Millijoule-level Yb-doped photonic crystal fiber laser passively Q-switched with AlGaInAs quantum wells

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Abstract: We report on a millijoule-level Yb-doped photonic crystal fiber (PCF) laser passively Q-switched with AlGaInAs quantum wells (QWs). Three types of AlGaInAs devices with different QW numbers are fabricated to investigate the performance. With 50 groups of three AlGaInAs QWs as a saturable absorber (SA), the PCF laser generates an average power of 7.1 W with a pulse repetition rate of 6.5 kHz at a pump power of 16 W, corresponding to the pulse energy of 1.1 mJ. The maximum peak power is up to 110 kW.

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OCIS codes: (140.3510) Lasers, fiber; (140.3540) Lasers, Q-switched.

References and links

1. Y. Jeong, J. K. Sahu, D. N. Payne, and J. Nilsson, "Ytterbium-doped large-core fiber laser with 1.36 kW continuous-wave output power," Opt. Express **12**(25), 6088–6092 (2004).
2. A. Liem, J. Limpert, H. Zellmer, A. Tünnermann, V. Reichel, K. Mörl, S. Jetschke, S. Unger, H.-R. Müller, J. Kirchhof, T. Sandrock, and A. Harschak, "1.3 kW Yb-doped fiber laser with excellent beam quality," in Proc. Conference on Lasers and Electro-Optics 2004, San Francisco, USA, May 16–21, 2004, postdeadline paper CPDD2.
3. J. Limpert, F. Roser, S. Klingebiel, T. Schreiber, C. Wirth, T. Peschel, R. Eberhardt, and A. Tünnermann, "The Rising Power of Fiber Lasers and Amplifiers," IEEE J. Sel. Top. Quantum Electron. **13**(3), 537–545 (2007).
4. S. D. Jackson, and A. Lauto, "Diode-pumped fiber lasers: a new clinical tool?" Lasers Surg. Med. **30**(3), 184–190 (2002).
5. L. Quintino, A. Costa, R. Miranda, D. Yapp, V. Kumar, and C. J. Kong, "Welding with high power fiber lasers – A preliminary study," Mater. Des. **28**(4), 1231–1237 (2007).
6. Z. J. Chen, A. B. Grudinin, J. Porta, and J. D. Minelly, "Enhanced Q switching in double-clad fiber lasers," Opt. Lett. **23**(6), 454–456 (1998).
7. L. Pan, I. Utkin, and R. Fedosejevs, "Passively Q-switched ytterbium-doped double-clad fiber laser with a Cr^{4+}:YAG saturable absorber," IEEE Photon. Technol. Lett. **19**(24), 1979–1981 (2007).
8. J. Y. Huang, H. C. Liang, K. W. Su, and Y. F. Chen, "High power passively Q-switched ytterbium fiber laser with $Cr^{(4+)}$:YAG as a saturable absorber," Opt. Express **15**(2), 473–479 (2007).
9. J. Y. Huang, W. Z. Zhuang, W. C. Huang, K. W. Su, C. Hu, K. F. Huang, and Y. F. Chen, "Comparative studies for Cr^{4+}:YAG crystal and AlGaInAs semiconductor used as a saturable absorber in Q-switched Yb-doped fiber lasers," Opt. Express **17**(23), 20800–20805 (2009).
10. T. Hakulinen, and O. G. Okhotnikov, "8 ns fiber laser Q switched by the resonant saturable absorber mirror," Opt. Lett. **32**(18), 2677–2679 (2007).
11. W. Z. Zhuang, W. C. Huang, Y. P. Huang, K. W. Su, and Y. F. Chen, "Passively Q-switched photonic crystal fiber laser and intracavity optical parametric oscillator," Opt. Express **18**(9), 8969–8975 (2010).
12. W. T. Tsang, and N. A. Olsson, "New current injection 1.5-μm wavelength $Ga_xAl_yIn_{1-x-y}$As/InP doubleheterostructure laser grown by molecular beam epitaxy," Appl. Phys. Lett. **42**(11), 922–924 (1983).
13. K. Alavi, H. Temkin, W. R. Wagner, and A. Y. Cho, "Optically pumped 1.55-μm double heterostructure $Ga_xAl_yIn_{1-x-y}$As/Al_uIn_{1-u}As lasers grown by molecular beam epitaxy," Appl. Phys. Lett. **42**(3), 254–256 (1983).
14. D. A. Bender, J. G. Cederberg, and G. A. Hebner, "Parametric Results of the AlGaInAs Quantum-Well Saturable Absorber for Use as a Passive Q-Switch," in *Conference on Lasers and Electro-Optics*, (Optical Society of America, San Jose, California, 2010), paper CThL3.
15. 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).
16. A. Piper, A. Malinowski, K. Furusawa, and D. J. Richardson, "High-power, high-brightness, mJ Qswitched ytterbium-doped fibre laser," Electron. Lett. **40**(15), 928–929 (2004).

