All fiber pulsed coherent lidar development for wind profiles measurements in boundary layers

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An all fiber pulsed coherent Doppler lidar (CDL) system at 1.54 μm wavelength is developed for wind profiles measurements. This lidar affords 43.0-μJ pulse energy at 10-kHz pulse repetition frequency with 500-ns pulse width. The lidar is operated in monostatic mode with 50-mm diameter telescope. The heterodyne mixing signals are acquired with 500 M/s analog to digital converter and 2048 points fast Fourier transform (FFT) is implemented. Line of sight wind speeds are measured with more than 3.0-km range in a horizontal direction and about 1.9 km in the vertical direction with 75-m range resolution. Systematic error of speed measurement of 0.2 m/s is validated.

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Coherent Doppler lidar (CDL) systems have been developed to measure atmospheric wind velocity for many years[1,2]. They are proved to be effective tools for wind profiles measurement[3−5], windshear and wake vortices detection[6] and warning in clear air condition with high temporal and spatial resolution and high accuracy. All-fiber CDL system[7,8] has attracted much attentions because of eye safe wavelength, compact size, flexible arrangement, and using mature fiber components from telecommunication industry. The CDL transmitter is divided into two categories: high pulse energy laser with low repetition rate[9] and low pulse energy laser with high repetition rate[10]. Fiber laser has the advantages of high repletion rate and narrow linewidth, and is acted as the preferred laser source for short- and medium-range CDL system[11]. Kameyama *et al.*[12] developed an all-fiber CDL system for wind measurement at 1.5 μm with 1-km range and 150-m range resolution. A CDL system with 50-m range resolution and 0.2-m/s velocity accuracy was developed to measure wind speed to 2000-m range by Cariou *et al.*[13,14]. Fiber laser transmitters at 1.5 μm were recently developed for atmospheric sounding[15−17].

The schematic diagram of the CDL system is shown in Fig. 1. The CDL system is composed of a transceiver, a heterodyne detection unit, and a signal processor. The main parameters of the system are given in Table 1. Polarization maintaining (PM) fibers are applied in all CDL fiber components to ensure the high heterodyne efficiency. The transceiver consists of a laser seeder, a 5/95 splitter, an acousto-optic modulator (AOM), multi-stage fiber amplifier, an optical circulator, and a telescope. Special laser pulse shape and heterodyne intermediate frequency (IF) are achieved through the AOM simultaneously. The telescope connected to the fiber end of the circulator port 2 can be rotated around a specific position with rotation angel α ($0 \leqslant \alpha \leqslant \pi/2$). The heterodyne detection unit is composed of a 50/50 coupler, a balanced detector, and an amplifier. The signal processor consists of an analog to digital converter (ADC) acquisition card and personal computer (PC) based software platform.

Table 1. Main Parameters of the CDL System

Parameters	Value
Wavelength	1540 nm
PRF	10 kHz
Pulse Energy	43.0 μJ
Pulse Width (FWHM)	500 ns
Telescope Aperture	50 mm
IF	56.2 MHz
Detector (PDB130C, Thorlabs)	Balanced Detector, InGaAs
Analog to Digital Signal Acquisition (CSE21G82G, GAGE)	500 M/s, 8bit
ADC Sampling Length	40 μs
Pulse Spectrum Accumulation	3000–18000
Range Resolution	75 m

The homemade seeder laser outputs 30-mW power with a linewidth of less than 5 kHz at 1540 nm[18]. The seeder is modulated by AOM and amplified by multi-stage fiber amplifier, as described in detail in Ref. [19]. The laser pulse shape and pulse repetition frequency (PRF) are adjusted by the AOM driver, where the pulse duration is 500 ns and the PRF is 10 kHz. The CDL system is operated in monostatic condition. The telescope diameter is 50 mm with 200-mm focal length. The transmitted beam could operate in collimation or focusing mode through adjusting the fiber end position. The fiber end is polished with 8° tilt angle to reduce back reflected laser pulse influence. About 5% of the seeder laser is split to be local oscillator for optical coherent mixing. A PM circulator is utilized to separate atmosphere scattering signal from transmitting laser pulse. The scattering signal then enters the 50/50 PM coupler and mixes with the local oscillator laser in the heterodyne detection unit.

