

Impact of Laser Phase Noise on Ranging Precision Within and Beyond Laser Coherence Length in FMCW LiDAR

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Abstract: We study the impact of laser phase noise on ranging precision in a frequency-modulated continuous-wave (FMCW) LiDAR system, demonstrating ranging of 384.72 m with ~ 15 cm precision at $7\times$ intrinsic laser coherence length. © 2022 The Author(s)

1. Introduction

The booming of the autonomous vehicles market and other sensing applications in recent years have stimulated the development of light detection and ranging (LiDAR) techniques. In particular, frequency-modulated continuous-wave (FMCW) LiDAR has attracted a lot of interest, as it offers a higher receiver sensitivity, ranging resolution and precision over a longer distance compared to time-of-flight (TOF) LiDAR [1–3].

In FMCW LiDAR systems, the maximum ranging distance is commonly assumed to be limited by the laser coherence length, as the ranging precision is degraded by incoherent measurement [4]. To enable long-distance ranging of a few hundred meters, a low-linewidth laser is often assumed to be necessary, which potentially increases the system cost. A number of studies have explored the possibility of mitigating precision penalties from laser phase noise [5]. However, although a certain reduction in ranging precision would be expected in the incoherent regime, its dependence on ranging distance and laser linewidth has not been thoroughly assessed. If the performance is acceptable, the use of a relatively high-linewidth laser source might be a compromise solution for many cost-sensitive applications. Therefore, in this paper, through both experiments and simulations, we assess the penalties arising from laser phase noise on the ranging precision when operating within and beyond the laser coherence length. We show that, using a 1.2 MHz linewidth laser, a precision of ~ 15 cm is still achievable when operating at a ranging distance of 384.72 m, corresponding to $7\times$ intrinsic laser coherence length.

2. Experiment and simulation setup

The system design used for experiments and simulations is shown in Fig. 1a. In order to evaluate the impact of laser phase noise, lasers with linewidths of 100 kHz and 1.2 MHz were used in the experiment, both with an output power of 9.6 dBm. The light was then externally modulated using an in-phase and quadrature modulator (IQM), avoiding the impact of modulation nonlinearity or limited tuning speed suffered from using directly-modulated laser sources. The single-sideband (SSB) FMCW signal was generated by independently modulating the in-phase (I) and quadrature (Q) arms of the IQM by [6]:

$$V_I(t) = V_D \cos\left(2\pi f_1 t + \frac{\pi B t^2}{T_m}\right) \quad V_Q(t) = V_D \sin\left(2\pi f_1 t + \frac{\pi B t^2}{T_m}\right) \quad (1)$$

where t denotes the time instance, V_D is the amplitude of the driving voltage, f_1 represents the starting frequency of the chirp signal, B is the chirping bandwidth and T_m is the chirp period. In both simulation and experiment, $f_1 = 2$ GHz, $B = 5$ GHz and $T_m = 5$ μ s. The IQM was biased at the null point with a peak-to-peak driving voltage of approximately V_π . Fig. 1b shows the optical spectrum of the transmitted signal at a resolution bandwidth of 0.01 nm. Fiber delay lines were used to emulate the time-of-flight. For laser linewidths $\Delta\nu$ of 100 kHz and 1.2 MHz respectively, the corresponding coherence lengths are approximately 53 m and 637 m in the standard single-mode fiber (SSMF), given by $L_{coh} = \frac{c}{n\pi\Delta\nu}$ where c is the speed of light, and n is the refractive index of the SSMF [5]. The fiber delay length L was varied from 43.68 m to 384.72 m to evaluate the impact of laser phase noise on the ranging precision.

