Research Article | Vol. 27, No. 6 | 18 Mar 2019 | OPTICS EXPRESS 8387

Optics EXPRESS

55 W actively Q-switched single oscillator Tm^{3+}, Ho^{3+}-codoped silica polarization maintaining 2.09 µm fiber laser

NICOLAS DALLOZ,[1,*] THIERRY ROBIN,[2] BENOIT CADIER,[2] CHRISTELLE KIELECK,[1,3] MARC EICHHORN,[1,4] AND ANNE HILDENBRAND-DHOLLANDE[1]

[1]*French-German Research Institute of Saint-Louis (ISL), 5 rue du Général Cassagnou, 68301 Saint-Louis Cedex, France*
[2]*iXblue Photonics, rue Paul Sabatier, 22300 Lannion, France*
[3]*now at Fraunhofer Institute of Optronics, System Technologies and Image Exploitation IOSB, Gutleuthausstraße 1, 76275 Ettlingen, Germany*
[4]*now at Fraunhofer Institute of Optronics, System Technologies and Image Exploitation IOSB, Gutleuthausstraße 1, 76275 Ettlingen, Germany, and Institute of Systems Optimization (ITE), Karlsruhe Institute of Technology (KIT), Fritz-Haber-Weg 1, 76131 Karlsruhe, Germany*
**nicolas.dalloz@isl.eu*

Abstract: A bidirectional 793 nm diode-pumped actively Q-switched Tm^{3+}, Ho^{3+}-codoped silica polarization-maintaining (PM) double-clad (DC) fiber laser is reported. With this fiber laser, 55 W of average output power with 100 ns pulse width at 200 kHz repetition rate and 2.09 µm wavelength is obtained. The pump power injection with end-caps fusion-spliced on fiber tips provides good power stability (< 1.1%) and beam quality factors (M^2 < 1.7). The fiber laser output beam polarization factor is 97.5%. At 55 W, no thermal-induced damage is observed on any optical element, and power scaling of the laser is only pump-power-limited in the range of the total available pump power (180 W).

1. Introduction

Pulsed fiber lasers emitting at wavelengths around 2 µm are promising sources of laser radiation for eye-safe lidar systems, range finders or countermeasures by nonlinear optical generation of mid-infrared radiation via optical parametric oscillation (OPO). Short pulse durations in the nanosecond range are necessary for these applications, with high peak and high average output powers delivery. Two different fiber laser designs can fulfill these requirements which are master oscillator power-amplifier (MOPA) fiber systems and single oscillator fiber lasers.

In MOPA systems, a low power modulated seed emitting around 2 µm is power-amplified with several amplification stages to get the desired output power. Thanks to the growing availability of 2 µm fiber components, MOPA systems can be designed in all-fiber format, which provides excellent stability, robustness and reliability of these laser sources. Nanosecond pulse generation at 2 µm with all-fibered MOPA systems, delivering high average output power up to 100 W, have been successfully demonstrated in several studies [1–3]. However, fiber MOPA sources suffer from higher volume due to the number of isolated amplification stages needed to get a stable high power delivery laser source. Moreover, in some cases where a Distributed Feedback (DFB) laser diode is used as a seed laser, MOPA systems may suffer from higher sensitivity to fiber nonlinearities compared to single oscillator fiber laser sources [4]. Indeed, the picometer range linewidth of DFB laser diodes decreases the power threshold of the Brillouin scattering nonlinear effect.

In the case of single oscillator fiber lasers, different techniques can be used to get a pulsed mode of operation in the nanosecond range, which are gain switching and passive/active Q-switching. Stable short pulses at high repetition rates have been obtained using direct gain

#355965 https://doi.org/10.1364/OE.27.008387
Journal © 2019 Received 20 Dec 2018; revised 15 Feb 2019; accepted 18 Feb 2019; published 7 Mar 2019

