1.55-μm coherent lidar based on SPA sinusoidal frequency demodulation techniques

Dezhao Yang (杨德钊)*, Ningfang Song (宋凝芳), Zhili Lin (林志立), Pan Ou (欧 攀), Yudong Jia (贾豫东), and Mingjie Sun (孙鸣捷)

School of Instrument Science and Opto-electronics Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100191, China

**Corresponding author: yangdezhao1234@163.com*

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A 1.55-μm all-solid frequency-modulated continuous-wave (FMCW) coherent lidar based on the sinusoidal frequency demodulation technique for range and velocity measurement is presented. Both the nonlinearity of linear modulation waveform and the difficulty in measuring the frequency of sinusoidal modulation system are circumvented by utilizing segmental-processing-average (SPA) techniques. The results demonstrate that the resolutions of range and velocity measurement are better than 2 mm and 0.1 mm/s, respectively. The system has numerous practical and potential applications in space missions.

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Accurate range and velocity measurement has been urgently demanded in numerous space missions, such as the space rendezvous and docking and vehicle autonomous landing[1,2]. With the emergence of narrower line-width laser source, the important role of the frequency-modulated continuous-wave (FMCW) coherent lidar, based on FMCW technology has been enhanced[3−5]. One of the key features of the system is the generally linear modulation of the transmitting light frequency in a periodic time-domain segment. However, its performance in range and velocity measurement has deteriorated because the stringent requirement for a perfect linear modulation is frequently unfulfilled due to the defects of the driving electronic circuit board and the intrinsic nonlinearity of the seed laser[6,7]. In this letter, we propose a 1.55-μm all-solid FMCW coherent lidar based on segmental-processing-average (SPA) sinusoidal frequency demodulation techniques. The transmitting power of the system is approximately 500 mW. It is capable of measuring the range and velocity of a long-range target, which guarantees its applications in various practical situations.

The schematic configuration and time-frequency relationship of the sinusoidal frequency modulation (FM) signal of a FMCW coherent lidar are depicted in Fig. 1. ω_0 is the average angular frequency, $\Delta\omega$ is the peak-to-peak angular frequency modulation excursion, $\omega_{\rm d}$ is the angular Doppler frequency shift, $T_{\rm m}$ is the period of the FM waveform, and τ is the time-of-flight (TOF) of the received light.

In the system, a seed laser with a line-width of less than 10 kHz is modulated by a driving current of sinusoidal waveform, and coupler 1 divides the energy of the transmitting light into two portions. The minor portion serves as reference local oscillator (LO) light and its polarization is adjusted by a polarization controller (PC). The major portion is amplified by an Erbium-doped fiber amplifier (EDFA) pumped by a laser diode pump (LDP) after passing through a wavelength division multiplexing (WDM). Subsequently, the light enters into the circulator and optical antennas. The reflected or scattered light from the detected object is collected by the same antennas and recombined with the LO light by coupler 2. Finally, the recombined light is transformed into an electric signal by the photo detector (PD). Based on the Fourier-transform (FT) analysis of this electric signal, the range and velocity information of the detected target can be extracted.

The angular frequency of the sinusoidal FM signal is[8]

$$\omega(t) = \omega_0 + \Delta\omega \sin(\alpha t)/2, \tag{1}$$

where α is the modulation angular frequency. Considering the influence of Doppler angular frequency shift, $\omega_{\rm d}$, the LO and received signal can be expressed as

$$E_{\rm lo}(t) = E_1 \exp\left\{{\rm j}\left[\omega_0 t - \frac{\Delta\omega\cos(\alpha t)}{2\alpha} + \phi_0\right]\right\}, \tag{2}$$

$$E_{\rm rec}(\tau, t) = E_2 \exp\left\{{\rm j}\left[(\omega_0 + \omega_{\rm d})(t-\tau) - \frac{\Delta\omega\cos\alpha(t-\tau)}{2\alpha} + \phi_0\right]\right\}, \tag{3}$$

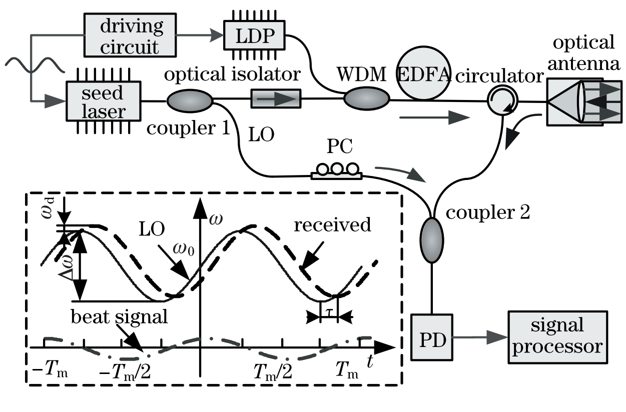

Fig. 1. System configuration and time-frequency relationship of FM signal.