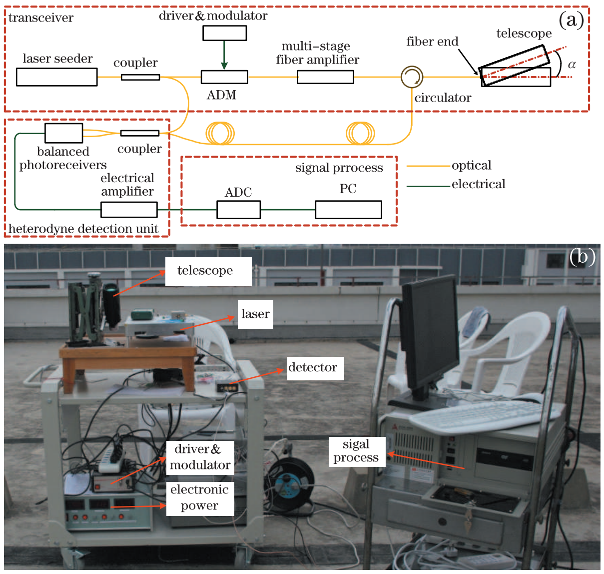

Fig. 1. (Color online) (a) Schematic diagram and (b) prototype of the CDL system.

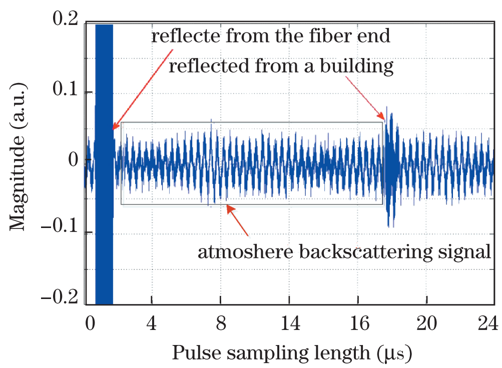

Fig. 2. (Color online) Single sampled CDL heterodyne mixing signal with fiber reflected signal, atmospheric backscattering signal, and hard target reflected signal inside.

The ADC sampled signals are stored in the PC hard disk for offline data processing. Because of memory and transfer rate limit, only 40 pulses backscattered signals are sampled per second, although the laser PRF is 10 kHz. It needs more than 3 GB of disk space and about 7 min for acquiring 18000 pulses. An field-programmable gate array (FPGA) based real-time signal processing board is being developed to acquire the mixing signal and implement fast Fourier transform (FFT) power spectrum processing simultaneously. For each pulse, the ADC sampling time is 40 μs and the time range gate is 500 ns, corresponding to 6-km maximum measurement range and 75-m range resolution respectively. The nearest effective measurement range of the lidar is 75 m, which is induced by backscattered or reflected signal from fiber end and telescope optics. The signal processing program includes range gate slicing of sampling signal, 2048 points FFT algorithm, spectrum accumulation, noise spectrum correction, frequency calculation of peak power spectrum, line of sight (LOS) wind speed retrieval, and so on. The signal to noise ratio (SNR) is improved through FFT power spectra accumulation method with about 3000 or more pulses accumulated.

For the CDL system, the stability of IF is important to calculate accurate Doppler frequency shift and is measured with heterodyne mixing method. The backscattered light from the fiber end of the circulator is employed to monitor the stability of the IF signal. Through 2048 points FFT, the IF is measured to be 56.18 MHz with standard deviation of 0.033 MHz. And the IF is also stable with the environment temperature variations of $\pm 10°$. A hard target speed is measured to validate the accuracy of the CDL system. Single sampled heterodyne mixing signal is show in Fig. 2. The strongest echo is reflected from the fiber end. Another strong echo in the end is reflected from a building about 2500-m range away. The signals between the two strong echoes are scattered by aerosols in the atmosphere. Retrieved LOS speed profiles are illustrated in Fig. 3 with 3000-pulses accumulated. The calculated wind and hard target speed profiles and the corresponding power spectrum density (PSD) are given in dash line and solid line respectively. The speed of the hard target is measured to be -0.2 m/s, so the systematic error of speed measurement of less than 0.2 m/s is validated.