17. 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).
18. J. Limpert, A. Liem, H. Zellmer, A. Tünnermann, S. Knoke, and H. Voelckel, "High-average-power millijoule fiber amplifier system," Lasers and Electro-Optics, 2002. CLEO'02. Technical Digest, Long Beach, CA, paper CThX3, 591–592 (2002).
19. C. D. Brooks, and F. Di Teodoro, "1-mJ energy, 1-MW peak-power, 10-W average-power, spectrally narrow, diffraction-limited pulses from a photonic-crystal fiber amplifier," Opt. Express **13**(22), 8999–9002 (2005).
20. F. D. Teodoro, M. K. Hemmat, J. Morais, and E. C. Cheung, "High peak power operation of a 100μm-core, Yb-doped rod-type photonic crystal fiber amplifier," Fiber Lasers VII: Technology, Systems and Applications, Proc. of SPIE vol. 7580, 758006 (2010).
21. M. Salhi, A. Hideur, T. Chartier, M. Brunel, G. Martel, C. Ozkul, and F. Sanchez, "Evidence of Brillouin scattering in an ytterbium-doped double-clad fiber laser," Opt. Lett. **27**(15), 1294–1296 (2002).
22. Y. X. Fan, F. Y. Lu, S. L. Hu, K. C. Lu, H. J. Wang, G. Y. Zhang, and X. Y. Dong, "Narrow-linewidth widely tunable hybrid Q-switched double-clad fiber laser," Opt. Lett. **28**(7), 537–539 (2003).
23. A. A. Fotiadi, P. Mégret, and M. Blondel, "Dynamics of a self-Q-switched fiber laser with a Rayleigh-stimulated Brillouin scattering ring mirror," Opt. Lett. **29**(10), 1078–1080 (2004).
24. Z. J. Chen, A. B. Grudinin, J. Porta, and J. D. Minelly, "Enhanced Q switching in double-clad fiber lasers," Opt. Lett. **23**(6), 454–456 (1998).
25. Y.-X. Fan, F.-Y. Lu, S.-L. Hu, K.-C. Lu, H.-J. Wang, X. Y. Dong, J. L. He, and H. T. Wang, "Tunable high-peak-power, high-energy hybrid Q-switched double-clad fiber laser," Opt. Lett. **29**(7), 724–726 (2004).
26. M. Laroche, H. Gilles, S. Girard, N. Passilly, and K. Ait-Ameur, "Nanosecond pulse generation in a passively Q-switched Yb-doped fiber laser by Cr^{4+}:YAG saturable absorber," IEEE Photon. Technol. Lett. **18**(6), 764–766 (2006).
27. L. Pan, I. Utkin, R. J. Lan, Y. Godwal, and R. Fedosejevs, "High-peak-power subnanosecond passively Q-switched ytterbium-doped fiber laser," Opt. Lett. **35**(7), 895–897 (2010).
28. Y. F. Chen, S. W. Tsai, and S. C. Wang, "High-power diode-pumped Q-switched and mode-locked Nd:YVO$_4$ laser with a Cr^{4+}:YAG saturable absorber," Opt. Lett. **25**(19), 1442–1444 (2000).
29. Y. F. Chen, and S. W. Tsai, "Simultaneous Q-switching and mode-locking in a diode-pumped Nd:YVO$_4$-Cr^{4+}:YAG laser," IEEE J. Quantum Electron. **37**(4), 580–586 (2001).
30. S. Zhang, E. Wu, H. Pan, and H. Zeng, "Q-switched mode-locking with Cr^{4+}:YAG in a diode pumped Nd:GdVO$_4$ laser," Appl. Phys. B **78**(3–4), 335–338 (2004).
31. J. Yang, J. Liu, and J. He, "A compact Q-switched and mode-locked diode-pumped Nd:GdVO$_4$ laser with Cr^{4+}:YAG," Laser Phys. **15**(8), 1137–1141 (2005).
32. J. A. Fleck, Jr., "Ultrashort-pulse generation by Q-switched lasers," Phys. Rev. B **1**(1), 84–100 (1970).
33. P. G. Kryukov, and V. S. Letokhov, "Fluctuation mechanism of ultrashort pulse generation by laser with saturable absorber," IEEE J. Quantum Electron. **8**(10), 766–782 (1972).

