980-nm all-fiber mode-locked Yb-doped phosphate fiber oscillator based on semiconductor saturable absorber mirror and its amplifier*

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A 980-nm semiconductor saturable absorber mirror (SESAM) mode-locked Yb-doped phosphate fiber laser is demonstrated by using an all-fiber linear cavity configuration. Two different kinds of cavity lengths are introduced into the oscillator to obtain a robust and stable mode-locked seed source. When the cavity length is chosen to be 6 m, the oscillator generates an average output power of 3.5 mW and a pulse width of 76.27 ps with a repetition rate of 17.08 MHz. As the cavity length is optimized to short, 4.4-mW maximum output power and 61.15-ps pulse width are produced at a repetition rate of 20.96 MHz. The output spectrum is centered at 980 nm with a narrow spectral bandwidth of 0.13 nm. In the experiment, no undesired amplified spontaneous emission (ASE) nor harmful oscillation around 1030 nm is observed. Moreover, through a two-stage all-fiber-integrated amplifier, an output power of 740 mW is generated with a pulse width of 200 ps.

Keywords: 980-nm fiber laser, SESAM mode-locking, Yb-doped phosphate fiber, fiber amplifier

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1. Introduction

In the past few years, high-power ultra-short pulsed fiber lasers have been widely used in ultrafast spectroscopy, nonlinear microscopy, laser micromachining and nonlinear frequency conversions, since they have the advantages of excellent beam quality, high pulse energy, less thermal effect, etc. In addition, these inherent benefits of fiber-lasers make them easy for engineering application and become the real contenders with the conventional solid-state lasers. Therefore, particular attention has been paid to fiber lasers especially to the Yb-doped mode-locking fiber lasers. This is because Yb-doped fibers always offer ideal gain media for the generation and amplification of ultrashort pulsed lasers around 1 μm, which benefits from the characteristics of Yb-ions such as their broad gain bandwidths, high optical-to-optical conversion efficiencies and large saturation fluences. Generally speaking, saturable absorbers[1,2] and nonlinear polarization evolution effects[3,4] are known as conventional mode-locked mechanisms to obtain Yb-doped mode-locked fiber lasers. Usually, mode-locked fiber lasers with saturable absorbers are easy to demonstrate and to achieve excellent characteristics such as stability, self-started mode-locking and supporting the generation of femtosecond and picosecond pulses.[5] In contrast, nonlinear polarization evolution suffers long-term reliability and produces broad pulse duration. It is mainly because the performance of the nonlinear polarization rotation technique, which usually works as a fast saturable absorber in the mode-locked system, needs to adjust the mode-locked elements which are sensitive to vibration and general environment perturbations. Furthermore, a long passive fiber is always inserted into the cavity of nonlinear polarization rotation (NPR) mode-locked fiber laser to accumulate enough nonlinear phase shifts so as to degrade the mode-locked threshold. Nevertheless, long fiber in the cavity always leads to large normal dispersion, so that NPR mode-locked Yb-doped fiber lasers usually deliver pulses of hundred picoseconds and even nanosecond level duration without any dispersion compensation elements into the cavity. Hence, saturable absorbers are usually used as mode-locked elements for shorter pulse generation. Recently, Yb-doped mode-locked fiber laser with the semiconductor saturable absorber mirror (SESAM) as a mode-locked component has been demonstrated. Most of the mode-locked fiber oscillators were based on SESAM operated in a spectral range from 1030 nm to 1100 nm. For example, Katz and Sintov demonstrated an all-fiber SESAM mode-locked laser operating around 1064 nm with a repetition rate of 50 MHz and a pulse duration of 3.8 ps. Through a two-stage amplifier, they attained 1.2-W average power and 6.45-ps pulse width.[6] Chen *et al*. reported a 20-mW average power with 13-ps pulse width and 59.8-MHz repetition rate Yb-doped single mode SESAM mode-locking fiber laser emission around 1064 nm. To avoid the nonlinear effects during direct amplification of the seed, the repetition rate was octupled to 478 MHz and the ultimate output laser exhibited an average power of 94 W

