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Fabrication of 16 W all-normal-dispersion mode-locked Yb-doped rod-type fiber laser with large-mode area*

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A mode-locked ytterbium-doped rod-type fiber laser with 85 μm core diameter is developed based on the nonlinear polarization evolution in an all-normal-dispersion ring cavity, in which a uniaxial birefringent plate is used as the spectral filter. Average power up to 16 W is obtained at the repetition rate of 58 MHz, and the pulse duration is compressed to 182 fs with a grating-pair compressor. The output laser pulses show very good beam quality and power stability.

Keywords: diode pump, rod-type fiber, femtosecond mode-locking

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1. Introduction

Recently, rapid developments on high power mode-locked thin-disk and fiber lasers at high repetition rates have been achieved for wide scientific and industrial applications. In particular, the high power fiber laser is gradually becoming one of the dominant lasers in the ultra-short pulse laser systems due to its excellent heat dissipation, high single pass gain, diffraction limited beam quality, and broader bandwidth than the thin-disk and bulk solid state lasers.[1–10]

In fiber lasers, large-mode-area photonic crystal fibers (LMA-PCF) have been widely used to generate the higher power so as to meet a wide range of applications. For example, in 2014, Zeng *et al.* reported the generation of 80 W 38 fs laser pulse by use of the LMA-PCF with 40 μm core diameter and 200 μm inner cladding diameter to drive the generation of high power XUV frequency comb.[11] Compared to the general LMA-PCF, the rod-type PCF has become increasingly interesting due to the substantive characteristics of higher peak power damage threshold and lower bending loss from the rigid structure, which is widely used for the generation of the high power femtosecond lasers.[8–10] Secondly, as a novel paradigm, the all-normal-dispersion (ANDi) fiber scheme based on the chirped pulse spectral filtering has been widely employed for the generation of the high energy ultrashort pulses without pulse breakup due to the advantage of the removal of the anomalous-dispersion segment. To combine the advantages of the rod fiber and the ANDi scheme, compact high average power rod-type fiber mode-locked ANDi lasers have been demonstrated in recent years using SESAM and nonlinear polarization rotation technique.[12–14] The highest average power achieved from the mode-locked ANDi fiber laser to date has reached 66 W with an 80 μm core diameter rod-type fiber as the key component for gain and spectral broadening, in which a two-stage filter was employed as the modulation component to provide a sufficient pulse shaping mechanism.[15] However, the specific parameters on the long term power stability and the beam quality factors during the mode-locked operation were not discussed in detail in that work.

In this paper, we report an experimental study on the nonlinear polarization evolution (NPE) based passively mode-locked Yb-doped rod-type fiber laser with a single-stage birefringent plate as the spectral shaper in an ANDi ring cavity configuration rather than a two-stage filter. Compared to the experimental scheme in Ref. [15], the present experiment setup is more concise and compact in structure. Mode-locked laser pulses with durations as short as 182 fs are obtained at a repetition rate of 58 MHz. The maximum average output power is 16 W at the central wavelength of 1033 nm. The power stability and the beam quality are also measured, and excellent power stability and robust fundamental mode operation are demonstrated.

2. Experiment and discussion

The high power NPE-based passively mode-locked fiber laser is constructed in a backward-pumped ring cavity configuration around a 1.2 m long very large mode area (VLMA) rod-type fiber with a 22 dB cladding absorption at 976 nm,

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as shown in Fig. 1. By comparison with the previous rod-type fibers employed in the high power mode-locked fiber lasers,[12–15] the available double clad rod fiber implemented in this work provides a much larger gain core size with a diameter of 85 μm, which provides the potential for higher power operation. Around the signal core, the carefully dimensioned air-holes are embedded, which form a 260 μm pump core with a high pump cladding numerical aperture (NA ≥ 0.5). Considering the practicability of the rod fiber and to keep the rod straight along the full length, we tightly mount the gain fiber in a 120 cm long aluminum block with a V-groove, which is cooled down to 18 °C by circulating water for efficient heat dissipation under high power operation. Simultaneously, for the efficient suppressions of the end facet damage and the parasitic feedback from the amplified spontaneous emission (ASE), two $\sim 3°$ anti-refection (AR) coated end-caps are spliced to both fiber ends with dimensions ($D \times L$) of 6 mm $\times$ 5 mm. By consideration of the parameters of the available aspherical lens and rod-type fiber, a high-brightness diode laser, which emits 976 nm light out of a 200 μm multimode fiber with an NA of 0.22, is used as the pump laser.

