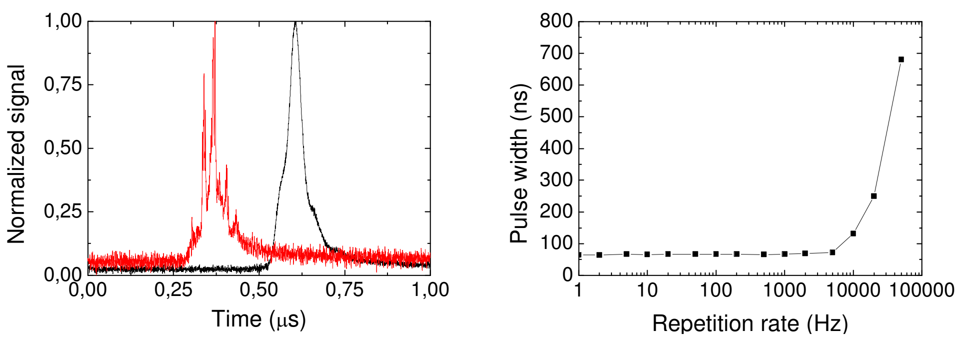


Fig. 3. Pulse energy and peak power versus absorbed pump power at a constant repetition rate of 5 Hz.



(a) (b)

Fig. 4. (a) 1.6-mJ pulse before (black) and after (red) the onset of SBS-induced pulse breakdown; (b) pulse width versus repetition rate at constant pump power.

A pulse energy as high as 1.58 mJ corresponding to a peak power of 24.3 kW was achieved. Above this value, irregular backward-propagating pulses and pulse breakdown were observed, as illustrated in Fig. 4a. Figure 4b shows the dependence of pulse width on the repetition rate. Independent of pump power, single-shot operation was also achieved by manually triggering the AOM control pulse, without notable changes in pulse energy or pulse shape.

Figure 5 shows the optical spectra of the laser at a repetition rate of 500 Hz for 0.1 mJ and 1.6 mJ pulse energy, and the ASE spectrum peaking at 1035 nm when the cavity was blocked. At repetition rates below a few kHz, ASE grows rapidly relative to the signal with decreasing repetition rate, constituting an increasing fraction of the output power.

Finally, we measured the output beam quality of the laser by the clip level method. M^2 determined at the narrow and wide taper ends resulted in $M^2 = 1.8$ and $M^2 = 2.7$, respectively.

#129597 - $15.00 USD Received 4 Jun 2010; revised 28 Jul 2010; accepted 29 Jul 2010; published 16 Aug 2010

It is interesting to note that the spatial distribution of ASE observed below the lasing threshold from the wide end of the taper with a core diameter of 83 µm had an $M^2 = 4.2$.

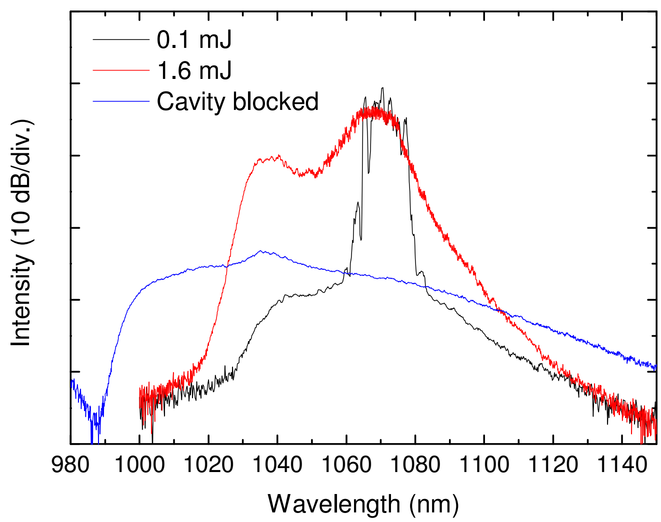


Fig. 5. Optical spectra of the Q-switched T-DCF laser at 500 Hz repetition rate with 0.1 mJ (black) and 1.6 mJ pulse energy (red, FWHM = 14 nm), and without lasing when the cavity is blocked (blue).

