Eye-safe, single-frequency pulsed all-fiber laser for Doppler wind lidar

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A single-frequency pulsed erbium-doped fiber (EDF) laser with master-oscillator power-amplifier configuration at 1 533 nm is developed. A short-cavity, erbium-doped phosphate glass fiber laser is utilized as a seeder laser with a linewidth of 5 kHz and power of 40 mW. The seeder laser is modulated to be a pulse laser with a repetition rate of 10 kHz and pulse duration of 500 ns. The amplifier consists of two pre-amplifiers and one main amplifier. The detailed characteristics of the spectrum and linewidth of the amplifiers are presented. A pulse energy of 116 μJ and a linewidth of 1.1 MHz are obtained. This laser can be a candidate transmitter for an all-fiber Doppler wind lidar in the boundary layer.

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A coherent Doppler lidar has been proven to be a powerful tool to measure wind in low troposphere with high altitude resolution and high speed accuracy. Conventional ground-based Doppler lidar uses high-energy pulsed laser, such as 1.06-μm Nd:YAG or 2.02-μm Tm, Ho:YAG laser, a large aperture telescope, and a separate transceiver optical component. For a portable, mobile, and airborne application, a compact, eye-safe, and rugged coherent Doppler wind lidar is required. The all-fiber pulsed Doppler wind lidar has attracted attention because of its maintenance-free, lightweight, high efficiency, and good beam qualities[1,2]. An eye-safe, narrow-linewidth local oscillator and a single-frequency pulsed fiber amplifier with a high repetition rate are necessary for an all-fiber Doppler wind lidar[3]. An all-fiber Doppler lidar to measure wind field up to a 1-km altitude is currently being developed by our group. Therefore, a single-frequency, polarization-maintaining, pulsed fiber laser with an energy of higher than 100 μJ and a narrow linewidth of less than 1.3 MHz is required to develop an all-fiber Doppler wind lidar.

Philippov *et al*. reported an erbium-ytterbium co-doped fiber (EYDF) master-oscillator-power-amplifier (MOPA) system with a space-coupling power amplifier stage; 0.29-mJ and 100-ns pulses with a repetition rate of 4 kHz were obtained[4]. Shi *et al*. presented a single-frequency fiber laser at 1 550 nm with an output energy of 52 μJ and a linewidth of 5 MHz using a Q-switched seeder and the MOPA[5]. Canat *et al*. introduced a narrow linewidth erbium-ytterbium fiber MOPA for coherent detection lidars; the seeder laser was a distributed feed back (DFB) diode laser with a linewidth of 500 kHz, and the fiber is a pedestal and multifilament core erbium-ytterbium large mode area (LMA) fiber[6]. Another single-frequency fiber laser with the MOPA configuration was also presented[7,8]. In a previously reported result, most all-fiber single-frequency lasers use the commercial DFB laser as seeder with a linewidth of greater than 500 kHz and an energy of less than 100 μJ. Thus, both the linewidth of the local oscillator and the pulse energy are not optimized in the all-fiber Doppler lidar. In this letter, we develop a narrow-linewidth, polarized, pulsed fiber laser with an energy of greater than 100 μJ and a local laser linewidth of less than of 10 kHz at an eye-safe wavelength.

The experimental setup of the polarization maintaining (PM) all-fiber MOPA laser system is shown in Fig. 1. The seeder laser is split into two beams. One beam is taken as the local oscillator, and the other seeder beam is modulated as a pulsed laser and amplified by two pre-amplifiers and one main amplifier.

