Research on technology of 1550nm all-fiber continuous wave coherent Doppler wind lidar

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Abstract. In order to obtain the telemetry data of wind field 80 m ahead of the wind turbine, an all-fiber continuous wave coherent Doppler lidar (CW-CDL) system is demonstrated in this paper. The CW-CDL of all-fiber structure has advantages of the compact structure, good stability and low cost. However, there is inherent crosstalk in the optical circulator of the optical fiber module, the crosstalk light and the reference light enter the photon detector together to produce phase induced intensity noise (PIIN). Aiming to effectively solve the noise, we proposed a polarization control method by combining a polarization beam splitter and a quarter wave plate to reduce the PIIN in the system. The wind speed Doppler signal at 80 meters is obtained on a sunny day, and the typical signal-to-noise ratio can reach 21.7 dB.

1 Introduction

Human beings use air flow to generate wind power. which is a renewable and clean energy. We can solve the problem of energy shortage in the world by using this kind of resources reasonably [1-2]. According to the "global wind energy report 2021", the global wind power industry has set a new record in 2020: the global of new installed capacity will be 96 GW, up 53% year on year. As one of the largest wind energy markets in the world, China has higher requirements for wind farm location, wind turbine control and power curve correction. The commercial application of lidar is generally considered as the blue ocean area in the wind energy market.

Since the advent of CO₂ laser in 1970s [3], researchers began to use laser as a detection carrier to measure wind speed. With respect to wind measurement, due to its shorter wavelength, lidar is easier to obtain effective echo in clear sky than microwave wind lidar [4]. High quality laser source can determine the upper limit of lidar, and allfiber CW-CDL working at 1.55 μm has attracted much attention with the development of erbium-doped fiber amplifier (EDFA) and fiber technology. Aiming to extend the detection range of lidar, researchers usually use fiber or semiconductor laser and EDFA to form the main oscillator power amplifier (MOPA) as the detection light source of lidar [5-6], which improves the detection range of lidar system. All-fiber CW-CDL structure using 1.55 μm laser has some special advantages [7-8], such as high maximum allowable exposure of human eye, simple structure, low cost of key devices, good reliability and stability of all-fiber structure, etc. However, this kind of lidar exists some disadvantages. The main disadvantage is that the fiber device will introduce multiple stray light

sources, such as the crosstalk of the circulator, polarization controller, and the reflection of angled physical contact (APC) end face. The above stray light source will introduce PIIN [9-10] into the beat signal, and excessive PIIN will reduce the signal-to-noise ratio (SNR) of the system, resulting in the loss of lidar data in practical application.

Generally, when the optical path difference (OPD) between stray light and reference light is significantly shorter than the coherence length of the laser, the PIIN will appear as white noise in the signal spectrum. What's more serious is that, PIIN often exceeds other noises and becomes the main factor restricting system performance. To reduce the PIIN, P. Rodrigo et al. reported a polarization control method based on single-mode fiberbased optical path in 2010 [11]. In this method, the polarization states of the backscattered light and the reference light are rotated 90 degrees relative to the stray light, and then they are sent to the detector for detection. However, the report does not use balance detection, which will limit its use in weak signal detection scenarios. In addition, methods such as antireflective (AR) coating on the surface of optical devices, tilt mounting of lens and shortening the optical path difference between stray light and reference light are also widely used to suppress PIIN in all-fiber CW-CDL systems [11-12].

In recent years, we are committed to reducing the noise in all-fiber CW-CDL system. In this paper, a new all-fiber system is proposed to suppress the PIIN generated by the optical circulator crosstalk in the system, thereby realizing the telemetry of the wind field 80 m in front of the wind turbine.

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2 Principle

This chapter mainly introduces the basic principles of coherent Doppler lidar. First, the Doppler effect is briefly described, which is the basic principle of coherent Doppler lidar that can realize speed measurement. Then, the principle of homodyne detection is introduced. Due to the Mie scattering signal is very weak, the system uses coherent detection to maximize the detection capability. By describing the noise in the CW-CDL system, the calculation method of PIIN power and system signal-tonoise ratio is given. Finally, the wind speed vector inversion method of the CW-CDL system is introduced.

