Application of fiber interferometer in coherent Doppler lidar

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A novel coherent Doppler lidar (CDL) system based on single-mode fiber (SMF) components and instruments is presented to measure the speed of target. A fiber interferometer used in CDL system is reported. This fiber mixer is employed as a coherent receiver to resolve the shifts of signal-to-noise ratio (SNR) and mixing efficiency induced by backscattered field's wavefront error. For a certain wavelength, the maximum coupling efficiency between signal and SMF is determined by the ratio of pupil diameter to focal length of the coupling lens. The legible interference patterns and spectrum signals show that fiber interferometer is suitable to compensate for amplitude and phase vibrations. This robust coherent receiver can achieve improved CDL system performance with less transmitter power.

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Coherent lidar is a remote-sensing technology that can generate speed-resolved Doppler frequency shift from either distributed or hard targets. Systems utilizing gas[1,2], optically pumped solid-state and semiconductor laser sources have been developed. Applications of coherent lidar include the measurement of atmospheric winds, vortices, pollution dispersion, and target features[3,4]. Conventional coherent Doppler lidar (CDL) system performs combining and mixing between the signal field and local oscillator (LO) field in free space. Only portion of the received power which is collected by the receiving aperture in the same temporal and spatial mode as the LO will contribute to the intermediate frequency (IF) signal. In such system, the mixing efficiency can be influenced greatly by the fields' wavefronts. Recently, there has been interest in developing systems operating at wavelengths near 1.55 μm based on fiber interferometer[4−6]. The maximum permissible exposure for human eyes at 1.55 μm is ten times higher than that at 2 μm[7]. In addition, reliable optical fiber components and instruments for the optical communication are easily available at this wavelength. In this paper, we report the application of fiber interferometer in CDL system.

As the main parameter for estimating the ability of coherent lidar to measure and offering the instruction in designing, signal-to-noise ratio (SNR) can be expressed as[8,9]

$$\mathrm{SNR} = \eta_{\mathrm{m}} \cdot \eta P_{\mathrm{S}}/h\nu_0 B, \tag{1}$$

where η_{m} is the mixing efficiency, η is the quantum efficiency, P_{S} is the signal power, h is the Plank's constant, ν_0 is the optical frequency, B is the detector noise bandwidth. Single-mode fiber (SMF) only allows the propagation of a fundamental mode (LP_{01}), and its output has a constant and radial symmetry spatial structure independent of the input field distribution. Under this condition, the wavefront errors of the entrance pupil caused by the partial or complete incoherence can be converted into power fluctuations[10]. The polarization state is controlled automatically by inline polarization controller (PC). The signal and LO fields are matched both spatially and temporally at the detector, yielding 100% mixing efficiency. The signal power is averaged over a long time compared with the optical frequency, but short compared with intermediate frequency. This means that wavefront errors have a far less detrimental effect on SNR for an interferometer system incorporating SMF. Since an all-fiber unit is not as sensitive to fluctuant effects as non-fiber system, instrumental noise is also minimized, and the interference fringe visibility is maximized. Additionally, optical background noise is typically not a problem in coherent lidar for two reasons: there is a low coupling efficiency of optical background signals, and most of the background photons that produce heterodyne beats fall outside the electronic bandwidth of the receiver.

Thanks to the above properties, fiber optic devices offer a reliable and novel solution to transport and combine beams in coherent detection. We developed a 1.55-μm CDL system, as shown in Fig. 1.

All devices of optical circuit are connected by single-mode fibers, which makes the system reliable and setup arrangement flexible.

Since all the light that injects into fiber will contribute to the IF signal, any work increasing the coupling efficiency is meaningful. The instantaneous coupling efficiency is determined by the overlap integral between the distribution of the electric fields in the focal plane and in the guided mode[11],

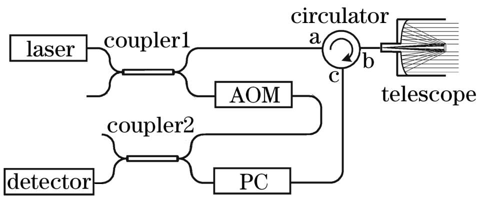

Fig. 1. Block diagram of the coherent lidar system. AOM: acousto-optic frequency modulator.