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and a pulse width of 16 ps.[7] A high repetition rate narrow bandwidth SESAM mode-locked Yb-doped fiber laser operating at 1064 nm was demonstrated by Liu *et al*.[8] The laser generated a maximum output power of 17 mW with a fundamental repetition of 490 MHz.[8] Except for operating on a four-level system at the wavelength ranging from 1030 nm to 1100 nm, the Yb-doped fiber laser has an additional interesting feature that can also operate in the three-level-system around 980 nm under certain conditions, which makes them desirable pump sources for erbium-doped fiber amplifiers and lasers. Moreover, 980-nm Yb-doped fiber lasers can generate blue light by doubling frequency, which can replace bulky inefficient argon ion lasers and blue semiconductor lasers with excellent beam quality and simpler thermal management.[9–11] However, it is more difficult to achieve Yb-doped fiber lasers operating at 980 nm, which is mainly because there exist serious re-absorption effects around 980 nm and the gain competition between the three-level (around 980 nm) and the four-level system (around 1030 nm–1100 nm) inside the Yb-doped fiber. Therefore, it is more significant to suppress the unwanted 1030-nm laser for effective 980-nm laser operation. Usually, reasonable fiber structure and fiber length are chosen to avoid the re-absorption at 980 nm and the harmful oscillation at 1030 nm.

More recently, several groups have investigated 980-nm mode-locked fiber lasers. Okhotnikov *et al*. reported a 3-mW, 1.6-ps mode-locked single-mode Yb-doped fiber laser. It operates at 980 nm by using an SESAM as the mode-locking element.[12] Lhermite *et al*. reported a passive mode-locking usual double-clad fiber laser operating around 976 nm with NPE technique, which attained an average output power of 480 mW and a pulse energy of 12 nJ at a repetition rate of 40.6 MHz.[13] A 976-nm SESAM mode-locking Yb-doped rod-type PCF fiber oscillator with an average output power of 4.2 W and a pulse energy of 0.5 μJ at a repetition rate of 84 MHz with a pulse duration of 14 ps was also demonstrated. Through the external compression with diffraction gratings, the pulse duration was compressed down to 460 fs.[14] From the above results published, we can know that there are some discrete elements in the laser oscillator, which damage the all-fiber structure of the cavity. All-fiber 980-nm Yb-doped fiber lasers have tremendous practical potential applications due to their advantages of better stabilities and compactions. As far as we know, although the developments of 980-nm fiber lasers have received comprehensive attention, there are few reports about all-fiber integrated SESAM mode-locked lasers around 980 nm.

In this work, we demonstrate an all fiber 980 nm SESAM mode-locking Yb-doped phosphate fiber laser for the first time. The oscillator produces 3.5-mW average output power and 76.27-ps pulse duration at a repetition rate of 17.08 MHz in the longer linear cavity of 6 m. In the shorter linear cavity of 5 m, a maximum output power of 4.4 mW and a pulse width of 61.15 ps are attained at a repetition rate of 20.96 MHz. The output spectrum of the oscillator is centered at 980 nm with a 3-dB bandwidth of 0.13 nm. Then, with a two-stage all-fiber MOPA system the laser power is amplified to 740 mW and the pulse width is broadened to 200 ps.

2. The 980-nm all fiber SESAM mode-locked linear-cavity Yb-doped phosphate fiber oscillator

The experimental configuration of 980-nm all-fiber SESAM passively mode-locked Yb-doped phosphate fiber oscillator is presented in Fig. 1. The oscillator is a typically linear cavity configuration. The front mirror of the cavity is a fiber coupled SESAM which is mounted on an FC/PC connector. The SESAM possesses an absorption of 50%, a modulation depth of 30%, an unsaturation loss of 20%, and a saturation fluence of 65 μJ/cm^2. A narrow bandwidth FBG with a reflectivity of 60% is not only as a back mirror of the cavity, but also as an output coupler. The center wavelength and bandwidth of the FBG are 980 nm and 0.06 nm respectively. One side of the FBG is spliced with a fiber FC/APC (8°) to avoid the parasitic oscillator. The laser is pumped by a fiber coupled single mode 915-nm laser diode with a maximum available power of 230 mW. Through a 915-nm/980-nm wavelength division multiplexer (WDM), the pump source is coupled into the linear cavity. Compared with the traditional Yb-doped fiber, the Yb-doped phosphate fiber is well-known for its superior cluster-free Yb ion solubility, relatively low attenuation and highly light-induced darkening threshold. So a highly Yb-doped phosphate fiber is selected as the gain medium, which has an absorption coefficient of 589 dB/m at 915 nm and a GVD of 32.58 ps^2/km at 980 nm. The absorption coefficient to pump light is so high that a short fiber with a length of 3.2 cm can afford enough gain, which is also helpful in reducing the re-absorption at 980 nm and inhibiting the operation at 1030 nm ∼ 1080 nm. The total length of the cavity is about 6 m and the net GVD value of the entire cavity length is 0.17 ps^2, which demonstrates our laser operates in a normal dispersion region.

