A Random Amplitude Modulated Continuous Wave Lidar System Based on Lens-assisted Beam Steering for Ranging and Velocimetry

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***Abstract*—A non-coaxial Lidar system based on lens-assisted beam-steering technology is demonstrated. A coherent random amplitude modulated continuous wave detection method is applied in the Lidar system to enable the capabilities of unambiguous ranging and velocimetry.**

Keywords—Lidar, beam steering, RAMCW, ranging and velocimetry.

I. Introduction

Light detection and ranging (Lidar) technology has attracted increasing attention in the past few years owing to its potential for high resolution three-dimensional mapping. The conventional Lidar systems are bulky and somewhat unreliable due to the mechanically rotating components. For solid-state beam steering, the optical phased array (OPA) technology has provided a favorable option and become a research hotspot[1, 2]. Although great progresses have been made in recent years, such as a large field of view (FOV) of 180°[3] and a long-distance ranging of about 200 m[4], the OPA technology still faces many challenges, including increasing power consumption and complex packaging.

Recently, the lens-assisted beam steering (LABS) technology, also known as focal plane switch array (FPSA) technology has been demonstrated with different configurations[5-18]. The LABS technology realizes solid-state beam steering by switching the beam to different emitters located on the focal plane of the lens, which has the advantages of low power consumption, low control complexity and high background suppression. This technology has also been used in many fields as optical wireless communications (OWC)[19] and frequency transfer [20]due to the benefits mentioned above.

In our previous work, a Time-of-Flight (ToF) pulse Lidar system based on LABS technology has been proved[5]. However, ToF detection method is sensitive to ambient noise, which limits its ranging applicability. Meanwhile, the frequency modulated continuous wave (FMCW) detection method has advantages as immunity to environmental noise and the capability of measuring the velocity of moving object without any additional complexity. However, a high linearity of frequency sweep is essential in FMCW detection[21-24]. In addition, the conventional FMCW Lidar system suffer from unavoidable ambiguities caused by Doppler frequency shifts.

In this work, we have demonstrated a LABS based random amplitude modulated continuous wave (RAMCW) Lidar system. Based on the structure of LABS Lidar system, an acousto-optic modulator (AOM) is applied to modulate the laser amplitude as well as shift the optical frequency of probe light. The velocity and moving direction of an illuminated object can be unambiguously recognized. The proposed RAMCW LABS Lidar system has the advantages of immunity to environmental noise, no velocity-distance aliasing, no reliance on spectral separation, as well as low control complexity and power consumption. This work indicates the feasibility of RAMCW Lidar application based on LABS technology.

II. Principle and Methodology

A. Principle of LABS

Firstly, the principle of LABS is briefly explained. A schematic diagram of LABS is shown in Fig. 1(a). The focal plane of a lens is overlapped with the emission plane of an emitter array. Beam emitting and steering are achieved by a switchable emitter array and the lens respectively. The beam divergence after collimated by the lens is denoted as $\delta\theta = tan^{-1}(w/f)$, where w is the width of the emission beam, and f is the focal length of the lens. The steering angle is expressed as $\theta_n = -tan^{-1}(np/f)$, where p is the pitch between two adjacent emitters, and n is the index number of the emitter, assuming the emitters are numbered starting from the central axis. Therefore, after adjusting the arrangement of the emitters reasonably, beam steering is realized by switching the light into different emitters. This technology can greatly diminish challenges of power consumption and control complexity. For example, if a binary-tree switch array is employed, LABS technology only requires $\log_2 N$ switches to operate simultaneously for N emitters (i.e. the power consumption is $O(\log_2 N)$) whereas the OPA technology requires all N phase shifters to operate (i.e. the power consumption is O(N)).