The receiver comprised a 3-dB coupler combining the local oscillator (LO) and the delayed SSB FMCW signal, followed by a single-ended photodiode, previously shown to be a strong candidate for low-cost and low-complexity

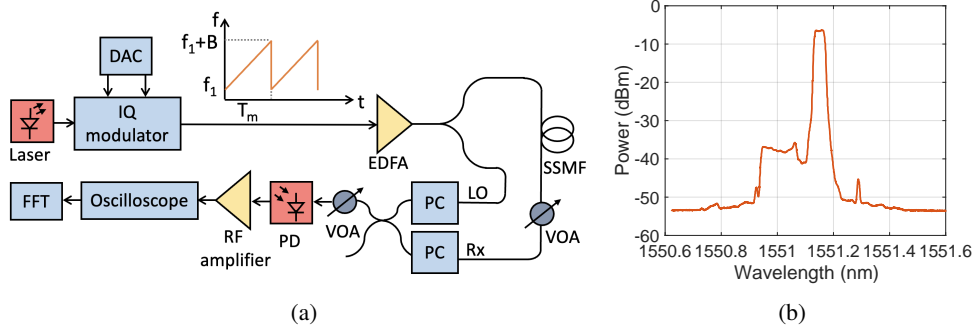


Fig. 1: (a) System setup of single-photodiode based coherent FMCW LiDAR. IQ: in-phase and quadrature; DAC: digital-to-analog converter; EDFA: Erbium-doped fiber amplifier; SSMF: standard single-mode fiber; VOA: variable optical attenuator; LO: local oscillator; Rx: received signal; PC: polarization controller; PD: photodiode; RF: radio frequency; FFT: fast Fourier transform. (b) Optical spectrum of transmitted SSB FMCW signal.

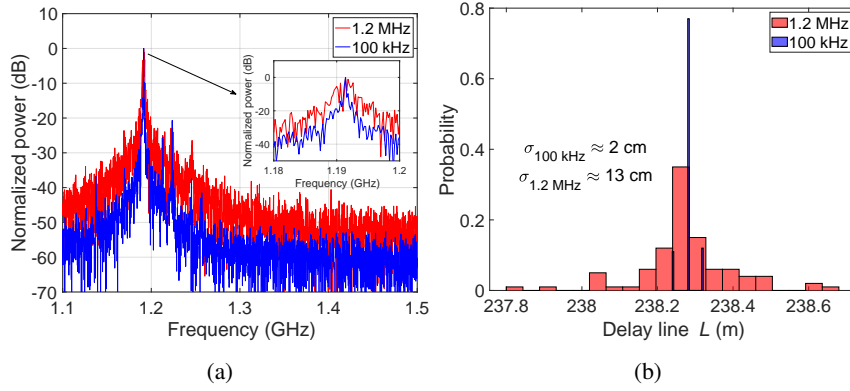


Fig. 2: At a delay line $L = 238.28$ m, comparing 1.2 MHz and 100 kHz laser source: (a) normalized frequency-domain power spectra of detected beat signals; (b) distributions of estimated distance over 100 traces.

coherent LiDAR systems [6]. The received FMCW signal was first aligned with the LO using a polarization controller. The LO power was set to 13.4 dBm, and the Rx power was set to -21 dBm across all the measurements to ensure that the beat signal could always be discerned from the noise floor. The output of the single-ended photodiode, which had a responsivity of 0.6 A/W, was sampled by an oscilloscope at 50 GSa/s, each measurement capturing 25,000 points, corresponding to one chirp period. One hundred traces were saved at each distance. The detected beat frequency f_b was identified by a peak search after applying a fast Fourier transform (FFT) to the received signal waveform. The estimated distance was calculated from f_b through $L = \frac{f_b c T_m}{nB}$. The ranging precision was quantified by the standard deviation σ of the estimated distance over 100 measurements.

The same system was assessed through simulations using MATLAB. The laser phase noise was modeled as a Wiener process, with laser linewidth $\Delta\nu$ varying from 100 kHz up to 1.2 MHz. The SSMF delay lines L were varied from 10 m up to 490 m, the maximum ranging distance being limited by the discontinuity of the frequency chirp sawtooth waveform. Monte Carlo simulations were carried out to assess the ranging precision with 1000 measurements performed at each delay length and laser linewidth.