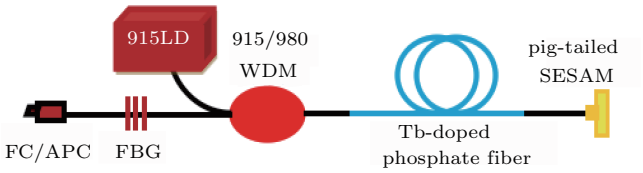


Fig. 1. (color online) The 980-nm all fiber SESAM mode-locked linear cavity Yb-doped fiber laser.

With appropriately increasing the pump power, the stable self-started mode-locking occurs when pump power is 110 mW with a repetition rate of 17.08 MHz, which is given in Fig. 2(a). The oscillator produces a maximum output power of 3.5 mW, pulse duration of 76.27 ps, signal-to-background ratio of 49.57 dB. In our experiments, we find that the amplified pulse train is unstable when this seed is amplified directly. It is because low power seed laser cannot afford enough power for the last stage power amplifier. Moreover, the insufficient seed power also results in large amplified spontaneous emission (ASE) around 1030 nm in the amplifier, especially at a high pump power. Therefore, a more powerful seed is needed and we obtain a maximum output power of 4.4-mW stable mode-locked fiber laser by shortening the cavity length to 5 m. We find that the threshold of the mode-locked fiber laser for the shorter length cavity is higher than that of longer cavity. Due to the limitation of the maximum available pump power, the length of cavity cannot be further shortened. In the shorter linear cavity region, stable mode-locked laser pulses occur at an incident pump power of 220 mW with a repetition rate of 20.96 MHz just as shown in Fig. 2(b).

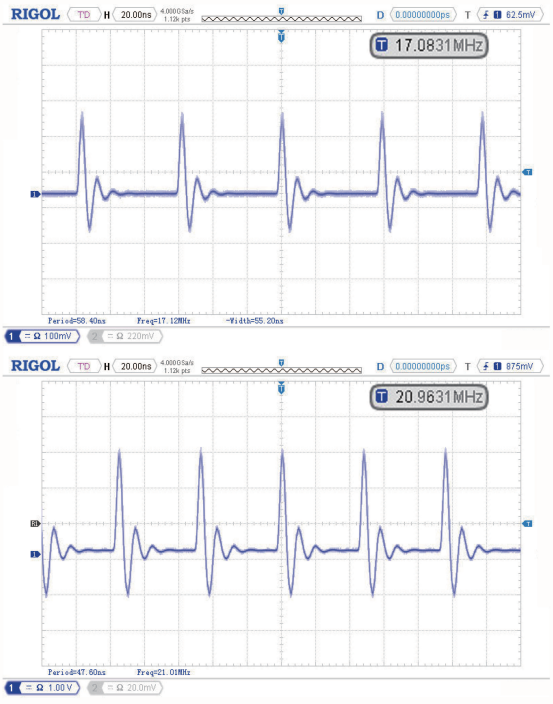


Fig. 2. (color online) (a) Stable mode-locked pulse train of 980-nm Yb-doped fiber laser at a repetition of 17.08 MHz, and (b) the stable mode-locked pulse train of 980-nm Yb-doped fiber laser at a repetition of 20.96 MHz.

Figure 3 shows the output power versus pump power. The maximum average output power is 4.4 mW. An optical spectral analyzer (YOKOGAWA AQ6370B) with a resolution of 0.02 nm is utilized to measure the output spectrum of the laser and the result is depicted in Fig. 4. The center wavelength is 980 nm without the ASE around 1030 nm and the full width at half maximum (FWHM) bandwidth is about 0.13 nm. A 2-GHz photo detector and a 40-GHz electrical spectrum analyzer are used to evaluate the stability of the mode-locking regime. The signal-to-noise ratio is 43.28 dB as shown in Fig. 5, which indicates the good mode-locked quality. An autocorrelator (ACOR-Femod, FR-103XL) is utilized to measure the pulse duration of the mode-locked fiber laser and the results present 3.48 ms for longer cavity and 2.79 ms for shorter cavity, respectively, as shown in Fig. 6.

