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Original research article

Premixing photon-counting chirped amplitude modulation lidar for range and velocity measurement in photon starved scenes

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ABSTRACT

A symmetric chirped amplitude modulation of the up-ramp and the down-ramp is implemented on the basis of previous work of premixing photon-counting chirped amplitude modulation lidar. This system is capable of obtaining the range and velocity of target simultaneously in photon starved scenes due to the high sensitivity of single-photon detectors. With the advantages of the premixing method this system breaks the limit of the maximum modulation frequency of the chirped amplitude modulation signal by the sampling rate of the Gm-APD and allows the use of much higher fundamental frequency and modulation bandwidth to improve the range and velocity detection accuracy. This paper demonstrates the working principle of this system, and analyzes the relationship of accuracy and system parameters from theory and experiment.

1. Introduction

Due to the advantages of good directionality, high spatial resolution and detection accuracy, Lidar (Light Detection and Ranging) was widely used in the past several decades [1–3]. High accuracy range and velocity information are beneficial to autonomous navigation, robot vision system and other domains [4–6]. Velocity measurement includes two main ways: range differentiation and Doppler shift velocity measurement [7]. Doppler lidar can improve the accuracy of velocity measurement by about two orders of magnitude compared with range differentiation [8,9]. Piracha used a 20 MHz mode locked laser and chirped fiber Bragg gratings to establish a coherent detection lidar system, which could realize simultaneous range and velocity measurements of fast moving targets, with the experimental demonstration of a target moving at >330 km/h inside the laboratory [10]. Wang proposed frequency diverse array (FDA) radar for estimating direction, range, and velocity simultaneously [11]. Gao researched the simultaneous range and vector velocity measurement under the complex optical field [12]. Yang presented a 1550-nm all-fiber lidar system based on linear chirp amplitude modulation and heterodyne detection for the measurements of range and velocity [13]. Park presented a Digital Image Correlation (DIC) method for improving the measurement of cloud velocity [14]. Many researchers have made a lot of meaningful work in the field of range and velocity measurement.

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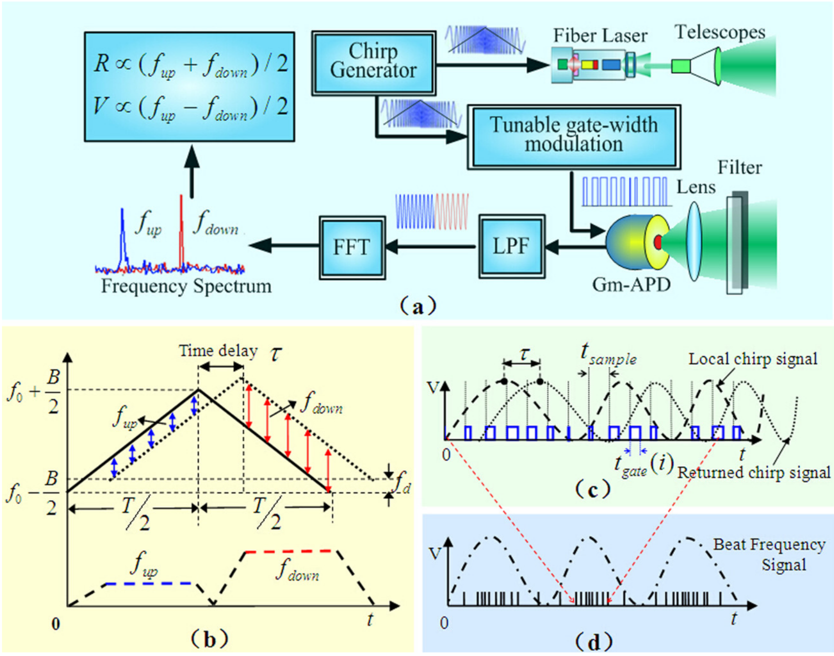

Fig. 1. (a)The schematic diagram of the PPCCAML system with the up-ramp and the down-ramp chirped amplitude modulation. (LPF, low-pass filter; FFT, fast Fourier transform.) (b)Frequency content of the transmitted (solid lines) and received (dotted lines) signal and the time varying beat frequency, f_{up} and f_{down} (dashed lines). (c)The sampling gate width of the Gm-APD is modulated by the local chirp signal. Sampling gates are equidistant; however, their widths are proportional to the local Chirped Amplitude Modulation (CAM) signal intensity. (d) Photon counting results of tunable sampling gates. The density of photon counting pulses corresponds to the intensity of beat frequency signal that is the mixing results of local CAM signal and returned CAM signal.

However, when the scattered photons are very rare (called photon starved scenes), a few photons or less than a single photon, the conventional approaches are quite helpless due to the limitation of conventional detector sensitivity, such as remote targets, light propagation through a highly scattered and/or absorbing medium. The simultaneous detection of range and velocity of target in photon starved scenes becomes a problem to be solved [15–17]. Reilly and Kanter firstly applied single photon detectors to velocity measurement. They judiciously chose a GHz gated single photon detector to perform detection of range and velocity with high accuracy at low received powers [18].

We propose an alternative strategy to realize the simultaneous detection of range and velocity in photon starved scenes. A symmetric chirped amplitude modulation of the up-ramp and the down-ramp is applied to premixing photon-counting chirped amplitude modulation lidar (PPCCAML). First, the signal processing model of calculating the range and velocity information is described. Then the accuracies of range and velocity are further analyzed. Finally, a proof-of-principle experiment is performed, and experimental results show that this system can break the limit of the maximum modulation frequency and allow the use of much higher fundamental frequency and modulation bandwidth to realize higher accuracy range and velocity detection.

2. The theoretical analysis

2.1. The working principle of system

This PPCCAML system employs a symmetric chirped amplitude modulation of the up-ramp and the down-ramp to obtain range and velocity simultaneously. This system continues to use the premixing method, which is detailed in our previous work [19]. The principle diagram of PPCCAML system is sketched in Fig. 1(a). A signal generator is used to generate a Chirped Amplitude Modulation (CAM) electric signal, and the CAM signal's frequency varies linearly over a range of modulation bandwidth B centered on the fundamental frequency f_0, and the modulation periods of the up-ramp and the down-ramp are the same $T/2$, shown as the solid line in Fig. 1(b). The generated CAM electric signal is divided into two channels: one channel is used to modulate a fiber laser to emit a continuous laser signal whose intensity is proportional to the external CAM electric signal; the other channel as a local CAM signal is transmitted to a sampling gate controlling module to modulate the sampling gate width. The modulated laser signal is emitted through a telescope. With atmosphere attenuation and target reflection, a part of laser signal remains chirp information and returns back to the lidar receiver.

The returned signal is detected by Gm-APD with tunable gate-width sampling gates. These sampling gates are equidistant, and their widths are modulated by the local CAM signal and proportional to the local CAM signal intensity, shown as Fig. 1(c).