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Generation of Broadband Spectrum from a Simple Nonlinear-Polarization-Evolution Mode-Locked Yb-Doped Fiber Oscillator *

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We demonstrate a nonlinear polarization evolution mode-locked Yb-doped fiber oscillator with the broadband spectrum output operating in a dispersion-managed regime. Pumped by a 976 nm single-mode laser diode, stable mode-locked ultrashort pulses are emitted with an average power of 198 mW at a repetition rate of 124 MHz, corresponding to a pulse energy of 1.6 nJ. The output spectrum spans from 950 nm to 1150 nm so that the transform-limited pulse duration is as short as 23 fs. Due to the imperfect dispersion compensation, we compress the pulses to 32 fs in this experiment.

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The pursuit for the generation of a broader spectrum and shorter pulses from a laser oscillator is one of the fundamental interests of ultrafast science.[1−3] Due to their ability to produce stable pulses with a broadband spectrum and high power, Yb-doped fiber oscillators mode-locked by the nonlinear polarization evolution (NPE) technique have attracted much attention in recent decades.[4−9] They have become the ideal seeds in many applications such as frequency metrology, chirped-pulse amplification, attosecond science, nonlinear microscopy, and extreme ultraviolet comb.[10,11]

A broadband spectrum spanning from 950 nm to 1090 nm generated from a mode-locked Yb-doped fiber oscillator was reported by Kurita *et al.* in 2012.[12] They used two 915 nm polarization-maintaining laser diodes (LD) as the pump source. The chirped pulse was compressed to 21.6 fs by an extra-cavity dispersion compensation device. In the same year, Chong *et al.* presented another result that the maximum output spectrum bandwidth approached 200 nm in a self-similar evolution Yb-doped fiber laser pumped by a 980 nm LD, in which strong spectral breathing and elimination of gain-bandwidth limitation were aroused.[3] Parabolic pulses were established in the gain fiber and their spectrum had the structure of a chirped parabolic pulse. After the gain fiber, the spectrum was dramatically broadened in the PCF with a spectral breathing ratio of 27. The pulse width had been de-chirped to about 21 fs by a complicated extra-cavity compressing device. In 2013, Lan *et al.* also showed a broadband spectrum generation from a Yb-doped fiber oscillator pumped by a 975 nm LD.[13] To enhance the intra-cavity spectral breathing effect, a moderate dissipation by a 30 nm bandpass filter was inserted into the cavity. The measured −20 dB output spectrum covered a broad range from 985 nm to 1125 nm, corresponding to a transform-limited pulse duration of about 23.5 fs.

In this Letter, we demonstrate a dispersion-managed Yb-doped fiber oscillator mode-locked by the regular NPE scheme. Pumped by a 976 nm single-mode LD, stable mode-locked pulses were produced with the broadband spectrum spanning 950–1150 nm, corresponding to a transform-limited pulse duration of 23 fs. The average output power reached 198 mW without any signs of soliton fission, which often occurs in such high power cases. The repetition rate was 124 MHz, while the pulse energy is 1.6 nJ. Such a Yb-doped fiber oscillator with the merits of both broadband spectrum and high power will become the ideal seed for amplifiers.

The schematic diagram of the experimental setup is depicted in Fig. 1. The Yb-doped fiber oscillator consisted of a fiber section and free-space section. The free-space section contained a polarization dependent isolator (ISO), a polarization beam splitter (PBS), a pair of 600 lines/mm transmission gratings (TG), two high-reflection mirrors (HR), two quarter-wave plates (QWP), and one half-wave plate (HWP). The fiber section contained a 976 nm single-mode LD with a maximum power of 660 mW (JDSU, S30-7602-660), a wavelength division multiplexer (WDM), two segments of single mode fiber (SMF), two collimators, and a section of highly Yb-doped single cladding fiber with an absorption coefficient of 473 dB/m at 915 nm (Coractive, Yb125). The pump laser was coupled into the ring cavity via the WDM. The ISO ensured the

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unidirectional laser propagation. A set of one HWP and two QWPs were placed in the ring cavity to change the intra-cavity polarization. The lengths of SMF and Yb-doped fiber were about 96 cm and 20 cm, respectively. The GDD and third order dispersion (TOD) of all fibers are about 29000 fs^2 and 46400 fs^3. The total GDD of other optical components except the fibers and TG pair is about 9000 fs^2. The TG pair was placed parallel at the Littrow angle to compensate for the normal cavity GDD introduced by the fibers and other optical components. The net GDD in the cavity was tuned by adjusting the distance between the TG pair.

