Linearly-Polarized Mode-locked Yb^{3+}-doped Phosphate Fiber Ring-Cavity Laser at 976 nm

Joshua Lee, Xiushan Zhu, Shijie Fu, Lizhu Li, Robert A. Norwood, and N. Peyghambarian

***Abstract*—Compact and robust linearly-polarized pulsed laser sources at 976 nm are in great demand for high-efficiency harmonic generation of blue and deep ultraviolet lasers. In this paper, we report a semiconductor saturable absorber mirror mode-locked fiber ring-cavity laser at 976 nm, in which only 2.4 cm highly ytterbium-doped phosphate fiber was used as the gain fiber. Fundamental mode-locking operation with 5-ps pulses at a repetition rate of 16.53 MHz and with average output power of 2 mW was obtained at a pump power of 215 mW. The pulse energy and peak power of the mode-locked pulses were estimated to be 0.12 nJ and 24.4 W, respectively. The polarization extinction ratio was measured to be 21.5 dB.**

***Index Terms*—976 nm, Yb^{3+}-doped fiber laser, three-level laser, mode-locked laser, phosphate fiber, SESAM**

I. INTRODUCTION

LASERS at blue and ultraviolet (UV) wavelengths have found many applications including color displays, spectroscopy, biophotonics, underwater optical communications, and material processing [1-5]. Although excimer lasers, argon lasers, and GaN diode lasers can generate blue light through direct transitions, some of their specifications, such as output power, beam quality, repetition rate, size, and efficiency, do not meet the requirements for the applications mentioned above. For example, excimer lasers generally can operate with low repetition rate (< 1 kHz) and pulse duration in the nanosecond range. Argon ion lasers are a source of high-power continuous-wave (CW) output in the blue. However, argon ion lasers are bulky, expensive, and have low efficiency. Over the last decade, wide-bandgap GaN semiconductor diode lasers have experienced tremendous progress and their output power, efficiency, and lifetime have met the requirements for a variety of applications [6, 7]. However, semiconductor diode lasers usually suffer from poor beam quality and low thermal dissipation capability which makes their performance more temperature-dependent than other lasers. Moreover, current GaN diode laser technology still cannot produce high-energy pulses and be used for high-efficiency harmonic generation either.

In comparison, fiber lasers can not only produce CW output up to 10-kW level due to their unique high heat dissipation capability, but they also produce pulsed output with a wide range of repetition rates, pulse durations, and pulse energies due to their cavity design flexibility for pulse generation. In addition, fiber lasers have the advantages of high beam quality, convenient manufacturing, and low maintenance. Direct-transition blue fiber lasers have attracted great interest during the last decades. Most efforts have been conducted with rare-earth-doped fluoride fibers that were up-conversion-pumped by near-infrared (NIR) lasers [8, 9]. However, their output power levels are always constrained by photo-darkening effects, low mechanical strength, and the hygroscopicity of fluoride fibers. Therefore, nonlinear wavelength conversion pumped by NIR fiber lasers is still the most effective way to obtain high power blue and UV (especially deep UV with wavelength < 250 nm) for lasers operating at either CW or pulse mode. For this reason, fiber lasers at 9xx nm have attracted intense attention and much research has been done with ytterbium (Yb^{3+}) and neodymium (Nd^{3+}) doped fiber lasers operating with their three-level systems in this wavelength region [10-17].

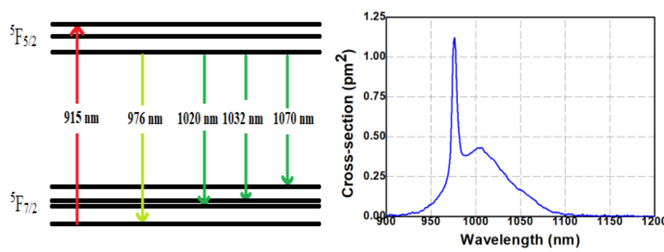

Fig. 1. (a) Energy level diagram of Yb^{3+}; (b) Emission cross-section of Yb^{3+}-doped phosphate.

