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High power mode-locked rod-type fiber femtosecond laser with micro-joule energy

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ABSTRACT

We report a high power all-normal-dispersion (ANDi) mode-locked laser based on nonlinear polarization evolution (NPE) technique using rod-type fiber with polarization maintaining (PM) characteristic. With 85 μm gain core diameter, 31 W of average power at repetition rates of 57.93 MHz, which corresponds to the pulse energy of 0.53 μJ, is demonstrated under a pump power of 93 W. The pulse duration of 124 fs after compressor is obtained at the central wavelength of 1033 nm as well as the measured power jitter of 0.3% over a period of 2 h.

1. Introduction

With the progress of the ultra-short pulse laser technology, stable high average power ultra-fast lasers at MHz repetition rate are increasingly demanded in a wide variety of industry and science research applications [1–4]. To date, among the various gain media used in laser technology, Yb-doped gain fibers and thin disk crystals are the most promising candidates to realize this goal as a result of the excellent heat dissipation and beam quality [5–6]. In particular, the Yb-doped double-clad large mode area (LMA) fibers [7] and large core diameter photonic crystal fibers (PCF) [8] increasingly dominate the realization of the high power ultra-short pulse laser amplifiers because of the inherent advantages than thin disk lasers. With the development of the femtosecond fiber lasers, the mode-locked mechanisms of the fiber oscillators have been demonstrated as soliton with only anomalous dispersion [9], stretched-pulse with dispersion map [10], self-similar in net normal group velocity dispersion (GVD) domain [11] and ANDi types [12]. Today, compared to laser amplifiers with chirped pulse amplification technique, the mode-locked femtosecond fiber lasers not only could emit comparable power level at MHz repetition rate, but also have advantages of compact configuration and low-cost. However in comparison to other types of mode-locked fiber lasers, due to the unique dissipative pulse shaping mechanism introduced in the ANDi fiber lasers, they support the generation of the positive chromatic dispersion laser pulses with higher energy and power in theory, which also have been experimentally demonstrated [13].

To meet the demands of the different applications, various types of Yb-doped gain fibers have been employed in mode-locked ANDi fiber lasers, such as single-clad fibers [14], double-clad LMA PCF [15] and rod-type fibers [16]. Among them, rod-type fibers are the best choice for the generation of high power high energy femtosecond mode-locked lasers, due to low bending loss and high pointing stability from the rigid structure as well as supporting high power pumping. Therefore, mode-locked ANDi fiber lasers with only rod-type fiber as gain and nonlinear medium have been developed over the last few years using saturable absorber and passively mode-locked approach and the highest mode-locked output power is still 66 W [13,17–18]. However, because of the random birefringence introduced in frequently-used gain fiber, the mode-locked operation is sensitive to the external environmental perturbations, which makes it difficult to be operated beyond the laboratory.

In this paper, we aim at realizing stable high power mode-locked output with compact and concise configuration, rod-type fiber with PM characteristic (aeroGAIN-ROD-PM85, NKT photonics) is employed as gain medium and NPE mode-locking technique is adopted. To our knowledge, this is the first realization of the highest power of ANDi fiber laser by pure NPE mode-locking technique based on fibers with PM characteristic as gain media. Compared with other environmentally stable fiber lasers, which only consist of PM fibers as gain media and SESAM as modulation component [19–21], the fiber laser presented here overcomes certain substantial limitations of the SESAM and makes the power

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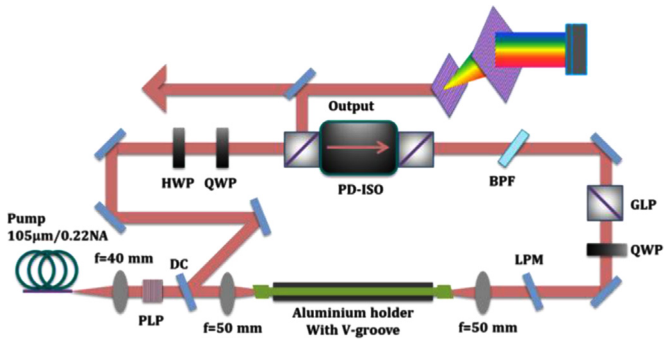

Fig. 1. Schematic diagram of the rod-fiber based ANDi laser. DM, dichroic mirror; PLP, pump laser protector; HWP (QWP), half- (quarter-) waveplate; PD-ISO, polarization-dependent isolator; BPF, birefringent plate filter; GLP, Glan laser polarizer; LPM, pump dump mirror. The rest unspecified mirrors are high reflective mirrors for the oscillated laser pulses in the ring cavity.

