

# 240 W narrow-linewidth Yb-doped double-cladding fiber amplifier operated in the 100-ps pulse regime

Yaoyao Qi<sup>1,2,3</sup> · Haijuan Yu<sup>1,2,3</sup> · Jingyuan Zhang<sup>4</sup> · Shuzhen Zou<sup>1,2,3</sup> · Ling Zhang<sup>1,2,3</sup> · Chaojian He<sup>1,2,3</sup> · Zhangwang Miao<sup>1,2,3</sup> · Xuechun Lin<sup>1,2,3</sup>

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**Abstract** High average power picosecond (~ 100 ps) lasers with narrow-linewidth are in great demand for some specific applications. In this paper, a 240 W Yb-doped double-cladding fiber amplifier system at 1064 nm delivering 112 ps pulses at 40 MHz repetition rate was demonstrated. To prevent possible double-cladding fiber damage, a bandwidth-limited (0.1 nm) fiber Bragg grating (FBG) was used to force a stretched pulse-width of 72 ps and a narrow-linewidth of 23 pm. The laser pulses were then stretched to ~ 100 ps after dispersion management and amplified without notable spectral distortion by nonlinear management. The output of the amplifier produces a pulsed energy of 6  $\mu\text{J}$ , which corresponds to a peak power of 54 kW. The  $M^2$  factor was measured to be about 1.2 at the maximum power of 240 W. The spectral width was 0.45 nm after the power amplification. Further power-scaling was only limited by available pump power.

## 1 Introduction

High average power fiber laser sources with ~ 100 ps-scale pulse duration and narrow spectral linewidth are of great interest for a variety of applications, such as, nonlinear frequency conversion, pulsed time-of-flight (TOF) distance measurement, shock ignition, micro-machining and nonlinear micro-spectroscopic [1–6]. For the nonlinear frequency conversion application, the narrow linewidth can effectively avoid the walk-off effect and the temporal broadening ps pulses would avoid the damage of coating on the crystals in the process of high power nonlinear frequency conversion [1]. While for TOF distance measurement, to reach centimetre-level measurement accuracy and precision within a wide measurement range in a short measurement time, eventually in a single shot, the laser pulse width needs to be of the order of about 100 ps [2, 3]. At the same time, nonlinear micro-spectroscopic imaging applications such as CARS strongly profit from such 100-ps scale pulses with narrow spectral width, since the narrow bandwidth and the wide pulse width enables a high spectral resolution and minimizes parasitic pulse distortion due to dispersion [6].

All of the papers have indicated that such a ~ 100 ps narrow-linewidth laser pulse with an output energy of ~  $\mu\text{J}$  (or higher) is in pressing need. Ytterbium-doped fiber amplifiers (YDFAs) have been recognized as an effective way to generate high-power ultra-short pulse laser because of their high single-pass gain, very high optical-to-optical efficiency, diffraction-limited beam quality and the efficient heat dissipation owing to its large surface-to-active-volume ratio [7–10]. However, in the ps pulse regime, nonlinear effects such as self-phase modulation (SPM) and stimulated Raman scattering (SRS) arising in the active core has become more pronounced with the increase of the peak power intensity and the fiber length, thus they have restricted average power

✉ Xuechun Lin  
xclin@semi.ac.cn

<sup>1</sup> Laboratory of All-solid-state Light Sources, Beijing Engineering Research Center, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China

<sup>2</sup> Beijing Engineering Technology Research Center of All-Solid-State Lasers Advanced Manufacturing, Beijing 100083, China

<sup>3</sup> College of Materials Science and Opto-Electronic Technology, University of Chinese Academy of Sciences, Beijing 101407, China

<sup>4</sup> Department of Physics, Georgia Southern University, Statesboro, GA 30460, USA

obtained from DCF fiber amplifiers to hundreds of watts in the present study [11–13].