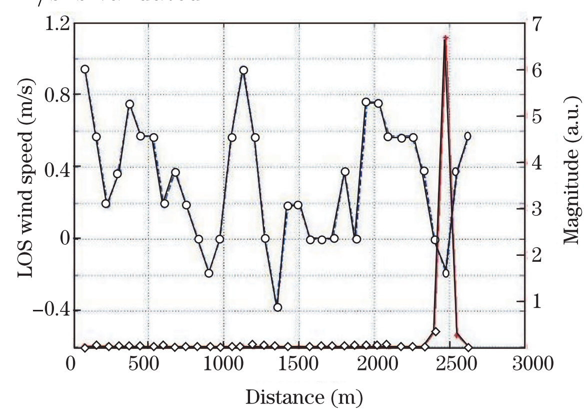

Fig. 3. (Color online) LOS speeds measurement of wind and hard target with 3000 pulses spectra accumulated. Relative signal power profile is also shown with peak power at hard target range.

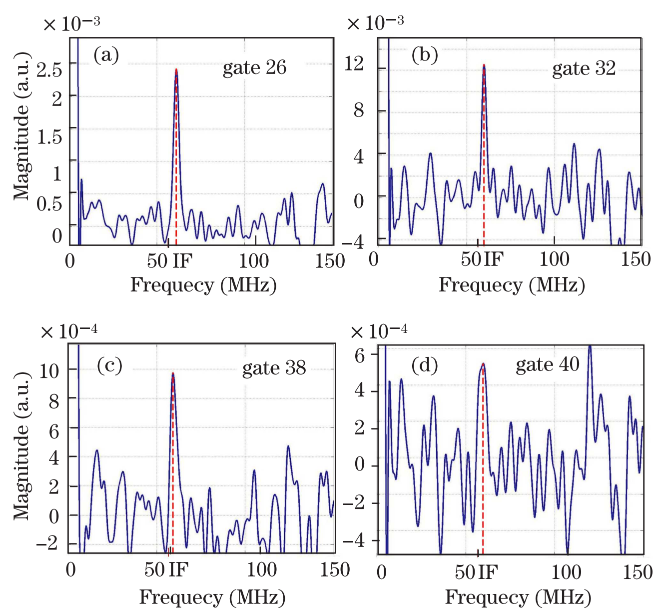

Fig. 4. (Color online) LOS wind speed power spectra at several different range gates with Doppler shifted frequency peak around IF (56.18 MHz) and 3000 pulses accumulation. The distances are (a) 1950, (b) 2400, (c) 2850, and (d) 3000 m.

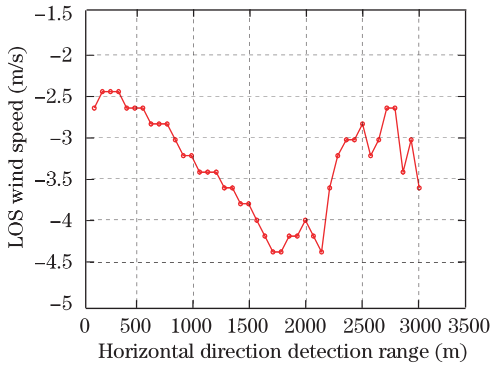

Fig. 5. (Color online) LOS wind profile at 20° elevation in the horizontal direction with 3000 pulses accumulated.

