Applied Physics B (2018) 124:169
https://doi.org/10.1007/s00340-018-7026-6

Applied Physics B
Lasers and Optics

Highly stable Yb-fiber laser amplifier of delivering 32-μJ, 153-fs pulses at 1-MHz repetition rate

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Received: 6 February 2018 / Accepted: 12 July 2018 / Published online: 3 August 2018

Abstract

We demonstrated a sub-200-fs polarization-maintaining Yb-fiber laser amplifier based on chirped-pulse amplification (CPA) technology with high energy and stability. The seeding laser pulses were picked to 1 MHz from a nonlinear polarization evolution (NPE) self-similar mode-locked Yb-fiber laser oscillator at 40.3 MHz. A specially designed chirped fiber Bragg grating (CFBG) was employed as the pulse stretcher, which provide compensation for higher order dispersion introduced by grating compressor. Laser pulse as short as 153 fs with energy of 32 μJ was obtained after the compressor, which corresponds to a peak power of 209 MW. The measured output power fluctuation of root mean square was 0.64% in 24 h and the M^2 factor was 1.3. It shows a great potential in many applications such as scientific researches, medical therapy, and industrial micromachining.

1 Introduction

Femtosecond Yb^{3+}-doped all-fiber lasers with high average power have attracted increasing attention on medical surgery [1], industrial applications [2, 3], and scientific researches [4, 5]. Up to now, remarkable progresses have been achieved on exploration of fiber lasers via CPA or pre-chirp management amplification (PCMA) techniques [6–9]. For all-fiber CPA or PCMA systems in those works, usually, a single-mode fiber was used as the stretcher [10, 11], which is accessible, low cost, and can provide considerable normal group velocity dispersion (GVD) at the laser wavelength around 1 μm. Nevertheless, higher order dispersion and nonlinearity deteriorate the pulse quality, and greatly limit the compressibility of the amplified pulses. Together with gain-narrowing effect in the cascaded amplifiers, fiber CPA lasers always deliver pulses with long duration with duration typically longer than 200 fs [8, 12]. As a matter of fact, the long pulse duration and high repetition rate induce undesirable thermal accumulation in some applications such as precision micromachining, biomedical sciences, and medical surgery [13]. PCMA is a relatively new amplification technique by introducing a pair of gratings to manage the dispersion and broaden spectrum by nonlinear effects in main fiber amplifier. By tuning the final grating-pair compressor and pre-chirp grating pair, PCMA produces amplified pulses with sub-100-fs duration [9, 14]. It seems a good solution to the long pulse duration of CPA system. Unfortunately, PCMA has lots of limitations including the introduction of an additional grating pair, more free space components, more loss to lower the system efficiency inevitably, and compromised system stability. The peak power limitation is also a big barrier in PCMA system. Because of the limitation of nonlinearity, the peak power cannot be too high to avoid undesirable nonlinear effect, this technique is more suitable for system with high repetition rate like tens of megahertz. A fiber amplification system with broad spectrum and effective high-order dispersion (HOD) compensation scheme can overcome the drawbacks of both the traditional CPA and PCMA techniques, and achieve high peak power pulses with duration of about 100 fs at low repetition rate (< MHz) with long-term stability.

In this letter, we demonstrate an all-fiber femtosecond laser amplification system with high energy and stability

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based on the CPA technique. In this experiment, we used a self-similar broadband seeding pulse in combination with a specially designed CFBG as pulse stretcher and HOD pre-compensator to generate nearly Fourier-transform-limited (FTL) pulses at 1-MHz repetition rate. The laser works with a very good long-term stability in power standard deviation of 0.21 W.