A general way for simultaneously mitigating most nonlinear effects is to reduce the intensity of the light in the fiber core. This can be achieved by increasing the core diameter, but it would result in multimode light propagation and the deterioration of the beam quality. For example, in 2006, an ytterbium-doped fiber amplifier chain seeded by a gain-switched laser diode at 1060 nm produced 321 W of multimode output ( $M^2 = 2.4$ ) [14]. So the most effect way to suppress nonlinear effects under the precondition of the fundamental mode operation is to decrease the peak power by increasing the repetition rate to hundreds MHz or GHz, it usually achieved by a GHz gain-switched semiconductor laser diode (SLD) or a mode-locked fiber laser with the addition of repetition rate increasing system. For example, in 2012, up to 157 W of diffraction-limited output was demonstrated using a mode-locked fiber laser seeded MOPA at 480 MHz using a repetition rate increasing system [15]. After that, Teh et al. demonstrated a fully fiberized picosecond fiber MOPA system based on a gain-switched SLD oscillator that produced an average output power of 200 W at variable repetition frequencies higher than 206 MHz with a pulse width of 28 ps [16]. Then they extended their earlier work up to a maximum average output power of 513 W (35 ps pulse duration and a corresponding peak power of 68 kW, 2.4 nm linewidth) with the repetition rate of 215 MHz in 2014 [17].

The sub-nanosecond pulse width ( $> 100$  ps) can also improve average output power. In 2015, Chi et al. demonstrated a 100-W 430-ps all-fiber (several nm linewidth) picosecond amplifier using 10/130  $\mu\text{m}$  Yb-doped double-clad fiber with the repetition rate of 22.7 MHz (oscillation pulse width of  $\sim 500$  ps) [18]. Most recently, Ma et al. reported an average power of 608 W (pulse width  $\sim 810$  ps, pulse energy  $\sim 60.8$   $\mu\text{J}$ ) all-fiber MOPA architecture seeded by a commercial sub-nanosecond source [19]. Another alternative way to mitigate nonlinear effects in pulsed fiber systems is to stretch the laser pulse in the time domain appropriately by dispersion element. From the specific applications point of view, the 100 picosecond-scale pulse with a narrow linewidth could be an ideal pulse pattern which is needed for the applications mentioned above; hence we employed this strategy in our work.

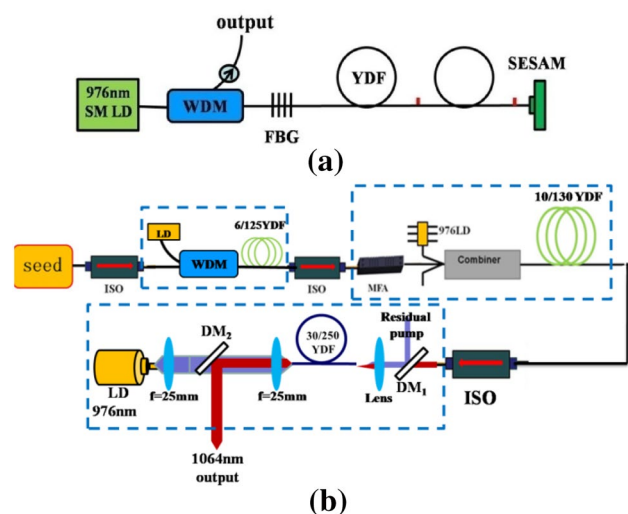
In fact, gain-switched SLD oscillator is easy to obtain with high frequency, but it has many inherent limitations, such as lower output power (which means more amplifier stages), the stronger chirp, larger pulse jitter, and poor frequency spectrum. Heavy as laser frequency of passive mode-locking technology is limited by the cavity length, about tens MHz, but the system is more simple, stable, and cost effective. So for our oscillator, the way to produce largely stretched output pulses with narrow linewidth (keeping a

small time-bandwidth product) was to use a bandwidth-limited (0.1 nm) FBG to generate the seed pulses, whose pulse duration is  $\sim 72$  ps and the linewidth is 23 pm. For our amplifiers, the methods of dispersion management and nonlinear management are adopted simultaneously to achieve higher average power and higher pulse energy. It includes (a) gain partitioning each amplification stages, (b) stretching the pulse duration in the time domain mainly in the first pre-amplification stage to  $\sim 100$  ps, (c) keeping the fiber length (including both active and passive fibers) down to only 4.5 m in the second pre-amplification stage to limit spectral broadening due to the self-phase modulation (SPM), and (d) minimizing the gain fiber length of the main power amplifier stage.

In addition, we bind the fiber into an elliptical shape to eliminate the high-order mode and use an appropriate seeding power for the power amplifier stage to reduce the ASE. Eventually, the main power amplifier yielded 240 W of average power at 40 MHz repetition rate with pulse energy of 6  $\mu\text{J}$ , delivering 112 ps pulses at the maximum output power. The spectral linewidth was only slightly and symmetrically broadened to 0.45 nm after deconvolution from the linewidth of the instrument and it is mainly due to SPM. To the best of our knowledge, this is the first reported high power  $\sim 100$  ps narrow-linewidth laser source for many applications above.