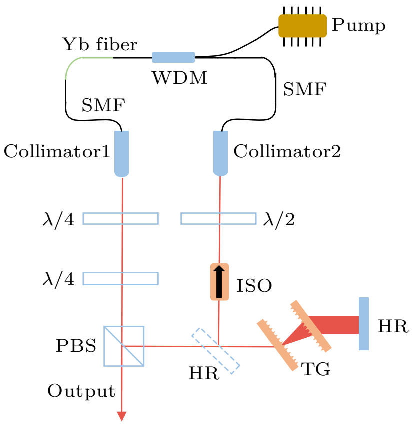

Fig. 1. The schematic diagram of the experimental setup: WDM, wavelength division multiplexer; SMF, single mode fiber; PBS, polarization beam splitter; ISO, polarization dependent isolator; TG, transmission grating; $\lambda/2$, half-wave plate; $\lambda/4$, quarter-wave plate; and HR, high reflection mirror.

Under an average pump power of more than 300 mW, the net cavity GDD was set to a very large negative value, and stable mode-locked pulses were produced easily by rotating the wave plates in the ring cavity. Then the net cavity GDD was set in the range of near-zero by changing the distance between the TG pair to about 17 mm. Increasing the average pump power to 600 mW, the mode-locking state maintained stably. The chirped pulses emitted from the intra-cavity PBS with the repetition rate of 124 MHz. The average output power was 198 mW, corresponding to a pulse energy of 1.6 nJ. As shown in Fig. 3, the repetition rate was measured by a radio frequency analyzer (Agilent E4407B). The signal-to-noise ratio of the fundamental frequency was about 70 dBc with a bandwidth resolution of 100 kHz, which indicated robust mode-locking. In terms of the bandwidth of the output spectrum, according to previous research, the spectrum and the duration of pulses vary as the pulses propagate in the cavity.[14,15] The broadest spectrum is normally produced by the SMF following the active fiber based on the interaction of GVD and the self-phase modulation effect, while the spectrum will be narrowed slightly after passing through the intra-cavity PBS. In our experiment, the output spectrum from the intra-cavity PBS was measured by an optical spectrum analyzer (Yokogawa, AQ-6315 A). It was found that as the pump power increased, the output spectrum was broadened and the broadening to the long-wavelength region was more than that to the short-wavelength region. In our case, due to the damage threshold of optical components, the maximum pump power allowed was only 600 mW. Therefore, the output spectrum was optimized at such a pump power by rotating the wave plates carefully. The broadest spectrum spanned 950–1150 nm at the central wavelength of 1055 nm, as shown in Fig. 2. The −20 dB laser optical spectrum spanned from 984 nm to 1136 nm, corresponding to a transform-limited pulse duration of about 23 fs.

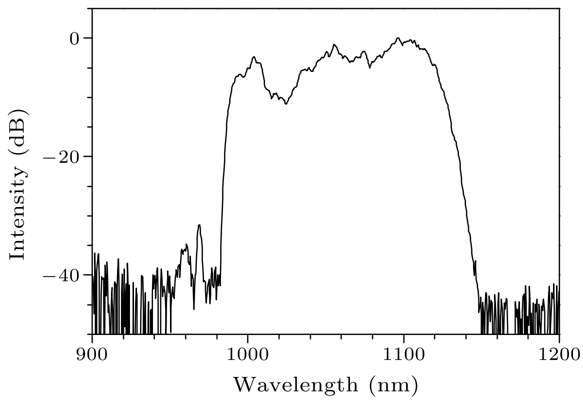

Fig. 2. The direct output spectrum from the oscillator with a bandwidth resolution of 1 nm.