switching techniques [5,6]. In these papers, setup is limited to short fiber lengths to avoid chaotic pulsing and is thus limited in average output power. Passive modulation methods have been mostly used in the literature using saturable absorbers. Passive Q-switching using saturable absorbers based on semiconductor saturable-absorber mirrors (SESAMs) [7,8], graphene layer [9], distributed stimulated Brillouin scattering nonlinear effect [10,11], anti-resonant Fabry-Perot [12] and nonlinear polarization evolution [13] have been demonstrated. The output power and pulse energy in passive modulation techniques from single oscillators are limited, on one hand, to a certain output power level for stable operation, and on the other hand, by the damage threshold of the available modulators. Single oscillator actively Q-switched fiber sources emitting around 2 µm have been already successfully demonstrated by directly pump Tm^{3+}-doped or Tm^{3+}, Ho^{3+}-codoped silica fibers with 793 nm high power diodes [14–17]. In [14–16], nanosecond pulses around 2 µm have been generated at tens of kilohertz of repetition rates, with average output powers reaching a maximum of 25 W. Further power scaling of these fiber lasers were limited by thermal-induced damaging observed on both uncooled fiber tips. Stutzki *et al* [17] demonstrated a 15 ns single pulse operation with a maximum average output power of 39 W at 14 kHz repetition rate around 1.9 µm. Nevertheless, this Q-switched fiber laser presents a high power oscillation threshold of 190 W with a 21% slope efficiency. Furthermore, the laser cavity of this setup is composed of broadband reflectors resulting in a broad multimode output spectrum.

In this letter we report, to the best of our knowledge, the highest ever demonstrated average output power emitted from an actively Q-switched single oscillator Tm^{3+}, Ho^{3+}-codoped silica PM 2.09 µm single-mode fiber laser, with a low oscillation power threshold of 15.9 W and a 35% slope efficiency. Thanks to home-made end-caps fusion-spliced on both fiber tips, appropriate cooling of the entire fiber (fiber tips included) lead to a power scaling of the fiber laser only pump-power-limited in our experiment.

2. Experimental setup

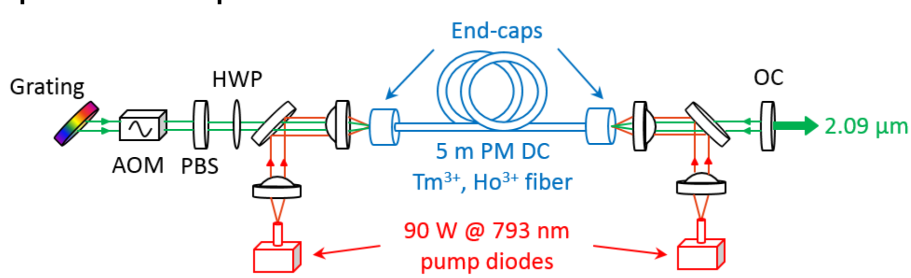

Fig. 1. Experimental setup.

The experimental setup is shown in Fig. 1. The intracavity silica DC PM (Panda type) fiber (iXblue Photonics, France) is 5 m long with a Tm^{3+}, Ho^{3+}-codoped core of 20 µm diameter and a numerical aperture (NA) of 0.12. The Tm^{3+} and Ho^{3+} ions doping concentrations are respectively 3.6% wt. and 0.4% wt. and are similar to previous papers [14–16]. The diameter of the fiber round shape cladding is 300 µm (NA = 0.46) with a cladding absorption at 793 nm of 3.5 dB/m. The diameter of the fiber acrylate polymer coating is 465 µm.

Fused-quartz end-caps, with end-face antireflection (AR) coatings at pump and laser wavelengths, are fusion-spliced on both preliminary cleaved fiber tips using commercial CO_2 splicer and cleaver. The AR-coated fused-quartz end-caps have a 9 mm outer diameter and thickness. Fiber with both fusion-spliced end-caps are placed into a metallic box where they are immersed and directly cooled by de-ionized water at 19 °C. No specific surface treatment has been applied to the fiber to eliminate water ingress and no degradation of the fiber has been observed after one year of immersion. The 9 mm diameter parts of the end-caps are mounted into the metallic sides of the cooling box with a tight O-ring seal to prevent water from getting on AR-coated end faces of the end-caps.

Optics EXPRESS

The laser cavity is closed on one side by an uncooled standard diffraction grating. The grating, made of an aluminum coating and a copper substrate, is blazed at 2.8 µm to choose accurately the emitted wavelength. The other side of the cavity is closed by a one-side-AR-coated output coupler (OC). The 3% Fresnel reflections at 2.09 µm of the OC uncoated side provides the feedback. A half-wave plate (HWP) and a polarizing beam splitter (PBS) are placed into the cavity to select the output beam polarization. An AR-coated acousto-optic modulator (AOM) with a deflection efficiency of 80% is inserted into the cavity and is operated to Q-switch the cavity losses at different repetition rates from 40 kHz to 200 kHz.