## 2 Experimental setup

The experimental setup of the proposed high-power picosecond laser is schematically shown in Fig. 1, which was constructed in a three-stage MOPA configuration. As Fig. 1a



**Fig. 1** a Schematic setup of the all-fiber picosecond oscillator. b Schematic diagram of the high-power picosecond fiber amplifier

shows, the fiber laser seed was passively mode locked by a semiconductor saturable absorber mirror (SESAM), which worked as one of the cavity mirrors in the 2.5 m long linear cavity. The SESAM has a modulation depth of 25%, non-saturable loss of 15%, relaxation time of 500 fs, and a saturation fluence of  $300 \mu\text{J}/\text{cm}^2$ . To force a temporal broadening of Gaussian-shaped pulse and the more narrow linewidth spectrum, a fiber Bragg grating (FBG) at a center wavelength of 1064 nm with a 3 dB bandwidth of 0.1 nm and a reflectivity of 24.5% worked as another cavity mirror in the linear cavity. Because the gain bandwidth and the reflectance spectral band-width of the SESAM was too wide ( $> 40$  nm) to limit the spectral bandwidth of the mode-locked pulse, the narrow-bandwidth uniform FBG was used as a spectral filter to balance the nonlinearity induced spectral broadening effect and stabilize the mode-locking. A three-stage ytterbium-doped fiber amplifier chain was employed for further power scaling by gain partition to suppress nonlinear effects and ASE, as shown in Fig. 1b.

In the first stage of the preamplifier, a long passive fiber was used to stretch the pulse width. After single-end pumped by a pigtailed single-mode laser diode (LD) (with central wavelength at 975 nm and maximal power of 480 mW) through a wavelength division multiplexing (WDM), the pump-stripped output power of the amplifier was controlled to be 80 mW in the later work. A fiberized isolator (ISO) and a homemade all-fiber mode field adaptor (MFA) were used to efficiently couple picosecond pulses to the next stage preamplifier. The second-stage YDFA comprised a 2.5 m long cladding-pumped gain fiber with a relatively large core diameter of 10  $\mu\text{m}$ , core NA of 0.08 and an inner-cladding diameter of 130  $\mu\text{m}$  with 0.46 NA. The gain fiber was co-directionally pumped by a 10 W, multimode (MM) pump diode at 975 nm through a fiberized  $(2 + 1) \times 1$  MM pump combiner. The length of matched passive fibers was reduced to only 2 m to suppress nonlinear effects such as SPM. A pigtailed isolator is connected after each stage to block off the backward power in the following amplified stages, which can be used to ensure the safety of the whole MOPA configuration.