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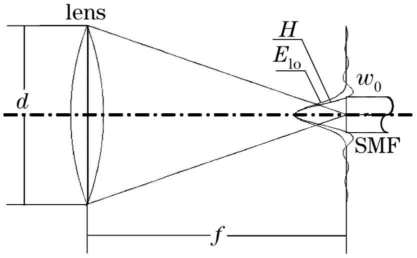

Fig. 2. Coupling scheme.

$$\rho=\frac{\left|\iint E_{\mathrm{lo}}\left(r\right)H^{*}\left(r\right)\mathrm{d}^{2}r\right|^{2}}{\iint\left|E_{\mathrm{lo}}\left(r\right)\right|^{2}\mathrm{d}^{2}r\cdot\iint\left|H\left(r\right)\right|^{2}\mathrm{d}^{2}r},\tag{2}$$

where r is the coordinate in transverse plane, $E_{\mathrm{lo}}(r)$ is the mode output of SMF, $H(r)$ is the focal electric field, the symbol $*$ denotes a complex conjugate. Figure 2 shows the coupling scheme, where d is the pupil diameter, f is the focal length. The spot at the input pupil of fiber can be considered as diffraction limit.

The signal light from distributed or hard targets can be filtered to a fundamental mode LP_{01} by keeping only the central part of the point spread function (Airy pattern) through SMF,

$$H(r)=2\frac{J_1(kdr/(2f))}{kdr/(2f)},\tag{3}$$

where k is wave number, J_1 is the first order Bessel function. Paraxial Gaussian beam is an appropriate approximation for the SMF fundamental mode LP_{01} output,

$$E_{\mathrm{lo}}(r)\approx\mathrm{e}^{-(\frac{r}{w_0})^2},\tag{4}$$

where w_0 is fundamental mode radius. By substituting Eqs. (3) and (4) into Eq. (1), the coupling efficiency is obtained as

$$\begin{aligned}\rho(A)&=\frac{\left[\int_0^{\infty}\mathrm{e}^{-\frac{r^2}{A}}\cdot 4\pi\sum\limits_{n=0}^{\infty}\frac{(-1)^n}{n!(1+n)!}\left(\frac{r}{2}\right)^{1+2n}\mathrm{d}r\right]^2}{4\pi\cdot\int_0^{\infty}\left[\exp(-\frac{r^2}{A})\right]^2\cdot 2\pi r\mathrm{d}r}\\&=8\frac{\left(1-\mathrm{e}^{-A/4}\right)^2}{A}\end{aligned}\tag{5}$$

with

$$A=k^2d^2w_0^2/(4f^2).\tag{6}$$

Coupling efficiency as a function of parameter A is shown in Fig. 3. The coupling efficiency is maximized when $\partial\rho(A)/\partial A=0$. As a result, the maximum efficiency is 81.45% when $A=5.026$ (see Fig. 3). But it drops quickly as the parameter changes.

For the ideal condition, the fundamental mode radius can be determined by

$$w_0=0.71\lambda f/d.\tag{7}$$

For the given wavelength 1.55 μm and the fiber SMF-28, the ratio $d/f=0.213$.

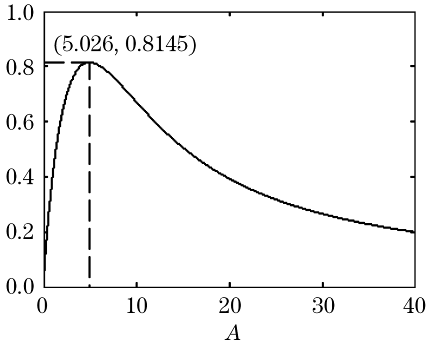

Fig. 3. Coupling efficiency ρ as a function of parameter $A=k^2d^2w_0^2/(4f^2)$.

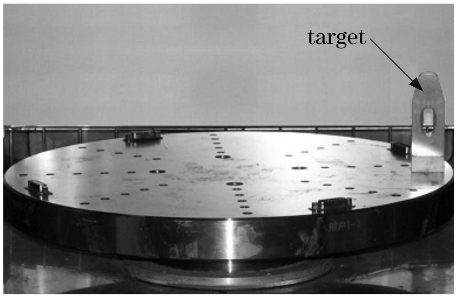

Fig. 4. Experimental setup.