The seeder laser was developed in our laboratory. It was made of a high concentration of doped erbium, ytterbium, and phosphate glass fiber laser with a gain coefficient of 4.2 dB/cm. The cavity consisted of a half reflective (HR) mirror and a fiber Bragg grating (FBG) output coupler. The output laser was polarized by a polarizer controller. The PM output power was 30 mW with a linewidth of less than 5 kHz at 1 533 nm, and the detailed characteristics of the seeder laser were published[9]. An isolator was inserted between the seeder and the beam split coupler. The seeder beam was split into two beams by a 10/90 fiber coupler. One beam with 10% of the seeder power was taken as the local oscillator of the developing coherent lidar. Another beam with 90% of the seeder power was directly modulated to a square-shaped waveform with a high-pulse repetition rate by an acousto-optic modulator (AOM) (AMF-55-1550-2FP(+),
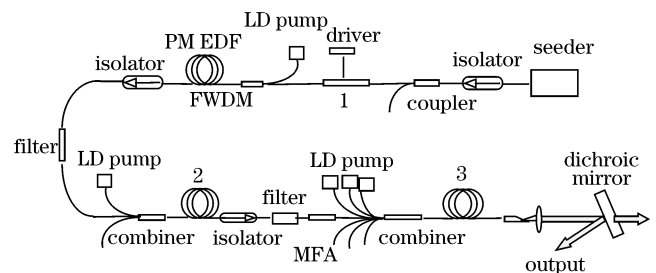

Fig. 1. Experimental setup of the MOPA fiber laser system. LD: laser diode; MFA: mode field adaptor; 1. acousto-optic modulator (AOM); 2. PM double-clad EYDF; 3. LMA PM double-clad EYDF.

Brimrose, USA). The pulse duration was 500 ns, and the repetition rate was set to 10 kHz, as shown in Fig. 2. The average output of the pulsed seed was 40 μW, and the peak power reached 12 mW because the AOM insertion loss was 2.5 dB. This modulator produced a frequency shift of 55 MHz, which served as the heterodyne coherent detection intermediate frequency.

The first pre-amplifier was a 1.4-m PM erbium-doped single-mode fiber with a peak absorption of 55 dB/m at 1 530 nm. It was pumped by a single-mode, fiber-coupled diode laser with a power of 200 mW at 976 nm through a filter wavelength division multiplexer (FWDM). A narrow-pass band filter with 0.8-nm bandwidth was used to suppress the forward propagating amplified spontaneous emission (ASE). An isolator with a 58-dB isolation was inserted between two pre-amplifiers. In the second pre-amplifier, a 3.3-m-long PM 7/130 erbium-ytterbium-doped double-clad fiber with a peak absorption of 38 dB/m at 1 530 nm was used. The double-clad fiber was pumped by a diode laser through a fiber combiner. The pump diode laser operates at a wavelength of 976 nm with a maximum power of 4 W through a 105-μm-diameter fiber. Following the second pre-amplifier, a filter and an isolator were also used to limit the output spectrum and back propagation laser or ASE. Although the erbium-ytterbium fiber was highly absorbed at 1 530 nm, the population inversion by pump laser at 976 nm restrainsed the absorption at 1 530 nm, and the signal at 1 535 nm induced the radiation at 1 535 nm from the level structure. This problem is similar to that with the ytterbium fiber in the amplifier working at 1 064 nm[10].

Typically, the peak power in a fiber amplifier is limited
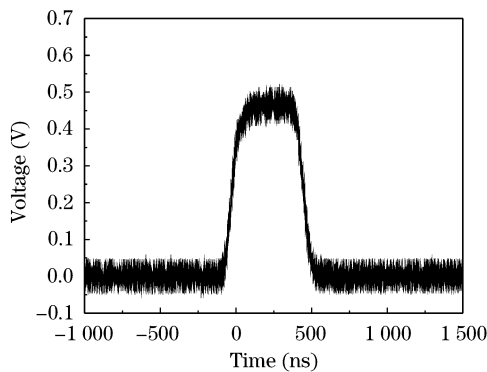

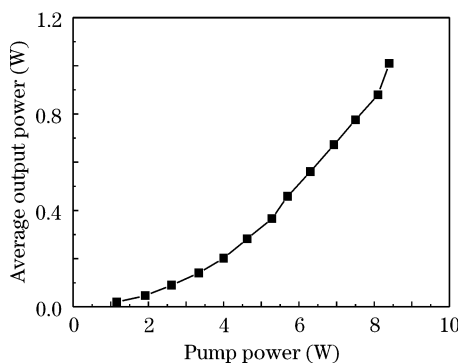Fig. 2. Pulse shape of the pulsed seeder laser.