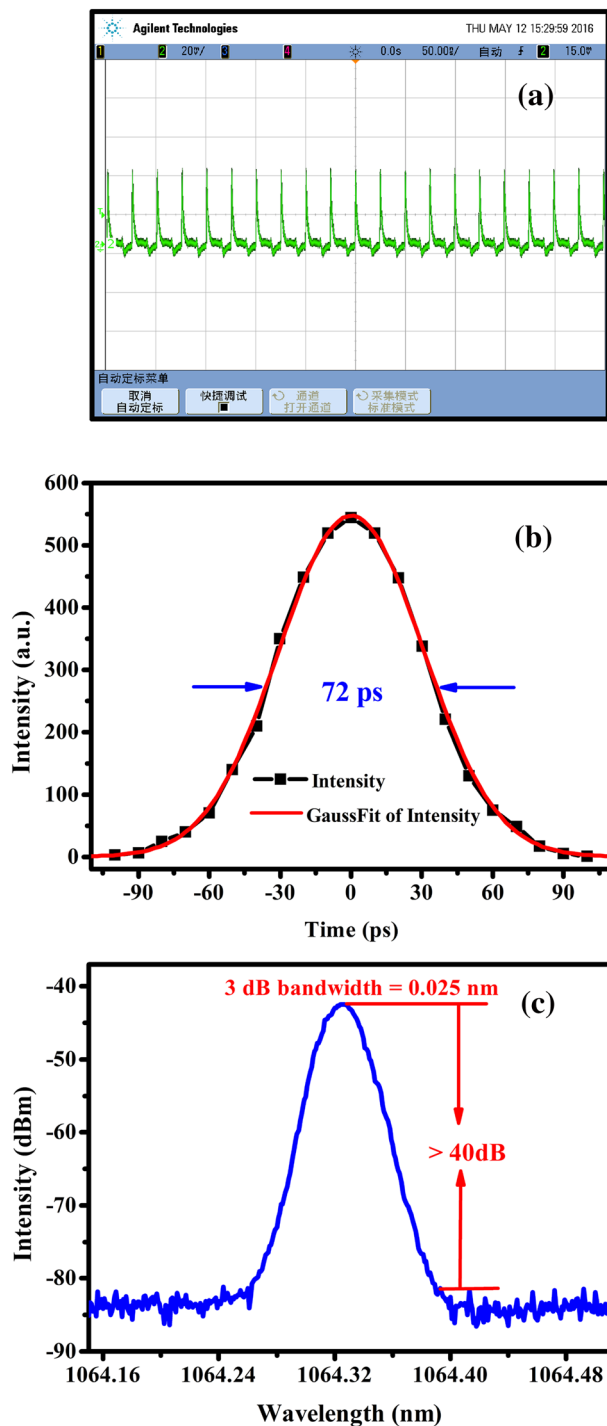
The output of the second-stage preamplifier was then coupled into the final-stage amplifier, which comprised a 3-m long LMA fiber (Nufern LMA-YDF-30/250-HI-8) with diameter parameter of 30/250  $\mu\text{m}$  ( $\text{NA} = 0.06/0.46$ ). The V-number of the core was 5.3, which means that, in theory, the core can support approximately 7 modes, such as  $\text{LP}_{01}$ ,  $\text{LP}_{11}$ ,  $\text{LP}_{21}$ ,  $\text{LP}_{02}$ . The gain fiber was coiled into an elliptical shape in the air to filter out the high-order transverse modes. In this case, the introduced bending loss allows only the fundamental mode to be guided through and amplified [20]. The fiber port adjacent to the laser diode (LD) pump launched side was cleaved at an angle of  $8^\circ$  to suppress the feedback of the broadband ASE in the high-power fiber

amplifier and hence the parasitic lasing between the fiber-end facets. The power amplifier was pumped backward by a 976-nm LD with a 220- $\mu\text{m}$  core diameter and 0.22 NA using free-space coupling. The amplified output was selected by a dichroic mirror  $\text{DM}_2$  [high transmission (HT) at 976 nm and high reflectivity (HR) at 1064 nm], while the residual pump power rejected by a dichroic mirror  $\text{DM}_1$  (HR at 976 nm and HT at 1064 nm).

### 3 Experimental results and discussion

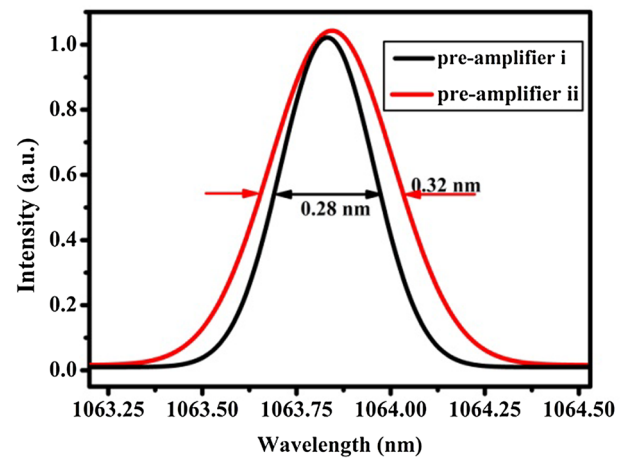
In our experiment, stable self-started continuous-wave mode-locked (CWML) optical pulses occurred at 107 mW incident pump power. The fiber oscillator generated stable nearly transform-limited picosecond pulses with a repetition rate of 40 MHz is presented in Fig. 2a. With the incident pump power of 122 mW, the average output power of the passively mode-locked fiber oscillator was 20 mW. The pulse duration was measured by an autocorrelator (APE-150), the full width at half maximum (FWHM) of the pulses from the fiber laser seed was 72 ps (see Fig. 2b). Figure 2c shows the optical spectrum of the passively mode-locked Yb-doped fiber oscillator, which was measured by an optical spectral analyzer (Advantest Q8384) with a resolution of 0.01 nm. The spectrum has a smooth bell shape which exhibits a high peak-to-background separation of about 40 dB, indicating that the mode-locked state was stable. The central lasing wavelength of the fiber oscillator was around 1064.3 nm, which was the same as the resonant peak of the FBG. At room temperature, the central output wavelength of the master oscillator was 1063.8 nm and the measured output wavelength of 1064.3 nm was obtained by heating up the FBG to about  $50^\circ\text{C}$ . Assuming a Gaussian-shape spectral profile for the oscillator, the measurement indicates the 3 dB bandwidth was 0.025 nm at 1064.3 nm. Taking into account the 0.01-nm spectral resolution of the system, it corresponds to a 3 dB bandwidth of 0.023 nm after deconvolution. As SPM spectral broadening is kept relatively low for the short cavity due to the long pulse duration, in turn, the temporal stretching also remains moderate as consequence of the narrow spectral width. Hence, the time–bandwidth product (TBP)  $\Delta\nu \cdot \tau_p$  is very moderate with the value of 0.441, which indicates that the mode-locked pulses are nearly transform-limited.