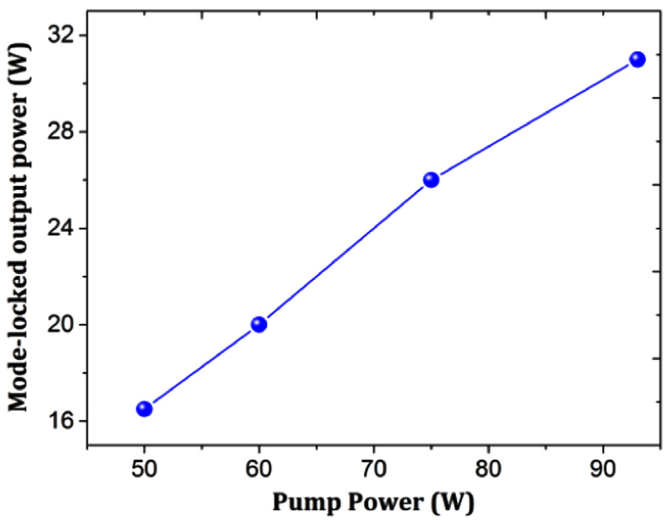

Fig. 2. Variation of the output power as a function of pump power.

scalable higher through the use of pure NPE technique. It should be noted that the mentioned above PM characteristic of the adopted rod-type fiber does not originate from PM structure, but the excellent isotropy without random birefringence, which is characterized by the polarization extinction ratio (PER) of >15 dB and has been widely used for PM amplification [22]. So, the presented mode-locked rod-type ANDi fiber laser is indeed robust against environmental perturbations and the maximum average mode-locked output power of 31 W is obtained at repetition rates of 57.93 MHz under the pump power of 93 W, which corresponds to the single pulse energy of 0.53 μJ. The pulse duration of 124 fs after compressor is obtained at the central wavelength of 1033 nm. The performance of the short term power fluctuation is also measured to be less than 0.3% (RMS), which shows excellent mode-locked operation and we believe that this high power rod-type femtosecond laser has potential research applications.

2. Experiment and discussion

The experiment setup is shown in Fig. 1, which consists of a wavelength-stabilization pump laser diode (LD), a LMA rod-type gain fiber, counter-pumped ring cavity, and a grating-pair compressor. The LMA rod-type gain fiber has a core diameter of 85 μm, and its pump cladding has a diameter of 260 μm and a cladding numerical aperture (NA) of 0.5. Two angle-cleaved rod-type fiber end-caps facilitate the improvement of the fiber end facet damage threshold and effectively suppress the generation of the self-excited oscillation in high power pumped mode-locked operation. The ring cavity mainly consists of two Plano-convex lens, a polarization-dependent isolator (PD-ISO), polarization controller and birefringent modulation component. As spectral filter, the birefringent filter introduces a narrow spectral shaping in frequency domain so as to accumulate more intense nonlinear phase to initiate mode-locking [23]. For this process, the rod-type fiber not only provides a laser gain, but also acts as a nonlinear medium to generate new frequency components and simultaneously provides NPE to promote mode-locked operation. In addition, during the process of NPE evolution in rod-type fiber, the polarization states don't vary with surrounding perturbations due to the PM characteristic attributed to the excellent isotropy, and it ensures the environmentally stable operation. Considering efficient heat dissipation and stable mode-locked operation, the rod-type gain fiber is cooled down to 12 °C through circulated cooling water.

The pump laser emitted from the wavelength-stabilization LD is firstly collimated using an $f=40$ mm aspherical lens, while an $f=50$ mm aspherical lens is then used for coupling the pump laser into the pump cladding with an approximate spot size of 150 μm and collimating the oscillated laser pulses from the rod-type fiber. Considering mode matching, which meets the condition of self-consistent as stable laser oscillation is built, a spherical lens with a focal length of $f=50$ mm is employed in the cavity to coupling the oscillated laser pulses into the 85 μm core rod fiber. In order to avoid the damage of the LD from the backward transmitted oscillated high peak power laser pulses, a PLP which consists of four dichroic mirrors is inserted into the optical path between aspherical collimated lens and focused lens. In order to eliminate the

