Simultaneous Real-Time Ranging and Velocimetry via a Dual-Sideband Chirped Lidar

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***Abstract*— A dual-sideband (DSB) chirped lidar for simultaneous real-time ranging and velocimetry is proposed and demonstrated, in which a Mach–Zehnder modulator (MZM) is applied to generate the required optical DSB frequency-modulated continuous-wave (FMCW) signal. The inherent opposite frequency chirp and contrary wavelength offset to the optical carrier of the two generated sidebands make it possible to measure the distance and velocity by frequency mixing without complex post digital signal processing, meanwhile, make the measurement of velocity immune to the nonlinearity of the FMCW optical signals. An experiment is carried out, in which an 8–18 GHz saw-tooth FMCW signal is used to drive an MZM, generating a wideband optical DSB FMCW signal. The distance and the velocity are simultaneously derived from the real-time frequency spectra. Accurate velocimetry with a nonlinear FMCW signal is also investigated.**

***Index Terms*— Lidar, frequency-modulated continuous-wave (FMCW), lidar ranging, lidar velocimetry.**

I. INTRODUCTION

WITH the advantages of high intensity, good directivity and high precision, lidars have been widely used for 3D imaging, automatic drives, remote sensing and meteorological observation [1]–[4]. Typical lidar systems include pulsed lidar [5], phase coding lidar [6] and frequency-modulated continuous-wave (FMCW) lidar [7]–[9]. Among them, FMCW lidar applies a continuous-wave laser at low peak power, which can provide simultaneously large dynamic range and excellent ranging resolution. In FMCW lidars, saw-tooth and triangular frequency-modulated waveforms are widely used [10], [11]. For saw-tooth FMCW lidars, an additional Doppler shift is superimposed on the difference frequency related to the distance for moving targets. Because this shift is difficult to be isolated, saw-tooth FMCW lidars were thought to be unsuitable for simultaneous ranging and velocimetry [12]. Since the up-ramping and down-ramping have unequal difference frequencies for moving targets, triangular FMCW lidars are able to measure the distance and velocity [10]. However, the unequal difference frequencies are actually located in different time slots (up-ramping and down-ramping). The sum and difference of the two unequal difference frequencies are required to be calculated to obtain the distance and velocity, which increases the difficulty for getting the real-time velocity of fast accelerating targets. In addition, if the frequency modulation is not strictly linear, there would be significant distance and velocity measurement errors.

To implement simultaneous real-time ranging and velocimetry, several lidars with elaborately-designed architectures have been proposed [12]–[15], which can be generally classified into two categories. In the first category, multiple laser sources are employed, with one laser for ranging and the other for Doppler velocimetry [13]. The key problem associated with this kind of lidars is their complex structure. In the second category, advanced modulation schemes on a single laser source are applied. For instance, the laser in [14] is modulated by two different frequencies in a cascaded structure, with the lower and higher frequencies used for respective ranging and velocimetry. In [12] a complex-optical-field lidar is reported, in which the negative sideband of the transmitted signal is single tone (for velocimetry) and the positive sideband is linearly frequency modulated (for ranging). This kind of lidars, however, not only requires sophisticated schemes in the transmitter but also complicate dramatically the receiver architecture. Recently, a FMCW lidar based on a pair of oppositely frequency-swept lasers is proposed for simultaneous real-time ranging and velocimetry [15]. Thanks to the contrary frequency modulation in the two individual lasers, both of the distance and velocity are accurately determined from the spectrum of a frequency mixer. However, a phase-locked loop is needed for synchronization of the two lasers, and a dual-channel transmitter and receiver are required.

