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Broadband and Tunable 920-nm Femtosecond Pulse Generated by an All-Fiber Er:Fiber Laser System

KAI QIAN[1], HAO LUO[2], DA QIU[1], SHENGLI PU[3], AND WENCAI YAO[1]
[1]School of Advanced Materials and Mechatronic Engineering, Hubei Minzu University, Enshi 445000, China
[2]Nanjing Movelaser Company Ltd., Nanjing 210012, China
[3]College of Science, University of Shanghai for Science and Technology, Shanghai 200093, China

Corresponding author: Kai Qian (kaiqian@sjtu.org)

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ABSTRACT Fiber-optic Cherenkov radiation (FOCR) is a promising nonlinear process that is widely used for nonlinear wavelength conversion. In this study, an all-fiber 920-nm femtosecond pulse source is experimentally demonstrated by using Cherenkov radiation. The 4-nJ 150-fs 1550-nm amplified seed pulse source ensures highly efficient 920-nm pulse generation. Cherenkov radiation is stimulated by inputting the high-energy ultrashort pulse to a highly nonlinear fiber. The dispersion values of the highly nonlinear fiber (HNLF) are carefully chosen to generate CR pulses at 920 nm. The generated pulse has a 150-pJ single pulse energy and a 232-fs pulse duration. The typical 30-nm bandwidth can support a sub-50-fs transform-limited pulse duration. The pump current can be adjusted to tune the central wavelength of the pulse source over 905-930 nm. This very simple approach can generate 920-nm femtosecond pulses. The wavelength range is useful for a wide range of applications, such as two-photon microscopy (TPM) in bio-imaging and so on.

INDEX TERMS Fiber laser, laser mode locking, nonlinear optics.

I. INTRODUCTION

The 900-nm spectral region is very useful for applications such as two-photon microscopy in bio-imaging [1], [2]. These applications have created an urgent demand for an ultrafast pulse source at ~900 nm. Fiber lasers are superior to traditional solid-state lasers, such as Ti:sapphire lasers, in terms of cost efficiency, compactness, and ease of use.

Considerable effort has been expended to develop ultrafast fiber lasers at ~900 nm [3]–[7]. Qian *et al.* [3] demonstrated a passively mode-locked neodymium-doped oscillator featuring a W-type fiber operating at 930 nm with a pulse energy of 2.2 nJ and a pulse duration of 126 fs. Gao *et al.* [4] reported a core-pumped all-normal dispersion mode-locked Nd-doped fiber laser at 910 and 935 nm with a pulse energy of 1.3 nJ and a pulse duration of 198 fs. Recently, Chen *et al.* [5] demonstrated 4.4-nJ 114-fs pulses at ~910 nm using an optimized Nd-doped fiber amplifier, as well as 17-nJ 220-fs pulses at 930 nm [6]. Becheker *et al.* [7] have reported a dissipative soliton fiber laser with a maximum energy of 20 nJ at 927 nm. However, the gain bandwidth limits the spectrum bandwidth of the mode-locked pulse to ~20 nm, which can only support a transform-limited pulse width of 65 fs, assuming a Gaussian profile. It is difficult to tune the center wavelength of a mode-locked Nd-doped fiber laser.

The use of fiber-optic Cherenkov radiation for wavelength upconversion has been widely studied [8]–[13]. For practical applications, such as two-photon microscopy, a simple design for an all-fiber 920-nm femtosecond pulse source is urgently required. In 2014, Kotov *et al.* [11] experimentally obtained a supercontinuum source that emits a center wavelength of 0.9 μm with a spectral width of ~100 nm.

In this study, we propose a simple design for an all-fiber 920-nm femtosecond pulse source. Fiber-optic Cherenkov radiation (FOCR) is used to convert the wavelength from 1550 nm into 920 nm [14]–[17]. We use FOCR in a highly nonlinear fiber to successfully convert a 1550-nm pulse into a 920-nm pulse. The 4-nJ 150-fs amplified seed pulse source ensures highly efficient 920-nm pulse generation.

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The dispersion values of the HNLF are carefully chosen to generate CR pulses at 920 nm. The pump current can be adjusted to tune the central wavelength of the pulse source over 905-930 nm. The typical 30-nm bandwidth can support a sub-50-fs transform-limited pulse duration. Our pulse source can deliver pulses with a duration of 232 fs and an energy of ~150 pJ. The pure and clear spectrum at 900 nm indicates a high frequency efficiency from the pumping wavelength to the desired wavelength. This all-fiber, broadband and tunable source is an ideal seed source for 920-nm laser systems.