2.1. Doppler effect of light

The lidar system realizes the measurement of wind speed by receiving the scattered light back of Mie and analyzing the Doppler frequency shift information relative to the emitted light. Fig. 1 is the schematic diagram of the Doppler effect of light. It is assumed that a stationary laser source emits a with frequency of f and a center wavelength of λ to a particle with a velocity of v, β is the angle between the emitted laser beam and the motion direction of the particle to be measured. The frequency difference between the laser source and the particle is as follows:

$$\Delta f = \frac{2\nu}{\lambda} \cos\beta \tag{1}$$



Fig. 1. Schematic diagram of the Doppler effect of light

2.2. Principle of homodyne detection

Homodyne detection is a kind of coherent detection, in which the detection light and the reference light are separated from the same light source through a beam splitter. and the reference light and the feedback signal light are mixed to produce the signal. The computer is used to demodulate the zero difference signal to obtain the Doppler frequency shift information. The basic principle is shown in Fig. 2.



Fig. 2. Principle of homodyne detection

The light field of the feedback signal is:

$$E_S(t) = E_S cos(\omega_S t + \varphi_S)$$
(2)
The light field of the reference signal is:

$$E_L(t) = E_L \cos(\omega_L t + \varphi_L) \tag{3}$$

Here, E_S is the amplitude of the feedback signal light, φ_S is the initial phase of the feedback signal light, ω_S is the frequency of the feedback signal light; E_L is the amplitude of the reference light, φ_L is the initial phase of the reference light, ω_L is the frequency of reference light, and t is the time.

The light field vector entering the detector through the beam coupler can be expressed as:

 $E(t) = E_S cos(\omega_S t + \varphi_S) + E_L cos(\omega_L t + \varphi_L)$ (4)

The optical current received by photodetector is linear with the square of total optical field vector, which can be expressed as:

$$i(t) = \alpha \overline{[E_S(t) + E_L(t)]^2}$$

$$(5)$$

$$i(t) = \alpha \begin{cases} E_S \cos(\omega_S t + \varphi_S) + E_L \cos(\omega_L t + \varphi_L) \\ + \overline{E_S E_L \cos[(\omega_S t + \varphi_S) + (\omega_L t + \varphi_L)]} \\ + \overline{E_S E_L \cos[(\omega_S t + \varphi_S) - (\omega_L t + \varphi_L)]} \end{cases}$$
(6)

Here, α is the photoelectric conversion coefficient. After the photocurrent expression is expanded, the first two terms are DC terms, the third term is sum frequency, and the fourth term is difference frequency. The difference frequency can be expressed as:

 $i(t) = \alpha E_S E_L \cos[(\omega_S - \omega_L)t + (\varphi_S - \varphi_L)]$ (7)

According to formula (7), the output current of the photodetector depends on the intensity of the reference light and the signal light. Therefore, enhancing the reference light within a certain range can increase the output current, thereby amplifying the signal.

2.3. Noise power

Several noise sources have to be considered in a CW-CDL system. the noise related to photon detectors includes shot noise (SN), thermal noise (TN), and dark current noise (DCN). Additionly, the laser sources can also cause noise, which includes relative intensity noise (RIN) introduced by semiconductor lasers and phase induced intensity noise introduced by random phase fluctuations. Among them, the PIIN is mainly caused by the stray light, including the crosstalk light of the optical circulator and the reflected light of the end face of the device in each fiber device of the system. Due to the inherent phase fluctuation of the laser, when the reference light and stray light produce interference beat frequency in the fiber, excessive intensity noise will be introduced, resulting in the increase of the overall noise of the system. When the reference light and stray light generate interference beat frequencies in the fiber, the inherent fluctuation of the phase (ie, the phase noise of the laser) will introduce excessive intensity noise, which causes the overall noise of the system to rise. In the literature, this type of excessive noise is called phase induced intensity noise or beat interference noise [14-16]. The mean square value of the photon current induced by PIIN can be described as:

$$\langle i_{PIIN}^{2} \rangle = \mathcal{R}^{2} \frac{2P_{r}P_{st}l_{c}}{\pi c} \left[1 - exp\left(-\frac{l_{d}}{l_{c}} \right) \left(1 + \frac{l_{d}}{l_{c}} \right) \right] B \quad (8)$$

Where \mathcal{R} is the responsivity of the photon detector, P_r and P_{st} are the intensities of the reference light and stray light respectively, l_d denotes the OPD between stray light and reference light, l_c represents the coherence length of the laser source, and B is the resolution bandwidth of the system.