To get  $\sim 100$  ps scale pulse duration and decrease the detrimental nonlinear effects in the fiber of the main power amplifier, a long total silica-based 6/125  $\mu\text{m}$  matched passive (1060-XP) fiber having a mean positive group velocity dispersion (GVD) of about  $+25 \text{ ps}^2/\text{km}$  at 1  $\mu\text{m}$  wavelength was used in the pre-amplifiers. The 20 mW average output powers from the seeder was amplified to 80 mW under a moderate gain extracted from the first



**Fig. 2** **a** Pulse train of the passively mode-locked Yb-doped fiber oscillator. **b** Pulse duration from the ps seed source. **c** Output spectrum of the passively mode-locked Yb-doped fiber oscillator

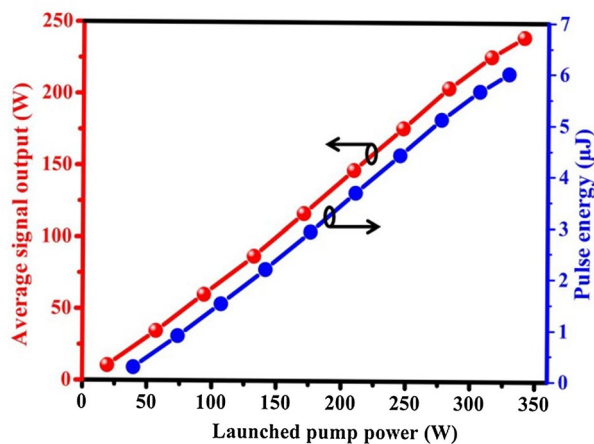
stage preamplifier. The average power after the second-stage cladding-pumped preamplifier was measured to be 1 W when the pump power was 3 W. All the fibers of the preamplifiers have elongated the laser pulse from the original nearly transform limited duration of  $\sim 72$  ps up



**Fig. 3** Output spectrum measured by the optical spectral analyzer system after the first stage pre-amplifier and the second-stage pre-amplifier

to about 100 ps. This gain partitioning scheme ensured the minimum spectral broadening and maximum optical signal to noise ratio without ASE before seeding into the main power amplifier stage. Figure 3. shows the spectra of the pulses after pre-amplifier-I and pre-amplifier-II, which were measured by an optical spectral analyzer (AvaSpec 3548-2-USB2) with a resolution of 0.2 nm. The gain peak of the two stages pre-amplifiers was optimized consonant with the central wavelength of seed laser. Due to the self-phase modulation (SPM) in the gain fiber, the spectrum was broadened in pre-amplifier-I and pre-amplifier-II, which are centered at around 1063.8 nm (at room temperature) and has a 3 dB bandwidth of 0.28 and 0.32 nm, respectively. Taking into account the 0.2-nm resolution of the optical spectral analyzer system, the corresponding 3 dB bandwidth was 0.196 and 0.25 nm, respectively, after deconvolution.

In the main power amplifier, after comprehensively taking into account of the factors of optical signal to noise ratio (OSNR), spectral width, output power, and ASE suppression, etc., it was found that a relatively low seeding power is feasible. In fact, as mentioned in [16, 21], Teh et al. pointed out that the improvement of optical signal to noise ratio brought about by the reduction in seeding power to the booster amplifier [16], Chen et al. found that the degree of spectral broadening observed from the power amplifier would be larger when the signal increased [21]. Also, the reduction in the seeding power also increased the amplifier gain, which in turn reduced the effective length of the amplifier. Therefore, we limited the average output power to 700 mW after the second-stage pre-amplifier and finally, in fact, it was found that reducing the seeding power for the final power amplifier to such a level was sufficient to suppress ASE level in the final stage of power amplifier.