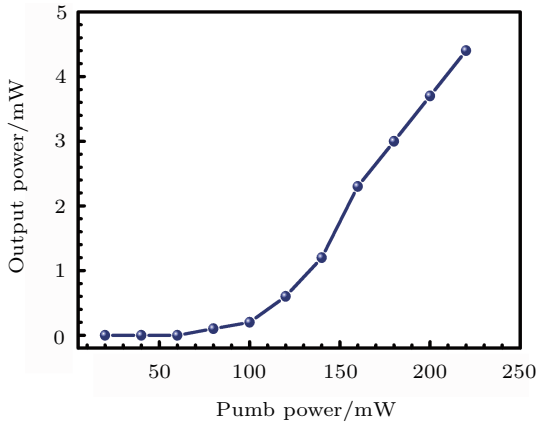


Fig. 3. (color online) Plot of output power of 980-nm short linear cavity mode-locked Yb-doped fiber laser versus incident pump power.

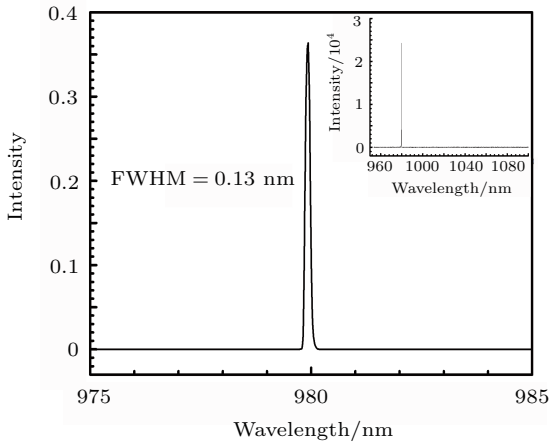


Fig. 4. Output spectrum of 980-nm mode-locked fiber laser at 20.96-MHz repetition rate.

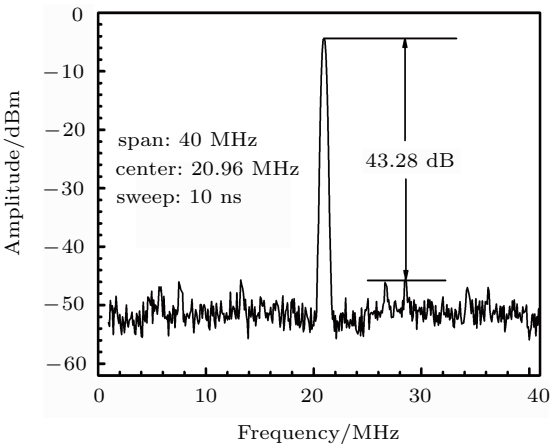


Fig. 5. RF spectrum of the 980 nm mode-locked fiber laser at a repetition of 20.96 MHz.

With regard to the measurement mechanism of the autocorrelator, the result should be multiplied by a factor of 31×0.707. As a result, the real pulse durations of 76.27 ps at a repetition of 17.08 MHz and 61.15 ps for the repetition rate of 20.96 MHz can be obtained respectively. Thus, the peak power of 2.62 W and per pulse energy of 0.20 nJ are attained in a longer cavity. Meanwhile, in a shorter cavity, the peak power and single pulse energy present 3.43 W and 0.21 nJ, respectively.

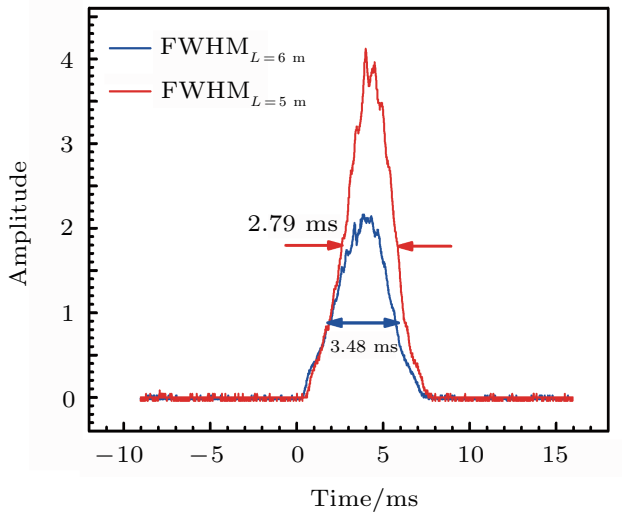


Fig. 6. (color online) Autocorrelation traces of the 980-nm SESAM mode-locked fiber laser.