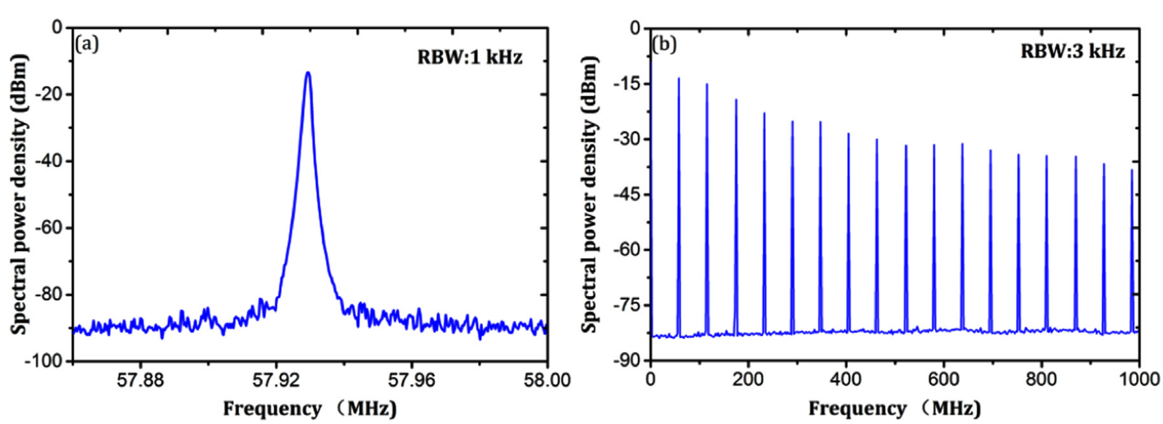

Fig. 3. RF spectra monitored with a photodiode and a frequency spectrum analyzer (Agilent E4407B). (a) The center repetition rate with 1 kHz resolution. (b) RF spectra with 1 GHz span.

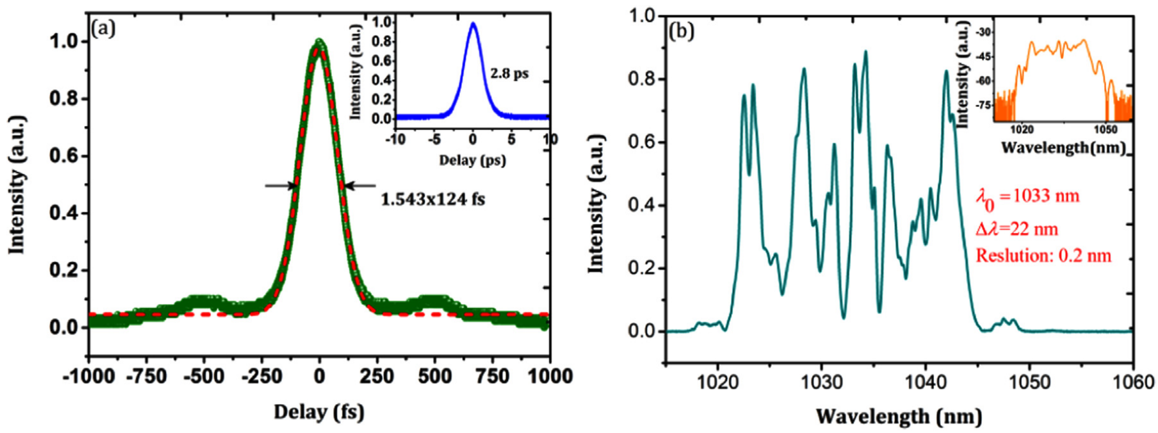

Fig. 4. (a) Autocorrelation traces of the dechirped (olive curve) and chirped (blue solid curve) output pulses of the mode-locked rod-type fiber laser. (b) Mode-locked output spectra on linear and logarithmic (inset) scale.

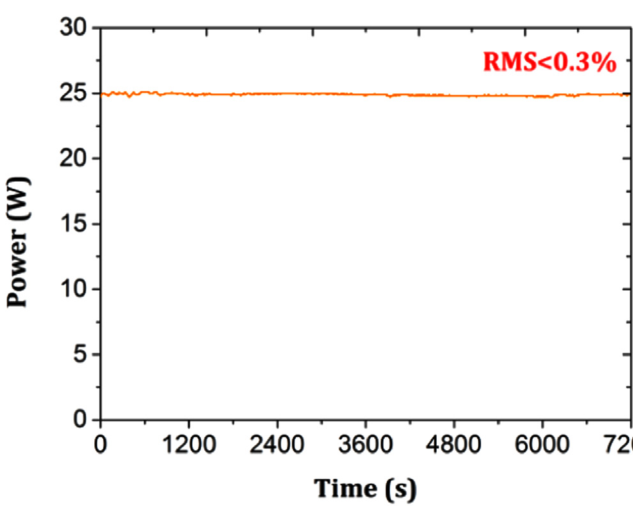

Fig. 5. Power stability measurement of the environmentally stable mode-locked rod-type fiber laser over 2 h.

unnecessary heat generation for optical components in the cavity, as shown in Fig. 1, we dump the unabsorbed counter propagating pump light out of the cavity utilizing a dichroic mirror.