2 Experiment setup

The detailed experimental schematic of the fiber CPA (FCPA) system is shown in Fig. 1. It was seeded by a self-similar and self-starting NPE mode-locked oscillator and amplified by five Yb-doped fiber cascade amplifier stages. The compressor is constituted by a pair of gratings and a 0° high reflectivity mirror. The oscillator is typical mode-locked by NPE mechanism at the repetition rate of 40.3-MHz, capable of 30-mW output power and 32-nm spectrum bandwidth (Fig. 2a), the top of the spectrum in linear axes is bell like, and in log axes (as shown in the inset of Fig. 2), the top of the spectrum is flat, which is similar to the self-similar mode-locking spectrum. The autocorrelation (AC) traces show that the pulse duration was 3 ps, which is shown in Fig. 2b. We measure the radio frequency (RF) spectrum by an RF analyzer (ROHDE & SCHWARZ FSW26); Fig. 2c shows the measured repetition rate of 40.3 MHz with the signal noise ratio (SNR) of higher than 80 dB in 1-kHz resolution bandwidth (RBW), indicating a very stable mode-locked state.

Because the output pulses from oscillator via output coupler (OC) are not linearly polarized, we used a fiber-based in-line optical polarizer (FIP) to convert them to be linearly polarized with average power of 18 mW; the corresponding spectrum bandwidth is 32 nm. The spectrum shape can be optimized by tuning the polarization controller (PC); the measured polarization extinction ratio (PER) of the pulses from the FIP is over 20 dB. The seeding laser