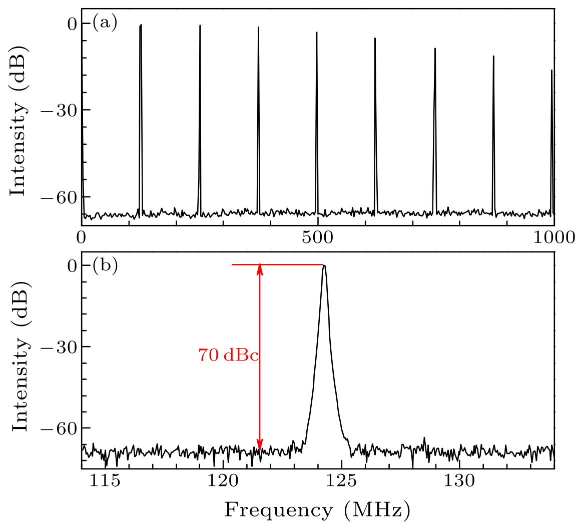

Fig. 3. (a) Radio frequency spectrum of 1 GHz wide-span range with a bandwidth resolution of 100 kHz. (b) The rf spectrum of the fundamental frequency, and the signal-to-noise ratio is 70 dBc with a bandwidth resolution of 100 kHz.

As depicted in Fig. 4(a), the duration of pulses extracting directly from the oscillator was about 652 fs assuming a $sech^2$ shape measured by an intensity autocorrelator (Femtochrome, FR-103MN). There was no substructure on either side of the autocorrelation trace, which confirmed the single pulse operation of the fiber oscillator. A pair of 600 lines/mm TG was used as extra-cavity to de-chirp the laser pulses. Due to the fact that the gratings can only compensate the GDD effectively while not the TOD, the pulse duration was only compressed to about 32 fs, as shown in Fig. 4(b). The pedestals on both sides were caused by the TOD introduced while the ultrashort pulses propagated in the fibers. The average power of de-chirped pulses was about 175 mW and the peak power reached 44 kW. There is a lot of potential to acquire directly more than an octave-spanning spectrum by rejecting those de-chirped pulses into a section of highly nonlinear fiber.[16] This Yb-doped fiber oscillator has advantages of simple structure, small size, low cost and superior stability. It maintained the stable mode-locked state for more than one month without the packing. Meanwhile, the self-starting mode-locking was observed in a very short time after the pump laser was put on.

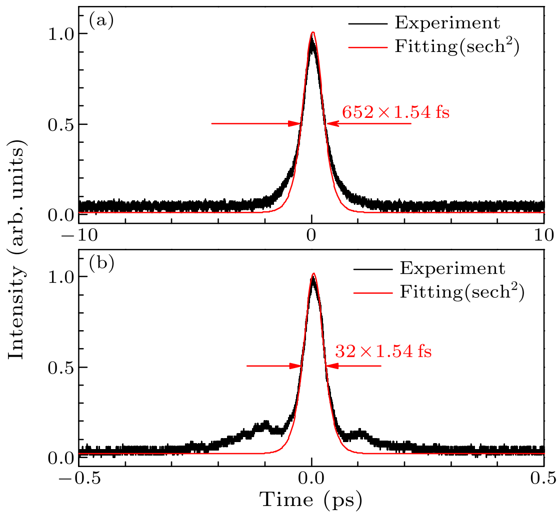

Fig. 4. (a) The intensity autocorrelation trace of the pulse train directly from the oscillator (black curve) and sech^2-fitting result (red curve). (b) The intensity autocorrelation trace of de-chirped pulse (black curve) and sech^2-fitting result (red curve).

In conclusion, we have demonstrated a simple NPE mode-locked Yb-doped fiber oscillator operating in the dispersion-managed regime. When the pump power of 976 nm LD is approaching 600 mW, mode-locked pulses with a super broad spectrum spanning from 950 nm to 1150 nm are generated. The mode-locked state is very robust with no signs of soliton fission. The average output power is 198 mW with a repetition rate of 124 MHz, corresponding to a pulse energy of 1.6 nJ. The duration of pulses extracted directly from the oscillator is about 652 fs. Due to the imperfect dispersion compensation extra-cavity, the shortest duration of the de-chirped pulse achieved in the experiments is 32 fs. Such a high power and broadband mode-locked oscillator is an ideal seed in many applications.

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