In this letter, we propose and demonstrate a FMCW lidar based on optical dual-sideband (DSB) modulation, which can simultaneously implement real-time distance measurement and velocimetry. In the transmitter of the proposed lidar, a single laser source together with a Mach-Zehnder modulator (MZM) driven by an electrical saw-tooth FMCW signal is used to generate an optical carrier-suppressed DSB signal. Thanks to the inherent opposite frequency chirps in the $\pm$1st-order sidebands, for moving targets, unequal difference frequencies would be produced if a de-chirping receiver is employed, i.e. a dual-tone signal is generated. By self-mixing of the dual-tone signal, the real-time distance and velocity of the targets can be directly extracted without arithmetic post-processing (addition and subtraction). Because of the contrary instantaneous frequency offsets of the two sidebands, the DSB

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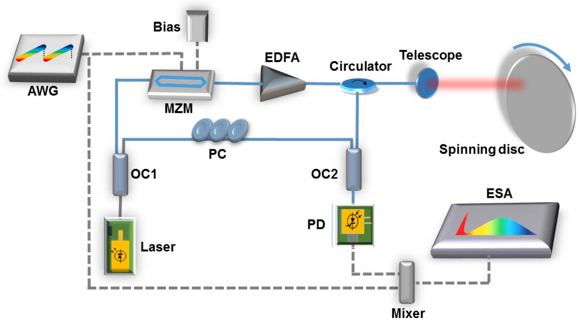

Fig. 1. Experiment setup of the proposed DSB lidar. The solid blue lines are optical fibers and the dashed gray lines are electrical cables. OC: optical coupler; PC: polarization controller; MZM: Mach-Zehndar modulator; EDFA: erbium doped fiber amplifier; AWG: arbitrary waveforms generator; ESA: electrical spectra analyzer; PD: photodetector.

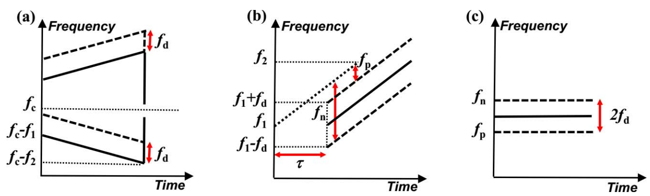

Fig. 2. Illustration of the signal evolution in the DSB lidar with a saw-tooth FMCW signal. (a) The instantaneous frequencies of the optical DSB signal (solid lines) and the reflected light experienced a Doppler shift (dashed lines). (b) The electrical signal generated by the PD (solid or dashed lines) and the saw-tooth FMCW signal from the AWG used for de-chirping (dotted line). (c) The de-chirped signal for static targets (solid line) and moving targets (dashed lines).

lidar is feasible for velocimetry even though there is obvious nonlinearity in FMCW signals. The proposed DSB lidar features real-time measurement, which may be attractive for simultaneous detection of the distance and velocity of fast moving and fast accelerating targets.

II. Principle

Figure 1 shows the schematic diagram of the proposed DSB lidar. In the transmitter, a continuous-wave (CW) light from a laser diode (LD) is split in two parts by an optical coupler (OC), of which one part is directed to a MZM and the other is used as the reference light for the coherent receiver. The MZM is driven by a saw-tooth FMCW signal generated by an arbitrary waveforms generator (AWG). By biasing the MZM at the minimum transmission point, a carrier-suppressed DSB optical signal can be generated. The generated DSB optical signal is amplified by an erbium-doped fiber amplifier (EDFA) and projected on the target by a telescope. In the receiver, the reflected light collected by the same telescope beats with the reference light in a photodetector (PD). The obtained electrical signal is then mixed with the original saw-tooth FMCW signal, to perform de-chirping. The output is analyzed by an electrical spectra analyzer (ESA) to derive the distance and velocity of targets.