1. Introduction

High-power diode-pumped double-clad rare-earth doped fiber lasers have been proved to be efficient and compact with excellent beam quality, high efficiency, and good thermal management [1–3]. Q-switched fiber lasers are practically useful in a variety of applications in virtue of their high pulse energy, such as remote sensing, industrial processing, and medical needs [4–6]. Compared with active Q-switching techniques, passive Q-switching methods that employ saturable absorbers can considerably enhance the compactness and simplify the operation [7–10]. By enlarging the active volume of the gain medium, corresponding to the doped core size of the fiber, one can achieve the merit of the high pulse energy. However, the conventional large-core fibers suffer from mode-quality degradation and their long lengths usually lead to long pulse widths and low peak powers. For improving these deficiencies, photonic crystal fibers (PCFs) have been developed to provide large single-mode cores and high absorption efficiencies. The PCF was recently employed to demonstrate a passively Q-switched laser with a Cr^{4+}:YAG crystal as a saturable absorber in which under a pump power of 14.2 W, an average output power of 3.4 W with a repetition rate of 5.6 kHz was generated, corresponding to a pulse energy of 630 μJ [11]. However, the scale-up of the pulse energy is hindered by the nonsatuarble loss of the Cr^{4+}:YAG crystal [9].

In recent years, an AlGaInAs semiconductor material with a periodic quantum-well (QW) structure grown on a Fe-doped InP structure has been successfully used as a saturable absorber in an Yb-doped fiber laser to produce pulse energy up to 450 μJ [9]. It was found that the saturation fluence of the AlGaInAs QW absorber was two orders of magnitude smaller than that of Cr^{4+}:YAG crystal. This property enables the AlGaInAs QW devices to be appropriate saturable absorbers for high-gain lasers. More importantly, experimental results

also revealed that the AlGaInAs QW absorber has a lower nonsatuarble loss than the Cr^{4+}:YAG crystal with the same initial transmission. This result indicates that AlGaInAs QW absorbers have a potential to generate much higher pulse energies. So far, AlGaInAs QWs have not been employed to passively Q-switch Yb-doped PCF lasers.

Here we report, for the first time to our knowledge, on a millijoule-level passive Q-switched Yb-doped photonic crystal fiber laser with AlGaInAs QWs as a saturable absorber. We fabricate three types of AlGaInAs devices with different QW numbers to investigate the performance of passively Q-switched PCF lasers. With 50 groups of three AlGaInAs QWs as a saturable absorber and under a pump power of 16 W, the PCF laser generates an average power of 7.1 W at the pulse repetition rate of 6.5 kHz, corresponding to a pulse energy of approximately 1.1mJ. The overall pulse-to-pulse amplitude fluctuation and the temporal jitter are found to be well below 10% in root mean square (rms). We also calculated the peak power by integrating the photodiode traces and found its maximum value to reach 110 kW.

