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Environmental measurement of atmospheric wind field based on a 1.5 μm all-fiber lidar source

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In this paper, we propose a 1.5 μm all-fiber lidar system for atmospheric wind field measurements. The lidar emission source adopts the master oscillator power amplifier 1532 nm single-frequency all-fiber structure with a repetition frequency of 10 kHz. The lidar output energy is 427 μJ, and the maximum peak power is 610 W at the pulse width of 700 ns. The system utilizes Doppler wind speed coherent measurement technology, and the lidar source modulates an 80 MHz intermediate frequency carrier. The maximum longitudinal height signal distance of the lidar system is 4.5 km for atmospheric wind field, and the measurement accuracy can be within the range of 10^{-2} level. The lidar system can be used to detect high-altitude or long-distance high-precision wind field information. At the same time, the system can play an important role in future atmospheric environment engineering research.

Keywords: fiber laser, lidar, coherent Doppler measurement, wind field, vertical measurement.

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Fiber lasers have characteristics of compact structure, portable weight, excellent beam quality, stability, and maintenance-free [1,2]. In the field of atmospheric remote sensing, fiber laser can be used as a lidar emission source to provide a stable laser output. The C-band is one of the main bands of atmospheric measurements, and fiber laser sources possess powerful atmospheric transmission in the C-band [3]. In the lidar atmospheric wind field measurement system, the lidar adopts an all-fiber emission source with excellent performance, which can measure atmospheric environment information to a greater degree. In atmospheric wind speed measurement research, coherent Doppler lidar wind speed detection technology possesses high precision and resolution, which can effectively and objectively evaluate the atmospheric environment [4,5]. This form of coherent detection requires narrow laser linewidth and long pulse duration ($>$ 100 ns) to enhance the coherence length and meet the energy budget [6]. The quality of the lidar source is particularly important in lidar atmospheric measurements.

In recent years, Jia et al. developed a 1550 nm wind measurement lidar that adopted the master oscillator power amplifier (MOPA) structure, with a repetition frequency of 10 kHz. The lidar pulse energy was 120 μJ at a pulse width of 400 ns, with a maximum longitudinal detection range of 3.6 km, and the wind speed accuracy was 0.5 m/s [7]. In 2017, Zhou et al. developed a 1550 nm all-fiber erbium-ytterbium co-doped fiber amplifier (EYDFA) wind lidar, with a repetition frequency of 10 kHz. The lidar pulse energy was 150 μJ at a pulse width of 200 ns, and the lidar wind speed horizontal detection range was $<$ 10 km [8]. In 2018, Abdelazim, Santoro, et al. developed a 1.5 μm all-fiber wind sensing Coherent Doppler Lidar (CDL) system, with a pulse repetition frequency of 20 kHz. The lidar pulse energy was 14 μJ at a pulse width of 200 ns, and the lidar wind speed horizontal detection range was 3 km [9]. In 2019, Augere, Valla, et al. developed a 1.5 μm fiber three-dimensional wind profiling lidar, with a pulse repetition frequency of 14 kHz. The lidar used EYDFA emission source, and the pulse energy was 410 μJ at a pulse width of 700 ns. The lidar wind speed horizontal detection resolution range was 3 km [10]. In 2021, Meng, Pedersen, et al. developed a 775 nm novel continuous wave (CW) direct detection lidar (DDL) and a 1.5 μm CW coherent detection lidar (CDL). The lidar power was 300 mW, and the lidar high wind speed detection range was 40 m [11]. In 2022, Yue, Yu, et al. developed a 1.5 μm lidar system incorporating differential absorption lidar (DIAL) and coherent Doppler wind lidar (CDWL). The lidar used EYDFA emission source. The lidar pulse energy was 80 μJ, with a pulse repetition frequency of 5 kHz. The Lidar system can detect atmospheric CO_2 concentration within 6 km of the transverse atmospheric wind field [12]. In summary, the excellent lidar source can be further enhanced or improved comprehensive performance in atmospheric wind field information measurements.

The 1.5 μm lidar wind measurement system comprised three main parts: the emission, reception, and processing

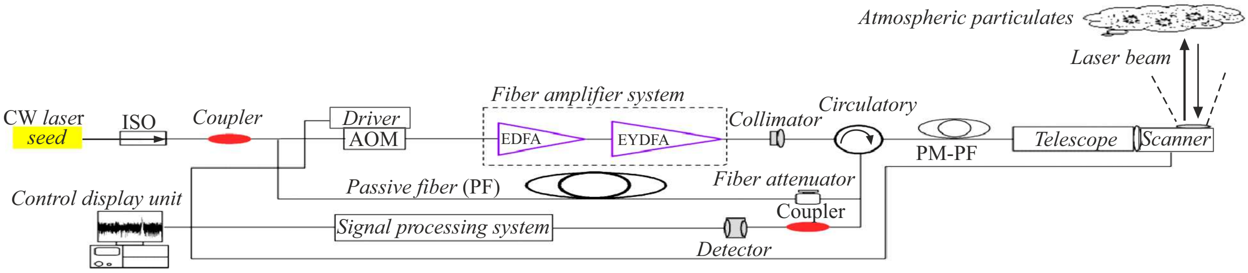

Figure 1. Lidar atmospheric wind field measurement system.