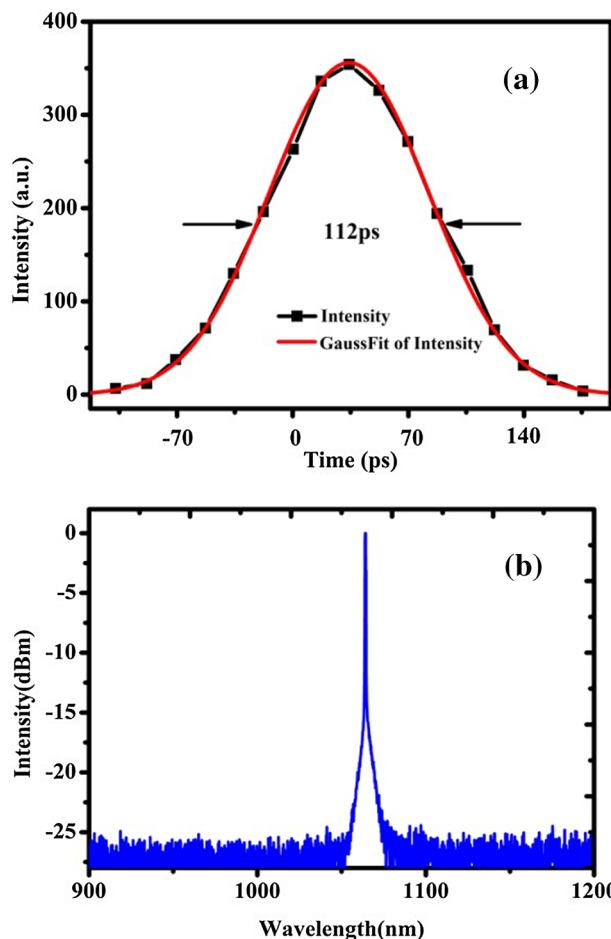


**Fig. 4** Average output power and the pulse energy of the final power amplifier with the increase of incident pump power

As depicted in Fig. 4, the average output power and pulse energy almost linearly increases when increasing the launched pump power of the main amplifier. When the launched pump power is 340 W, the maximum average output power and pulse energy reaches to 240 W and 6 μJ, respectively, and the corresponding optical-to-optical efficiency is 71%. At the present time, the output power is only limited by the available pump power and based on our experience, at least a 350 W output should be possible using the same type fibers and the dispersion and nonlinear-management scheme.

The pulse width at the maximum average power of 240 W is shown in Fig. 5a. It was measured by the autocorrelator (APE SM-1200), and the FWHM was about 112 ps, corresponding to a pulse peak power of 54 kW. Figure 5b shows the output spectra from the main amplifier stage, measured by Anritsu MS9710B spectrometer, the center wavelength is around 1064 nm, and the 3 dB spectral bandwidth was < 0.5 nm. Neither obvious ASE nor stimulated Raman scattering (SRS) can be observed in the amplification process. The 1064-nm signal peak was about 30 dB above the peak of the background amplified spontaneous emission, and therefore, there is no need to have a mid-stage spectral filtering to improve the spectral quality. The SRS threshold of the 30/250 μm LMA fiber was estimated to be 76-kW peak power based on the diameter of our fiber and, as expected, SRS was not observed even at the maximum power.

We also investigated the spectral broadening in the power amplifier. Figure 6a shows the 3 dB spectral bandwidth as a function of signal output power, while Fig. 6b shows output spectrum measured by the optical spectral analyzer system at 100 and 240 W output power, respectively. The center wavelength is around 1063.8 nm, the spectral linewidth is measured to be 0.37 nm at 100 W and 0.5 nm at 240 W. In fact, the linewidth at two outputs correspond to 0.31 and 0.45 nm after