2. AlGaInAs QWs absorber and experimental setup

Similar to the previous structure [9] the saturable absorbers that offered by TrueLight Corporation were AlGaInAs QW/barrier structures grown on a Fe-doped InP substrate by metalorganic chemical-vapor deposition. The saturable absorbers were designed to consist of many groups of several QWs, spaced at half-wavelength intervals by InAlAs barrier layers with the band-gap wavelength around 806 nm and with the luminescence wavelength near 1064 nm. The thickness of the saturable absorbers was approximately 400 μm. Compared with other similar QWs devices, AlGaInAs material has the advantages of lattice match with the substrate InP over InGaAs/GaAs that output pulse energy of the passive Q-switch and the conversion efficiency are limited as a result of the lattice mismatch. AlGaInAs materials is also superior to InGaAsP material which can be grown on InP substrate because of its better electron confinement covering the wavelength range in 0.84-1.65μm provided by the larger conduction band offset [12,13]. In this work we fabricated three types of AlGaInAs QWs that posses 50 groups of three QWs (3×50 QWs), 30 groups of three QWs (3×30 QWs), and 30 groups of two QWs (2×30 QWs). Figures 1(a)–1(c) depict the schematic diagrams of three periodic AlGaInAs QWs structures. Figure 1(d) shows the measured results for the low-intensity transmittance spectrum of the three QW saturable absorbers. The initial transmissions of the absorbers near the wavelength of 1030 nm can be seen to be 18%, 36%, and 48% for the devices of 3×50 QWs, 3×30 QWs, and 2×30 QWs, respectively. With the z-scan method [9], we found that the modulation depths between low and high intensities were approximately 77%, 59%, and 47% for the absorbers of 3×50 QWs, 3×30 QWs, and 2×30 QWs, respectively. We also found that the nonsaturable losses for three devices were less than 5%. The low nonsaturable losses indicate the quality of the QW devices to be rather high. Furthermore, the saturation fluence of the QW absorbers was measured to be in the range of 1 mJ/cm^2 and the relaxation time to be on the order of 100 ns [14]. The damage threshold for the AlGaInAs QWs was found to be approximately 300 MW/cm^2. Both sides of the semiconductor absorber have a simple single layer coating to reduce back reflections and the couple-cavity effects. The scheme of the experimental setup is shown in Fig. 2(a). The cavity is composed of a 0.55 m polarization maintaining Yb-doped PCF (NKT photonics) that is the same one described in Ref. 11 and an external feedback cavity with a saturable absorber. Figure 2(b) depicts the image of the cross section of the PCF pumped by a 532 nm light source. Since the absorption coefficient of the PCF was approximately 30 dB/m at 976 nm, the overall absorption efficiency could reach 95%. The rod-type PCF has a mode field diameter of 55 μm and a low numerical aperture (NA) of 0.02 to sustain the excellent beam quality. The pump cladding of the PCF has a diameter of 200 μm and an air-cladding to maintain a high NA of 0.6. The PCF was surrounded with a 1.7-mm thick outer cladding and was sealed with end-caps for protection. The boron doped stress-applying parts near the core were adopted to induce birefringence that produces diverse spectral losses to form a linearly polarization state for the fundamental mode.
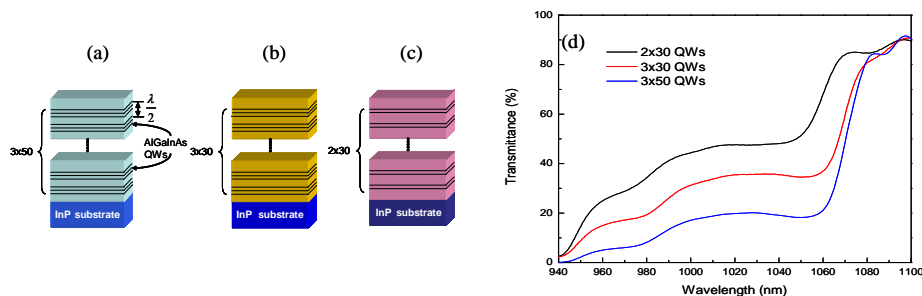
Fig. 1. (a)-(c) Schematic diagrams of three periodic AlGaInAs QWs structures. (b) Low-intensity transmittance spectrum of the three QW saturable absorbers.