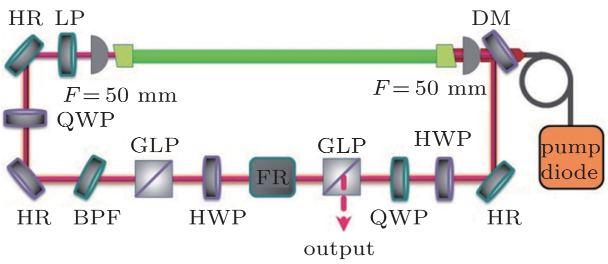

Fig. 1. (color online) Schematic of the rod-fiber based ANDi laser (DM: dichroic mirror, LP: long pass mirror, HR: high reflective mirror, QWP (HWP): quarter (half) wave plate, BPF: birefringent plate filter, GLP: Glan laser polarizer, FR: Faraday rotator).

The pump laser is first collimated through an aspherical lens with a focal length of 40 mm, then passes through a set of dichroic mirrors, which consists of four low-pass mirrors to protect the pump diode from damage coming from the oscillating ultrashort laser pulses, and finally the multimode 976 nm pump light is coupled into the rod fiber via a 50 mm focal length aspherical lens. For the residual unabsorbed pump light, we conduct a dumping treatment utilizing a long pass mirror, as shown in Fig. 1. To realize more laser gain, the backward pumping is adopted with a polarization-dependent isolator, which consists of a Faraday rotator, a half-wave plate and two Glan laser polarizers. Its function is to ensure the one-sided communication of the signal in clockwise direction and its first polarizer is treated as the output coupler. In view of the mode-locked mechanism for the all-normal dispersion fiber laser, a single-stage birefringence filter with a narrow spectral filtering bandwidth of 8.6 nm is introduced to chirp the pulses in the spectral domain. Due to the normal dispersion introduced into the laser cavity, the temporal width is also reduced accompanied by the narrowing of the spectrum, which in turn motivates more intense nonlinear effects to generate wider spectrum components to assist mode-locking.

Due to the ultra-large gain core and the corresponding low nonlinear phase accumulation in the signal core, to reach the threshold of the self-phase modulation (SPM) and start NPE-based mode-locking, a high enough peak power is of the essence. For a 22 W maximum CW output power, the stable self-starting mode-locking could be obtained by adjusting the orientations of the waveplates. For this configuration, the extracted highest average power from the mode-locked domain is 16 W at the repetition rate of 58 MHz, which corresponds to the highest pulse energy of ~ 0.28 μJ extracted from the fiber laser. The output power is mainly limited by the pump power provided by the 976 nm diode laser, which has a maximum 53 W output.

The radio frequency (RF) spectra monitored with a photodiode and a frequency spectrum analyzer (Agilent E4407B) are shown in Fig. 2. The RF spectra exhibit a high peak-to-pedestal extinction (~ 73 dB) and a high stability during the mode-locking operation. Once the mode-locking is built, the mode-locked high power rod fiber laser is stable for several hours, and when the laser is switched off and on, a reproducible state is demonstrated.