As given by the energy level structure, the operating wavelength of a Nd^{3+} three-level laser is shorter than that of Yb^{3+}. However, the complex energy level structure of Nd^{3+} allows both excited-state absorption and cross relaxation, which results in concentration quenching, thereby limiting the doping level of Nd^{3+} in optical fibers and impairing the efficient operation of Nd^{3+}-doped fiber lasers [18]. As shown in Fig. 1(a), the much simpler energy level structure of Yb^{3+} frees Yb^{3+}-doped fiber lasers from these problems and enables in-band pumping more efficiently than pumping Nd^{3+} at 808 nm. Therefore, the Yb^{3+} three-level system is preferable to the Nd^{3+}

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J. Lee, X. Zhu, S. Fu, L. Li, R.A. Norwood, and N. Peyghambarian are with the College of Optical Sciences, The University of Arizona, Tucson, AZ 85721 USA (email: joshualee@arizona.edu; xszhu@email.arizona.edu; shijiefu@email.arizona.edu; lizhuli@arizona.edu; rnorwood@optics.arizona.edu; nasser@optics.arizona.edu).

three-level system for high power lasers at 9xx nm. Moreover, the emission cross-section of Yb^{3+} at 976 nm is much higher than at the wavelengths of 1 µm lasers as shown in Fig. 1(b), making it easier to achieve high power output with a Yb^{3+}-doped laser than with a Nd^{3+}-doped laser at 9xx nm. Several tens of watts three-level Yb^{3+}-doped fiber lasers operating in CW and Q-switched modes have been reported [19-21].

In the past few decades, there has been increased interest in developing ultrashort pulsed lasers (USPLs) near 9xx nm because their nonlinear wavelength down-conversions can produce USPLs at blue and deep UV wavelengths, where USPLs have found many applications; however these wavelengths are hard to reach with direct-transition lasers. Much of the research on 976 nm USPLs has been done with mode-locked Yb^{3+}-doped fibers based on various techniques [22-27]. In 2003, Okhotnikov et al. reported a wavelength tunable mode-locked Yb^{3+}-doped fiber laser [22]. Pulses of 1.6-2 ps with a tunable range from 980 to 1070 nm and average power of 3 mW were obtained by using a semiconductor saturable absorption mirror (SESAM) and an external grating pair. By using a nonlinear polarization evolution technique, Lhermite et al. obtained 1 ps pulses with average power of 480 mW at 976 nm [23]. However, these mode-locked fiber lasers were demonstrated with several free-space optical components and thus didn't have the advantages of all-fiber lasers, such as ease of manufacturing, exceptional robustness, and freedom from alignment issues.

Mode-locked three-level Yb^{3+}-doped fiber lasers in all-fiber configurations have been demonstrated with either linear or ring cavities [24-26]. In previous work, we used 50 cm Yb^{3+}-doped silica fiber and an all-fiber linear cavity configuration to obtain 10.9 ps pulses with 2.5 mW average power at 976 nm and used multiple Yb^{3+}-doped fiber amplifiers to increase the average power to over 8 W [25]. However, this laser system suffered from the polarization instability because the output of the mode-locked all-fiber linear cavity oscillator was not linearly polarized and a polarization-maintaining (PM) optical isolator was used to achieve a linearly-polarized USPL suitable for down-stream PM fiber amplifiers. This problem can be addressed by developing a linearly-polarized mode-locked Yb^{3+}-doped fiber laser oscillator at 976 nm. In 2020, Aleshkina et al. demonstrated a linearly-polarized mode-locked all-fiber laser at 980 nm using a ring-cavity configuration with cladding-pumping [26]. They used 16-cm long Yb^{3+}-doped phosphate-aluminosilicate fiber as the gain medium and achieved 9.5 ps pulses with 3.25 mW average output power. But due to the low effiency cladding pumping, stable mode-locking of this 980 nm all-fiber laser was obtained at a high pump power of ~4.6 W. In this paper, we report a linearly-polarized mode-locked all-fiber ring-cavity laser at 976 nm using only 2.4 cm of highly Yb^{3+}-doped phosphate fiber. Stable fundamental mode-locking with an output power > 2 mW was obtained at a pump power of only 215 mW.