Fig. 3. Average output power of the third fiber amplifier at 1 533 nm versus pumping power at 976 nm.
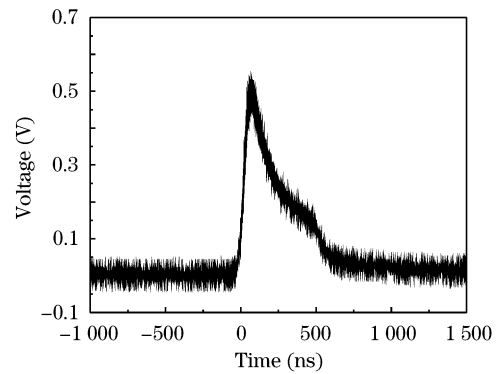

Fig. 4. Pulse shape of the main amplifier output.
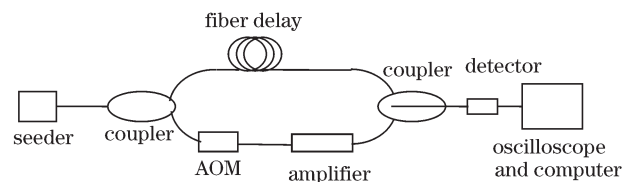

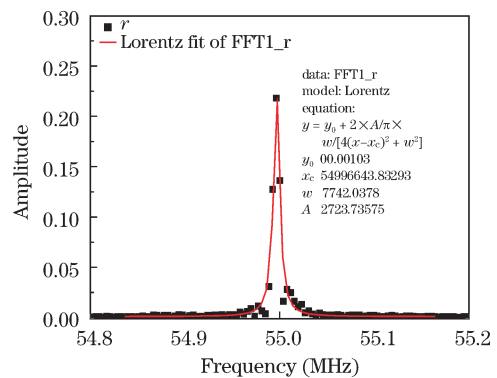Fig. 5. Linewidth measurement setup of the fiber laser.

Fig. 6. Linewidth of the CW seeder.

by the stimulated Brillouin scattering (SBS), especially in a narrow linewidth laser[11−13]. A solution to avoid SBS is the use of a larger mode fiber. Therefore, a 6-m-long erbium-ytterbium co-doped PM LMA double-clad fiber with a 25-μm core, 300-μm cladding diameter, and 0.1 numerical aperture (NA) is used as the main amplifier. With the lower NA of the LMA fiber, the fiber can reduce the mode number to obtain good beam quality required in a coherent Doppler lidar. The cladding pump absorption coefficient of the fiber at 975 nm is 3.4 dB/m. Three diode lasers are operated at the wavelength of 976 nm with maximum power of 4 W through a 105-μm fiber coupling into the LMA fiber by a (6+1)×1 fiber combiner. The output laser beam from this LMA double-clad fiber is collimated by an aspheric lens and a dichroic mirror is used to filter the pump laser.

The average power of the pulsed seeder is around 40 μW after the acousto-optic (AO) modulation, and the pulse duration is 500 ns, as shown in Fig. 2. The average output power of the first pre-amplifier is 4 mW, which corresponds to the 20-dB gain. The second pre-amplifier
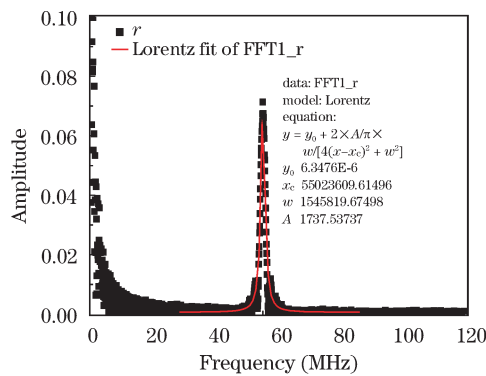
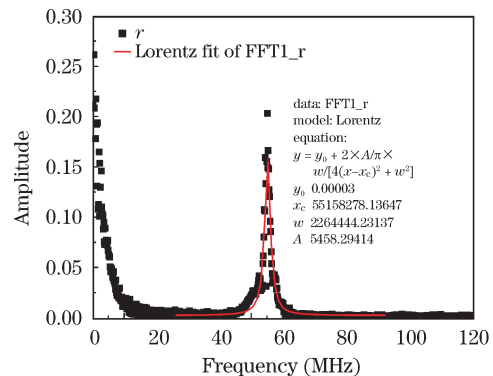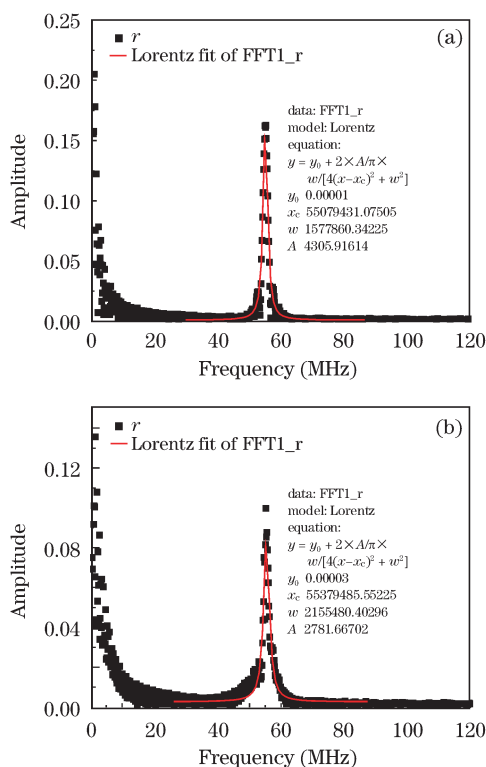Fig. 7. Frequency spectrum measurement of the pulsed seeder.

