Dual-Heterodyne Mixing Based Phase Noise Cancellation for Long Distance Dual-Wavelength FMCW Lidar

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Abstract: A coherent dual-wavelength frequency-modulated continuous-wave (FMCW) lidar utilizing dual-heterodyne mixing which permits efficient phase noise cancellation has been proposed. Consistent ranging resolution about 1.4×10^{-6} over distances beyond tens of intrinsic coherence length is achieved.

1. Introduction

Coherent laser interferometry based coherent lidar systems generally aim at precise depth, displacement or absolute distance measurement [1]. Thanks to the potentials to achieve simultaneously long range and high resolution, they have been playing important roles in a variety of fields ranging from scientific researches, industrial manufacturing, and civil scenarios, such as precision metrology, atmospheric monitor, free-space optics for satellite formatting, autonomous-system based automatic pilot, and 3D imaging.

Different from conventional pulsed or amplitude-modulated lidars, in coherent FMCW lidars, linearly frequency modulated (LFM) waveforms is utilized. The ranging information is imprinted onto the frequency domain, alleviating the trade-off between peak power and spatial resolution [2], namely, the detection range and timing precision. Many recent works focus on the sub-millimeter precision with few centimeters to hundreds millimeter spatial resolution at distance within a few meters, showing about 10^{-5} level range resolution [3], which is assessed according to the ration between the spatial resolution and effective detection range. For long range detections and sensing, coherent single-frequency lidars are sensitive to environment tabulations [4] such as atmospheric turbulence, resulting in severe limit in detection accuracy and precision. Coherent dual-wavelength lidars detects the variations between two correlated optical wavelengths, allowing mitigating the influences due to atmospheric turbulence and other effects [5].

To date, dual-wavelength lidars with fixed wavelengths have been demonstrated [6], showing robust measurement ability with, nevertheless, limited detection range. In this work, we demonstrate coherent dual-wavelength FMCW lidar. By exploiting the phase-correlation nature, dual-heterodyne mixing based phase noise cancellation is utilized to compensate for the laser phase noise. It allows achieving transform-limited spatial resolution at distances beyond tens of intrinsic coherence length with about 1.4×10^{-6} range resolution along the entire measurement range.

2. Operation principle

The operational principle of the proposed dual-heterodyne mixing based dual-wavelength FMCW lidar is depicted in Fig. 1. Two phase correlated lightwave signals with one being the fixed wavelength and the other being the FMCW wavelength, respectively, act as a pair of dual-wavelength probes. They can be readily obtained with proper external modulation or frequency comb. The probe E_{prb} and the reference E_{ref} can be expressed as:

$$\begin{aligned} E_{\mathrm{prb}}(t) &= A_{01}\exp\left\{2\pi\nu_0 t+\varphi_0(t)\right\}+A_{11}\exp\left\{2\pi\nu_1 t+\pi\gamma t^2+\varphi_0(t)+\varphi_1(t)\right\} \\ E_{\mathrm{ref}}(t) &= A_{02}\exp\left\{2\pi\left(\nu_0+f_{\mathrm{A}}\right)t+\varphi_0(t)\right\}+A_{12}\exp\left\{2\pi\left(\nu_1+f_{\mathrm{A}}\right)t+\pi\gamma t^2+\varphi_0(t)+\varphi_1(t)\right\} \end{aligned} \tag{1}$$

where A_{01}, A_{02} and A_{11}, A_{12} represent the complex amplitude for the fixed and the FMCW probe and reference, respectively. Also, γ holds for the FMCW chirp rate, φ_0 is the intrinsic laser phase noise while φ_i is the phase noise term due to the FMCW generation technique, and f_{A} is a frequency shift can be usually introduced by an acousto-optic frequency shifter.

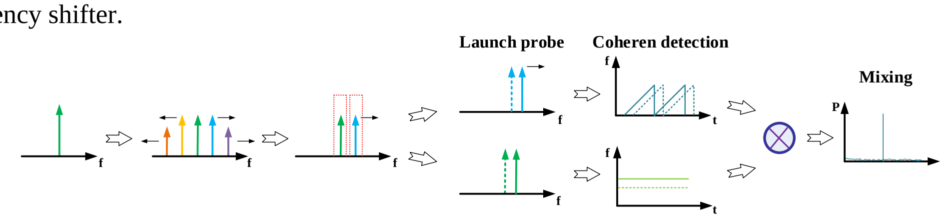

Fig. 1. Operational principle of the proposed lidar system.