II. Experimental Methods

The schematic of the mode-locked all-fiber laser cavity is depicted in Fig. 2. A single-mode laser diode with its central wavelength at around 910 nm (Lumics LU0915M300) was used as the pump source. A 2.4-cm long piece of PM 6wt% Yb^{3+}-doped phosphate fiber with a core diameter of 6 µm, numerical

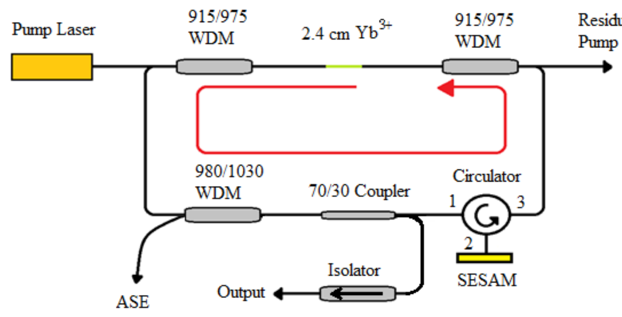

Fig. 2. Schematic of the linearly-polarized SESAM-mode-locked ring-cavity fiber laser cavity based on 2.4-cm 6 wt% Yb^{3+}-doped phosphate fiber.

aperture (NA) of 0.14, and cladding diameter of 125 µm was used as the gain fiber. Such a short length of gain fiber was possible due to very high doping concentration of Yb^{3+} ion enabled by the host phosphate fiber. It was pumped by the 910 nm diode laser through a 915/975 nm PM wavelength division multiplexer (WDM) based on a dielectric filter. Since the three-level fiber laser usually has a large amount of residual pump power, a second 915/975 nm WDM was placed after the gain fiber to remove the residual pump light to eliminate potential thermal issues with the circulator and the semiconductor saturable absorption mirror (SESAM, BATOP SAM-980-15-500fs), which has 9% modulation depth and 60 $\mu J/cm^2$ saturable fluence. The SESAM was butt-coupled to the fiber tip from port 2 of the PM circulator, which only allows the laser at one linear polarization state to circulate inside the ring cavity. To minimize the effect of amplified stimulated emission (ASE) at long wavelengths on the stability of the 976 nm ring-cavity laser, a 975/1030nm PM WDM was used to extract the ASE around 1030 nm from the cavity. A 70/30 PM fused coupler was used to couple the 976 nm laser out of the ring cavity. It should be noted that there was no specific bandpass filter used in the ring cavity to achieve self-starting of the laser mode-locking in the normal dispersion region. The filtering effect of the ring cavity, caused by the wavelength dependent performance of the fiber components, including the WDMs, the fused fiber coupler, and the saturable absorption of the SESAM, enabled the mode-locking of the 976 nm Yb^{3+}-doped fiber laser.

III. Experimental Results and Discussion

The output power of the mode-locked Yb^{3+}-doped fiber laser as a function of the 910 nm pump power was measured with an optical power meter (Thorlabs, S122C) and is shown in Fig. 3. The laser threshold is about 112 mW. The laser output increases linearly with the pump power and reaches 3.87 mW at the maximum available pump power of 300 mW. The slope efficiency of this ring cavity laser is about 2.3%. The low slope efficiency can be attributed to the presence of many fiber components, which introduce a high total loss to the ring cavity.

Stable fundamental mode-locking started at a pump power of 127 mW and was maintained until the pump power was up to 215 mW, at which point the average output power was 2 mW. The fundamental mode-locking became unstable as the pump power was further increased, and harmonic mode-locking was observed at a pump power of 225 mW and beyond. The linearly polarized operation of the mode-locked all-fiber laser was confirmed by measuring the polarization extinction ratio (PER) of the output with a Glan-Thompson polarizer (Thorlabs, GTH10M). A PER of 21.5 dB was measured.