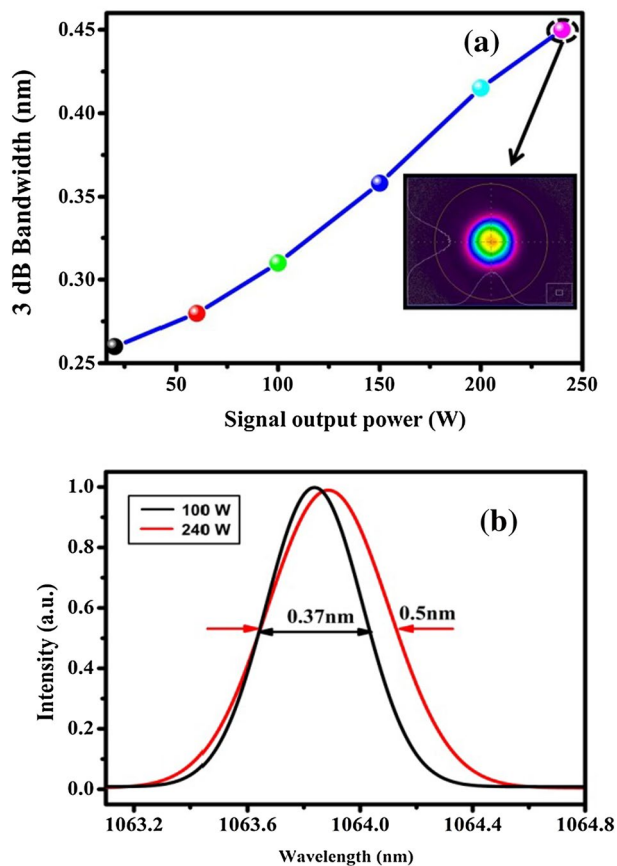


**Fig. 5** **a** Pulse duration of the main power amplifier. **b** Optical spectrum obtained from amplifier at output power of 240 W

deconvolution from the bandwidth of the instrument. There is slightly spectral broadening when the pulse power and energy are scaled up, which can be attributed to the increased nonlinear effects induced by high peak power density, such as self-phase modulation (SPM), as it plays a dominating role in the symmetrical spectral broadening. The dispersion length  $L_D$  and the nonlinear length  $L_{NL}$  provide the length scales over which dispersive or nonlinear effects become important for pulse evolution. The dispersion length  $L_D$  of the main amplifier can be calculated to be about  $L_D = T_0^2/|\beta_2| = 357$  km, and the nonlinear length is about  $L_{NL} = 1/\gamma P_0 = 21$  m. The length of main amplifier is 3 m, so that we have  $L \ll L_D$  and  $L \approx L_{NL}$ , the dispersion is negligible compared to the nonlinear effect.

Assuming that the active fiber length of the fiber amplifier is  $L_g$  and the passive fiber length is  $L_p$ , the maximum nonlinear phase shift (B-integral)  $\phi_{max}$  induced by SPM can be calculated by the following:

$$\phi_{max} = \phi_{max}^g + \phi_{max}^p = \gamma(w_0)P_0\{[\exp(gL_g) - 1]/g + [\exp(gL_g)L_p]\}. \tag{1}$$



**Fig. 6** **a** Measured 3 dB spectral bandwidth of the final fiber power amplifier as a function of signal output power and the far field beam profile at the maximum output power level. **b** Optical spectrum measured from amplifier at output power of 100 and 240 W, respectively

In this formula,  $\phi_{\max}^g$  and  $\phi_{\max}^p$  represent the maximum nonlinear phase shift accumulated in the active and passive fiber, respectively,  $\gamma(w_0)$  is the nonlinear parameter, which can be calculated from:

$$\gamma(w_0) = \frac{n_2 w_0}{c A_{\text{eff}}} \quad (2)$$

where  $n_2$  is the nonlinear index parameter of the fiber with a typical value of  $2.2\text{--}3.4 \times 10^{-20} \text{ m}^2/\text{W}$ . From the above equation, it can be deduced that the  $\gamma(w_0)$  can be calculated using the effective fiber area,  $A_{\text{eff}}$ , and the operating wavelength.  $P_0$  is the peak power of the input pulses and  $g$  is the gain coefficient [22]. The nonlinear parameter is calculated to be  $0.3 \text{ W}^{-1}\text{km}^{-1}$  and the gain coefficient is estimated to be  $1.35 \text{ m}^{-1}$ , so that the B-integral accumulated in the main amplifier at 240 W is about 1.97 radians at maximum peak power of 54 kW. The output spot was always maintained as good  $\text{TEM}_{00}$  fundamental mode during the amplification of this picosecond fiber laser and the  $M^2$  factor was measured

to be about 1.2 at the maximum power of 240 W. A high quality beam is critical for tight focusing.