where ϕ_0 is the initial phase of the signal, and E_1 and E_2 are the amplitudes of the LO and received signals with a beat signal given by

$$\begin{aligned} I(\tau,t) &= |E_{\rm lo}(t)+E_{\rm rec}(\tau,t)|^2 \\ &= E_1^2+E_2^2+2E_1E_2\cos\Big\{\frac{\Delta\omega}{2\alpha}\Big[\cos\alpha(t-\tau) \\ &\quad -\cos(\alpha t)\Big]-\omega_{\rm d}t+(\omega_0+\omega_{\rm d})\tau\Big\}. \end{aligned} \tag{4}$$

The phase of the beat signal can be extracted by utilizing the band pass filter

$$\phi_{\rm b}(t)=\frac{\Delta\omega}{\alpha}\sin\Big(\alpha t-\frac{\alpha\tau}{2}\Big)\sin\Big(\frac{\alpha\tau}{2}\Big)-\omega_{\rm d}t+(\omega_0+\omega_{\rm d})\tau. \tag{5}$$

Generally, $\alpha\tau/2$ has a small value and thus, the angular frequency can be simplified as

$$\begin{aligned} \omega_{\rm b}(t) &= \Delta\omega\sin\Big(\frac{\alpha\tau}{2}\Big)\cos\Big(\alpha t-\frac{\alpha\tau}{2}\Big)-\omega_{\rm d} \\ &\approx \frac{\Delta\omega\alpha\tau}{2}\cos\Big(\alpha t-\frac{\alpha\tau}{2}\Big)-\omega_{\rm d}. \end{aligned} \tag{6}$$

Equation (6) shows that the frequency of the beat signal is not constant. In this situation, the average absolute angular frequency $\overline{|\omega_{\rm b}|}=\Delta\omega\kappa\alpha\tau/2-|\omega_{\rm d}|$ is generally introduced, where $\kappa=\overline{|\cos(\alpha t-\alpha\tau/2)|}=2/\pi$. Supposing that the average angular frequencies of the beat signal in the rising period $(-T_{\rm m}/4, T_{\rm m}/4)$ and in the falling period $(T_{\rm m}/4, 3T_{\rm m}/4)$ are $\overline{\omega_{\rm br}}$ and $\overline{\omega_{\rm bf}}$, respectively, we obtain $\overline{\omega_{\rm b}}=(\overline{\omega_{\rm br}}+\overline{\omega_{\rm bf}})/2$ and $\overline{\omega_{\rm d}}=(\overline{\omega_{\rm br}}-\overline{\omega_{\rm bf}})/2$, respectively, where $\overline{\omega_{\rm d}}$ is the average Doppler angular frequency shift. The principle of the SPA signal processing method is shown in Fig. 2. The beat signal is divided into M segments and each segment is processed with the help of the FT method. The average absolute frequency is utilized for the TOF calculation.

Figure 2 indicates that the spectrum width of the beat signal is larger in the temporal range centered at the peaks and valleys of the modulation waveform than that of the median range between them. Therefore, the accuracy of the measurement of the average angular frequency is deteriorated. To circumvent the problem, the data of beat signal close to the peaks and valleys of the

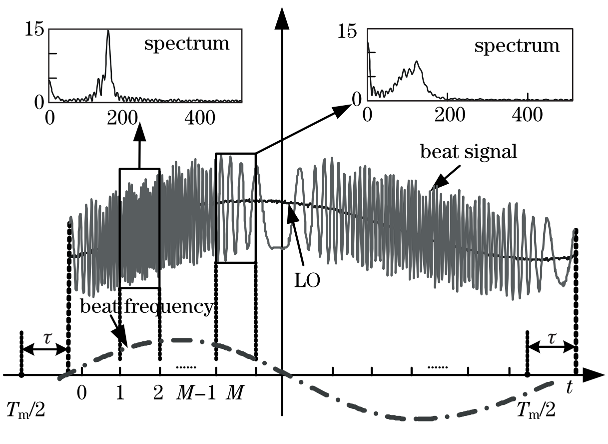

Fig. 2. Principle of the SPA signal processing method.

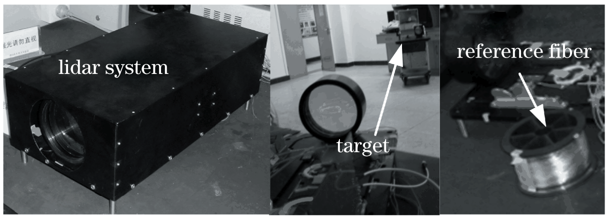

Fig. 3. FMCW coherent lidar system.