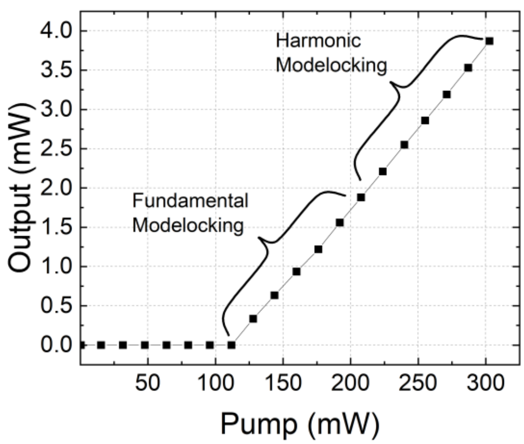

Fig. 3. Measured average output power as a function of the pump power for the linearly-polarized SESAM-mode-locked Yb^{3+}-doped fiber laser at 976 nm.

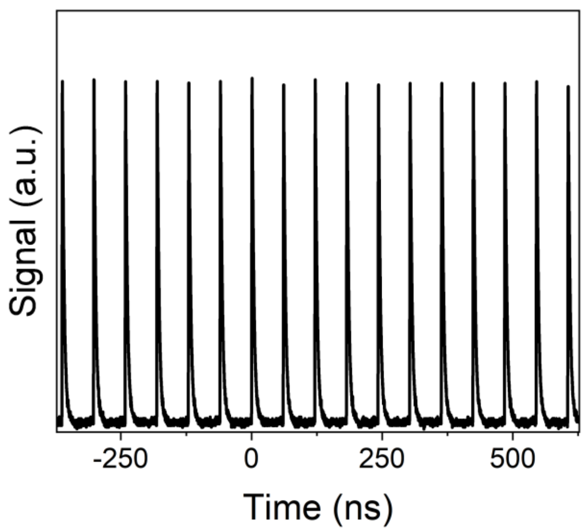

Fig. 4. Measured pulse train of the linearly-polarized SESAM-mode-locked Yb^{3+}-doped fiber laser at 976 nm.

The mode-locked pulse train was observed with an oscilloscope (Tektronix DPO 7254) and is shown in Fig. 4. The pulse repetition rate is 16.53 MHz, as dictated by the ring cavity length of ~ 12.6 m. The cavity length could be reduced to obtain a higher repetition rate. The radio-frequency (RF) spectrum of the 976 nm mode-locked fiber laser was measured with an electrical spectrum analyzer (Tektronix MDO 3024) with a resolution of 1 kHz and is shown in Fig. 5. A signal-to-noise (SNR) ratio of > 70 dB was measured, indicating that the fundamental mode-locking is exceptionally stable. The RF spectrum measured in a range of 0-200 MHz is shown in the inset of Fig. 5, exhibiting > 20 dB improvement of the SNR when it is compared to that of the linear cavity mode-locked fiber laser presented in [24].

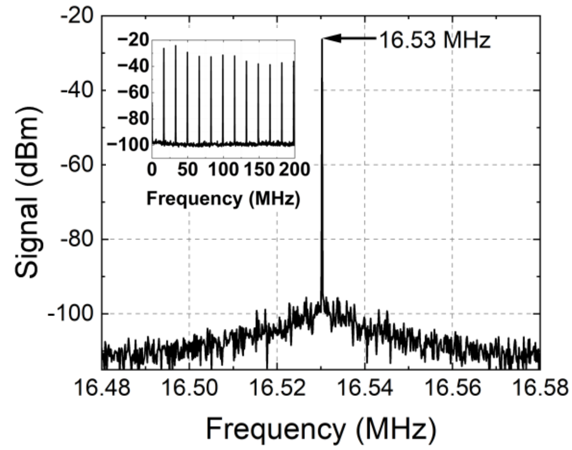

Fig. 5. The RF spectrum of the linearly-polarized SESAM-mode-locked fiber laser at 976 nm. Inset: RF spectrum measured at a frequency range of 0-200 MHz.