The fiber is symmetrically pumped by two fiber-coupled laser diodes emitting a maximum power of 90 W each at a wavelength of 793 nm out of a 200 µm core multimode fiber (NA = 0.22). The pump light is collimated by an AR-coated aspheric lens with an effective focal length (EFL) of 15 mm, which is directed onto the Tm^{3+}, Ho^{3+}-codoped fiber using a dichroic mirror and focused into the fiber cladding using another aspheric lens with an EFL of 15 mm. This AR-coated lens is also used to collimate the fiber laser output beam. The measured pump beam diameter on the fiber end-face using this lens injection system is 275 µm, that being smaller than the fiber cladding diameter (300 µm). Preliminary tests with passive DC PM fiber with same core/cladding diameter and NA ratios, and with same end-caps fusion-spliced to both fiber tips, has been performed to measure the pump power injection efficiency which was close to 98%.

3. Results and discussion

The average output power of the Q-switched fiber laser as a function of the total incident pump power on the fiber end-caps is shown in Fig. 2 for different AOM repetition rates.

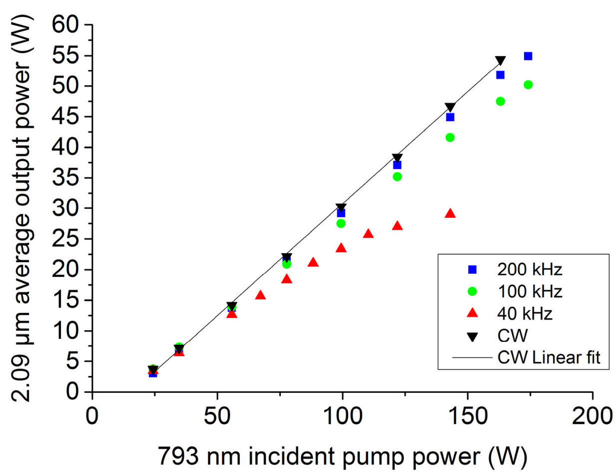

Fig. 2. Measured average output power versus incident pump power for different repetition rates. The plot with black triangular dots corresponds to CW mode of operation when AOM is turned off.

At 200 kHz repetition rate, a maximum of 55 W of average output power is generated, with 35.0% slope efficiency and 15.9 W power threshold. To the best of our knowledge, this is the highest ever demonstrated average output power emitted from an actively Q-switched single oscillator Tm^{3+}, Ho^{3+}-codoped silica PM 2.09 µm fiber laser. Slope efficiency (laser threshold) decreases with the repetition rate and reaches 31.3% (11.3 W) at 100 kHz and 26.1% (9.0 W) at 40 kHz. The end-caps fusion-spliced on both fiber tips lead to a decrease of the end-face pump power density that was responsible for the fiber end-face damaging in previous experiments (without end-caps) [14–16]. Water cooling of the entire fiber (fiber tips included) is also enabled thanks to these components. As a result, no thermal-induced damaging is observed on the fiber or any bulk optics when pump power is increased, and the

Optics EXPRESS

power scaling of the laser is only pump-power-limited in the range of the total available pump power of our setup.

At 40 kHz, the laser presents a non-linear behavior with a deviation from linearity at approximately 25 W output power. A deviation from linearity of the output power in a Q-switched single oscillator Tm^{3+}, Ho^{3+}-codoped silica fiber laser has already been reported in [15]. In this laser, the deviation comes from the inversion-dependent amplified spontaneous emission (ASE) generated inside the fiber that is strong enough to saturate the inversion. Increasing the pump power further increases the ASE while the inversion stays fixed at the ASE threshold. The pulse peak power does not increase and Q-switched operation becomes less effective. Since the additional ASE generated is emitted nearly equally from both ends of the fiber, the output power increases by approximately half the slope efficiency of the unidirectional saturated fiber laser. In our experiment, the Tm^{3+}, Ho^{3+}-codoped silica fiber laser presents a similar behavior at 40 kHz repetition rate, and further increase of the average output power leads to a decrease of the laser slope efficiency by a factor of 2 approximately.