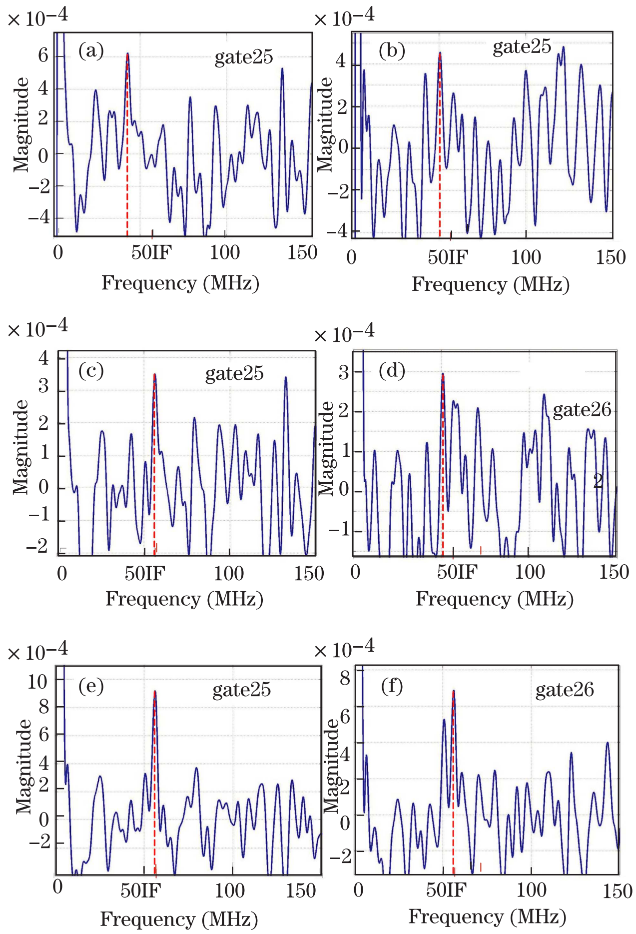

Fig. 6. (Color online) LOS wind speed FFT power spectra at several range gates in the vertical direction. The detection distance and accumulated number are (a) 1875 m, 3000 pulses; (b) 1950 m, 3000 pulses; (c) 1875 m, 9000 pulses; (d) 1950 m; 9000 pulses, (e) 1875 m, 18000 pulses; (f) 1950 m, 18000 pulses, respectively.

The CDL measurement range depends on aerosols concentrations. About 3000 pulses are used for the LOS wind speed measurement in a horizontal direction at 20° elevation. Figure 4 shows the FFT power spectra of LOS wind speed with 75-m range resolution at some reference distances of 1950, 2400, 2850, and 3000 m with 3000-pulses accumulated. The calculated LOS wind speeds profile within 3000-m range is shown in Fig. 5. We can see that the SNR is decreasing with increasing range.

The wind speed in the vertical direction is measured with the CDL system on the same day. However, the detection range is strictly dependent on the aerosol concentrations spread, which are attenuated quickly with altitude. To acquire high SNR of the echo mixing signal, we employ different accumulation numbers for comparisons, with 3000, 9000, and 18000 pulses respectively. At the ranges of 1875 and 1950 m, the power spectra of LOS wind speed with different accumulated pulses are shown in Fig. 6. Figure 6(a) shows a very low SNR and hard to resolute where is the Doppler frequency shift peak, especially to achieve automatic operation is unbelievable in this case. To the contrary, Fig. 6(e) shows a clear power spectrum chart. It is a contradictory that obtaining long-range wind speed in shorter time. What the pulsed accumulation number and how long the detection time needed are all dependent on the application requirements. As shown in Fig. 7, the LOS wind speed profiles in the vertical observation are presented. Usually the wind speeds are close to the true value with a longer time average. Wind speed standard errors of 3000 and 9000 accumulation pluses relative to 18000 pulses are 0.40 and 0.22 m/s respectively. Both wind speed accuracy and detection range are improved with increasing accumulated pulses. A real-time signal processor based on FPGA board is being developed to reduce the measurement time and retrieve LOS wind profiles in less than 2 s. The CDL system demonstrates good performance in short-range wind profiles measurement with high accuracy.

In conclusion, an all fiber pulsed CDL system is developed to measure wind speed at 1.54 μm with 43.0-μJ pulse energy, 10-kHz PRF, 500-ns pulse width, and 50-mm telescope diameter. The nearest range of the lidar is 75 m and the LOS wind speed profiles measurements are demonstrated with 3-km range in the horizontal direction and 1.9-km range in the vertical direction and with 75-m range resolution. Different accumulated pulses are compared to improve SNR. The systematic error of speed measurement of about 0.2 m/s is validated through hard target measurements experiment. The CDL system performance will be improved by increasing the laser pulse energy and telescope diameter with optical scanner added in future, which will show important applications for real-time wind profiles in lower atmospheric layer. We are developing real-time processing board for heterodyne

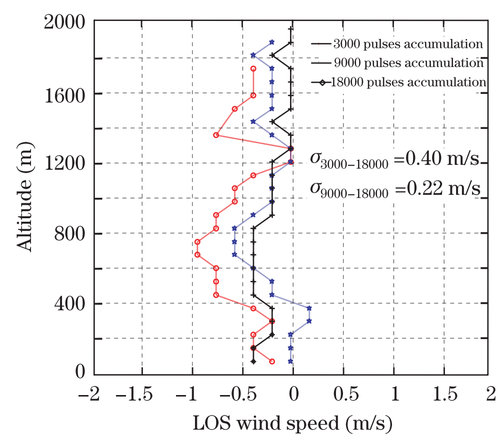

Fig. 7. (Color online) LOS wind speed with 3000, 9000, 18000 pulses accumulated in the vertical observation.

mixing signal to increase LOS wind profiles refresh rate and SNR.

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