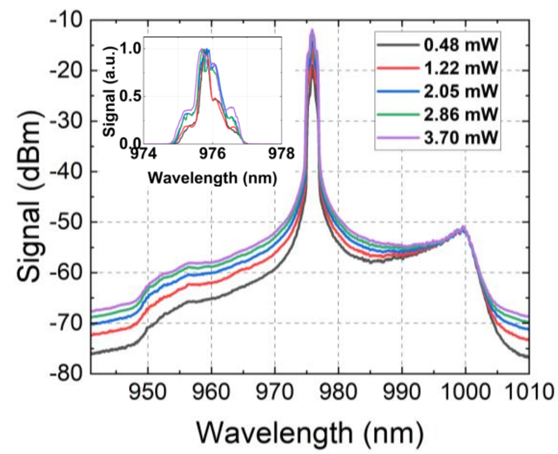

Fig. 6. The optical spectra of the linearly-polarized SESAM-mode-locked Yb^{3+}-doped fiber laser at different output power levels measured in the wavelength range from 940-1010 nm. Inset: The optical spectra were measured in the wavelength range from 974-978 nm and plotted on a linear scale.

The optical spectra of the mode-locked Yb^{3+}-doped fiber laser operating at different output power levels were measured with an optical spectrum analyzer (ANDO AQ-6315A) in the wavelength range from 940 to 1010 nm with 0.05 nm resolution and is shown in Fig. 6. The insets show the optical spectra in a wavelength range from 974 to 978 nm on a linear scale. The full width at half maximum (FWHM) of the optical spectrum at an output power of 2 mW was about 0.34 nm.

Since the 2 mW mode-locked laser was insufficient to obtain an autocorrelation trace with high SNR with our autocorrelator, (Femtochrome FR-103XL), the mode-locked laser power was increased to over 40 mW with a 4-cm 6wt% Yb^{3+}-doped phosphate fiber amplifier and then launched into the

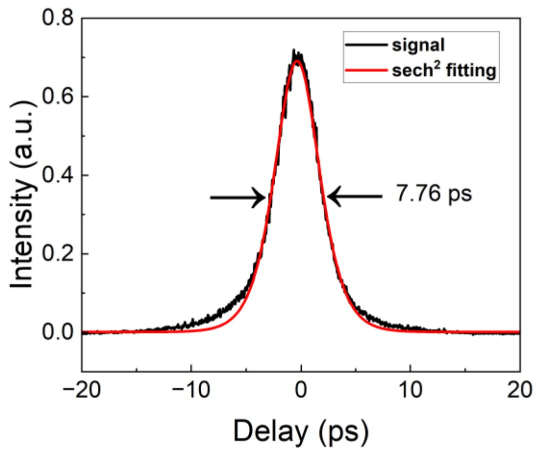

Fig. 7. Measured autocorrelation trace and the $sech^2$ fitting curve for the linearly-polarized SESAM-mode-locked Yb^{3+}-doped fiber laser at 976 nm.

autocorrelator. The measured autocorrelation signal trace and the curve fit with a $sech^2$ function are shown in Fig. 7. The FWHM is about 7.76 ps and thus the pulse width was estimated to be about 5 ps. The product of the spectral bandwidth and pulse-width is about 0.535, indicating that the pulse is slightly chirped. The pulse energy and peak power of the 2-mW fundamental mode-locked laser are estimated to be 0.12 nJ and 24.4 W, respectively.

IV. CONCLUSION

We have demonstrated a linearly-polarized SESAM-mode-locked fiber laser at 976 nm in a ring cavity, in which a 2.4 cm PM 6 wt% Yb^{3+}-doped phosphate fiber was used as the gain medium. 5 ps pulses at a repetition rate of 16.53 MHz were obtained. The PER of the mode-locked laser was measured to be 21.5 dB, making this laser oscillator very promising for master-oscillator and power amplifier (MOPA) configurations to achieve high polarization stability, high-power 976 nm lasers for high-efficiency single-pass harmonic generation of USPL in the blue and deep UV.