Table 1. Key Parameters of the System

Key Component	Parameter	Value
Seed Laser	Wavelength λ (nm)	1 550
	Peak Power (mW)	10
LDP	Wavelength λ (nm)	980
Antenna Aperture	Diameter (mm)	100
	FM Rate (kHz)	1
Driving Circuit	FM Bandwidth (MHz)	500

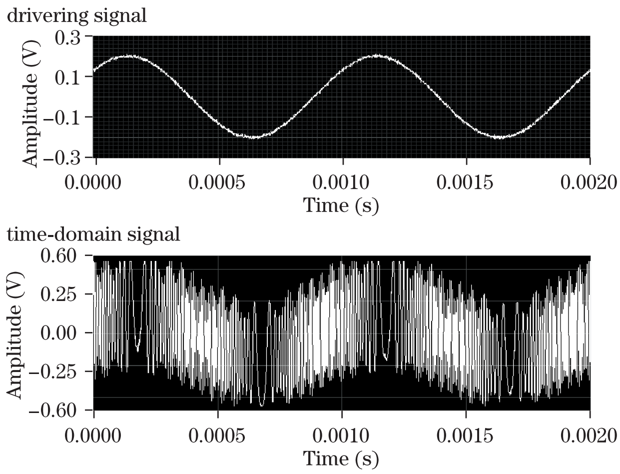

Fig. 4. System experimental signals.

modulation waveform are discarded, and the data in the midway segments $(-T_{\rm m}/8, T_{\rm m}/8)$ and $(3T_{\rm m}/8, 5T_{\rm m}/8)$ of each period are selected. During the process involving these two segments, the average absolute angular frequencies of both is derived by $\overline{|\omega_{\rm b}|}=\kappa\Delta\omega\alpha\tau/2$, where $\kappa=\overline{|\cos(\alpha t-\alpha\tau/2)|}\approx 0.8992$. The TOF can be obtained by

$$\tau=\frac{(\overline{\omega_{\rm br}}+\overline{\omega_{\rm bf}})}{\kappa\Delta\omega\alpha}=\frac{(\overline{\omega_{\rm br}}+\overline{\omega_{\rm bf}})}{0.8992\Delta\omega\alpha}. \tag{7}$$

On the other hand, the range and velocity of the target can be expressed as

$$R=\frac{c\,(\overline{\omega_{\rm br}}+\overline{\omega_{\rm bf}})}{1.7984\Delta\omega\alpha},\quad V=\frac{\lambda(\overline{\omega_{\rm br}}-\overline{\omega_{\rm bf}})}{8\pi\cos\theta}, \tag{8}$$

where θ is the angle of the moving direction of the target relative to the radial direction. Different values of κ can be obtained when different sampled periods are applied, and it can be optimally selected to decrease the spectral broadening impact and improve the measurement accuracy of the whole system.

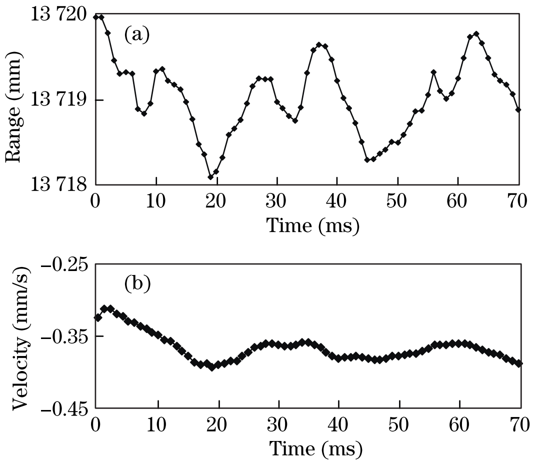

Fig. 5. Measurement results of system experiment (a) range and (b) velocity.

The lidar system and its key parameters are shown in Fig. 3 and Table 1, respectively.

Figure 4 shows the sinusoidal FM and beat signal sampled and collected by an NI PXI-5124 high-speed data acquisition system and processed by the software of Labview. The measurement results are given in Fig. 5. Due to the limitation of the experimental conditions, the long range test of the system was carried out with the light traveling in a reference fiber (shown in Fig. 3) inserted to the emitting light path rather than to an open space.

Figures 4 and 5 show that the waveform of the beat signal is clear, and the short-term drifts of the system in range and velocity measurement are less than 2 mm and 0.1 mm/s, respectively.

In conclusion, a 1.55-μm all-solid FMCW coherent lidar based on the sinusoidal waveform demodulation technique for range and velocity measurement is demonstrated. The disadvantage of sinusoidal modulation is addressed by utilizing the SPA signal processing method. The system experimental results indicate that the resolutions of range and velocity measurement are better than 2 mm and 0.1 mm/s, respectively. The system is not only eye-safe due to the light wavelength used, but also useful for long-range detection. Its application in numerous space missions, where highly accurate range and velocity measurements are demanded, is promising.

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