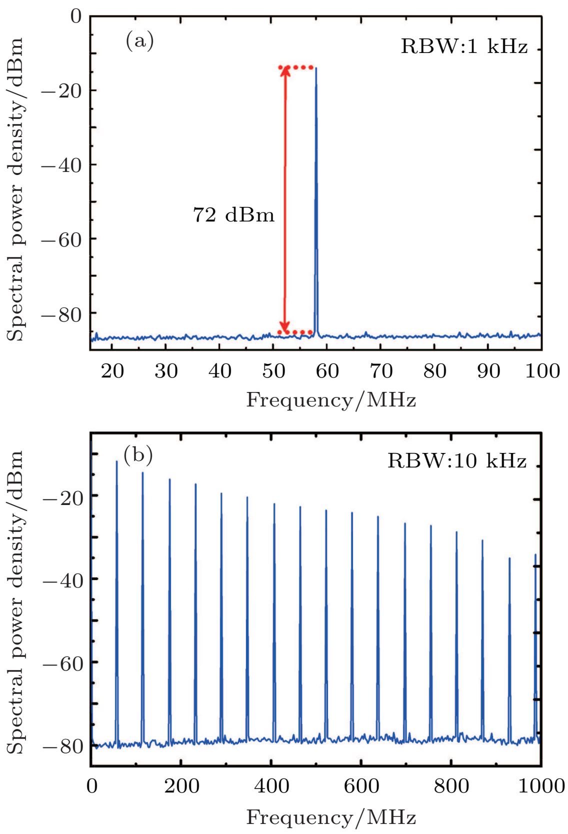

Fig. 2. (color online) Stable rod-fiber mode locking results. (a) RF spectrum with 1 kHz resolution. (b) RF spectrum with 1 GHz span.

The output laser has a broadened M-like spectral shape with multi-peak structure, which is a typical characteristic of the SPM. The obvious steep edges are originating from the combined effects of the SPM nonlinear spectral broadening and the introduced dissipation mechanism from the spectral filtering. The estimated nonlinear phase accumulation during the mode-locked operation is 5.5 π extrapolated from the measured optical spectrum, as presented in Fig. 3. The central wavelength is 1033 nm and the spectral bandwidth is 17.3 nm.

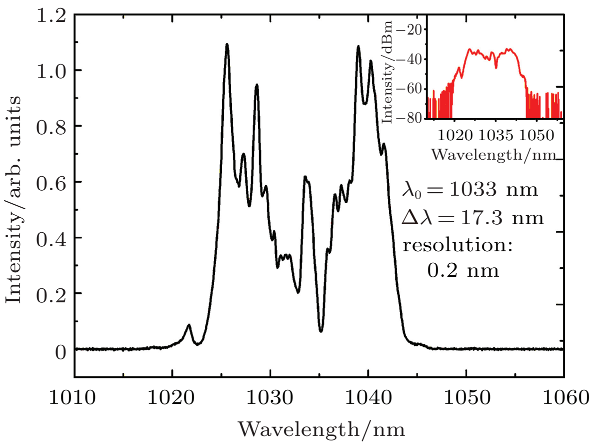

Fig. 3. (color online) Mode-locked optical spectrum on linear scale. Inset shows the counterpart on logarithmic scale.

The inset of Fig. 4 shows the measured positively chirped pulse duration directly from the mode-locked fiber laser and a 3.7 ps temporal span is obtained using a commercial intensity autocorrelator. In this case, the calculated positive chirp is approximately 0.08 ps^2, and it can be compensated by optics with anomalous dispersion. For this reason, a pair of transmission gratings with a line density of 1000 lines/mm are employed for compression with an incidence angle of 30°. The shortest pulse duration achieved after the compressor is 182 fs (full width at half maximum), as shown in Fig. 4. The stairs around the central peak are attributed to the uncompensated higher-order phase, which is mainly from the contribution of the SPM. Simultaneously, the long-term power stability for 1 hour is measured by using a power meter with a maximum tolerance power of 30 W (COHERENT PM30, USA), and the obtained power fluctuation is better than 0.3% (root mean square, RMS), as shown in Fig. 5, which shows a high tolerance for disturbance from the surrounding environment.