REFERENCES

[1] A. A. Bergh, "Blue laser diode (LD) and light emitting diode (LED) applications," Phys. Stat. Sol. (a) 201(12), 2740-2754 (2004).
[2] L. Smith, J. Sanders, R. Kaiser, P. Hughes, C. Dodd, C. R. Connell, C. Heiner, S. B. H. Kent, L. E. Hood, "Fluorescence detection in automated DNA sequence analysis," Nature 321, 673-679, 1986.
[3] N. Yoshida, N. Yagi, Y. Inada, M. Kugai, T. Okayama, K. Kamada, K. Katada, K. Uchiyama, T. Ishikawa, O. Handa, T. Takagi, H. Konishi, S. Kokura, A. Yanagisawa, Y. Naito, "Ability of a novel blue laser imaging system for the diagnosis of colorectal polyps," Dig. Endosc., 26(2), 250-258, 2014.
[4] T. Wu, Y. Chi, H. Wang, C. Tsai, G. Lin, "Blue Laser Diode Enables Underwater Communication at 12.4 Gbps," Sci. Rep. 7, 40480, 2017.
[5] M. Suwa, N. Wakabayashi, T. Hiroki, K. Tojo, S. Masuno, R. Higashino, M. Tsukamoto, "Development of BLUE IMPACT, a 450nm-wavelength light source for laser processing," Proc. SPIE 10900, 109000A, 2019.
[6] M. Kawaguchi, S. Nozaki, K. Morimoto, S. Takigawa, T. Katayama, T. Tanaka, "High-power GaN diode lasers and their applications," 2017 IEEE High Power Diode Lasers and Systems Conference (HPD), Coventry, UK, 2017, pp. 43-44.
[7] H. König, S. Gerhard, M. Ali, U. Heine, S. Tautz, C. Eichler, G. Brüderl, M. Peter, A. Lell, M. Behringer, M. Keidler, T. Haupeltshofer, C. Walter, M. Baumann, A. Balck, V. Krause, "Blue high power InGaN semiconductor laser diodes: design optimization of laser bars and single emitters for best performance and reliability," Proc. SPIE 11262, High-Power Diode Laser Technology XVIII, 112620Q (2020)
[8] M. Mollaee, X. Zhu, J. Zong, K. Wiersma, A. Chavez-Pirson, M. Akbulut, Y. Kaneda, L. LaComb, A. Schulzgen, N. Peyghambarian, "Single-frequency blue laser fiber amplifier," Optics Letters, vol 43, no 3, 423-426, 2018.
[9] X. Zhu, N. Peyghambarian, "High-power ZBLAN glass fiber lasers: review and prospect," Advances in Optoelectronics, vol 2010, 501956, 2010.
[10] M. Laroche, B. Cadier, H. Gilles, S. Girard, L. Lablonde, T. Robin, "20 W continuous-wave cladding-pumped Nd-doped fiber laser at 910 nm," Optics Letters, vol 38, no 16, 3065-3067, 2013.
[11] P. H. Pax, V. V. Khitrov, D. R. Drachenberg, G. S. Allen, B. Ward, M. Dubinskii, M. J. Messerly, J. W. Dawson, "Scalable waveguide design for three-level operation in Neodymium doped fiber laser," Opt. Express, vol 24, no 25, 28633-28647, 2016.
[12] S. Fu, X. Zhu, J. Zong, M. Li, I. Zavala, V. Temyanko, A. Chavez-Pirson, R. A. Norwood, N. Peyghambarian, "Single-frequency Nd^{3+}-doped phosphate fiber laser at 915 nm," J. Lightwave Technol., 2020.
[13] X. Zhu, W. Shi, J. Zong, D. Nguyen, R. A. Norwood, A. Chavez-Pirson, N. Peyghambarian, "976 nm single-frequency distributed Bragg reflector fiber laser," Optics Letters, vol 37, no 20, 4167-4169, 2012.