## 4 Conclusion

In summary, we have demonstrated a 112 ps, 240 W narrow-linewidth pulse source with 40-MHz repetition rate based on an ytterbium-doped DCF amplifier chain seeded by an all-fiber passively mode-locked ytterbium-doped laser at 1064 nm. The  $\sim 100$  ps pulse enabled the generation of high average power while maintaining high peak power in excess of 54 kW, without obvious ASE and other nonlinear effects in the fiber amplifier. The spectral linewidth at 240 W is only 0.45 nm. The  $M^2$  factor was measured to be about 1.2 at the maximum power of 240 W. Since the output power was only limited by available pump power, we believe that further power-scaling is possible with the current configuration. This kind of high average power, narrow-linewidth, hundred picoseconds source provides an attractive tool for many applications.

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## References

1. Q. Liu, X.P. Yan, M.L. Gong, X. Fu, D.S. Wang, *Opt. Express* **16**, 14335–14340 (2008)
2. L.W. Hallman, K. Haring, L. Toikkanen, T. Leinonen, B.S. Ryvkin, J.T. Kostamovaara, *Meas. Sci. Technol.* **23**, 025202 (2012)
3. J. Huikari, E. Avrutin, B. Ryvkin, J. Kostamovaara, *Opt. Rev.* **23**, 522–528 (2016)
4. R. Betti, C.D. Zhou, K.S. Anderson, L.J. Perkins, W. Theobald, A.A. Solodov, *Phys. Rev. Lett.* **98**, 155001 (2007)
5. X. Chen, X. Liu, *J. Laser Appl.* **11**, 268–272 (1999)
6. M. Baumgartl, T. Gottschall, J. Abreu-Afonso, A. Díez, T. Meyer, B. Dietzek, M. Rothhardt, J. Popp, J. Limpert, A. Tünnemann, *Opt. Express* **20**, 21010–21018 (2012)
7. J. Nilsson, D.N. Payne, *Science* **332**, 921 (2011)
8. M.N. Zervas, C.A. Codemard, *IEEE J. Sel. Topics Quantum Electron.* **20**, 0904123 (2014)
9. C. Jauregui, J. Limpert, A. Tünnemann, *Nat. Photon.* **7**, 861 (2013)
10. D.J. Richardson, J. Nilsson, W.A. Clarkson, *J. Opt. Soc. Am. B* **27**, B63 (2010)
11. H.L. Yu, P.F. Ma, R.M. Tao, X.L. Wang, P. Zhou, J.B. Chen, *Laser Phys. Lett.* **12**, 065103 (2015)
12. D. Jain, S. Alam, C. Codemard, Y. Jung, M.N. Zervas, J.K. Sahu, *Opt. Lett.* **40**, 4150 (2015)
13. Z.H. Yu, W. Shi, X.Z. Dong, J.H. Li, Y.Z. Zhao, H.X. Liu, *Appl. Opt.* **55**, 4119 (2016)
14. P. Dupriez, A. Piper, A. Malinowski, J.K. Sahu, M. Ibsen, B.C. Thomsen, Y. Jeong, L.M.B. Hickey, M.N. Zervas, J. Nilsson, D.J. Richardson, *IEEE Photonics Technol. Lett.* **18**, 1013 (2006)

15. R. Song, J. Hou, S. Chen, W. Yang, Q. Lu, *Appl. Opt.* **51**, 2497 (2012)
16. P.S. Teh, R.J. Lewis, S.U. Alam, D.J. Richardson, *Opt. Express* **21**, 25883 (2013)
17. P.S. Teh, S.U. Alam, R.J. Lewis, D.J. Richardson, *Laser Phys. Lett.* **11**, 085103 (2014)
18. J.J. Chi, P.X. Li, B.X. Liang, Y.F. Yao, H.W. Hu, G.J. Zhang, M.M. Zhang, *Appl. Phys. B* **3**, 369 (2015)
19. P. Ma, R. Tao, L. Huang, X. Wang, P. Zhou, Z. Liu, *J. Opt. Soc. Am. B* **17**, 075501 (2015)
20. J.P. Koplow, D.A.V. Kliner, L. Goldberg, *Opt. Lett.* **25**, 442 (2000)
21. H.W. Chen, Y. Lei, S.P. Chen, J. Hou, Q.S. Lu, *Appl. Phys. B* **109**, 233 (2012)
22. G.P. Agrawal, *Nonlinear fiber optics* (Academic Press, London, 2007)