The external cavity incorporates with a focusing lens of 50-mm focal length to focus the fiber output into the AlGaInAs QW absorber and a high reflective mirror behind the absorber for feedback. The AlGaInAs QW absorber was mounted in a copper block as a heat sink and with water cooling. The mode diameter on the saturable absorber was approximately 200 μm. The pump source was a 20-W 976-nm fiber-coupled laser diode with a core diameter of 200 μm and a numerical aperture of 0.2. Focusing lens with 25-mm focal length as one of the lens pairs depicted in Fig. 2(a) and 90% coupling efficiency was used to re-image the pump beam into the fiber through the dichroic mirror with high transmission (HT, T>90%) at 976 nm and high reflectivity (HR, R>99.8%) within 1030~1100 nm. The pump spot radius was approximately 100 μm, and the pump coupling efficiency was estimated to be around 80%. The laser spectrum was measured by an optical spectrum analyzer with 0.1 nm resolution (Advantest Q8381A). The pulse temporal behavior was recorded by Leroy digital oscilloscope (Wavepro 7100; 10G samples/sec; 4 GHz bandwidth) with a fast InGaAs photodiode.
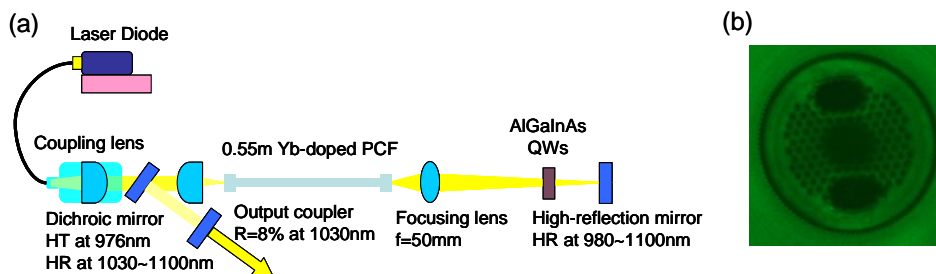

Fig. 2. (a) Setup for the passively Q-switched PCF laser; (b) image of the cross section of PCF.

3. Experimental results and discussions

Figure 3 depicts the average output power versus the launched pump power in CW and passive Q-switching operation. The external cavity in the CW operation contained only a re-imagining lens and a reflective mirror without the saturable absorber. At a launched pump power of 16 W, the CW PCF laser was found to generate an output power of 8.7 W, corresponding to a slope efficiency of 78%. In the passive Q-switching operation, the average output powers at a launched pump power of 16 W were 7.1 W, 7.7 W, and 8.0 W for the lasers with the saturable absorbers of 3×50, 3×30, and 2×30 QWs, respectively. The signal intensity of the amplified spontaneous emission (ASE) is 40 dB below the lasing signal of 1030 nm measured by the optical spectrum analyzer, so the fraction of the ASE output power can be neglected. As a result, the Q-switching efficiency (the ratio of the average power of Q-switched operation to that of CW one) were approximately 82%, 89%, and 92% for the lasers with the saturable absorbers of 3×50, 3×30, and 2×30 QWs, respectively. The overall Q-

switching efficiency was significantly superior to the results obtained with Cr^{4+}:YAG crystals as saturable absorbers [11]. The lasing spectra for CW and passive Q-switching operations were quite similar with the peaks near 1030 nm and bandwidths to be approximately 0.4 nm. The laser output was found to be linearly polarized with an extinction ratio of approximately 100:1, evidencing the function of the polarization maintaining in PCF. The M^2 factor was found to be generally smaller than 1.3 over the entire output power range, owing to the low-NA feature of the PCF.