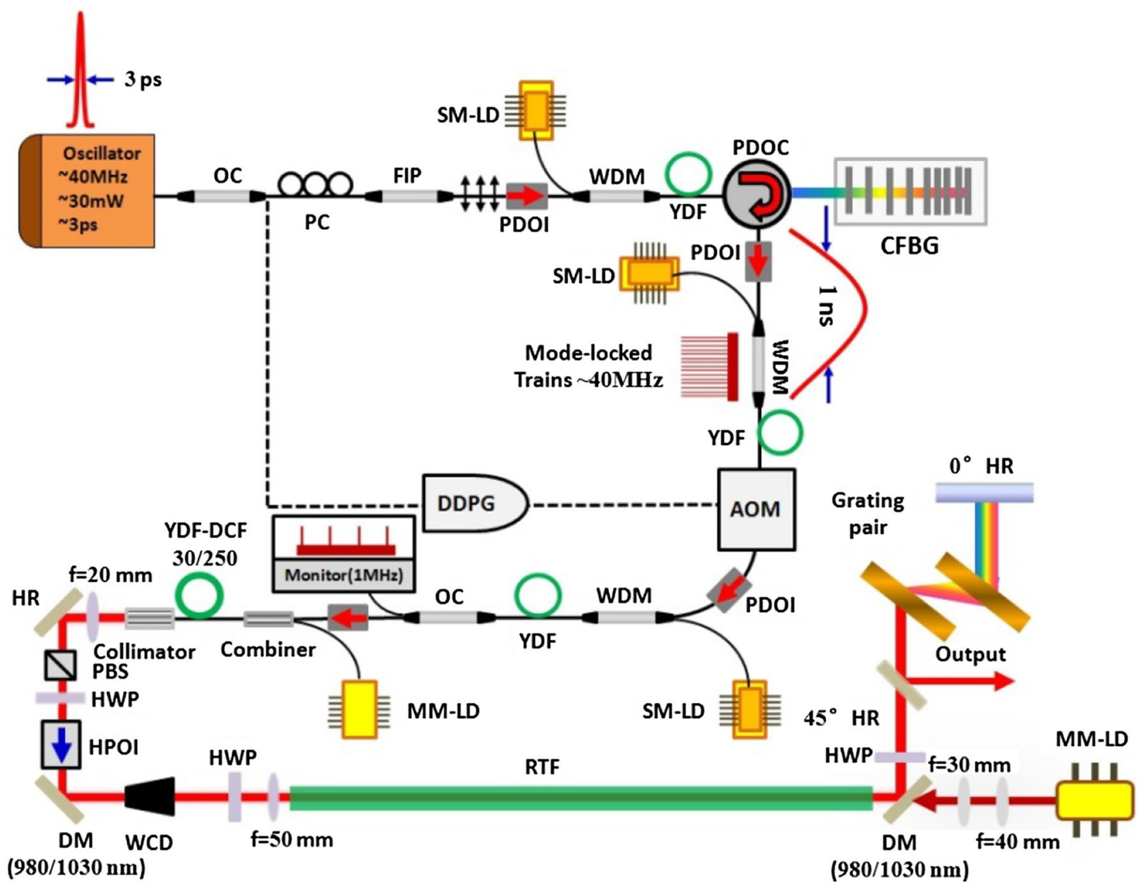

Fig. 1 Schematic diagram of the FCPA system [*OC* optical coupler, *FIP* fiber-based in-line optical polarizer, *PC* polarization controller, *PDOC* polarization dependent optical circulator, *WDM* wave division multiplexer, *CFBG* chirped fiber Bragg grating, *AOM* acoustic optical modulator, *YDF* Yb-doped fiber, *PDOI* polarization dependent optical isolator, *DDPG* digital delay and pulse generator, *QWP (HWP)* quarter- (half-) waveplate, *PBS* polarization beam spliter, *DM* dichronic mirror, *YDF-DCF* Yb-doped double-clad fiber, *HR* high reflectivity mirror, *HPOI* high-power optical isolator, *WCD* water-cooled diaphragm, *RTF* Yb-doped rod-type fiber, *SM (MM)-LD* single-mode (multimode) laser diode]

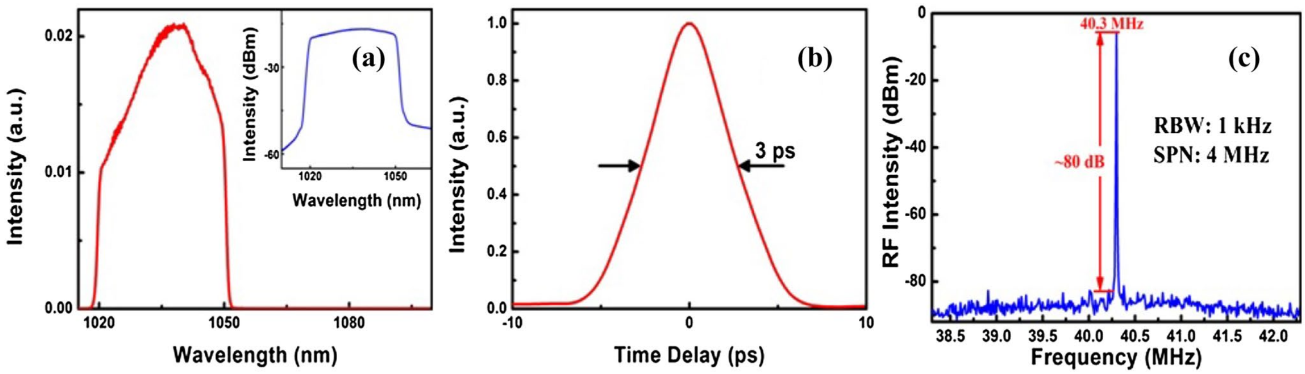

Fig. 2 **a** Pulses spectrum, **b** pulses duration, and **c** RF spectrum with 80-dB SNR measured with 1-kHz RBW of the oscillator

is then amplified to 120 mW by a single-mode amplifier unit, and injected into a polarization-maintaining reflecting CFBG which has minimum reflectivity of ~40% at central wavelength of 1040 nm. With 40-nm bandwidth, the CFBG has two fundamental purposes: pulse stretching and HOD compensation. Due to the high loss of the CFBG and acoustic optical modulator (AOM) (over 97.5% power attenuation rate), two stages of single-mode highly doped Yb-fiber pre-amplifiers are placed before the CFBG and AOM, respectively, to increase the signal power. The 90-cm single-mode ytterbium doped fiber YDF gain fiber (Model: PM-Yb-401, CorActive Ltd., Canada) has absorption coefficient of 150 dB/m at 976 nm. Being pumped by two 976-nm wavelength locked laser diodes and coupled via wave division multiplexer (WDM), the signal power is amplified to ~280 mW to compensate the power loss incurred from the CFBG and AOM, respectively. The output power from AOM is about 3 mW, and is amplified to 120 mW by the next single-mode amplifier stage. Then, the signal is further amplified by 2-m Yb-doped double-clad fiber (YDF-DCF, fiber model: YDF-PM-30/250, absorption coefficient of 6 dB/m at 976 nm), and this Yb fiber is coiled with a coiling diameter of 15 cm to obtain a good beam quality. At pump power of 15 W, the amplified signal with average power of 6.5 W is obtained after the isolator with 14-dB PER. We use a polarization beam splitter (PBS) to further optimize the signal PER to near 20 dB with 6.25-W average power. The main amplification is achieved by an 85-cm rod-type fiber with a large mode area of ~3300 μm^2.