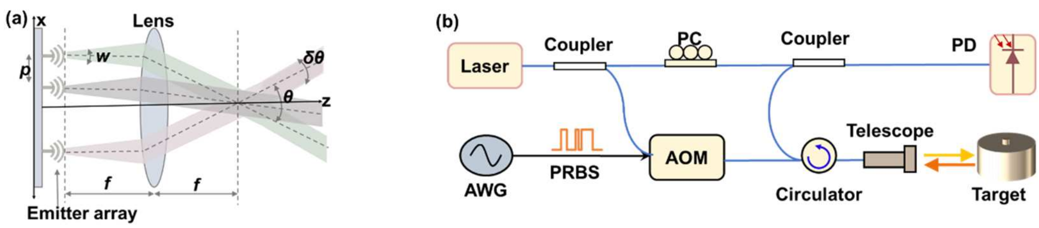

Fig. 1 (a) Principle of lens assisted beam steering (LABS). (b) Configuration of coherent RAMCW Lidar.

B. RAMCW Detection Method

The coherent RAMCW is a detection method in which a pseudo-random pattern is encoded into the amplitude of the light, and the received probe light is beaten with a local oscillator (LO) light at a photodetector (PD)[25-27]. By introducing an intentional frequency shift to probe light branch, beating the received probe light with LO light allows the interfered signal to oscillate near the heterodyne frequency. For the purpose of illustrative, an example configuration of a coherent RAMCW Lidar is shown in Fig. 1(b), where an AOM is employed to generate an optical frequency shift into probe light. It is emphasized that the pseudo-random bit sequence (PRBS) is encoded onto the amplitude of the probe light by the same AOM. Therefore, the ranging distance is extracted by cross-correlated the received signal with the synchronization signal of PRBS signal, and the speed information is obtained from the offset between the beat signal and the heterodyne frequency. This detection method is aliasing-free since the distance and velocity are extracted in time domain and frequency domain respectively. Furthermore, the velocity and moving direction of an illuminated object can be unambiguously recognized.

III. Experiment and Result

The experiment setup of the RAMCW Lidar system is shown in Fig. 2(a). The whole Lidar system is based on non-co-axial design. A continuous wave (CW) distributed feedback (DFB) laser emits a laser centered at 1550 nm. The output power of the light is 0 dBm and amplified by an erbium-doped fiber amplifier (EDFA) to 25 dBm, which is limited by the LABS device damage threshold. Then the light is split into two branches by a 99:1 coupler. The 1% light serves as LO light and the 99% light serves as probe light. The optical frequency of the probe light is shifted by 200 MHz via an AOM (China Electronics Technology Group, SGTF 200-1550-1) prior to the light emission. The driving voltages for AOM turn-on and turn-off are 3.7 V and 0 V, respectively. An arbitrary function generator (AFG) (RIGOL DG5102) encodes a PRBS to the amplitude of the probe light by driven this AOM. The amplitude modulation period is 1 µs and the number of sequence bits is 64 bits. In other words, this AOM plays the role of shifting optical frequency and modulating the amplitude of light simultaneously. Then the probe light is directed into the LABS device though an isolator. The LABS device consists of an integrated SiO_2 1×16 switch chip, a 4×4 fiber array and a lens. The SiO_2 1×16 switch chip is made of cascaded four 1×2 Mach-Zehnder interferometer (MZI) switches. A more detailed introduction about this device is found in [5]. Subsequently, the probe light is emitted to the free space by LABS device. and illuminates the edge of a spinning disk. The rotational speed of this spinning disk is controlled by the DC voltage applied to the motor. A retroreflective sheet is stuck to the edges of disk to enhance the intensity of the reflective. The backscattered light carries distance and velocity information of the spinning disk. The returning light is collected by a collimator, combined with the LO light by a 99:1 fiber coupler and enters an amplified PD. Different from the setup shown in Fig. 1(b), a non-coaxial optical system is applied to prevents a 4% end-face reflection appear in the interface between fiber array and air from interfering measurement. The frequency-shifted probe light beat with unaltered LO light and generate frequency down-converted signal. The beat signal is captured by an Analog-Digital Converter (ADC) with 10 Gsa/s sample rate.