The average output power stability registered at 45 W and for 200 kHz repetition rate during 45 min is depicted on Fig. 3.

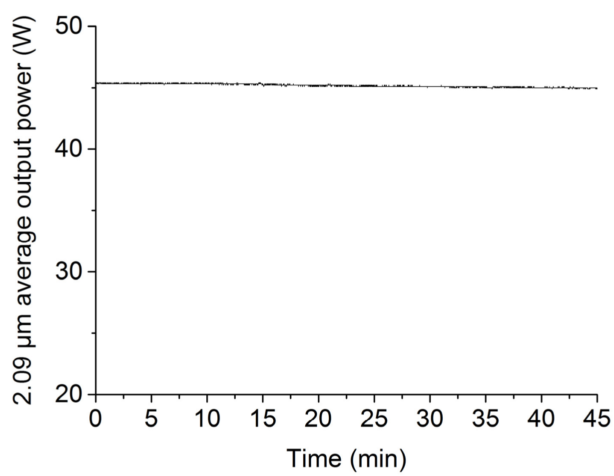

Fig. 3. Average output power stability over 45 min measured at 45 W output power and 200 kHz repetition rate.

Peak-to-peak output power fluctuations are below 1.1%, with a standard deviation of 125 mW for 45.2 W mean output power. This excellent stability of the fiber laser average output power is also an improvement brought by the end-caps implementation. Indeed, heating of the uncooled fiber-ends in previous setup without end-caps [16] was responsible for output power instabilities when the fiber laser was operated over long periods of time.

To evaluate the degree of polarization of the fiber laser output beam, the power is recorded after passing through a rotating HWP and a polarizer previously aligned with the initial polarization. Figure 4 shows the evolution of the polarizer transmitted power ratio with the rotation angle of the HWP. The extreme power values of the curve, P_{max} and P_{min}, lead to a polarization factor $(P_{max} - P_{min}) / (P_{max} + P_{min})$ of 97.5%.

Optics EXPRESS

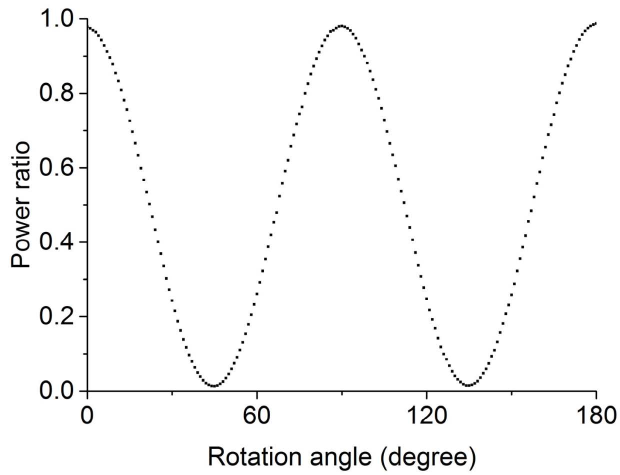

Fig. 4. Ratio of linear output power over the total Tm^{3+}, Ho^{3+}-codoped fiber output power after a polarizer versus rotation angle of a HWP placed between the output coupler and a fixed polarizer.

The beam quality factors M^2 of the laser output beam are depicted in Fig. 5. They have been measured with a Pyrocam III (Spiricon, Ophir) camera at 45 W average output power and 200 kHz repetition rate and using the second order moments method. The M^2 values in x and y transverse directions are below 1.7.