II. EXPERIMENTS AND RESULTS

Fig. 1 shows the four components of the experimental setup: an Er-doped fiber oscillator, an Er-doped fiber amplifier, a compressor and a Cherenkov wave convertor. The pulse output from the oscillator (multi milliwatt, 42.4 MHz) is launched into a 1-m-long highly Er-doped fiber (OFS EDF150), which is biodirectionally pumped by two 976-nm pump diodes (each with a maximum power of 600 mW) through two wavelength division multiplexers (WDM). The oscillator configuration has been described in [18], [19]. The laser is self-starting and quite stable because of a short cavity length and controlled dispersion. An optical isolator (ISO) is used to remove the backwards light. The amplified 1550-nm pulses are compressed using a piece of a single-mode fiber. The compressed pulses are then injected into a 5-cm length of a HNLF. The peak absorption, the mode-field diameter and the group velocity dispersion (GVD) of the EDF are 150 dB/m, 4.3 μm, and -48 ps/nm/km, respectively. The mode-field diameter and the zero-dispersion wavelength (ZDW) of the HNLF are 3.8 μm and 1346 nm, respectively.

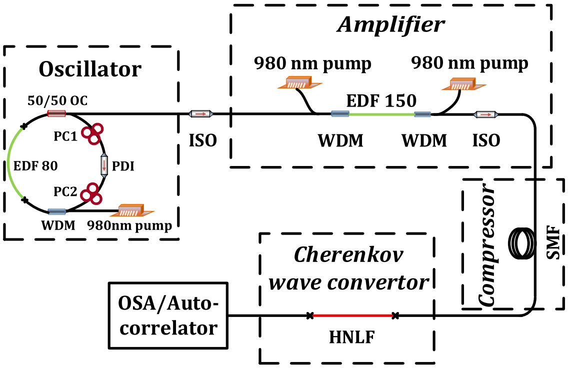

FIGURE 1. **Schematic of experimental apparatus used to generate all-fiber 920-nm femtosecond pulse source.**

The pulses propagating in the HNLF initially undergo high-order soliton compression. At maximum compression, the soliton is perturbed by high-order dispersion and emits dispersive waves with relatively short wavelengths in the normal dispersion region of the fiber [13]–[16]. This dispersive wave is also called Cherenkov radiation (CR). The CR center frequency is determined by the phase-matching condition given below [18]:

$$\frac{1}{2}\beta_2(\omega_{CR}-\omega_0)^2+\frac{1}{6}\beta_3(\omega_{CR}-\omega_0)^3=K_{NL} \tag{1}$$

where ω_{CR} and ω_0 are the CR and input pulse central frequency, respectively; β_2 and β_3 are the second and the third dispersion coefficients at the input central frequency, respectively; and $K_{NL} = 1\big/2\gamma P_0$ is a nonlinear term (γ is the nonlinear coefficient, and P_0 is the peak power of the input pulses). Higher-order dispersion terms and the Raman effect are not included.

To generate a CR pulse at 920 nm, we first analyze the relationship between the emitted CR wavelength and the ZDW of the HNLF. For simplicity, the nonlinear term in (1) is neglected temporarily. β_2 and β_3 are replaced by the dispersion parameter D and the dispersion slope S, respectively. The resulting relationship between the CR wavelength and the ZDW of the fiber is given below:

$$\omega_{CR}-\omega_0 \approx \frac{6\pi c}{\lambda_0}\frac{1}{2+\lambda_0/(\lambda_0-\lambda_{ZDW})} \tag{2}$$

Setting the center wavelength of the input pulse to 1550 nm yields the curve shown in Fig. 2. We conclude that the shorter the ZDW is, the shorter the emitted CR wavelength is. Consequently, we choose 1346 nm for the ZDW of the HNLF in the experiment. Fig. 2 shows that for a ZDW of 1346 nm, the corresponding wavelength near 1100 nm is far from 920 nm. However, consideration of the nonlinear term shows that the central wavelength of the CR pulse decreases as the input pulse power increases. Thus, a 920-nm CR pulse can be generated.

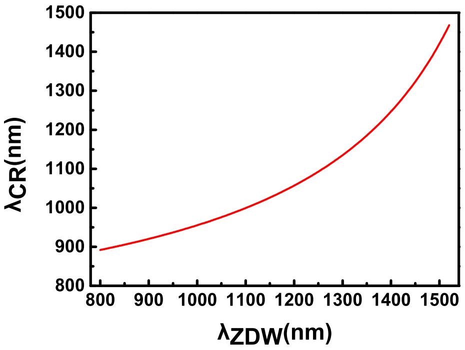

FIGURE 2. **Phase-matching CR wavelength vs zero-dispersion wavelength of a fiber.**

The output optical spectrum and the autocorrelation trace of the oscillator are shown in Fig. 3. For a pump power for the oscillator of 137 mW, the pulse is centered at 1573 nm with a 3-dB bandwidth of approximately 26 nm. The pulse duration is 1.34 ps. The blue line represents the experimental data, and the red line is a Gaussian fit. The repetition rate is approximately 42.4 MHz.