In this experiment, the velocity of spinning disk is set from -0.64 m/s to 0.27 m/s, as shown in Fig. 2(b). The radial velocity of the spinning disk is varied when the probe light illuminate different positions of the disk, as shown in Fig. 2(c). When the target moves towards the LABS device, the beat frequency decreases compared to the heterodyne frequency of 200 MHz due to the existence of Doppler frequency shift. Otherwise, the frequency offset is positive. The moving direction of a target can be straightforwardly distinguished via a single fast Fourier transform (FFT), which facilitates the backend digital signal processing compared with the conventional FMCW Lidar system. The beat frequency peak is broadened due to the instability of the rotational speed of the disk used in the experiment.

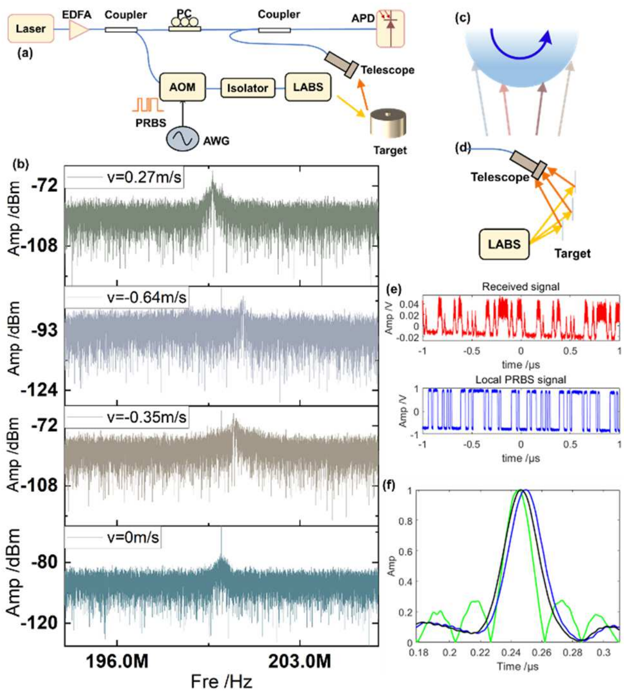

Fig. 2 (a) Experimental setup. (b) Measured results for the velocity measurement. (c) Schematic diagram of the effect of angle of incidence on Doppler shift. (d) Illustration of beam steering and ranging experiment. (e) Beat signal and local PRBS signal. (f) A normalized correlation with LO of scattered light

Furthermore, to verify the ranging and beam steering function of this Lidar system, three targets are placed horizontally in the distances of 0.21 m, 0.44 m and 0.89 m as illustrated in Fig. 2(d). The distance information is estimated by correlating the received signal with a synchronous copy of the PRBS applied to encode the amplitude of emitted light. A received signal and the synchronization copy of PRBS with time delay of 245 ns is shown in Fig. 2(e), which contains the delay time introduced by the fiber link. For interfering the probe with a copy of PRBS code can coherently amplify the received probe signal, it can be expected that RAMCW detection method has greater ranging distance compared with ToF detection method. By switching the laser to different emitters on the SiO_2 1 × 16 switch chip, different steering angles are achieved. The FOV is 1.05° × 1.05° limited by the size of emitter array. The scanning points and angle can be scaled to larger easily. The normalized correlation of PRBS code with three scattered beams are shown in Fig. 2(f), and the time delay are 245 ns, 246.5 ns and 249.5ns, respectively. The accuracy can be further improved by interpolating the peak of cross-correlation. Similar experiment is also performed when the three targets are placed vertically, which confirms the 2D beam steering function of the LABS based Lidar system.

IV. Conclusion

In conclusion, we have demonstrated a RAMCW Lidar system at 1550 nm based on LABS technology for unambiguous estimation on ranging distance and velocity. The Lidar system has 4 × 4 scanning directions and a steering angle of 1.05° × 1.05°. A heterodyne optical frequency shift and a PRBS encoding of the amplitude of probe light are implemented by one AOM simultaneously to simplify the system. The distance is extracted by correlating the received signal with a synchronous copy of the local PRBS, and the radial velocity is extracted from Doppler frequency shift respectively. because it does not rely Furthermore, this Lidar system is not only insensitive to environment noise, but also needs no high-performance laser source on spectral separation. This work proves the application potential of RAMCW detection in LABS based Lidar system.

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