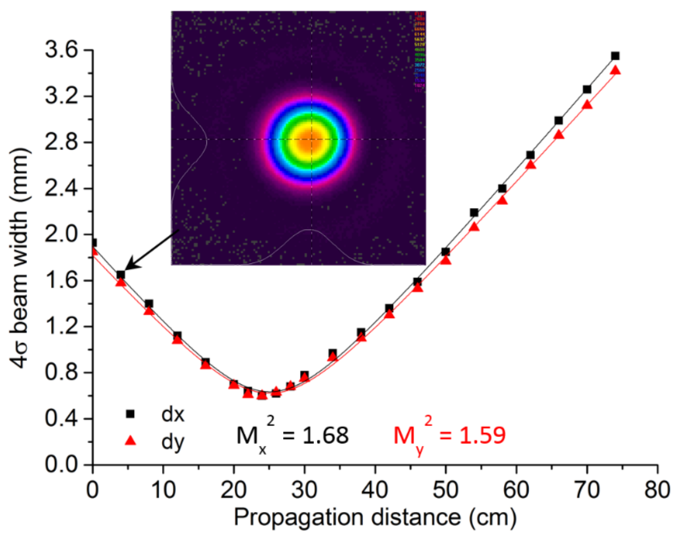

Fig. 5. Beam quality factors M^2 of the laser output beam measured at 45 W average output power and 200 kHz repetition rate. Inset shows beam profile registered at one specific propagation point.

Inset of Fig. 5 shows the output beam profile registered at one specific propagation point. A low power higher order mode is supported by the fiber and propagates in the high NA fiber cladding. This low power higher order mode is due to the presence of an intermediate refractive index pedestal located between core and cladding refractive indexes. This pedestal enables the propagation of a 2 µm higher order mode with higher NA, and thus cannot be suppressed by applying fiber bending losses. Indeed, increasing fiber bending losses by progressively decreasing the fiber coiling diameter, leads to observe fundamental mode power losses whereas the higher order mode still propagates in the cladding of the fiber.

Optics EXPRESS

In order to compare the beam quality factors of our actively Q-switched single oscillator Tm^{3+}, Ho^{3+}-codoped silica fiber laser to other setup, the actively Q-switched single oscillator Tm^{3+}-doped silica fiber laser presented in [16] presents a beam quality factor M^2 of 1.7 in both x and y directions, but measured at 10 W average output power. Better beam quality has been obtained by Stutzki *et al* in [17], where a diffraction-limited beam is demonstrated with a $M^2 < 1.3$ obtained thanks to a specific rod type Large Pitch Fiber (LPF). In recent demonstrated MOPA systems delivering up to 100 W average output power around 2 µm wavelength [1,2], no M^2 measurement has been performed. Nevertheless, the V number calculation of the final amplification stage fibers gives V = 3.34 in [1] and V = 4.02 in [2]. The V number of our fiber (see section 2 for fiber details) is V = 2.55. Lower beam quality factors for these MOPA systems should be thus expected.

The pulses generated are stable in time with respect to the AOM drive frequency. They have a pulse duration (FWHM) at maximum pump power of 100 ns, 75 ns and 45 ns at respectively 200 kHz, 100 kHz and 40 kHz repetition rates (see Fig. 6). The inset shows a pulse shape of a 60 ns pulse at 40 kHz and 100 W pump power.

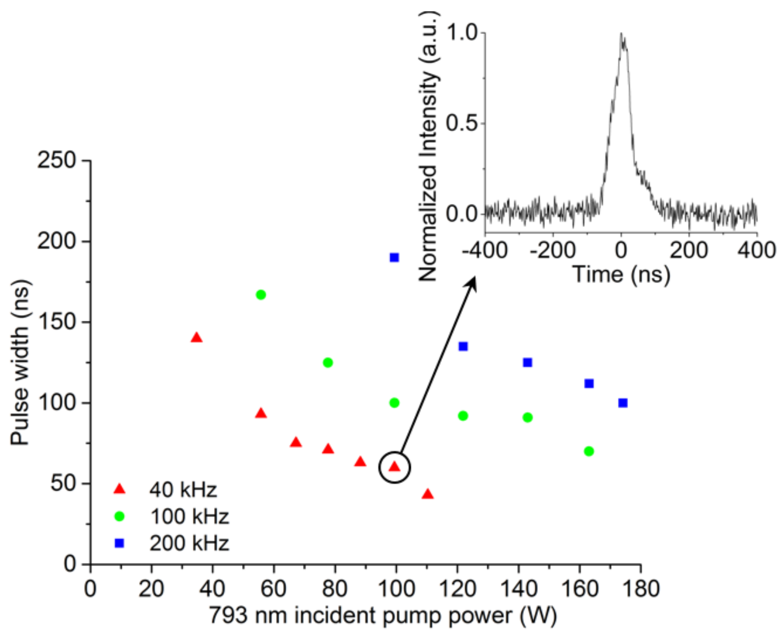

Fig. 6. Tm^{3+}, Ho^{3+}-codoped silica fiber laser pulse width versus incident pump power for different repetition rates. The inset shows a pulse shape of a 60 ns (FWHM) pulse.