3. The 980-nm all-fiber-integrated amplifier

In the following experiment, in order to achieve higher output power, a two-stage all-fiber-integrated Yb-doped amplifier chain is utilized to amplify the lower power seed source with a 20.96-MHz repetition rate. The schematic of the fiber main oscillator power amplifier (MOPA) is illustrated in Fig.7. In the fiber pre-amplifier, about 4-cm single-mode Yb-doped phosphate fiber is used as the gain medium which is pumped by two identical 915-nm SM pig-tailed 915-nm LD so as to improve the amplifier efficiency. Through two uniform 915-nm/980-nm WDMs, the pump sources are coupled into the amplified fiber, respectively. A commercial 90:10 output coupler (OC) divides the pre-amplified signal laser into two unbalanced parts. The 90% of the output power, i.e., about 90 mW, is coupled into the last amplified stage, 10% of the output power is monitored by an oscilloscope. The bandpass filter (BP) is utilized to eliminate deleterious ASE around 1030 nm. The gain fiber of the last stage is a home-made double-clad Yb-doped fiber with a core diameter of 20 μm and an inner diameter of 130 μm. To avoid the back reflections from the pre-amplifier, a 2-W isolator (ISO) is inserted between the BP and combiner. A multi-mode 915-nm LD is utilized to pump the gain medium via a $(2+1) \times 1$ combiner. The output end of the 20-μm/130-μm fiber is angle cleaved (8°) to avoid parasitic oscillation.

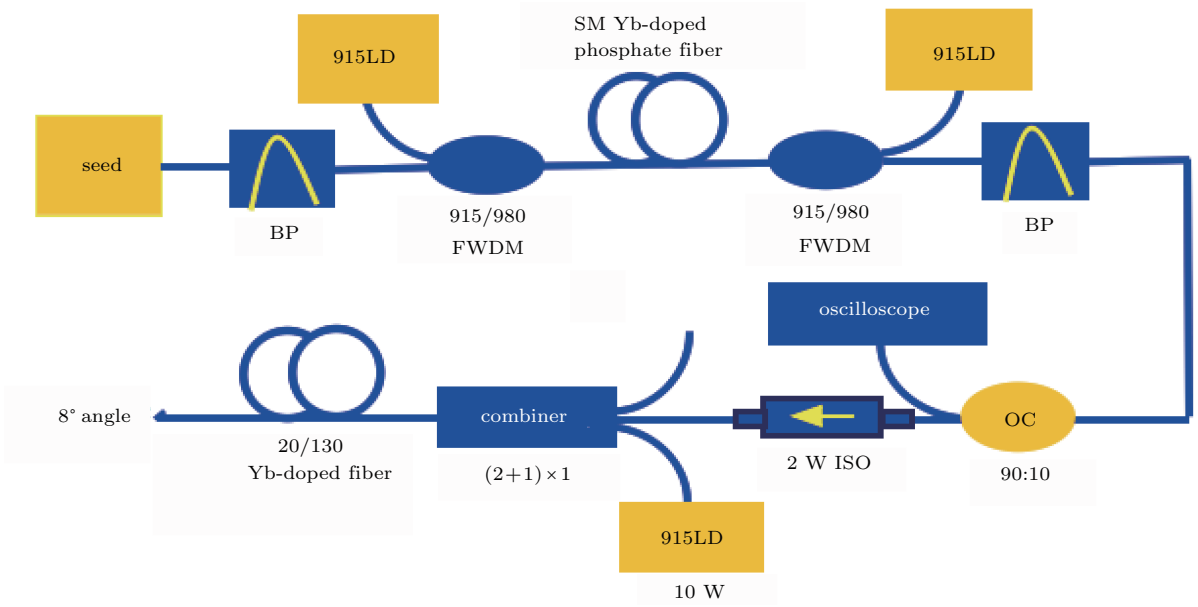


Fig. 7. (color online) Schematic diagram of all fiber 980-nm MOPA system.

