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A stepped FM/CW lidar system using a dual parallel Mach–Zehnder modulator

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ABSTRACT

A stepped frequency-modulated continuous-wave lidar system using a dual parallel Mach–Zehnder modulator with heterodyne detection is demonstrated. The lidar transmitter utilizes a modulation loop circuit composed of an electro-optic dual parallel Mach–Zehnder modulator and a fiber amplifier, as well as a tunable Fabry–Perot filter to generate a bandwidth-enhanced stepped frequency-modulated signal. In addition, a centroid algorithm is used in the receiver to process the signal with both high precision and high accuracy. The simulation results demonstrated that the ranging precision of the proposed lidar was 2.09 cm and the ranging accuracy was 0.16 cm. A validation experiment verified that the data obtained in the simulation had a modulation bandwidth of 4 GHz using a 200-MHz signal source. The improvements resulted in a frequency-modulated continuous-wave lidar system with high precision and accuracy by operating a modulated signal with a wider modulation bandwidth using signal sources with low bandwidth in a low-cost and compact structure.

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1. Introduction

Lidar systems have been used extensively for estimating atmospheric parameters [1,2], measuring velocity and vibrations [3,4], and imaging [5,6]. The frequency-modulated continuous-wave (FM/CW) lidar with heterodyne detection has become a common detection mechanism because of the fine temporal resolution and ranging precision provided by the bandwidth of the chirp with low bandwidth detectors and analog-to-digital converters (ADCs). For an FM/CW lidar system, the ranging precision σ_R is generally determined by the speed of light in a vacuum c, the modulated bandwidth B and the detection signal to noise ratio (SNR) [7]. The most pressing technical bottleneck in the system is the bandwidth, which requires improving because a higher precision is required for practical lidar applications such as metrology and tomography, while there are technical problems in producing a high-frequency signal source to drive the electro-optic modulator; this results in an increased volume and additional costs.

As a solution, tunable lasers have been adapted to generate a wideband frequency-modulated (FM) signal with a bandwidth of more than 1 THz; however, the stability, frequency sweep rate, and frequency stability of these laser sources are insufficient in high dynamic applications [8]. As a result, there is an intense need for high-speed wideband modulation methods in FM/CW lidar systems.

In recent years, research into the use of dual parallel Mach–Zehnder modulators (DPMZM) in orthogonal frequency-division multiplexing has increased because of the improved performance of the DPMZM with regard to carrier-suppressed single side band modulation [9,10]. It has been demonstrated that a loop circuit consisting of an electro-optic DPMZM and a fiber amplifier can be used in the generation of a flat frequency comb with an ultra-wide bandwidth as large as tens of GHz [11]. Compared to tunable lasers, this modulation method can provide a much higher modulation rate as well as good stability and the method demonstrates great potential for transferring photonics techniques for improving FM/CW lidar systems.

In this paper, we propose and experimentally demonstrate a stepped FM/CW lidar system based on a DPMZM. A modulation loop circuit consisting of a DPMZM and an Erbium Doped Fiber Amplifier (EDFA) was used to generate a wideband FM signal using a low bandwidth signal source; an optical heterodyne module was adopted in the receiver. In addition, a centroid algorithm is used in the receiver to process the signal with high accuracy. The proposed lidar system is flexible and suitable for practical applications due to the high ranging precision and accuracy when employing a wider modulation bandwidth with low bandwidth signal sources in an economical approach.

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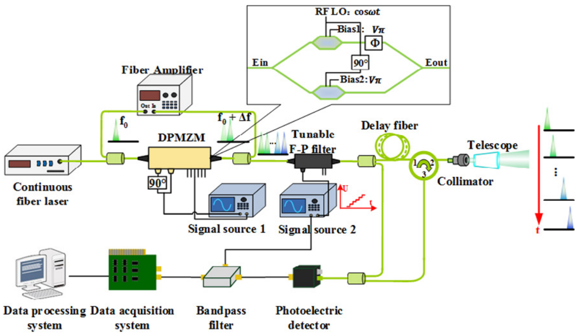

Fig. 1. Block diagram of the proposed FM/CW lidar system with coherent heterodyne detection.

2. System description and operating principle

Fig. 1 shows the block diagram of the proposed bandwidth-enhanced stepped FM/CW lidar system with coherent heterodyne detection.

As shown in the solid box in Fig. 1, a DPMZM consists of two Mach–Zehnder (M–Z) intensity modulators, named I and Q. Both of the modulators are biased at the minimum work point with a bias voltage of V_π, and the phase shifter between the two modulators is biased to generate a phase shift of $\Phi = 90°$ for carrier-suppressed single sideband (SSB) modulation. The form of the two voltage signals used to drive the arms of the modulator can be expressed as,

$$V_I(t) = V_0 \cos(2\pi\Delta f), \tag{1}$$

$$V_Q(t) = V_0 \sin(2\pi\Delta f), \tag{2}$$

where V_0 is the amplitude of the driving voltage waveform. The optical field at the modulator output can be derived as [12],

$$E_0 = E_S \cos\left[2\pi\left(f_0 + \Delta f\right)t\right], \tag{3}$$

where f_0 is the optical frequency of the laser and E_S is the amplitude of the input optical field.