3 Experimental results and discussion

With the absorption coefficient of 15 dB at 976 nm, the rod-type fiber is backwards pumped by a 90-W laser diode with the center wavelength locked at 976 nm. A half-wave plate (HWP) was used to adjust the polarization direction of the incident signal beam. With 80 W of pump power (the estimated coupling efficiency of about 90%), 5.3-W (the estimated coupling efficiency of about 85%) incident signal is amplified to more than 53 W, corresponding to an optical-to-optical efficiency larger than 60%, which is shown in Fig. 4a. The PER is 19.5 dB, which is considerably high due to the high PER of seed laser and the good PER maintaining property of rod-type fiber itself. Figure 3a shows the spectrum of pulses from oscillator and the rod-type fiber, and the spectral width is severely narrowed from 32 to 11.2 nm due to the strong gain-narrowing effect.

In the fiber CPA (FCPA) laser system, the designed CFBG introduces group-delay dispersion (GDD) of 20.24 ps^2, and third-order dispersion (TOD) of −0.146 ps^3, including pigtail fiber (single-mode fiber GVD ≈ 23 ps^2/km, TOD ≈ 0.044 ps^3/km) [11]. The fibers' length in this laser system is 22 m in total, which introduced GDD of 0.506 ps^2 and TOD of 0.986×10^{-3} ps^3. Considering the oscillators output pulses with 32-nm spectral bandwidth and chirped-pulse duration ~3 ps centered at 1038 nm, in consideration of the high pulse energy and long fiber length in system, to minimize the nonlinearity accumulation and obtain a better pulse compression result, a longer pulse duration is of great necessary; the signal pulses are finally stretched to ~1 ns (measured by a sampling oscilloscope and ultra-fast photodiode) by the CFBG. Due to the gain-narrowing effect, the pulse duration at the input port of RTF is less than 500 ps and the spectrum width is less than 12 nm. The spectrum corresponds to an FTL pulse duration near 110 fs, and the estimated total GDD of this system is near 20.74 ps^2 and accumulated total TOD is around −0.146 ps^3. We then employed a pair of transmission grating in a double-pass configuration to compress the pulse duration after the RTF. The size of the smaller one of the grating pair is 31.8×25.4 mm^2, and the larger one is 20×130 mm^2. After optimization of the compressor, the shortest pulse duration of 153 fs at average power of 32 W is obtained. The fine optimized grating-pair compressor can provide GDD of −20.5 ps^2 and TOD of 0.154 ps^3 at