3. Discussion

Tapered double-clad fiber is demonstrated to offer attractive features for energetic pulse generation, namely the large mode volume and intrinsic mechanisms for ASE and SBS suppression. The very large doped core area at the wide taper end (5410 µm^2) is useful for both efficient energy storage and for decreasing the power density at the fiber end face. Because of the reduced thermal load at the wide fiber end, optical damage has never been observed within this study. The tapered fiber with an average core area of ~3000 µm^2 allows values of extractable energy of ~3 mJ and saturation energy of 0.3 mJ to be estimated [5,12].

The detrimental effect of amplified spontaneous emission depleting the inversion limits the potential of pulse energy scaling and inhibits pulse operation with low duty cycle. Few techniques have been considered to alleviate ASE impact. They include doping the fiber with a saturable absorber to avoid significant ASE growth, using optical isolators to suppress backward ASE, and spectral filtering of broadband ASE radiation [13,14]. ASE suppression has been observed in a fiber with ring doping exhibiting a small signal gain, however this approach requires long-length gain fiber which would inevitably increase the pulse width and impede operation at low duty cycles [15].

An intrinsic attribute of the tapered fiber, essential for Q-switched operation, is the built-in mechanism of ASE filtering. ASE propagating in a T-DCF from the wide to the narrow end experiences vignetting, i.e. part of the spontaneous emission leaks out of the core thus mitigating the detrimental effect of inversion depletion. This effect becomes more pronounced with increasing tapering ratio [8–10]. Since the intensity of spontaneous emission is proportional to the number of propagating modes, counter-propagating ASE in a taper (from narrow to wide end) is also weaker compared to a cylindrical DCF with similar average core size due to mode selection in the small-core section of the tapered fiber [5]. ASE generated in the small-core section of the fiber and propagated towards the wide end is comprised primarily of low-order modes [5,16]. An estimation for the number of propagating modes N based on the ASE beam quality factor of $M^2 = 4.2$ measured from the wide fiber end yields N

#129597 - $15.00 USD Received 4 Jun 2010; revised 28 Jul 2010; accepted 29 Jul 2010; published 16 Aug 2010

$\sim(M^2)^2 \sim 18$. However, according to an estimation based on the V-parameter of the wide fiber end, the number of modes is $N \sim V^2/2 \sim 430$. A comparison of these values indicates an efficient mechanism of mode selection in the T-DCF resulting in a significant reduction of counter-propagating ASE modes, and thus contributing to ASE suppression.

Since most of the ASE is generated in the large-core section of the taper with large gain volume, the ASE spectrum peaks around 1035 nm, while the signal spectrum peaks at a longer wavelength of 1065 nm. This specific feature, intrinsic to the tapered structure, provides another opportunity for ASE suppression through spectral filtering. This observation is not typical for Q-switched fiber sources based on uniform fibers.

Finally, the variation of fiber diameter is a well-known technique for SBS suppression [10,17,18]. Using tapered waveguide structures is advantageous in terms of Brillouin gain reduction and is another attractive feature provided by the T-DCF.

4. Conclusion

We present the first actively Q-switched laser using a tapered double-clad fiber. The large mode volume, efficient energy storage, and intrinsic mechanisms of ASE and SBS suppression of the T-DCF enabled low-duty-cycle operation with the highest measured pulse energy of 1.6 mJ for a 64-ns pulse. Vignetting of the co-propagating ASE and a reduced number of spatial modes for the counter-propagating ASE result in an inherently low ASE background, which in turn allows for robust operation at very low repetition rates (up to single-shot generation) without degradation of the pulse energy, or shape, or stability of the train. For repetition rates above ~1 kHz, the pulse energy is limited by insufficient energy storage between pulses which is a general characteristic of Q-switched lasers, while at low repetition rates the energy is eventually limited by the onset of SBS, though its threshold is notably higher than in uniform cylindrical fibers. The results show the potential of tapered double-clad fibers for high-energy, low-duty-cycle pulse generation and amplification.

Acknowledgements

This research was supported in part by the Finnish Funding Agency for Technology and Innovation (LAMP project), the Graduate School in Electronics, Telecommunications and Automation (GETA), the Walter Ahlström Foundation, the Ulla Tuominen Foundation, and the KAUTE Foundation.

#129597 - $15.00 USD Received 4 Jun 2010; revised 28 Jul 2010; accepted 29 Jul 2010; published 16 Aug 2010