The existence of PIIN in the system may lead to the fluctuation of the output intensity of the balanced photon detector, and the noise floor will fluctuate up and down in the spectrum. The intensity of PIIN mainly depends on the intensity of stray light source, the coherence length of laser and the optical path difference between stray light and reference light. Assuming that the stray light source of the system is unique and weak, and the optical path difference between the stray light source and the reference light is close to 0, the PIIN will appear as white noise:

$$\langle i_{PIIN}{}^2 \rangle = \mathcal{R}^2 \frac{2P_r P_{st}}{\pi c} \frac{l_d^2}{l_c} B \tag{9}$$

Therefore, when considering all the above noises and using a balanced photon detector (BPD), the signal-tonoise ratio of the system satisfies the following relationship[17]:

$$SNR = \frac{\langle i_{s}^{2}(t) \rangle}{\langle i_{n}^{2}(t) \rangle} = \frac{\mathcal{R}^{2} P_{ms} P_{r}}{\frac{2KTB}{R} + 2eP_{r} \mathcal{R}B + 2ei_{d}B + \frac{\delta P_{r}^{2} \mathcal{R}^{2}B}{\beta} + \frac{\mathcal{R}^{2} P_{r} P_{s} t l_{d}^{2}B}{\pi cl_{c}}}$$
(10)

Here $i_s(t)$ is the signal photocurrent of the balanced photon detector, $i_n(t)$ is the total noise current of the system, P_{ms} is the intensity of the signal light (Mie scattering light for a wind measurement system), k and Tdenote the Boltzmann constant and the temperature respectively, R is the equivalent internal resistance of the detector, e and i_d represent the electron quantity and the dark current of the detector, δ is the RIN factor, and β is the common mode rejection ratio of the balanced detection. It can be seen that, when PIIN is much stronger than other noises, the SNR can be rewritten as:

$$SNR(t) \approx \frac{\langle i_s^2(t) \rangle}{\langle i_{PIIN}^2(t) \rangle} \approx \frac{\pi c l_c P_{ms}}{P_{st} l_d^2 B}$$
 (11)

2.4. Wind speed vector inversion

In order to obtain the wind field data in front of the generator accurately, it is necessary to measure at least two independent wind speed vectors, namely the projection of v_{LOS1} and v_{LOS2} in the wind speed direction, and obtain the actual wind speed data by vector synthesis method.



Fig. 3. Schematic diagram of wind speed vector inversion

As shown in Fig. 3, the wedge mirror is used for bidirectional switching of optical path, γ is determined by the wedge mirror in the system. Assuming that the angle between the measured wind direction and the optical terminal is θ , the actual wind speed is v, $\gamma > \theta$ ($\gamma < \theta$ the inversion process and results are the same). The speed v_{LOS1} and v_{LOS2} in two directions are calculated by computer, and then the actual wind speed v and the angle

between wind speed and optical terminal θ are synthesized by two velocity vectors.

$$v_{LOS1} = v \cos(\gamma - \theta)$$
(12)
$$v_{LOS1} = v \cos(\gamma - \theta)$$
(12)

 $v_{LOS2} = v \cos(\gamma + \theta)$ (13) According to the formulas (12) and (13), the following

results are obtained:

$$v = \sqrt{\left(\frac{v_{LOS1} - v_{LOS2}}{2 \sin \gamma}\right)^2 + \left(\frac{v_{LOS1} + v_{LOS2}}{2 \cos \gamma}\right)^2} \quad (14)$$

$$\theta = \frac{1}{2} \left(\arccos \frac{v_{LOS1}}{v} + \arccos \frac{v_{LOS2}}{v} \right) \quad (15)$$

3 Signal numerical simulation and analysis

All-fiber CW-CDL system was originally designed for vector wind speed measurement in wind power generation scenario. Generally, wind lidar can get the data support of traditional mechanical anemometer and work in the state of small wind direction deviation. However, considering the application expansibility of the system, the measurement of larger wind deflection angle is evaluated based on numerical simulation method. In the simulation, the range of the deviation angle is -90~90° and the wind speed is 10 m/s. White noise is added to the dual- channel line of sight wind speed, and the simulation results based on the selected vector wind speed solution algorithm are shown in Fig. 4.