In Fig. 2, we illustrate the signal evolution in the DSB lidar with a saw-tooth FMCW signal. Generally, the carrier-suppressed optical DSB signal generated from a MZM can be expressed as [16]

$$E = A\{J_1(m)\exp[j(2\pi(f_c + f_M)t)] - J_{-1}(m)\exp[j(2\pi(f_c - f_M)t)]\}, \quad (1)$$

where $J_1(m) = -J_{-1}(m)$, f_c and f_M are the frequencies of the optical carrier and the RF drive signal, respectively, A represents the amplitude of the electrical field and m is the modulation index. Since the instantaneous frequency of the saw-tooth FMCW signal shifts linearly from f_1 to f_2, the two sidebands of the optical DSB signal have opposite chirps and contrary instantaneous frequency offsets to the optical carrier. For static targets, the reflected signals shows the same frequency chirps with the original signal (solid lines in Fig. 2 (a)), while for moving targets, the reflected light experiences a Doppler shift f_d (dashed lines in Fig. 2 (a)). Since f_1 and f_2 are much smaller than f_c, f_d can be seen as identical over the signal period. The reflected light is coherently detected, i.e. beats with the reference light in a PD. The resulted electrical signal would be single chirped for static targets (solid line in Fig. 2 (b)) or dual chirped for moving targets (dashed lines in Fig. 2 (b)). By mixing the electrical signal with the saw-tooth FMCW signal from the AWG (dotted line in Fig. 2 (b)) at a mixer, a de-chirped single-tone or dual-tone signal is generated, which is shown as the solid line and dashed lines in Fig. 2 (c), respectively. For the dual-tone signal, the self-mixing can also be achieved in the same mixer, which produces the sum frequency and difference frequency of the dual-tone signal. From the sum frequency and difference frequency, the distance (R) and velocity (V) can be simultaneously derived [12],

$$f_R = \frac{f_p + f_n}{2}, \quad f_d = \left|\frac{f_p - f_n}{2}\right|,$$

$$R = \frac{f_R T c}{2(f_2 - f_1)}, \quad V = \frac{f_d c}{2 f_c}, \quad (2)$$

III. Experiment

To demonstrate feasibility of the proposed DSB lidar for simultaneously ranging and velocimetry, an experiment is performed. An optical lightwave at 1545 nm from a narrow-linewidth laser (PureSpectrum PS-TNL) is modulated at a 40-GHz MZM (Fujitsu FTM 7938EZ) by a saw-tooth FMCW signal with a frequency of 8-18 GHz and a period of 20 μs from an AWG (Keysight M9502A). A PD with a bandwidth of 19 GHz and a responsivity of 0.85 A/W is used to detect the reflected light from the spinning disc. In the measurement, the power of the light reflected is around -20 dBm and the reference light is about -10 dBm. The output signal of the PD is then de-chirped and measured by an ESA (Agilent E4447A).

Figure 3(a) shows typical electrical spectra of the de-chirped signals. For the static disc, a single-tone signal is observed at a frequency of 306.4 MHz, which indicates a distance of 37. 28 m according to (2). For the spinning disc, a dual-tone signal is presented, in which the sum frequency of the two peaks can be used for ranging. By varying the distance in a range from 36 to 55 m, the corresponding frequency of the single-tone signal is recorded to determine the distance, with the results shown in Fig. 3(b). The measured curve (red line) of the DSB lidar has a slope of 0.3 m/MHz. For comparison, the distances are also measured by a ruler, shown as the squared scatters in Fig. 3(b). The two measurements agree well with