Considering the special characteristics of Yb-doped fiber at 980 nm, the length of amplified fiber plays a key role in amplifying 980-nm light. That is, there is an optimum length for the amplified fiber. In our experiments, we adopt three different lengths of Yb-doped double-clad fibers, 24 cm, 36 cm, and 45 cm respectively, to amplify the 980-nm light. At the output end of the fiber amplifier, two identical dichroic mirrors each with high reflectivity at 980 nm and high transmission at 915 nm are used to filter the pump light at 915 nm. Here we find that the output powers increase monotonically with pump power at various lengths of gain fiber as shown in Fig. 8. Meanwhile, a spectrum analysis is used to monitor

the output spectrum. Some 915-nm pump light in the spectrum is observed from the fiber with a length of 24 cm. If we chose the 45-cm-long Yb-doped fiber as the gain medium, the output spectrum contains large 1030-nm ASE. As a result, 36-cm-long gain fiber is chosen to amplify the 980-light and find that the spectrum includes only 980-nm laser without 1030-nm ASE. Thus it demonstrates that the optimum length for the last stage is about 36 cm. We obtain a maximum output power of 740 mW from the last fiber amplifier. The low conversion efficiency is just because only 90 mW signal light is injected into the last stage and the absorption coefficient of amplified fiber of the last stage cannot afford enough gain to amplify 980-nm light.

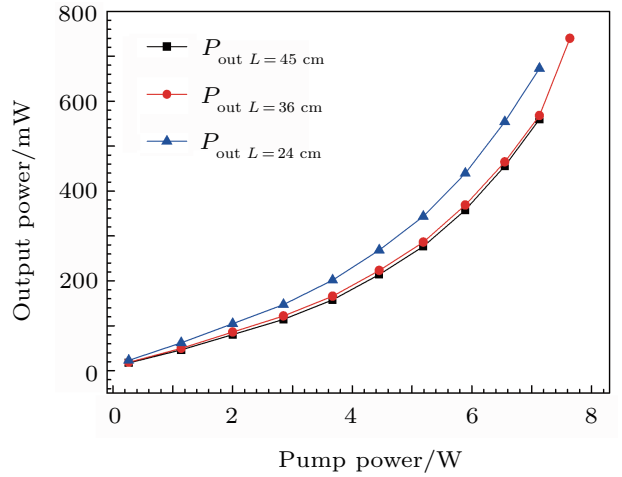


Fig. 8. (color online) Plots of output power versus pump power for different lengths of amplified fiber after the filter.

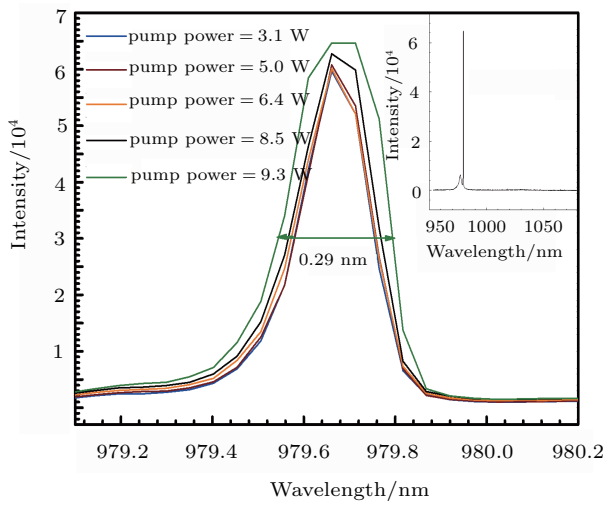


Fig. 9. (color online) Plots of spectrum intensity versus wavelength at various pump powers.

Figure 9 shows the characteristics of the output spectrum which is broadened slightly with increasing pump power. The FWHM of the spectrum ranges from ∼0.2 nm to ∼0.29 nm. It may be due to the intense nonlinear effect of the self-phase modulation (SPM). Moreover, the pulse width of the amplifier is largely stretched compared with the pulse duration of the seed source, which is mainly due to the nonlinear effect and the dispersion. In our experiment, a 10-GHz photoelectric detector and a 13-GHz high-speed oscilloscope are used to measure the amplified pulse width, and pulse duration about 200 ps is obtained as shown in Fig. 10. Thus, the time-bandwidth product of the pulse is ∼18.12, indicating that the amplified pulses contain larger normal dispersion component. Due to the lower resolutions of detector and the oscilloscope, the measurement results might be larger than the practical width of pluses. We also measure the intensity profile of output laser beam, and the beam profile exhibits nearly foundational mode with $M^2 \sim 1.6$. In order to improve the low conversion efficiency of the amplifier, high doped fiber and large core fiber will be utilized in the future work. Otherwise, several methods such as enlarging the fiber core, reducing the length of gain medium and upgrading the repetition rate[7] should be taken to reduce the peak power so as to degrade the nonlinear effects and obtain high average power level.