After launching for the object-under-test, the reflected dual-wavelength echo signals, being a delayed version of the original probes with a time delay τ containing the distance information, are mixed with their respective references at the photo-detectors. As in the following it shows the dual-heterodyne output photo-currents for the fixed probe and FMCW probe, respectively, which is in proportion to the intensity of the probes and the reflectivity of the object.

$$
\begin{aligned}
i_0(t) &\sim RA_{01}A_{02}\cos\left\{2\pi f_A t - 2\pi\nu_0\tau + \Delta\varphi_0(t,\tau)\right\} \\
i_1(t) &\sim RA_{11}A_{12}\cos\left\{2\pi f_A t - 2\pi\nu_1\tau - 2\pi(\gamma\tau)t + \pi\gamma t^2 + \Delta\varphi_0(t,\tau) + \varphi_1(t,\tau)\right\}
\end{aligned} \tag{2}
$$

where $\Delta\varphi_i(t,\tau) = \varphi_i(t) - \varphi_i(t,\tau)$ represent the phase noise terms. It is interesting to find that both outputs are composed by a same laser intrinsic phase noise term with an additional FMCW modulation noise on the FMCW probe. Since the phase correlation is maintained between the two probes, it is allowed mixing the corresponding photo-currents and applying proper filtering to eliminate the sum-frequency terms. Then the resulting output differential-frequency term can be written as

$$
i_{\text{mix}}(t) \sim \frac{1}{2}R^2 A_{01}A_{02}A_{11}A_{12}\left\{\cos\left[2\pi f_\tau t - \pi\gamma t^2 - \varphi_1(t,\tau)\right]\right\} \tag{3}
$$

where $f_\tau = \gamma\tau$ is the corresponding beat frequency containing the range information and the fixed phase term which is related to the frequency interval between the fixed and the initial FMCW probes can be ignored.

By conducting Fourier transform in the digital domain, we are able to retrieve the beat-frequency. With the pre-set FMCW chirp rate γ, the distance information can be obtain with a resolution determined by the inverse of the FMCW, namely, the frequency chirp range. While the other phase terms are almost deterministic, the eventual measurement accuracy is supposed to be deteriorated by the FMCW modulation induced phase noise $\varphi_1(t,\tau)$. Nevertheless, as the microwave phase noise is supposed to be smaller than off-the-shelf semiconductor lasers,

3. Experiment result and discussion

For a proof-of-concept experiment, here we use intensity modulation to generate one pair of phase-correlated probes. This way, the 0^{th} order carrier and the 1^{st} order mode are phase correlated while their instantaneous frequency difference follows the frequency of the modulation signal. The detailed experimental setup is illustrated in Fig. 2.

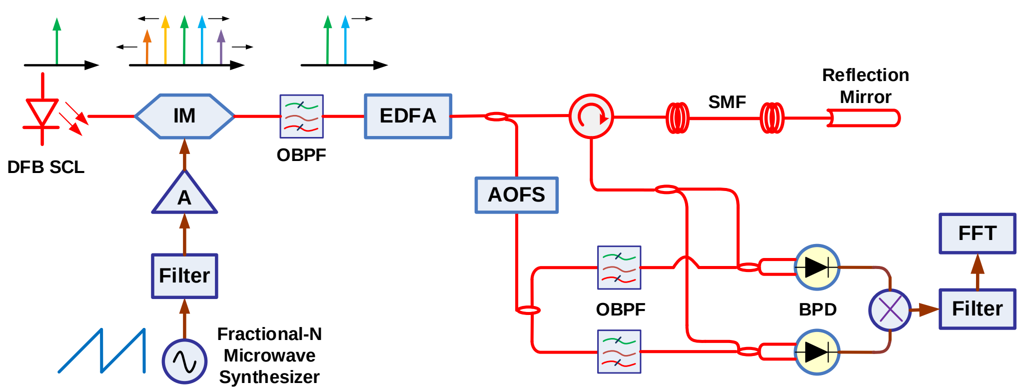

Fig. 2. Schematic of experiment setup for the proposed dual-frequency lidar system. A: amplifier.

A commercial Mach-Zehnder type intensity modulator (IM), driven by the amplified electrical linearly frequency chirped signal generated from home-made Fractional-N microwave synthesizer, is utilized to modulate the lightwave signal from a distributed-feedback semiconductor laser (DFB-SCL) with about 20 kHz nominal linewidth. We use a 25 GHz VCO in connection with Fractional-N synthesizer to generate a linearly frequency swept signal with 1 GHz range limited by the tuning range of the VCO itself, corresponding to $\gamma = 100\,\text{GHz/s}$. Driving by the amplified swept signal, the output 0th carrier and 1st order side mode from the IM is optically filtered and amplified with an optical bandpass filter (OBPF) and Erbium-doped fiber amplifier (EDFA) before being split into the reference and measurement branches. In order to perform dual-heterodyne mixing, an AOFS driven by 40 MHz is inserted in the reference branch before the extraction of the fixed and FMCW references separately. In order to emulate the long distance ranging scenario, the dual-wavelength probes propagate through spool of single-mode fiber (SMF), whose far end connector adopts a fiber reflection mirror to produce an end reflection. The echo is subsequently interfered with the filtered references, respectively. The beat notes are electrically mixed and filtered. After captured by the data acquisition card, we carried out fast Fourier transform to verify the ranging in frequency domain.