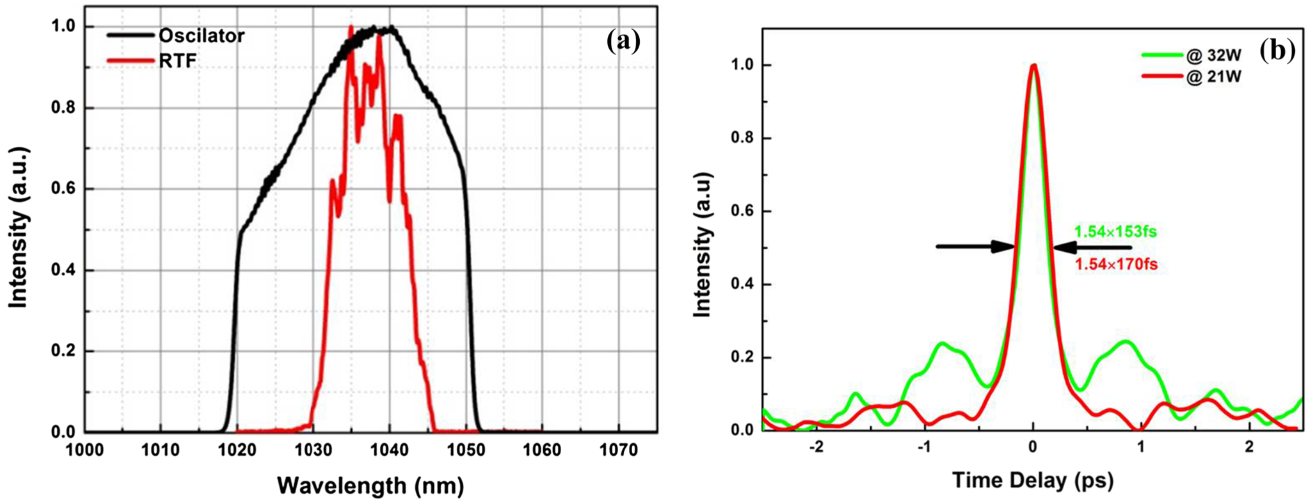

Fig. 3 **a** Measured spectrum from oscillator (black) and RTF (red), **b** compressed pulse duration of different powers

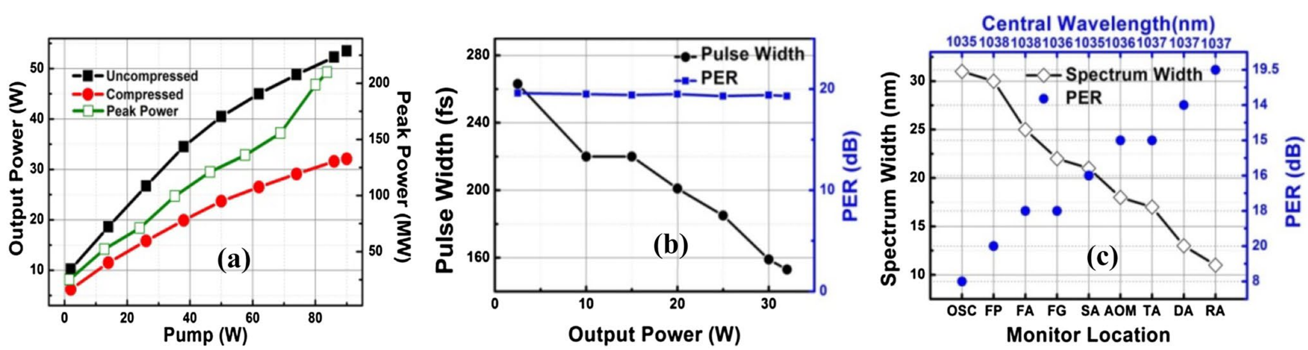

Fig. 4 **a** Output power characteristics of the RTF vary with pump power, **b** pulse duration and PER vary with the output power, **c** measured spectral width, PER, and central wavelength in different locations (*OSC* oscillator, *FP* fiber-based in-line optical polarizer, *FA* the first stage fiber amplifier, *FG* chirped fiber Bragg grating, *SA* the second-stage amplifier, *TA* the third stage amplifier, *DA* double-clad fiber amplifier, *RA* rod-type fiber amplifier)

the distance of 0.39 m, and the total compression efficiency near 60%. The measured compressed pulse AC traces at pulse energy of 21 and 32 μJ are presented in Fig. 3b, and the corresponding pulse duration is measured to be 170 fs (in red) and 153 fs (in green), assuming a $sech^2$ fitting. The apparent difference between two-pulse profiles measured at different pulse energy is that the pulse profile at 32-μJ pulse energy has a larger pedestal and pulse duration is shorter, which is mainly due to the higher pulse peak power that leads to higher nonlinearity. The estimated system nonlinearity phase shift and corresponding B-integral at average of 32 W is 3π, which means a large nonlinear accumulation and will greatly affect the compressed pulse profile. The estimated FTL pulse duration is around 115 fs at output pulse spectrum of 11.2 nm from RTF. The discrepancy between the experiment result and the FTL pulse duration is mainly due to the residual TOD of ~ 0.007 ps^3 and nonlinearity, which also explains the small sidelobe structures of the pulse profile.