Contrary to fiber MOPA systems presented in [1–3], in which the pulse width does not depend on the pump power (the initial pulse width is set by the seed laser source and is then power amplified by amplification stages), the pulse width of our Q-switched fiber laser is pump-power-dependent. Shortest pulse durations are achieved when the fiber laser pump power is set to the maximum, and are found in the range of 50-100 ns in our setup (depending on the repetition rate). This result is comparable to what has been achieved in previous actively Q-switched single oscillator fiber lasers [14–17], but shorter than pulse widths demonstrated in MOPA systems (typically 0.5-1 µs) for equivalent repetition rates [1–3].

Considering the pulse widths presented in Fig. 6, repetition rates and average output powers depicted in Fig. 2, the output peak powers achieved at maximum pump power are 15.3 kW, 6.7 kW and 2.8 kW at respectively 40 kHz, 100 kHz and 200 kHz.

The output power spectrum of the Tm^{3+}, Ho^{3+}-codoped silica fiber laser has been measured with a 0.01 nm wavelength resolution Optical Spectrum Analyzer (Yokogawa) at 50 W average output power and 200 kHz repetition rate. It is depicted in Fig. 7.

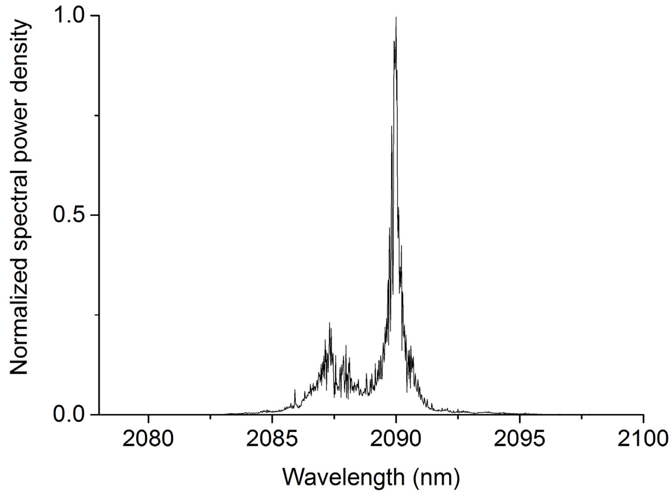

Fig. 7. Emitted power spectrum of the Tm^{3+}, Ho^{3+}-codoped silica fiber laser, registered at 50 W average output power and 200 kHz repetition rate. Central emission wavelength is 2090 nm with 0.2 nm spectral linewidth (FWHM).

The maximum emission wavelength of the laser is set with the diffraction grating to 2090 nm. The spectral linewidth (FWHM) is 0.2 nm and is comparable to what has been achieved in previous single oscillator actively Q-switched fiber lasers [14–16] and fiber MOPA systems [1–3], but lower than the linewidth achieved in [17] (broad multimode spectrum).

4. Conclusions

In conclusion, we have demonstrated an actively Q-switched single oscillator Tm^{3+}, Ho^{3+}-codoped silica polarization maintaining fiber laser emitting 55 W of average power at 2.09 nm wavelength, with good power stability (1.1%) and polarization factor (97.5%). Emitted pulses are stable in time and have 100 ns pulse width at 200 kHz repetition rate and maximum average output power. Spectral linewidth is 0.2 nm and beam quality factor M^2 is below 1.7. To the best of our knowledge, this is the most powerful pulsed single oscillator Tm^{3+}, Ho^{3+}-codoped linearly polarized 2.09 μm fiber laser that we found in the literature. By fusion-splicing fused-quartz end-caps to the fiber tips, the power scaling of the laser is only pump-power-limited in the range of the diodes pump power, and no thermal-induced damaging has been observed on any optical element of the laser. Future experiments will be devoted to power scaling of the laser with higher diodes pump power and direct OPO pumping for non-linear conversion in higher mid-infrared wavelengths.

Funding

French Direction Générale de l’Armement.