According to the simulation results in Fig. 4, the following conclusions can be obtained: The simulation results of the Speed deviation in Fig. (a) and Speed standard deviation in Fig. (b) show that the speed measurement error increases with the increase of deflection angle. When the wind speed fluctuates near zero deflection angle, the long-term smooth wind speed can maintain a more reliable output. The simulation results of the Wind direction deviation in Fig. (c) and standard deviation of Wind direction in Fig. (d) show that the measurement error of wind direction decreases with the increase of declination angle is not good for wind speed measurement with high refresh rate, but beneficial for wind direction measurement.

It should be pointed out that the above analysis is based on the same line-of-sight wind speed error under different deflection angles. In practical work, with the increase of wind speed, it is generally observed that the speed measurement error will also increase. Meanwhile, the zero-frequency interference of scattered light and the reversal of the frequency spectrum at the zero position in the extremely low-speed area also lead to increased velocity measurement errors.



Fig. 4. Wind speed and direction simulation results, (a) Speed deviation, (b) Speed standard deviation, (c) Direction deviation, diagram (d) Direction standard deviation.

4 Experiment and result

4.1. Experimental setup

We proposed a method to significantly reduce the PIIN in the all-fiber CW-CDL by adding a polarization control system to achieve the purpose of screening signal light and stray light sources. In order to directly prove the noise reduction effect of the polarization control method, two comparison schemes of the CW-CDL system with polarization control and the CW-CDL system without polarization control are given in the experiment. The diagram of polarization controlled all-fiber CW-CDL is shown in Fig. 5. The structure of all-fiber CW-CDL system without polarization control removes the polarization beam splitter and quarter wave plate on the basis of Fig. 5.



Fig. 5. CW-CDL experimental device for polarization control

The polarization control device based on all-fiber CW-CDL is shown in Fig. 5. Narrow linewidth semiconductor laser provides a seed light of 6 mW at 1550 nm, the wavelength stability is ± 0.05 nm, and the bandwidth is less than 20 kHz, indicating a coherent length of about 15 km. The output of EDFA is divided into two parts by a 99:1 optical coupler (OC₁). The 1% part is first reduced to about 400 μ W by a variable optical attenuator (VOA). Then it passes through a delay fiber and acts as the reference light in the coherent system. The 99% part with a power of about 300 mW is used as the detection light. The detection light is input from port-1 of the optical circulator. Due to the structural characteristics of the circulator, most of the detection light is output from port-2 of the circulator and goes into the collimator with a diameter of 3 mm. However, a small part of the detection light still goes into port-3 to form crosstalk (stray light source). The detection light output from the collimator passes through a quarter-wave plate, a plano-concave lens and a plano-convex lens with the fast axis and the polarization direction inclined at 45 degrees in turn. The aperture of the telescope is 50 mm and detection beam is focused 80 m ahead. The Mie scattering light caused by aerosol particles passes through telescope, quarter wave plate and collimator, and finally returns to port 3 of the circulator together with the crosstalk light of the circulator. The polarization state of the feedback signal light that has passed through the quarter-wave plate twice is rotated by 90 degrees. When passing through the polarization beam splitter (PBS), the crosstalk light and feedback signal light will be output from port-4 and port-5 respectively, and the feedback signal light from the port-5 outputs enters the 3 dB optical coupler (OC₂) and mixes with the reference light at the BPD with a bandwidth of 50 MHz. (detector conversion factor 1.2×10^{5} V/W).The output of BPD is sampled by DAQ card with a sampling rate of 80 MS/s. The fast Fourier transform (FFT) and average calculation are implemented by a field programmable gate array (FPGA) in DAQ card to obtain the signal spectrum.

4.2. System detection efficiency evaluation

As a kind of weak signal telemetry instrument, CW-CDL needs to evaluate the receiving efficiency of optical system after solving the problem of noise floor fluctuation through polarization control scheme. According to the requirements of practical application, we need to evaluate the signal efficiency of the system at a distance of 80 m.

When the focus point of the telescope is adjusted to 80 m, the detector target at the focus point has a certain length, so it needs to be fine adjusted at 80 m. After actual

measurement, the window aperture of CW-CDL system telescope is 50 mm, the power of 80 m focus is 61 mW, and the diameter of focus spot is 0.5 cm. The feedback signal provided by aerosol particles in the air is extremely weak, which increases the difficulty of evaluating the detection efficiency of the system. Moving white paper is used to replace the aerosol particles, assuming that the reflectivity of the white paper is 50%. Through theoretical calculation, the optical power received by the system is $2.97 * 10^{-6}$ mW. In the actual measurement process, the electrical signal output by the BPD is connected to the spectrum analyzer for data storage. The bandwidth of the spectrum analyzer is set to 1kHz, and the sampling range is 10MHz. The stored data is imported into MATLAB program for calculation. According to Eq. (7), the average total received power of the system is 4.3×10^{-7} mW.