We measured the pulse duration and PER at different output power, as shown in Fig. 4b. The PER maintains at ~ 20 dB at different output powers. The slight depolarization effect may be caused by amplified spontaneous emission (ASE) component in output power. The pulse duration decreases as increasing the output power, and the result indicates the compensation effect of TOD by the fiber nonlinearity [15]. We also explore the spectral bandwidth, PER, and central wavelength variation in different locations of amplifier chains, as shown in Fig. 4c. Strong spectral narrowing effects could be seen due to the multiple amplification stages (five amplification stages in total). The spectrum bandwidth after RTF amplifier is ~ 11.2 nm. The central wavelength of each stage also slightly varies due to the slight difference of bandwidth and transmittance of devices. The deterioration of polarization mainly results from the ASE accumulation and limitations of PER of devices.

For industrial applications, the long-term power stability is one of the key requirements. After a series of monitoring and experimental tests, we find that the key factors that affect the power stability is the heat accumulation from the residual pump power, which results in the mechanical instability. We specially design a water-cooled conical diaphragm which successfully solve this problem and keep the power fluctuation of standard deviation around 210 mW at average power of 32.5 W. The structure of the diaphragm and its working diagram are shown in Fig. 5. Figure 5a shows if without diaphragm, the residual pump power would cover the whole dichroic mirror mounts, will lead to heat accumulation, and is detrimental to the system long-time power stability. Figure 5b shows the water-cooled working diagram, the residual pump power beam can be shaped by the diaphragm and could easily pass the dichroic mirror, and the heat accumulation of the mirror mounts can be avoided effectively. In addition, the design of conical orifice can effectively avoid backward scattering light.

Using the diaphragm, the system power stability is improved, and the measured power fluctuation (root mean square) in over 24 h is 0.64% at average power of 32.5 W. The measured beam profile factor (M^2) is around 1.3 (M_x^2 factor value at this power level is 1.2 and M_y^2 value is 1.3) at 32.5 W (shown in Fig. 6), representing a good beam quality.

4 Conclusion

In conclusion, we demonstrate a fiber femtosecond laser system based on CPA scheme. To obtain much shorter compressed pulses, a specially designed CFBG is employed as the pulse stretcher and a HOD compensator. By optimizing the dispersion compensation of the compressor, laser pulses as short as 153 fs at 32-W output power are obtained, corresponding to a peak power of 209 MW. The stability measurement revealed a power standard deviation of 210 mW at an average power of 32.5 W within 24 h, corresponding to the power fluctuation of less than 0.64%. Further amplified power up to hundreds of Watts should be scalable if more pump power is used, and near FTL compressed pulse duration could be achieve by accurate design GDD and TOD in CFBG. Our results in this work show great potential in many applications such as scientific researches, high precision micromachining, and medical surgery.