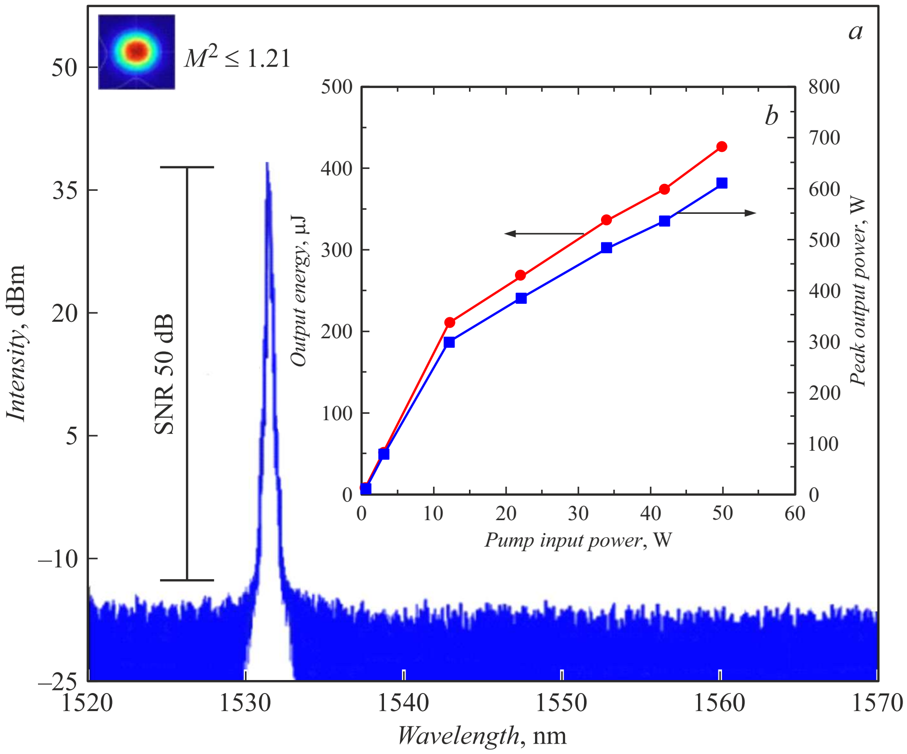

Figure 2. *a* — lidar source output spectrum; *b* — lidar source output energy and power.

components, as shown in Fig. 1. The emission component was the lidar fiber emission source. The distributed feedback (DFB) single-frequency continuous lidar source (the local oscillator) amplified the signal beam by an acousto-optic modulator (AOM) pulse. The fiber amplifier system used a combination of pre-amplification erbium-doped fiber amplifier (EDFA) and main amplification EYDFA. The beam signals are transmitted through the optical antenna, the collimator, and the polarization-maintaining passive fiber (PM-PF). The reception component (the optical antenna) used a Kepler expanding telescope to expand the laser beam, and the signals are scanned into the atmosphere by an optical rotary prism. The echo signals of the atmospheric Doppler measurement entered the lidar transmitting window (the optical antenna) and reached the fiber circulator. The echo signal beam and the local oscillator beam (10%) have been producing combined frequency (coherent beat frequency) when entered the balanced photodetector (InGaAs/PIN, DC-350 MHz). The detector outputs coherent differential frequency signals to the signal processing system. Finally, the signal processing system calculated the wind speed information by the fast Fourier transform (FFT) algorithm.

The lidar system seed source was a 1532 nm DFB single-frequency CW laser. The lidar seed source output power is 50 mW and the line width is < 2 kHz, and 90% of seed power was amplified. The seed signals were modulated by AOM, with a repetition frequency of 10 kHz and a pulse width (PW) of 700 ns. The seed pulse signal beam was amplified by a 976 nm pump light. The lidar source peak power was 74 W and the pulse energy of 52 μJ at pre-amplification. The lidar peak power was 610 W and the pulse energy of 427 μJ at main amplification. Moreover, the lidar source used water-cooled heat dissipation to