Eq. (3) represents a carrier-suppressed SSB optical signal with the frequency shift Δf from the central frequency f_0. The output optical field of the modulation loop circuit after a plurality of modulation cycles can be expressed as,

$$E_{\text{comb}} = \sum_{m=0}^{N-1} E_{S,m} \cos\left\{2\pi\left[f_0 + (m+1)\Delta f\right]t\right\}, \tag{4}$$

where $E_{S,m}$ is the amplitude of output optical field of frequency $f_0 + (m+1)\cdot\Delta f$, and N is the amount of the frequency components. Eq. (4) indicates that the output of the modulation loop circuit is equivalent to a series of frequency comb signals with a constant frequency shift of Δf. In an ideal case, the energy loss in the modulation loop circuit can be entirely compensated by the EDFA during each loop, the constant output optical field of each frequency would be equivalent to E_S, and N is equal to infinity. Under practical conditions, the compensation function of the EDFA cannot offset the loss; therefore $E_{S,m}$ decreases gradually along with m and N is equal to infinity. It has been reported that using a value of 100 for N is achievable for this type of modulation loop circuit where $E_{S,m}$ is used as a constant [13].

A tunable Fabry–Perot (F–P) filter with a pass bandwidth of Δf was used in this study. When the free spectral range (FSR) of the F–P filter is equal to the modulation bandwidth corresponding to the finite length of the frequency comb, expressed as $FSR = N\cdot\Delta f$, the stepped voltage waveform used to drive the filter can be expressed as,

$$V_{\text{F–P}}(t) = \sum_{m=0}^{N-1}\left(\frac{V_\pi}{T}t\right) * \text{rect}\left(\frac{t - mt_0}{t_0}\right), \tag{5}$$

where $T = N\cdot t_0$ is the modulation period of the FM signal, V_π is the driving voltage of the filter when the cavity length of the F–P filter changes half a wavelength. According to the frequency selective characteristic of the tunable F–P filter [14],

$$\Delta f = \Delta V / V_\pi \cdot FSR, \tag{6}$$

the light field of the transmission light can be derived as,

$$E_t(t) = E_S \sum_{m=0}^{N-1} \text{rect}\left(\frac{t - mt_0}{t_0}\right)\cos\left[2\pi\left(f_0 + m\Delta f\right)t\right]. \tag{7}$$

Eq. (7) indicates that the output of the tunable F–P filter is a stepped FM signal with a step time duration of t_0 and a step frequency of Δf, which can be used in the coherent heterodyne detection.

At the receiver, the optical field of the echo signal scattered by the target can be expressed as,

$$E_{\text{Echo}}(t) = E_r \sum_{m=0}^{N-1}\left\{\text{rect}\left[\frac{(t-\tau_R) - mt_0}{t_0}\right] \cdot \cos\left[2\pi\left(f_0 + m\Delta f\right)(t - \tau_R)\right]\right\}, \tag{8}$$

and the optical field of the local oscillator (LO) can be expressed as,

$$E_{\text{LO}}(t) = E_l \sum_{m=0}^{N-1} \text{rect}\left(\frac{t - mt_0}{t_0}\right)\cos\left[2\pi\left(f_0 + m\Delta f\right)t\right], \tag{9}$$

where $\tau_R = 2R/c$ is the time delay of the echo, R is the distance between the target and the lidar system, and E_r and E_l are the constant optical fields of the echo and the LO. When $f_R \in (0, B/2)$, the heterodyne IF signal can be expressed as,

$$I_{IF} = \begin{cases}\cos\left[2\pi\left(m_R - 1\right)\Delta f t\right], & t \in \left(m_R t_0, \tau_R\right)\\ \cos\left(2\pi m_R \Delta f t\right), & t \in \left(\tau_R, \left(m_R + 1\right)t_0\right)\end{cases}, \tag{10}$$

where $m_R = 0,1,2,\ldots$ is the integer part of τ_R/t_0. Eq. (10) shows that the heterodyne IF signal consists of two frequency components spaced at Δf, which are relative to m_R. A more intuitive view of I_{IF} is shown in Fig. 2(a). Subsequently, the IF signal is filtered using a bandpass filter and processed using a Fast Fourier Transform (FFT) function. The frequency spectrum is shown in Fig. 2(b), which indicates a dual-peak phenomenon in the frequency spectrum corresponding to the distance of the target.

When the time delay τ_R is less than t_0, the peak with the lower frequency of the heterodyne signal is covered by the zero frequency noise. In this case, the signal laser is delayed by t_0 before being transmitted to the telescope as shown in Fig. 1. Thus Eqs. (8) and (10) should be adapted as,

$$E_{\text{Echo}}(t) = E_r \cos\left[2\pi f_s\left(t - \tau_R - t_0\right)t\right], \tag{11}$$

and

$$I_{IF} = \begin{cases}\cos\left[2\pi\left(m_R + 1\right)\Delta f t\right], & t \in \left(m_R t_0, \tau_R\right)\\ \cos\left[2\pi\left(m_R + 2\right)\Delta f\right], & t \in \left(\tau_R, \left(m_R + 1\right)t_0\right)\end{cases},$$
$$m_R = 0, 1, 2, \ldots. \tag{12}$$

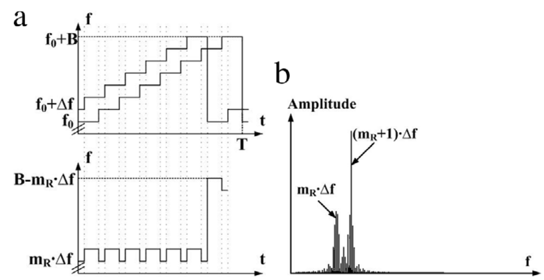

Fig. 2. Heterodyne IF signal of the proposed FM/CW lidar system, (a) frequency-to-time waveform; (b) frequency spectrum distribution.

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