Fig. 4(a) shows that output optical spectrum of the amplified pulses. Whereas the seeding pulse has a smooth spectral profile, the amplified optical spectrum is breaded with steep

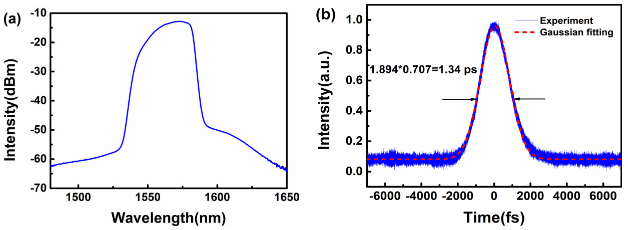

FIGURE 3. **(a) Optical spectrum and (b) autocorrelation trace of pulses.**

edges on both sides with complex structures; for instance, the dip at the top and the sidebands on the two sides indicate the occurrence of strong nonlinear effects, such as SPM, during the amplification process. Hence, the amplified pulse has a large chirp and can be compressed in the subsequent anomalous SMF. Similarly, increasing the pump power of the amplifier from 600 mW to 1200 mW increases the output power from 100 mW to 180 mW, as shown in Fig. 4(b). Accordingly, the energy of the amplified pulses ranges from 2 to 4 nJ. The variation in the oscillator pump power affects the seed pulse chirp and changes the duration of the amplified pulses.

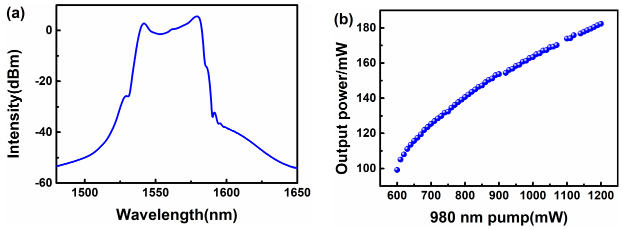

FIGURE 4. **(a) Typical optical spectrum of the amplified pulse and (b) output power of the amplifier vs 980-nm pump power.**

The pulses after the amplifier are chirped, and the measured duration is approximately 1 ps. A piece of SMF is used with the soliton-effect compression technique to further compress the pulses. Soliton-effect compression has been studied both experimentally and numerically [20]–[22]. The signal-to-background ratio of the amplified pulses is measured to be 70 dB. The matching between the input pulse parameters (the pulse energy and the duration) and the fiber length for compression [23] must be optimized to minimize the pulse duration. Changing the pump power of the oscillator and the amplifier affects the initial duration and energy of the amplified pulse, which leads to a variation in the compressed pulse duration. Fig. 5 shows the measured pulse duration for an optimized compression fiber length of 0.6 m. When the pump power of the oscillator is set between 120 mW and 150 mW, the pulse duration varies slightly at the sub-300-fs scale. Thus, we set the oscillator pump power to 137 mW, corresponding to the shortest pulse duration, as shown in Fig. 5. The corresponding average power and pulse duration directly output from the oscillator are 3.3 mW and 1.34 ps. Then, we adjust the pump power of the amplifier. The pulse duration output from the compressor can be varied at the 300-fs scale

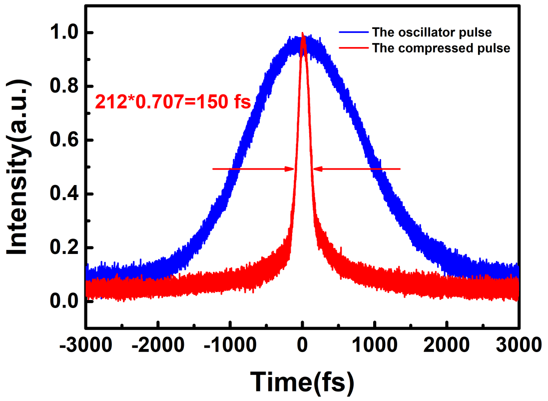

FIGURE 5. **Autocorrelation trace of the oscillator pulse (blue) and shortest compressed pulse (red).**

by increasing the pump power of the amplifier from 1000 to 1400 mW. The shortest pulse is obtained at a pump power of 1070 mW. The pulse duration output from the compressor is 150 fs with a 4-nJ single pulse energy. We inject this pulse into the HNLF to generate Cherenkov radiation.