The main parameters of lidar system

Parameters	Symbol	Value
Measuring range	L	0-5 km
Central wavelength	λ	1532 nm
Pulse energy	E	427 μJ
Repetition frequency	f_p	10 kHz
Intermediate frequency	IF	80 MHz
Antenna efficiency	η_a	0.422
Total system efficiency	η_{total}	0.61
Atmospheric transmissivity	T	0.7 dB/km
Scattering coefficient	β	$5 \cdot 10^{-6}$–$10 \cdot 10^{-6}\,\mathrm{m}^{-1} \cdot \mathrm{sr}^{-1}$
Beam truncation ratio	p_T	0.832
Bandwidth of detector	B	250 MHz

maintain the stability of the single-frequency lidar in long-term working. The lidar source spectrum output was stable, and no noise was observed for the non-linear SBS and ASE. The lidar source center wavelength was 1532.35 nm, with a spectral SNR of 50 dB and a signal beam quality factor of $M^2 \leq 1.21$, as shown in Fig. 2, *a* and *b*. In atmospheric measurements, as a result of the weakness of the echo signals, the detection range was relatively small, and the wind speed error in atmospheric environment detection was relatively large. Moreover, the detection ability for echo signals at different atmospheric heights was different. Therefore, it was necessary to accumulate detection quantity to improve the echo signal intensity and detection range. Echo signal quantities were collected by Doppler frequency non-coherent-integration superposition to further improve the SNR of lidar measurements. This was conducive to reconstructing atmospheric wind field information, as shown in Fig. 3.

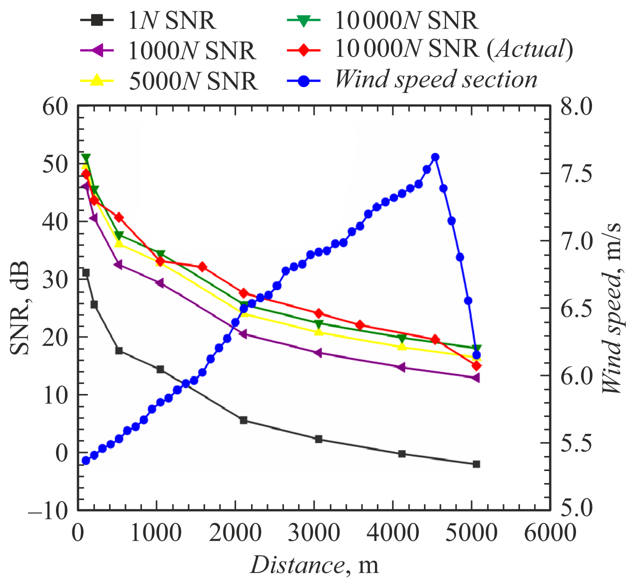

Figure 3. Lidar system SNR and wind speed.

As a result of the atmospheric environment complex changing, the echo signals were relatively weak. The power and energy of the echo signals gradually decreased as the detection range increased. The main measurement parameters of the lidar system, as shown in Table. In the optical system with high transmission efficiency and stable parameters, the lidar had a better ability to receive echo signals. The Lidar atmospheric measurement range was 5 km (48 range gates), and the unit range gate was 105 m. To further enhance the overall detection performance of the lidar system, the SNR was increased through accumulated processing of echo signal quantities, which gradually enhanced detection performance. The SNR accumulated maximum growth rate was 1000N, and the accumulated minimum growth rate of the SNR was reduced to 5000N–10 000N. This phenomenon can be explained as follows: on the one hand, the detection distance affected the SNR and echo signals power; on the other, the increase in echo sampling data and the accumulated echo signal quantities, and the limited hardware computing ability of system caused the SNR change rate to decrease. Therefore, detecting the probability density and restoring the wind field information were enhanced with cumulative quantities of echo signals to increase. The SNR of the accumulated (10000N) echo signals was 18–51 dB, which is a 20 dB enhancement per unit (1N) SNR. As regards assessing the lidar system, the measurement error was also one reliable method that was evaluated. The measurement error was inversely proportional to the accuracy of the system. The lidar signal sampling frequency was 500 MHz, with a signal processing quantity of 1024 points. The furthest measurement error was less than the unit resolution error, so the actual measuring signals were close to the real information concerning atmospheric wind speed. The accumulation of echo signals ranged from 1369N to 10 000N, with a measurement accuracy of up to 10^{-2} level. The wind speed resolution of the lidar was 0.37 m/s. The lidar can be used for atmospheric measurements in full-time. In our experiment, we measured the longitudinal wind field and atmospheric environment of the inner city of Tianjin, China in the day on May 4th, 2022.

We observed that the lidar SNR was reduced as the detection distance increased. The variation trends from the real-world data and the theoretical values were essentially coincident. After 4.5 km, the actual SNR became different from the theoretical value, and the actual SNR exhibited a larger deviation. The main reasons for this are as follows: on the one hand, only few lidar long-distance echo signals entered the lidar antenna aperture as detection distance increased, so relatively few echo signals were accumulatively processed; on the other, there was not much particulate matter (PM) as atmospheric longitudinal altitude increased, so the echo signals were a low intensity. Finally, the echo signals were weak at long distances (longitudinal altitude), and the noise signals (atmospheric stray light noises, detector current noise, etc.) were relatively large, so the echo signals were distorted. The detected distance was greater than 4.5 km, with dominant noise signals and sudden wind speed changes. The actual average wind speed range measured by the lidar system within the longitudinal height range of 4.5 km was 5.37 to 7.61 m/s. The actual results were in line with the weather forecast wind speed range for the day.

Conflict of interest

The authors declare no conflict of interest.

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