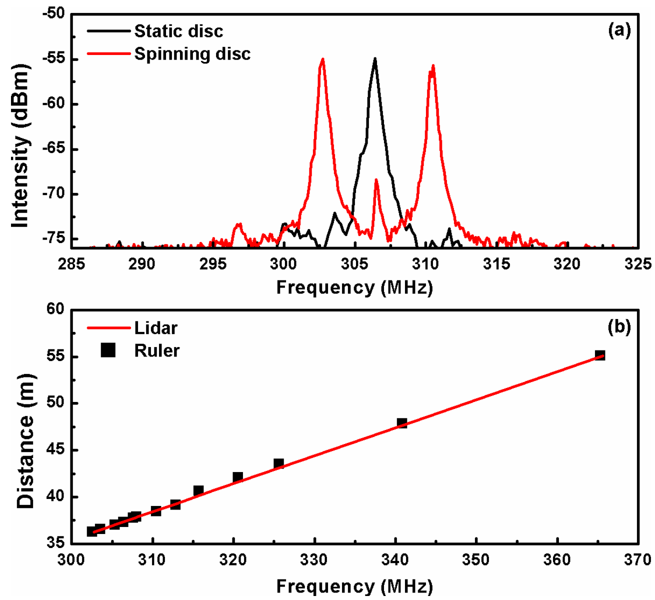

Fig. 3. (a) The de-chirped signal of the proposed DSB lidar spectra. (b) The distance measured by the Lidar (red line) and the Ruler (squared scatters).

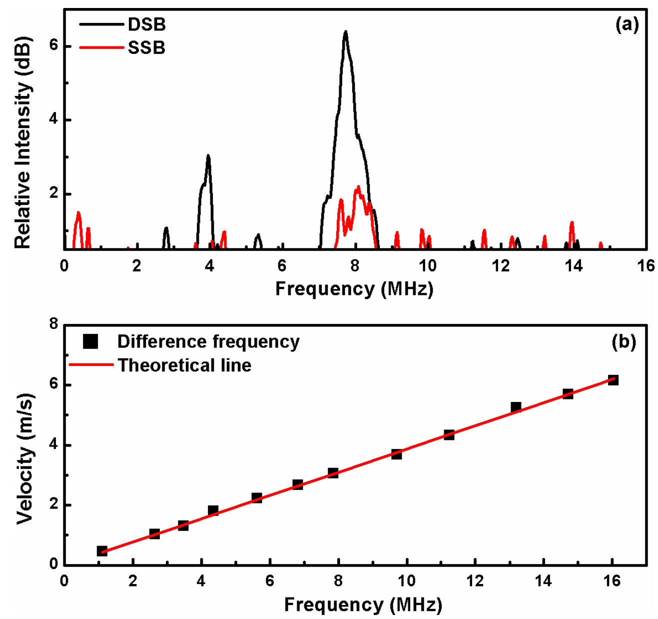

Fig. 4. Velocimetry via frequency mixing in the DSB lidar. (a) The frequency-mixing spectra in the DSB lidar and the SSB lidar. (b) The measured and theoretical frequencies for different velocities in the DSB lidar.

each other, with relative errors of less than 1.2%. Since the full-width at half maximum (FWHM) of the single-tone signal is about 500 KHz, the distance resolution of the DSB lidar is estimated to be around 1.5 cm. In practice, the ESA used in the experiment can distinguish a magnitude difference of 0.1 dB, so the actual resolution could be much higher.

Although the velocity is measurable via a single-sideband (SSB) triangular frequency modulation lidar, post-processing is required to calculate the gap frequency of the two peaks which actually locate at different time slot (up-ramping and down-ramping) [10]. For the proposed DSB saw-tooth frequency modulation lidar, the two peaks of the dual-tone signal arise at the same time and the difference frequency can be directly obtained via self-mixing in the mixer. As a result, by observing the low-frequency region of the ESA, we can obtain directly the difference frequency of the dual-tone signal, as shown in Fig. 4 (a). Velocimetry and ranging can thus be easily implemented simultaneously according to (2). As a comparison, the self-mixing spectrum for a lidar with the SSB triangular frequency modulation (red line) is also plotted in Fig.4 (a). As can be seen, the spectrum for the DSB lidar shows a clear spike of difference frequency, while no obvious peak is observed for the SSB lidar. In Fig. 4 (b), the difference frequencies are measured for varied velocities, which are shown as the squared scatters. The measured curve is in coincidence with the theoretical line (red line) calculated according (2), with a slope of 0.387 m/(s $\cdot$ MHz) and relative errors of less than 4%. Since the FWHM of the difference frequency signal is about 450 kHz, the velocity resolution is estimated to be 0.17 m/s.