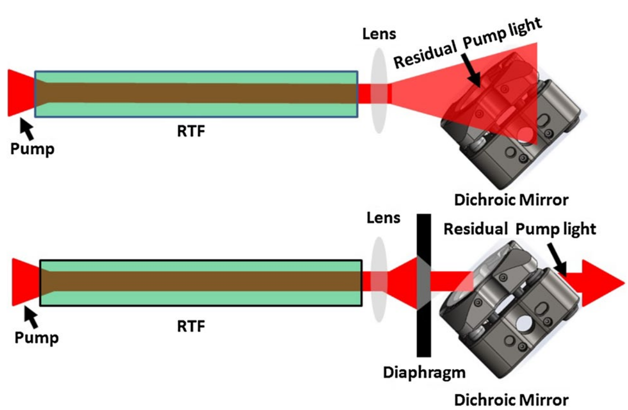

Fig. 5 Structure of the diaphragm and its working diagram

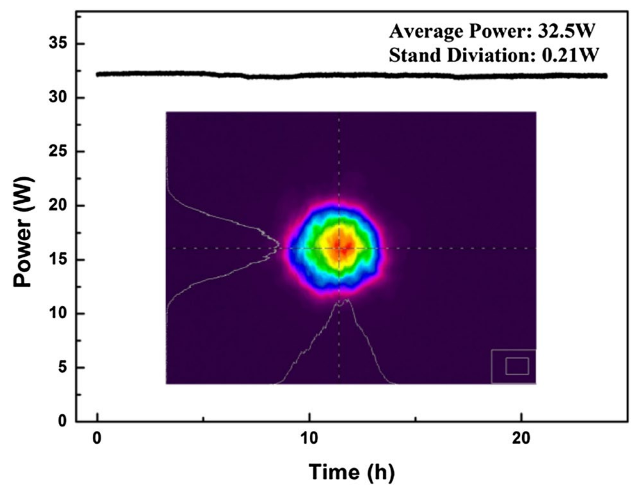

Fig. 6 Measured power stability, M^2 value and beam profile of this FCPA system

Acknowledgements This work is partially supported by the National Key Scientific Instrument and Equipment Development Project of China under Grant No. 2012YQ12004701, National Key R&D Program of China under Grant No. 2017 YFC0110301, and National Natural Science Foundation of China under Grants Nos. 11474002, 11674386, 61575219.

References

1. Y. Sotsuka, S. Nishimoto, T. Tsumano, K. Kawai, H. Ishise, M. Kakibuchi, R. Shimokita, T. Yamauchi, S. Okihara, Lasers Med. Sci. **29**, 1125 (2014)
2. G.D. Sucha, J. Bovatsek, A. Arai, Proc. SPIE Int. Soc. Opt. Eng. **5714**, 63 (2005)
3. A. Ancona, F. Röser, K. Rademaker, J. Limpert, S. Nolte, A. Tünnermann, Opt. Express **16**, 8958 (2008)
4. C. Gohle, T. Udem, J. Rauschenberger, M. Herrmann, in Cleo/ europe. 2005 Conference on Lasers and Electro-Optics Europe, (2005), p. 408
5. M. Krebs, S. Hädrich, S. Demmler, J. Rothhardt, A. Zaïr, L. Chipperfield, J. Limpert, A. Tünnermann, Nat. Photon. **7**, 555 (2013)
6. T. Schreiber, C.K. Nielsen, B. Ortac, J. Limpert, A. Tünnermann, Opt. Lett. **31**, 574 (2006)
7. J. Limpert, F. Roser, S. Klingebiel, T. Schreiber, C. Wirth, T. Peschel, R. Eberhardt, A. Tunnermann, IEEE J. Sel. Top. Quantum Electron. **13**, 537 (2007)

8. Z. Zhao, Y. Kobayashi, Appl. Phys. Express **9**, 012701 (2015)
9. W. Liu, D.N. Schimpf, T. Eidam, J. Limpert, A. Tünnermann, F.X. Kärtner, G. Chang, Opt. Lett. **40**, 151 (2015)
10. Z.G. Lv, H. Teng, L.N. Wang, J.L. Wang, Z.Y. Wei, Chin. Phys. B **25**, 364 (2016)
11. Y. Liu, W. Li, D. Luo, D. Bai, C. Wang, H. Zeng, Opt. Express **24**, 10939 (2016)
12. F.R. Ser, D. Schimpf, O. Schmidt, B. Orta, K. Rademaker, J. Limpert, A. Tünnermann, Opt. Lett. **32**, 2230 (2007)
13. A. Vogel, J. Noack, G. Hüttman, G. Paltauf, Appl. Phys. B **81**, 1015 (2005)
14. H. Song, B. Liu, Y. Li, Y. Song, H. He, L. Chai, M. Hu, C. Wang, Opt. Express **7**, 7559 (2017)
15. A. Tünnermann, D.N. Schimpf, E. Seise, J. Limpert, Opt. Express **17**, 4997 (2009)