Figure 4 shows the pulse repetition rates in the passive Q-switching operation versus the launched pump power. Experimental results reveal that the pulse repetition rates for all cases increase monotonically with the pump power. At a launched pump power of 16 W, the pulse repetition rates were found to be 6.5 kHz, 16 kHz, and 23 kHz for the lasers with the saturable absorbers of 3×50, 3×30, and 2×30 QWs, respectively. With the experimental results of the average output power and the pulse repetition rate, we calculated the pulse energies versus the launched pump power. It was found that the pulse energies were nearly independent of the pump power and their average values were 1.1 mJ, 0.49 mJ, and 0.35 mJ for the lasers with the saturable absorbers of 3×50, 3×30, and 2×30 QWs, respectively. Fiber laser systems with energy of millijoule-class had been demonstrated with either actively Q-switched oscillator [15–17] or the master oscillator power fiber amplifier scheme [18–20]. To the best of our knowledge, this is the first time that the millijoule-level energy output was achieved with the passive Q-switching scheme in a PCF laser.
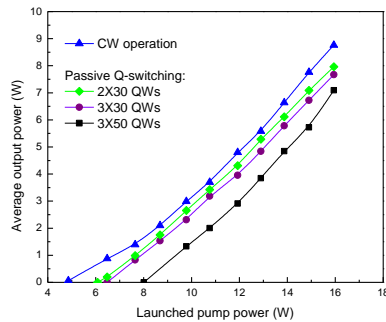

Fig. 3. Average output power with respect to launched pump power in CW and passive Q-switching operations.
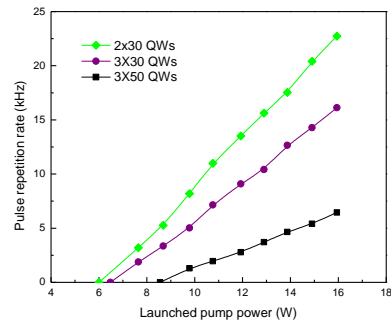
Fig. 4. Pulse repetition rates in the passive Q-switching operation versus the launched pump power.

Figures 5(a)–5(c) depict typical oscilloscope traces for the single Q-switched pulses of the lasers with the saturable absorbers of 2×30, 3×30, and 3×50 QWs, respectively. It can be seen that the temporal shape of the single Q-switched pulse obtained with the absorber of 2×30 QWs is a simple pulse, whereas the temporal shape obtained with the absorber of 3×50 QWs reveal conspicuous modulation whose period is nearly equal to the round trip time. The self-modulation phenomenon inside the Q-switched envelope has been frequently observed in pulsed fiber lasers. This phenomenon is generally considered to arise from the stimulated Brillouin scattering (SBS) which can provide strong feedback to the cavity together with pulse compression. The SBS-related pulses have been demonstrated in different fiber laser designs, such as self-Q switched [21–23], actively Q-switched [24,25], and passively Q-switched [26,27] fiber lasers. Note that another self-modulation phenomenon was found in passively Q-switched Nd-doped crystal lasers with Cr^{4+}:YAG crystals as saturable absorbers [28–31]; however, the origin is attributed to the excited-state absorption of the absorber and the fluctuation mechanism [32,33]. Our results reveal that the pulse energy obtained with the absorber of 3×30 QWs is just above the SBS threshold. As seen in Fig. 5(b), the rear end of the pulse exhibits a fast transient dynamics. On the other hand, the intense SBS effect leads to