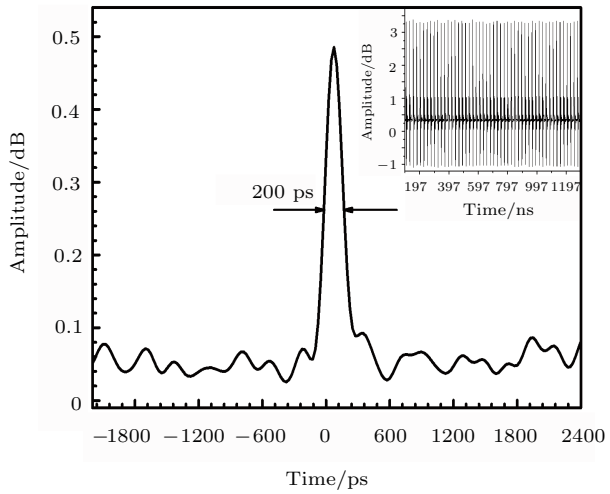


Fig. 10. Pulse duration of amplified pulse at maximum output power.

4. Conclusions

In this work, we demonstrate an all-fiber 980-nm passively mode-locked Yb-doped phosphate fiber laser based on SESAM. The oscillator exhibits an average output power of 3.5 mW with a repetition rate of 17.08 MHz by utilizing a 6-m-long linear cavity. A pulse duration of 76.27 ps is obtained. For a shorter linear cavity (5 m in length), we also achieve a stable self-started mode-locked fiber laser. The oscillator produces a maximum output power of 4.4 mW with a repetition rate of 20.96 MHz. The pulsed width is about 61.15 ps. Then, through the two-stage all-fiber-integrated amplifier by using the 980-nm oscillator as a seed source, an amplified output power of 740 mW is generated with a pulse width of 200 ps. The output spectrum is centered at 980 nm and the linewidth is 0.29 nm. As far as we know, such a narrow linewidth picosecond fiber laser emission around 980 nm is adapted to produce

490-nm blue light by doubling frequency. In the next work, the output power of ultrashort light at 980 nm will be improved by using the all-fiber Yb-doped photonic-crystal-fiber amplifier.

References

[1] Herda R and Okhotnikov O G 2004 *IEEE J. Quantum Electron.* **40** 893

[2] Yoon T H, Jang G H and Kim J H 2011 *Conference on Lasers and Electro-Optics, Laser Applications to Photonic Applications*, OSA Technical Digest (CD) (Optical Society of America), paper JWA24

[3] Mortag D, Wandt D, Morgner U, Kracht D and Neumann J 2011 *Opt. Express* **19** 546

[4] Özgören K and Ilday F Ö 2010 *Opt. Lett.* **35** 1296

[5] Okhotnikov O G, Gomes L, Xiang N, Jouhti T and Grudinin A B 2003 *Opt. Lett.* **28** 1522

[6] Katz O and Sintov Y 2008 *Opt. Commun.* **281** 2874

[7] Chen S P, Chen H W, Hou J and Liu Z J 2009 *Opt. Express* **17** 24008

[8] Liu J, Xu J and Wang P 2012 *IEEE Photon. Technol. Lett.* **24** 539

[9] Bouchier A, Lucas-Leclin G, Georges P and Maillard J 2005 *Opt. Express* **13** 6974

[10] Soh D B S, Codem C and Nilsson J, Sahu J K, Philippov V, Jeong Y, Alegria C and Baek S 2004 *IEEE Photon. Technol. Lett.* **16** 1032

[11] Zou S Z, Li P X, Wang L H, Chen M and Li G 2009 *Appl. Phys. B* **95** 685

[12] Okhotnikov O G, Gomes L A, Xiang N, Jouhti T, Chin A K, Singh R and Grudinin A B 2003 *IEEE Photon. Technol. Lett.* **15** 1519

[13] Lhermite J, Machinet G, Lecaplain C, Boullet J, Traynor N, Hideur A and Cormier E 2010 *Opt. Lett.* **35** 3459

[14] Lhermite J, Machinet G, Lecaplain C, Royon R, Hideur A and Cormier E 2011 *Conference on Lasers and Electro-Optics, Laser Applications to Photonic Applications*, OSA Technical Digest (CD) (Optical Society of America), paper CJ5_5