3. Results and discussion

Fig. 2a shows the frequency-domain power spectra at a delay line $L = 238.28$ m, exhibiting a beat frequency of 1.19 GHz. With a laser linewidth of 100 kHz, 238.28 m is still within the coherence length ($\frac{L}{L_{coh}} \approx 0.37$). The laser phase noise from the LO and the delayed copy are almost correlated, and close to canceling each other, resulting in a relatively narrow beat tone. In the case of the 1.2 MHz laser source, however, the incoherent measurement ($\frac{L}{L_{coh}} \approx 4.5$) causes spectral broadening in the frequency domain as can be seen in Fig. 2a. This leads to increased uncertainty in identifying the center frequency of the beat tone, degrading the ranging precision. Fig. 2b shows the distribution of estimated distances over 100 measurements in the experiment. In the case of

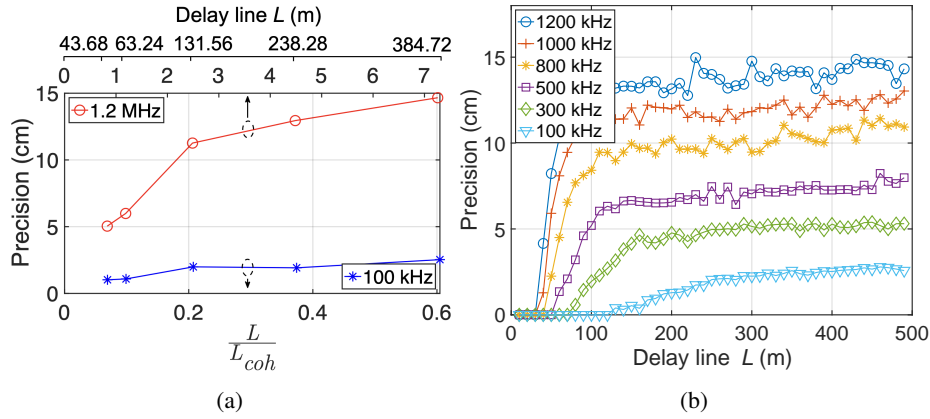


Fig. 3: (a) Ranging precision versus $\frac{L}{L_{coh}}$ with 1.2 MHz and 100 kHz laser source, for delay lines from 43.68 m to 384.72 m. (b) Numerical sweep of ranging precision with laser linewidth varying from 100 kHz to 1.2 MHz.

1.2 MHz laser linewidth, the spectral broadening results in a variation of estimated distances from 237.8 m to 238.6 m, with a standard deviation $\sigma \approx 13$ cm. For 100 kHz laser linewidth, the distance estimation is more certain, with 77% of measurements giving an estimated distance of 238.28 m, and the standard deviation is ~ 2 cm.

Fig. 3a compares the ranging precision with delay lines L varying from 43.68 m to 384.72 m when using 1.2 MHz and 100 kHz laser linewidth respectively. The top and bottom x-axes represent the delay lengths L normalized to the intrinsic laser coherence length L_{coh} . For the 100 kHz laser linewidth, all the delay lines used in the experiment were within the laser coherence length with maximum $\frac{L}{L_{coh}} \approx 0.6$. As the distance was increased, the ranging precision increased from 1 cm and plateaued at 2.5 cm. In the case of 1.2 MHz linewidth, at $L=43.68$ m, corresponding to $\frac{L}{L_{coh}} \approx 0.83$, the distance is approaching the coherence length, and ~ 5 cm ranging precision was measured. Beyond the coherence length, the ranging precision starts to deteriorate rapidly. However, at $\frac{L}{L_{coh}} \approx 7$ (delay line $L=384.72$ m), ~ 15 cm ranging precision is still achievable.

Simulations were performed next, investigating in detail how the ranging precision varies with laser linewidth and ranging distance as shown in Fig. 3b. Good agreement between simulation and experimental results presented above are achieved. At $L < 120$ m, the ranging precision could be sub-centimeter, while 1 cm precision is observed in the experiment in the case of 100 kHz laser source. This discrepancy might be due to additional noise and timing jitter in the experiments. Beyond the coherence length, the ranging precision degrades and then plateaus at a certain level for each laser linewidth. With delay lines extending to 490 m which is $9 \times$ intrinsic coherence length of 1.2 MHz laser source, ~ 15 cm ranging precision is still shown to be possible.

4. Conclusion

We studied, through both experiments and simulations, the impact of laser phase noise on the ranging precision of FMCW LiDAR systems when operating within and beyond the laser coherence length. We showed that, although the ranging precision deteriorates when operating beyond the coherence length, ~ 15 cm ranging precision is still achievable at a distance of 384.72 m which is about $7 \times$ intrinsic laser coherence length.

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