Firstly, the cavity performance of the laser is optimized until the maximum CW output under the pump power of 10 W, and then with the increase in pump power, an output power of 35 W is obtained under the pump power of 75 W, in which Q-switching is accompanied. In order to realize high power mode-locked operation, we continuously adjust the orientations of the waveplates so as to introduce the dissipation process to initiate mode-locking. Once mode-locking process works, ~26 W output power is obtained from the first polarizer of the PD-ISO. With increasing pump power from 75 W to 93 W, a maximum mode-locked output power of 31 W is obtained. Fig. 2 shows the linear increase in mode-locked output power with increasing pump power.

The measured radio frequency (RF) spectrum shows the fundamental repetition rate is centered at 57.93 MHz with side-mode suppression ratio of 69 dB, which indicates the high stability during the mode-locked operation as shown in Fig. 3(a), and (b) shows the RF spectra with a span of 1 GHz.

The duration of the output pulse directly from the mode-locked ring cavity is measured to be 2.8 ps, as shown in the inset of Fig. 4(a), and it can be compressed to 124 fs using an external transmission grating-pair compressor. The multi-peak structured spectrum in Fig. 4(b) shows the pulses are highly nonlinear phase accumulation and the characteristics of the spectrum are typical expression of SPM and chirped spectra filtering. As depicted in the spectrum, the pulse is centered at 1033 nm with 22 nm FWHM. According to the formula of time bandwidth product, the obtained value is 0.766, which is nearly twice than the Fourier-transform limit, which indirect explains the existence of uncompensated high order phase mainly caused by SPM, so small sidebands occur before and after the main autocorrelation trace, as shown in Fig. 4(a).

In order to further validate the operation performance of the rod-type mode-locked fiber laser, the power fluctuations over 2 h are also recorded, which are done by a combination of a HWP and a GLP to extract a portion of the maximum mode-locked output power to a power meter (COHERENT PM30, USA). The measured power deviations are better than 0.3% root mean square (RMS), as shown in Fig. 5, which shows stable mode-locked operation.

3. Conclusion

In conclusion, a high average power mode-locked femtosecond ytterbium fiber laser based on rod-type fiber with PM characteristic as gain medium and all-normal-dispersion scheme as mode locked mechanism is developed. 31 W of average power mode-locked femtosecond laser at repetition rates of 57.93 MHz is achieved under the pump power of 93 W, which corresponds to 0.53 μJ pulse energy. The pulse duration is 124 fs after a grating-pair compressor at the central wavelength of 1033 nm with bandwidth of 22 nm. The recorded short term power fluctuation is 0.3% RMS over than 2 h, which shows the potential applications in certain scientific research.

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References

[1] R.R. Gattass, E. Mazur, Femtosecond laser micromaching in transparent materials, Nat. Photonics 2 (2008) 219–225.
[2] Florian Adler, Kevin C. Cossel, Michael J. Thorpe, Ingmar Hartl, Martin E. Fermann, Jun Ye, Phase-stabilized, 1.5 W frequency comb at 2.8–4.8 um,