the pulse to be strongly modulated, as seen in Fig. 5(c). With the numerical integration, we found the maximum peak powers were 7.4 kW, 12.8 kW, and 110 kW for the lasers with the saturable absorbers of 2×30, 3×30, and 3×50 QWs, respectively. The corresponding optical intensity on the 3×50 QWs was 350 MW/cm^2 which is quite close to the damage threshold of the saturable absorber, but no optical damage was observed. Figures 6(a)–6(c) show typical oscilloscope traces of a train of output pulses obtained with the saturable absorbers of 2×30, 3×30, and 3×50 QWs, respectively. It can be seen that for the laser with the absorber of 2×30 QWs the pulse-to-pulse amplitude fluctuation was generally less than 4% in rms. Even for the case of 3×30 QWs, just above the SBS threshold, the pulse-to-pulse amplitude fluctuation was also smaller than 4% in rms. Although the strong SBS effect might deteriorate the pulse stability to some extent, the pulse-to-pulse amplitude fluctuation could still be maintained to be 8.5% in rms for the laser with the saturable absorber of 3×50 QWs, as shown in Fig. 6(c). Compared with the previous results, the pulse stability was superior to that obtained in Ref. 9 and slightly diminished with respect to Ref. 11 as a result of the high pulse energy induced SBS effect. The overall pulse energy scaling was 2.4 times as high as the one in Ref. 9 and 1.8 times as that in Ref. 11.
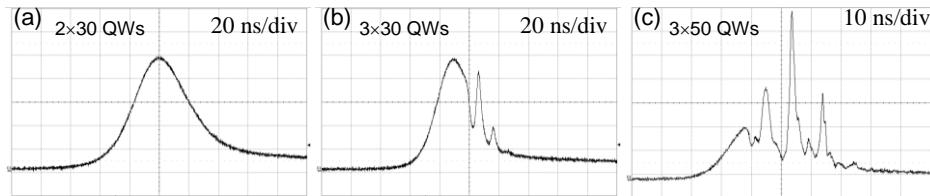

Fig. 5. Typical oscilloscope traces for the single Q-switched pulses of the lasers with the saturable absorbers of (a) 2×30, (b) 3×30, and (c) 3×50 QWs, respectively.
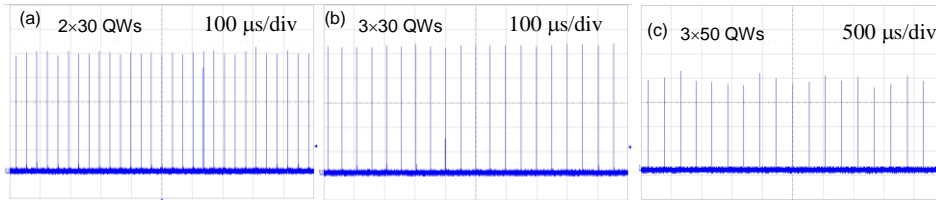

Fig. 6. Typical oscilloscope traces for a train of output pulses of the lasers with the saturable absorbers of (a) 2×30, (b) 3×30, and (c) 3×50 QWs, respectively.

4. Conclusion

In conclusions, we have, for the first time to our knowledge, demonstrated a millijoule-level passively Q-switched Yb-doped photonic crystal fiber laser with AlGaInAs QWs as a saturable absorber. At a launched pump power of 16 W, the average output powers were 7.1 W, 7.7 W, and 8.0 W for the lasers with the saturable absorbers of 3×50, 3×30, and 2×30 QWs, respectively. The pulse energies were found to be 1.1 mJ, 0.49 mJ, and 0.35 mJ for the lasers with the saturable absorbers of 3×50, 3×30, and 2×30 QWs, respectively. The maximum peak power could be up to 110 kW. The overall pulse-to-pulse amplitude fluctuation and the temporal jitter could be maintained to be well below 10% in rms. These high-pulse-energy high-peak-power passively Q-switched PCF lasers are potentially useful light sources for many technical applications.

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