Due to the bad signal-noise-ratio (SNR) in our lidar system, the range and velocity accuracy of DSB lidar are lower than the theoretical values. This bad SNR is because of the low power of reflected light, the large bandwidth of PD and the high noise in frequency mixing. If a large aperture telescope and a low-noise optical/electrical amplifier are applied, the distance and velocity accuracy can be further improved. However, it is the important feature that the real-time distance and velocity are able to be measured in DSB lidars. This real-time measurement is attractive for fast moving and accelerating targets. For example, if the velocity and acceleration of the targets are 1 m/s and 100 m/s^2, the variation of velocity is about 0.1 m/s in one period (1 ms). As a result, the error of measured velocity is around 10% in SSB lidars, while the real-time velocity can be measured by DSB lidars.

For conventional FMCW lidars, the linearity of the FMCW optical signal is of great importance to the measurement accuracy of the distance and velocity. If the optical frequency chirp is not strictly linear, there would be significant measurement errors [17]. In practice, the linearly frequency-modulated (LFM) optical waveform can be generated by directly modulating or extra modulating the laser [18], [19]. It has been addressed that the generation by directly modulation is very challenging, while it is easier to obtain strict LFM optical waveform with an extra modulator, such as a MZM. For the generation with extra modulation, the nonlinearity of LFM optical waveform is mainly caused by the modulation signal, in which the DAC of electrical signal may induce the obvious nonlinearity [19].

A reference line can be employed to remove the detriment of nonlinearity in lidar ranging [20], but for velocimetry, it is difficult to set a reference with an accurate and constant velocity. In the proposed DSB lidar, due to the contrary instantaneous frequency offsets of the two sidebands, the deviation caused by the nonlinearity in FMCW signal is opposite and can be cancelled out in the self-mixing, so the velocimetry can tolerate certain nonlinearity of the frequency modulation. To verify this, we introduce certain nonlinearity into the AWG-generated saw-tooth FMCW signal to obtain obvious nonlinearity in the optical waveform. Although the

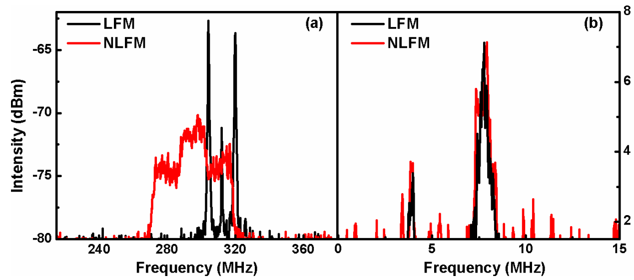

Fig. 5. (a) The dual-tone signal for LFM (black line) and NLFM (red line) (b) The difference frequency signals in the DSB lidar.

detriment of nonlinearity is magnified in the experiment, the mechanism is still equivalent to the practical measurement. The red line in Fig. 5 (a) shows the dual-tone signal obtained after de-chirping. As can be seen, the peaks generated by the nonlinear FMCW (NLFM) signal are severely broadened compared with the signal generated by the linear FMCW (LFM) so that determining the accurate frequencies of these peaks becomes difficult in NLFM. However, a clear spike of difference frequency is observed by self-mixing the dual-tone signal for both LFM and NLFM in Fig. 5 (b), from which the frequency can be easily identified, leading to accurate measurement of the velocity.

IV. CONCLUSION

In conclusion, we have demonstrated a FMCW lidar based on DSB modulation for simultaneously real-time ranging and velocimetry. Experiment results showed that the distance and velocity can be extracted from the real-time frequencies which are obtained by frequency mixing. The relative measurement errors for distance and velocity are less than 1.2% and 4%, respectively. The system also has good tolerance to the nonlinearity of the FMCW optical signals. The proposed DSB lidar might be a promising solution for simultaneously real-time ranging and velocimetry of fast moving and fast accelerating targets, which may be applied in automatic drives, remote sensing and meteorological observation.

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