Opt. Lett. 34 (2009) 1330–1332.
[3] Nicola Coluccelli, Alessio Gambetta, Davide Gatti, Marco Marangoni, Alberto Di Lieto, Mauro Tonelli, Gianluca Galzerano, Paolo Laporta, 1.6-W self-referenced frequency comb at 2.06 um using a Ho:YLF multipass amplifier, Opt. Lett. 36 (2011) 2299–2301.
[4] Ming Yan, Wenxue Li, Kangwen Yang, Hui Zhou, Xuling Shen, Qian Zhou, Qitian Ru, Dongbi Bai, Heping Zeng, High-power Yb-fiber comb with feed-forward control of nonlinear-polarization-rotation mode-locking and large-mode-area fiber amplification, Opt. Lett. 37 (2012) 1511–1513.
[5] Tino Eidam, Steffen Hädrich, Fabian Röser, Enrico Seise, Thomas Gottschall, Jan Rothhardt, Thomas Schreiber, Jens Limpert, Andreas Tünnermann, A 325 W average power fiber CPA system delivering Sub-400 fs pulses, IEEE J. Sel. Top. Quantum Electron 15 (2009) 187–190.
[6] Clara J. Saraceno, Florian Emaury, Oliver H. Heckl, Cyrill R.E. Baer, Martin Hoffmann, Cinia Schriber, Matthias Golling, Thomas Südmeyer, Ursula Keller, 275 W average output power from a femtosecond thin disk oscillator operated in a vacuum environment, Opt. Express 20 (2012) 23535–23541.
[7] Peng Wan, Lih Mei Yang, Jian Liu, All fiber-based Yb-doped high energy, high power femtosecond fiber lasers, Opt. Express 21 (2013) 29854–29859.
[8] Tino Eidam, Stefan Hanf, Enrico Seise, Thomas V. Andersen, Thomas Gabler, Christian Wirth, Thomas Schreiber, Jens Limpert, Andreas Tünnermann, Femtosecond fiber CPA system emitting 830 W average output power, Opt. Lett. 35 (2010) 94–96.
[9] F.M. Mitschke, L.F. Mollenauer, Ultrashort pulses from the soliton laser, Opt. Lett. 12 (1987) 407–409.
[10] V. Cautaerts, Stretched pulse Yb^{3+}:solica fiber laser, Opt. Lett. 22 (1997) 316–318.
[11] V.I. Kruglov, D. Méchin, J.D. Harvey, Self-similar solutions of the generalized Schrödinger equation with distributed coefficients, Opt. Express 12 (2004) 6198–6207.
[12] Andy Chong, William H. Renninger, Frank W. Wise, All-normal-dispersion femtosecond fiber laser with pulse energy above 20 nJ, Opt. Lett. 32 (2007) 2048–2410.
[13] Bülend Ortaç, Martin Baumgartl, Jens Limpert, Andreas Tünnermann, Approaching microjoule-level pulse energy with mode-locked femtosecond fiber lasers, Opt. Lett. 34 (2009) 1585–1587.
[14] Xiaojun Zhu, Chinhua Wang, Guoan Zhang, Ruji Xu, Tunable dual- and triple-wavelength mode-locked all-normal-dispersion Yb-doped fiber laser, Appl. Phys. B. 118 (2014) 69–73.
[15] Pingxue Li, Ziqiang Zhao, Junjie Chi, Chun Yang, Guangju Zhang, Haowei Hu, Yifei Yao, Yao Li, Xiongfei Wang, Guoshun Zhong, Hong Zhao, Dongsheng Jiang, Tunable picosecond SESAM mode-locking ytterbium-doped double-clad LMA PCF oscillator, Opt. Commun. 317 (2014) 62–66.
[16] Pierre Deslandes, Mathias Perrin, Julien Saby, Damien Sangla, François Salin, Eric Freysz, Picosecond to femtosecond pulses from high power self-mode-locked ytterbium rod-type fiber laser, Opt. Express 21 (2013) 10731–10738.
[17] Martin Baumgartl, Florian Jansen, Fabian Stutzki, Cesar Jauregui, B.ülend Ortaç, Jens Limpert, Andreas Tünnermann, High average and peak power femtosecond large-pitch photonic-crystal-fiber laser, Opt. Lett. 36 (2011) 244–246.
[18] Martin Baumgartl, Caroline Lecaplain, Ammar Hideur, Jens Limpert, Andreas Tünnermann, 66 W average power from a microjoule-class sub-100 fs fiber oscillator, Opt. Lett. 37 (2012) 1640–1642.
[19] C.K. Nielsen, B. Ortaç, T. Schreiber, J. Limpert, Self-starting self-similar all-polarization maintaining Yb-doped fiber laser, Opt. Express 23 (2005) 9346–9351.
[20] Andy Chong, William H. Renninger, Frank W. Wise, Environmentally stable all-normal-dispersion femtosecond fiber laser, Opt. Lett. 33 (2008) 1071–1073.
[21] B. Ortaç, C. Lecaplain, A. Hideur, T. Schreiber, J. Limpert, A. Tünnermann, Passively mode-locked single-polarization microstructure fiber laser, Opt. Express 16 (2008) 2122–2128.
[22] Zhi Zhao, Bruce M. Dunham, Frank W. Wiswe, Generation of 167 W infrared and 124 W green power from a 1.3-GHz, 1-ps rod fiber amplifier, Opt. Express 22 (2014) 25065–25070.
[23] Andy Chong, William H. Renninger, Frank W. Wise, Properties of normal-dispersion femtosecond fiber lasers, J. Opt. Soc. Am. B 25 (2008) 140–148.