References

1. W. Yao, C. Shen, Z. Shao, Q. Liu, H. Wang, Y. Zhao, and D. Shen, “High-power nanosecond pulse generation from an integrated Tm-Ho fiber MOPA over 2.1 μm,” Opt. Express **26**(7), 8841–8848 (2018).
2. D. Ouyang, J. Zhao, Z. Zheng, S. Ruan, C. Guo, P. Yan, and W. Xie, “110 W all fiber actively Q-switched thulium-doped fiber laser,” IEEE Photonics J. **7**(1), 1–6 (2015).
3. X. Wang, X. Jin, P. Zhou, X. Wang, H. Xiao, and Z. Liu, “105 W ultra-narrowband nanosecond pulsed laser at 2 μm based on monolithic Tm-doped fiber MOPA,” Opt. Express **23**(4), 4233–4241 (2015).

Optics EXPRESS

4. E. Lucas, L. Lombard, Y. Jaouën, S. Bordais, and G. Canat, “1 kW peak power, 110 ns single-frequency thulium doped fiber amplifier at 2050 nm,” Appl. Opt. **53**(20), 4413–4419 (2014).
5. M. Jiang and P. Tayebati, “Stable 10 ns, kilowatt peak-power pulse generation from a gain-switched Tm-doped fiber laser,” Opt. Lett. **32**(13), 1797–1799 (2007).
6. J. Swiderski and M. Michalska, “Generation of self-mode-locked resembling pulses in a fast gain-switched thulium-doped fiber laser,” Opt. Lett. **38**(10), 1624–1626 (2013).
7. S. Kivistö, R. Koskinen, J. Paajaste, S. D. Jackson, M. Guina, and O. G. Okhotnikov, “Passively Q-switched Tm^{3+}, Ho^{3+}-doped silica fiber laser using a highly nonlinear saturable absorber and dynamic gain pulse compression,” Opt. Express **16**(26), 22058–22063 (2008).
8. W. Yang, J. Hou, B. Zhang, R. Song, and Z. Liu, “Semiconductor saturable absorber mirror passively Q-switched fiber laser near 2 μm,” Appl. Opt. **51**(23), 5664–5667 (2012).
9. Y. Tang, X. Yu, X. Li, Z. Yan, and Q. J. Wang, “High-power thulium fiber laser Q switched with single-layer graphene,” Opt. Lett. **39**(3), 614–617 (2014).
10. Y. Tang, X. Li, and Q. J. Wang, “High-power passively Q-switched thulium fiber laser with distributed stimulated Brillouin scattering,” Opt. Lett. **38**(24), 5474–5477 (2013).
11. Y. Tang and J. Xu, “High-power pulsed thulium fiber oscillator modulated by stimulated Brillouin scattering,” Appl. Phys. Lett. **104**(1), 011103 (2014).
12. J. Y. Long, D. Y. Shen, Y. Sh. Wang, W. Zhao, Y. An, and W. Zhou, “Stable passively Q-switched operation of Tm^{3+} doped silica fiber laser by anti-resonant Fabry-Perot saturable absorber,” Laser Phys. **22**(5), 986–990 (2012).
13. X. He, A. Luo, W. Lin, Q. Yang, T. Yang, X. Yuan, S. Xu, W. Xu, Z. Luo, and Z. Yang, “A stable 2 μm passively Q-switched fiber laser based on nonlinear polarization evolution,” Laser Phys. **24**(8), 085102 (2014).
14. M. Eichhorn and S. D. Jackson, “High-pulse-energy actively Q-switched Tm3+-doped silica 2 μm fiber laser pumped at 792 nm,” Opt. Lett. **32**(19), 2780–2782 (2007).
15. M. Eichhorn and S. D. Jackson, “High-pulse-energy, actively Q-switched Tm3+,Ho3+ -codoped silica 2 μm fiber laser,” Opt. Lett. **33**(10), 1044–1046 (2008).
16. C. Kieleck, A. Berrou, B. Donelan, B. Cadier, T. Robin, and M. Eichhorn, “6.5 W $ZnGeP_{(2)}$ OPO directly pumped by a Q-switched $Tm^{(3+)}$-doped single-oscillator fiber laser,” Opt. Lett. **40**(6), 1101–1104 (2015).
17. F. Stutzki, F. Jansen, C. Jauregui, J. Limpert, and A. Tünnermann, “2.4 mJ, 33 W Q-switched Tm-doped fiber laser with near diffraction-limited beam quality,” Opt. Lett. **38**(2), 97–99 (2013).