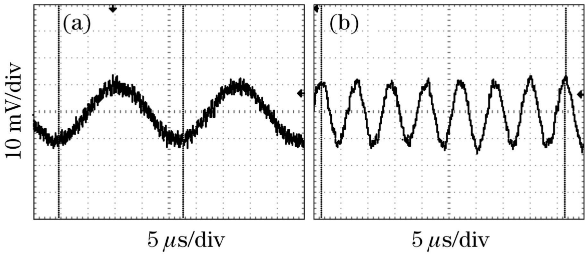

Fig. 5. Intermediate frequency signals. (a) Target speed is 34.8 mm/s; (b) target speed is 1.24 m/s.

According to the above design, we built the CDL prototype utilizing fiber interferometer. An ultra-stable Er-doped fiber laser at 1.55 μm with pigtail (Koheras, Denmark) was used as the transmitter. The output power of the laser was 13 mW and the linewidth was below 13 kHz. A low dark current PIN photodiode with high responsivity was used as photodetector. In addition, low-noise metal oxide semiconductor field emitting transistor (MESFET) was used in the amplifier stages to further enhance device performance. The PIN field emitting transistor (PIN-FET) module 44th Research Institute (China Electronics Technology Group Corporation), contained automatic gain control, and its dynamic range was approximately 35 MHz. The photograph of the experimental setup used for speed measurement is shown in Fig. 4. An object used as hard target was fixed on the plane of high precision (0.005 deg./s) monaxial speed turntable (China State Shipbuilding Corporation).

Then the interference patterns (IF signals) are shown in Fig. 5. The resulting signals are sinusoid curves with frequencies ν_{d} proportional to the target's speeds,

$$\nu_{\mathrm{d}}=2V/\lambda,\tag{8}$$

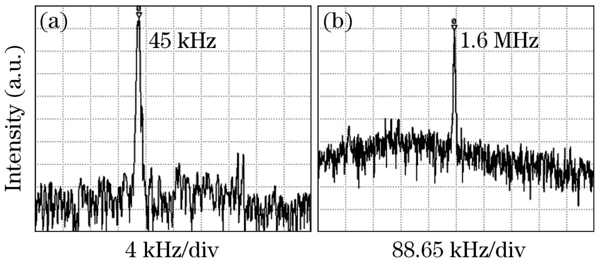

Fig. 6. Spectra of Doppler signals via spectrum analyzer. (a) Target speed is 34.8 mm/s; (b) target speed is 1.24 m/s.

where V is target speed. The spectral domain signals are shown in Fig. 6. The peaks in the spectral distribution at two speeds of 34.8 mm/s and 1.24 m/s are approximately 45 kHz and 1.6 MHz, respectively.

In summary, optical fiber components and instruments are of great importance for CDL systems. Indeed, this technology allows the implementation of a very stable optical system on a single chip, considerably reducing the volume and weight of a set-up and therefore the cost of system. In theory, we have seen that the fiber interferometer introduced by such waveguide can lead to a great improvement of SNR. Also, we calculate the coupling efficiency between a perfect Airy pattern and SMF's fundamental mode. From the experiment, we have also seen that fiber interferometer applied in CDL system achieved favourable signals in the time and spectral domains.

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References

1. C. Wang, X. Cheng, L. Liu, and Q. Wang, Chin. J. Lasers (in Chinese) **30,** 555 (2003).
2. L. Liu and Q. Wang, Chin. J. Lasers (in Chinese) **30,** 605 (2003).
3. O. Steinvall, Appl. Opt. **39,** 4381 (2000).
4. V. Philippov, C. Codemard, Y. Jeong, C. Alegria, J. K. Sahu, and J. Nilsson, Opt. Lett. **29,** 2590 (2004).
5. C. J. Karlsson, F. Å. A. Olsson, D. Letalick, and M. Harris, Appl. Opt. **39,** 3716 (2000).
6. G. N. Pearson, P. J. Roberts, J. R. Eacock, and M. Harris, Appl. Opt. **41,** 6442 (2002).
7. T. Yanagisawa, K. Asaka, and Y. Hirano, in *Proceedings of CLEO 2000* 438 (2000).
8. V. A. Banakh and C. Werner, Opt. Eng. **44,** 071205 (2005).
9. Z. Ma, C. Zhang, Z. Zhang, and T. Yan, Acta Opt. Sin. (in Chinese) **27,** 889 (2007).
10. M. P. J. L. Chang and D. F. Buscher, Proc. SPIE **3350,** 2 (1998).
11. T. Weyrauch, M. A. Vorontsov, J. W. Gowens, and T. G. Bifano, Proc. SPIE **4489,** 117 (2002).