Fig. 6 shows the Cherenkov radiation output for a pump power of 137 mW (the oscillator) and 1070 mW (the amplifier) with a 0.6-m compression fiber. Fig. 6(a) shows the output spectrum. The central wavelength of the CR pulses is 917 nm. The power at 917 nm can be calculated from OSA. The total power integrated from 750 nm to 1650 nm is 29.67 mW. The power of the 917-nm bandwidth is 6.37 mW, corresponding to a single pulse energy of 150 pJ. The output power at 917 nm is 21.5% of the total output power. Fig. 6(b) shows the AC trace duration is 328 fs. Assuming a sech-profile for the pulses results in a pulse width of 232 fs. The central wavelength is 918 nm with a 3-dB bandwidth of 30 nm, which can support a sub-50-fs transform-limited pulse duration.

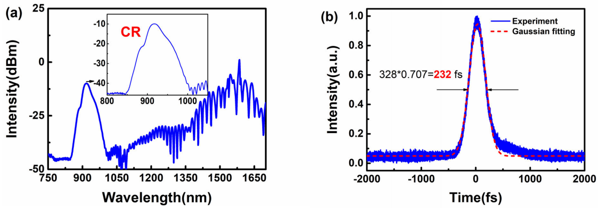

FIGURE 6. **(a) Optical spectrum and (b) autocorrelation trace of the shortest CR pulses.**

Eq. (1) shows that the central wavelength of the CR pulses can also be varied by changing the pump power of the amplifier. Fig. 7(a) shows the spectra of the CR pulses for different pump powers. The CR generation threshold occurs at a pump power of approximately 800 mW. The CR conversion efficiency grows significantly when the pump power reaches 950 mW. Thus, we set the pump power to above 1000 mW when we measure the CR output. As shown in Fig. 7(b), the pump power of the amplifier can be increased

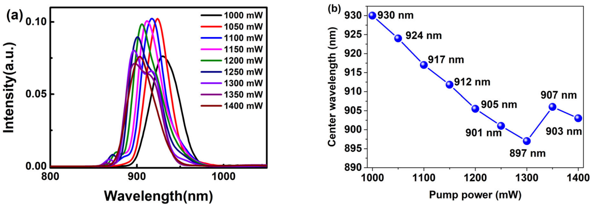

FIGURE 7. **(a) Optical spectrum and (b) central wavelength of CR pulses.**

from 1000 mW to 1200 mW to tune the central wavelength of the CR pulses over 905-930 nm. At the same time, there is no noticeable change in the pulse duration while tuning the central wavelengths. The kink at 1300 mW probably results from HNLF loss at short wavelengths.

III. CONCLUSION

In conclusion, we have presented a very simple approach to create a 920-nm femtosecond laser source. The pulses outputted from a homemade mode-locked fiber laser are amplified by an Er-doped fiber amplifier and then compressed by a piece of single mode fiber. These compressed pulses are injected into a 5-cm-long HNLF to generate CR. We observe pulses with a 150-pJ single pulse energy, a 232-fs pulse duration and a 918-nm central wavelength. This simple and cost-effective femtosecond fiber laser has considerable potential for bioimaging.

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KAI QIAN received the M.S. degree in optics from Anhui University, Hefei, China, in 2001, and the Ph.D. degree in optics from Shanghai Jiaotong University, Shanghai, China, in 2007. From 2012 to 2013, he was a Postdoctoral Fellow with CORIA (CNRS-UMR6614), Saint Etienne du Rouvray, France. He is currently an Associate Professor with the School of Advanced Materials and Mechatronic Engineering, Hubei Minzu University, Enshi, China. His current research interests include slow and fast light and ultrafast fiber lasers, as well as fiber sensors.

HAO LUO received the Ph.D. degree from Shanghai Jiaotong University, Shanghai, China, in 2017. He is currently an Optical Engineer with Nanjing Movelaser Company Ltd. His current research interests include ultrafast fiber lasers and coherent wind lidar.

DA QIU received the master's degree from Wuhan University, Wuhan, China, in 2011. He is currently teaches with the School of Advanced Materials and Mechatronic Engineering, Hubei Minzu University, Enshi, China. His current research interests include fiber lasers and fiber Bragg gratings.

SHENGLI PU received the Ph.D. degree from Shanghai Jiao Tong University, in 2006. From August 2012 to August 2013, he was a Visiting Associate Professor with Cornell University. He is currently a Professor with the College of Science, University of Shanghai for Science and Technology. He has coauthored over 100 peer-reviewed articles in physics and optics. His research interests include advanced photonic materials and devices, especially the novel optical properties and photonic applications of magnetic fluids/ferrofluids.

WENCAI YAO is currently pursuing the master's degree with Hubei Minzu University. His research interests include fiber sensors and fiber lasers.

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