We first verify the functionality of the proposed lidar system by testify a 20 km fiber. The detected fixed beating, FMCW beating, and the dual-heterodyne mixing are shown in Fig. 3(a) to Fig. 3(c), respectively. One can find clearly that the fixed heterodyne output contains the phase noise information which is attributed to the intrinsic phase noise. It should reflect the noise distribution lies in the pedestal of the FMCW heterodyne output (see Fig. 3(b)). The observed significant improvement in the noise performance as illustrated in Fig. 3(c) constitutes a strong support, indicating the efficient phase noise cancellation through dual-heterodyne mixing.

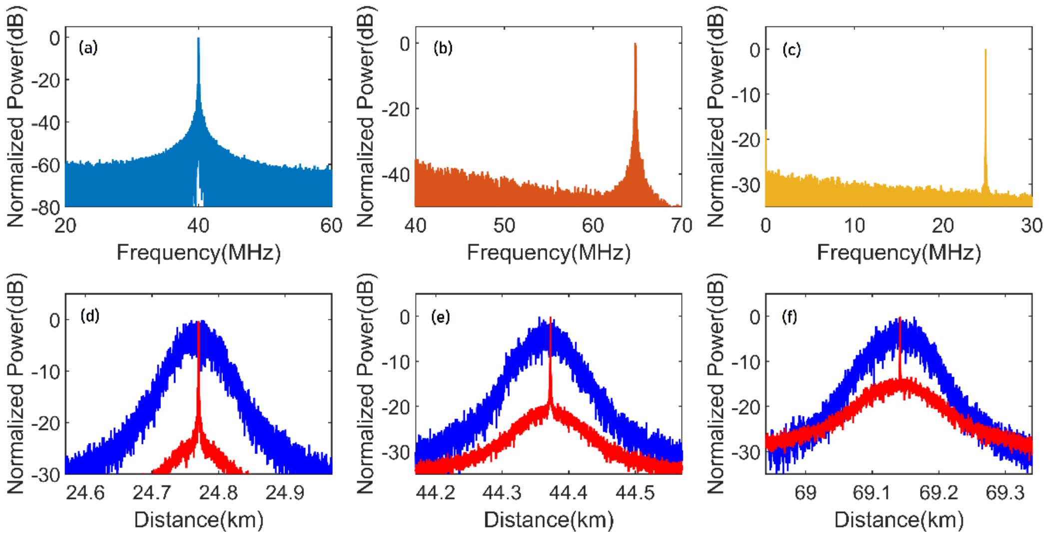

Fig. 3. Experiment result: Normalized power spectra for (a) fixed heterodyne, (b) FMCW heterodyne, (c) mixing output; normalized power spectra for ranging at (d) ~25 km, (e) ~44 km, (f) ~69 km, blue and red curves represent results at direct FMCW heterodyne output and mixing output, respectively.

Figure 3(d) to 3(f) describe dual-heterodyne mixing output at different ranging distances (at about ~25 km, ~44 km, and ~69 km) in comparison with the direct FMCW heterodyne, implying the effectiveness of the mixing. At all distances, the original FMCW heterodyne exhibit Lorentzian shape as it has gone far beyond the coherence length. After the dual-heterodyne mixing, the range resolution reaches the transform-limit (~10 cm in accordance with the 1 GHz FMCW sweep range) at all distances. Nevertheless, the gradual carrier-to-noise degradation along with the increase of the distance can be also observed. One can also find a small slope at the low frequency region in Fig. 3(c). Both these effects are probably attributed to the accumulated Rayleigh backscattering involved in the dual-heterodyne mixing process. Accordingly, up to about 1.4×10^{-6} range resolution has been obtained.

It should be mentioned that the range resolution of the current system is restricted by the frequency sweep range of the electrical FMCW signal, which could be readily improved by using broadband VCOs with a broader tuning range or by selecting higher-order mode from the IM or frequency combs.

4. Conclusion

We report dual-wavelength FMCW lidar system employing dual-heterodyne mixing based phase noise cancellation, allowing to achieve consistent transform-limited range resolution at several tens of intrinsic laser coherent length. Precise range resolution of about 1.4×10^{-6} has been experimentally verified at distance ~69 km. The extension to higher range resolution can be readily realized with broadband sources.

This work was supported by National Natural Science Foundation of China (NSFC) (61805014, 61827807, 61690193); China Postdoctoral Science Foundation funded project (2018M630082, 2019T120051).

5. References

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