The difference between the theoretical value and the actual value is 6.9 times, which is mainly due to the low coupling efficiency of the collimator and depolarization of the feedback signal light.

4.3. Result analysis

In the experiment, the noise floor of the CW-CDL system with or without polarization control was tested. In order to ensure the reliability of the comparative experimental results, the two sets of experimental devices are treated in the same way. The treatments include shielding the output window of the telescope, have anti-reflection coated on the APC end face of the optical fiber namely the APC end face connected with the collimator, have anti-reflection coated on the quarter-wave plate of the system and the telescope system lens. At the same time, the delay line is configured at the crosstalk position of the circulator to reduce the optical path difference between the stray light source and the reference light.

Three groups of representative experimental data are randomly selected and processed to Fig. 6. The black and red lines in the figure represent the noise floor spectrum of CW-CDL system with polarization control and CW-CDL system without polarization control respectively. The spectrum data has been smoothed for 20 points. The results show that the noise floor of CW-CDL system with polarization control scheme is stable, and the fluctuation range is from -75~-73 dBm. The noise floor of CW-CDL system without polarization control fluctuates abnormally between -73~-60 dBm. The results in Fig. 6 show that the polarization control system can greatly suppress the noise.



Fig. 6. Noise comparison of CW-CDL system with or without polarization control. The bandwidth of the Spectrum analyzer is 1kHz and the sampling range is 10MHz.

4.4. Outfield experiment

In September 2020, the prototype was used to carry out field measurement on the 6th floor of the Science and Technology Building E of Anhui University, and the typical Doppler signal at an altitude of 40 meters under clear sky conditions was obtained. On that day, the AQI index of air quality was 34 and PM2.5 was 21. In the experiment, the focusing distance of the telescope is 80 m and the spot diameter is about 0.8 cm. The sampling rate of DAQ card is 80MS/s, the sampling point is 1024, and the RBW is 80kHz. Fig. 7 is the On-site measurement, Fig. 8 is the two channel frequency shift data of CW-CDL in 20 minutes, and Fig. 9 is the wind speed and direction data in 20 minutes.

It can be seen from the two channel frequency shift data of CW-CDL in Fig. 8 that the overall performance of CW-CDL system is stable. Among them, 480 seconds and 1000 seconds of two channels of frequency shift data are selected respectively to calculate the ratio of signal height to standard deviation of noise background [18], i.e. system signal-to-noise ratio. The data shows that the spectrum of the two channels is narrow at 1000 seconds, and the signal-to-noise ratio is 21.2 dB and 21.7 dB respectively. In 480 seconds, the two spectrum peaks overlap, and the signal to noise ratio is reduced to 20 dB.

The data in Fig. 9 shows that the measured wind speed is $1.2 \sim 1.8$ m/s, and the wind direction varies from $-5^{\circ} \sim -30^{\circ}$ where the wind speed is relatively stable, but the wind direction changes obviously, which is mainly due to the obvious turbulence in the low altitude measurement in the campus, resulting in large wind direction error.



Fig. 7. On-site measurement



Fig. 8. Two channel detection frequency shift data of lidar



Fig. 9. Wind speed and direction data

5 Conclusions

The PIIN will seriously affect the signal-to-noise ratio of all-fiber CW-CDL system, and limits the practicability of this kind of lidar. In this paper, the polarization control, antireflection coating and reducing the optical path difference between stray light and reference light are used to suppress PIIN in all-fiber CW-CDL system. The experimental results show that this scheme can effectively control PIIN, and the typical signal-to-noise ratio of lidar system in clear sky can reach 21.7 dB. Finally, the proposal can also be simply extended to the development of others systems with the same basic principle, such as laser Doppler vibrometry.

Acknowledgments

This paper has been funded by the National Natural Science Foundation of China (61705001, 61905001 and 61665002), National Key Research and Development Program (2016YFC0301900), Natural Science Foundation of Anhui Province (2008085MF207).

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