Finally, to have a comprehensive understanding for the performance parameters of the mode-locked rod-type fiber laser, the beam quality factors M^2 are also measured by a commercial beam analyzer (Spiricon, M2-200s-FW). Although the fundamental mode assisted mode filter has not been installed in this cavity, as shown in the inset of Fig. 6, a robust fundamental mode TEM_{00} operation is demonstrated and the corresponding beam quality factors M^2 are 1.1 and 1.3 for the horizontal and the vertical directions respectively, which show the lesser divergence of the mode-locked laser pulses and the diffraction limited mode quality.

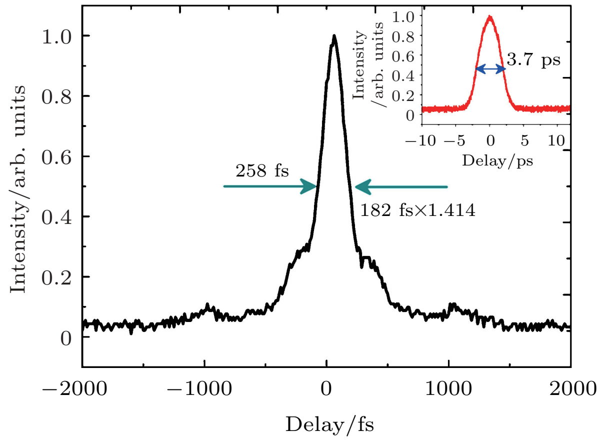

Fig. 4. (color online) Measured intensity autocorrelation traces of the compressed and the uncompressed (inset) output pulses.

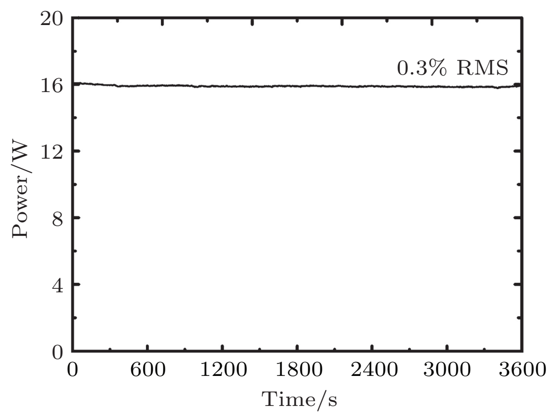

Fig. 5. Laser power long-term stability over 3600 s.

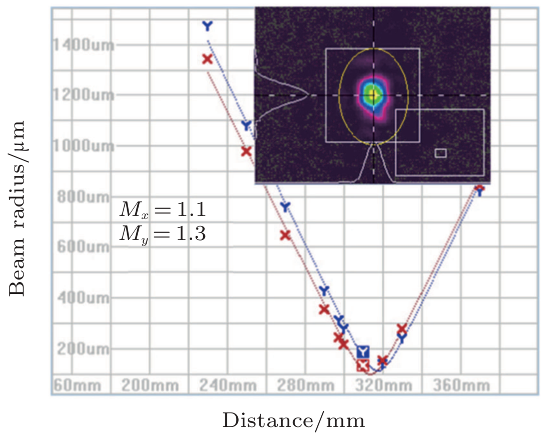

Fig. 6. (color online) The M^2 measurement of the mode-locked pulses from the Glan laser polarizer as the output end. Inset shows the mode-locked beam profile without accompanying of high-order modes.

3. Conclusion

Stable high average power ultra-short laser pulses from a mode-locked NPE-based Yb-doped rod fiber laser in the all normal dispersion domain are obtained. The average power of 16 W with a 53 W pump laser is achieved. The mode-locked laser has a repetition rate of 58 MHz, which corresponds to a pulse energy of 0.28 μJ and the spectrum is centered at 1033 nm with a bandwidth of 17.3 nm. The pulses are compressed to 182 fs using a pair of transmission gratings assuming a Gaussian beam distribution. The measurements of the long term power stability and the beam quality factors show the excellent performance of the mode-locked fiber laser. The laser developed has wide applications such as the generation of XUV source at high repetition rate.

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