Fig. 8. Linewidth of the (a) first- and (b) second-stage pre-amplifiers.

output is 258 mW with a gain of 18 dB. Figure 3 shows the output power of the main amplifier with different pump powers. The maximum power as high as 1.16 W at a pulse repetition rate of 10 kHz is obtained under the pump power of 8.4 W. The output power is linear with the pump power, and the slope and opt-opt efficiency is 15.7% and 13.8%, respectively. The pulse energy is about 116 μJ. The pulse waveform is shown in Fig. 4. The bottom of the pulse has a width of 500 ns, but the top is inclined. The raised edge of the pulse becomes sharp because the front part of the pulse consumes more high-level inverted population and obtains more gain than the posterior.

Figure 5 is the setup used to measure the linewidth of the fiber laser using the heterodyne beating method[14]. The local oscillator is coupled into a 30-km single-mode fiber, which beats with the output of the amplifier. An

Fig. 9. Linewidth of the third-stage amplifier.

InGaAs detector is used to capture the beat signal.

According to the analysis of Richter *et al.*[15], the delay line used is a 30-km-long ordinary single-mode communication fiber, the resolution of which can reach 3 kHz. The beating signal is acquired by a high-speed digital oscilloscope. The frequency spectrum analysis is implemented to obtain the linewidth of the amplifier.

The fast Fourier transform (FFT) spectrum of the beating signal is fit by the Lorentz function. The linewidth of the continue-wave (CW) seeder laser is initially analyzed. The linewidth of the CW seeder laser is about 4 kHz, as shown in Fig. 6. However, after the modulation, the linewidth of the pulsed seeder laser is analyzed to be 800 kHz, as shown in Fig. 7, which corresponds to the Fourier transfer limitation of the pulse width.

The output laser of the three-stage fiber amplifier system is analyzed. The FFT spectrum of the seeder is shown in Fig. 7. Figures 8(a) and (b) present the FFT spectrum results of the two pre-amplifiers, which are 900 kHz and 1 MHz, respectively. The linewidth of the power-amplifier stage is 1.1 MHz. Compared with the pulsed seed injected to the amplifier, the linewidth of the output laser from the three-stage amplified laser system slightly broadens from 0.8 to 1.1 MHz, as shown in Fig. 9, which may lead to a slightly narrower pulse duration of the amplifier and the long-term instability of the seed or phase noise[16]. Frequent stability may be an effective way to overcome this problem.

In conclusion, an erbium-ytterbium co-doped PM LMA double-clad fiber is utilized to establish a compact all-fiber MOPA laser system. It operates in an eye-safe region at 1 535 nm, with pulse energy of 116 μJ, 10-kHz pulse repetition rate, and 500-ns pulse duration. The linewidth of the seeder laser and the pulse laser is about 5 kHz and 1.1 MHz, respectively. The all-fiber single-frequency pulse laser can meet the requirements of a portable coherent Doppler wind lidar.

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