[14] X. Zhu, G. Zhu, W. Shi, J. Zong, K. Wiersma, D. Nguyen, R. A. Norwood, A. Chavez-Pirson, N. Peyghambarian, "976 nm Single-Polarization Single-Frequency Ytterbium-doped Phosphate Fiber Amplifiers," IEEE Photonics Technology Lett., vol. 25, no. 14 , 2013.
[15] J. Wu, X. Zhu, V. Temyanko, L. LaComb, L. Kotov, K. Wiersma, J. Zong, A. Chavez-Pirson, R. Norwood, N. Peyghambarian, "Double-clad Yb^{3+}-doped phosphate fiber for 976 nm single-frequency laser amplifiers," Opt. Mater. Express, vol 7, no 4, 1310-1316, 2017.
[16] V. Prosentsov, E. Sherman, A. Patlahn, Y. Ariel, D. Eger, "Efficient Yb-doped air-clad fiber laser operating at 980 nm and its frequency doubling," Proc. SPIE 4974, 193-201, 2003.
[17] D. B. S. Soh, C. Codemard, S. Wang, J. Nilsson, J.K. Sahu, F. Laurell, V. Philippov, Y. Jeong, C. Alegria, S. Baek, "A 980 nm Yb-doped fiber MOPA source and its frequency doubling," IEEE Photonics Technology Lett., vol 16, no 4,1032-1034, 2004.
[18] J. Wu, (2019). *High Power Single-Frequency 976 nm Fiber Laser Source and its Frequency Doubling for Blue Laser Generation* [Doctoral dissertation, University of Arizona]. ProQuest Dissertations Publishing.
[19] F. Roser, C. Jauregui, J. Limpert, A. Tunnermann, "94 W 980 nm high brightness Yb-doped fiber laser," Opt. Express, vol 16, no 22, 17310-17318, 2008.
[20] J. Boullet, Y. Zaouter, R. Desmarchelier, M. Cazaux, F. Salin, J. Saby, R. Bello-Doua, E. Cormier, "High power ytterbium-doped rod-type three-level photonic crystal fiber laser," Opt. Express, vol 16, no 22, 17891-17902, 2008.
[21] J. Wu, X. Zhu, H. Wei, K. Wiersma, M. Li, J. Zong, A. Chavez-Pirson, V. Temyanko, L. J. LaComb, R. A. Norwood, N. Peyghambarian, "Power scalable 10 W 976 nm single-frequency linearly polarized laser source," Optics Letters, vol 43, no 4, 951-954, 2018.
[22] O. G. Okhotnikov, L. Gomes, N. Xiang, T. Jouhti, A. B. Grudinin, "Mode-locked ytterbium fiber laser tunable in the 980-1070-nm spectral range," Optics Letters, vol. 28, no. 17, pp. 1522-1524, 2003.
[23] J. Lhermite, G. Machinet, C. Lecaplain, J. Boullet, N. Traynor, A. Hideur, E. Cormier, "High-energy femtosecond fiber laser at 976 nm," Optics Letters, vol 35, no. 20, pp. 3459-3461, 2010.
[24] P. Li, Y. Yao, J. Chi, H. Hu, G. Zhang, B. Liang, M. Zhang, C. Ma, N. Su, "980-nm all-fiber mode-locked Yb-doped phosphate fiber oscillator based on semiconductor saturable absorber mirror and its amplifier," Chinese Phys. B, vol. 24, no. 8, 2016.
[25] S. Fu, L. Li, X. Zhu, R. A. Norwood, N. Peyghambarian, "10-W Level Picosecond Yb3+-Doped All-Fiber Laser Source at 976 nm," Journal of Lightwave Technology, vol. 40, no. 13, pp. 4415-4419, 2022.
[26] S. S. Aleshkina, A. Fedotov, D. Korobko, D. Stoliarov, D. S. Lipatov, V. V. Velmiskin, V. L. Temyanko, L. V. Kotov, R. Gumenyuk, M. E. Likhachev, "All-fiber polarization-maintaining mode-locked laser operated at 980 nm," Optics Letters, vol. 45, no. 8, pp. 2275-2278, 2020.