Coherent FMCW LiDAR system Modelling for Advance Driving Assistance System

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We propose a generic model that can simulate the functioning of the coherent doppler LiDAR system from a given target speed, working distance and modulation pattern. The influence of solar glares, laser phase and intensity noise, electronic shot and thermal noise are taken into consideration for the calculation of theoretical beat signal SNR. The model can aid the prototyping of the coherent Doppler LiDAR system for the design of advance driving assistance system.

Introduction

Autonomous vehicle equipped with Advanced Driving Assistance System (ADAS) presents a promising solution for on-road vehicle accidents, commercial truck accident and ever-increasing traffic congestions in major cities [1,2]. For the ADAS system to accurately and efficiently sense the range and velocity of surrounding and approaching object, fast high-quality range-finding system that can robustly function in various weather condition and distance is needed. Several imaging solutions have already been developed and integrated into autonomous vehicles, including camera-based object recognition AI, vehicle radar and LiDAR [3]. For autonomous driving vehicle to function in extreme weather conditions with high ranging precision, Camera-based AI and radar become less attractive candidate due to the need of sufficient solar illumination and low resolution [4]. For this reason, FMCW LiDAR emerge as a well-rounded, high-precision solution, proving advantageous for various driving scenarios and object distances.

To prototype an FMCW LiDAR system, a model capable of simulating LiDAR functionality with various parameters setting is needed. The model enables the optimization of the system performance and the study of potential application scenarios of the LiDAR system. It also allows the development of signal processing algorithm when the measurement data is obtained from experiment. There are two ways to simulate an FMCW LiDAR system, convoluting the spectra of the mix signal with the frequency response of the Fast Fourier Transform (FFT) window [5], and simulating the time domain light signal before performing FFT to obtain beat signal frequency. The former provides much faster computation speed especially with large FFT sampling time. However, it is more difficult to measure the impact of signal loss and have realistic direct reconstruction of a functioning LiDAR system.

In this report, a FMCW Doppler LiDAR system model is built. It is used to simulate the beat signal frequency and SNR of a triangular wave modulated FMCW LiDAR system.

Coherent Doppler LiDAR System

FMCW LiDAR utilize a frequency-chirped laser source and coherent detection. The reflected light from the target is combined with the local osillator signal in a photodetector, converting the roundtrip distance to a beat note.

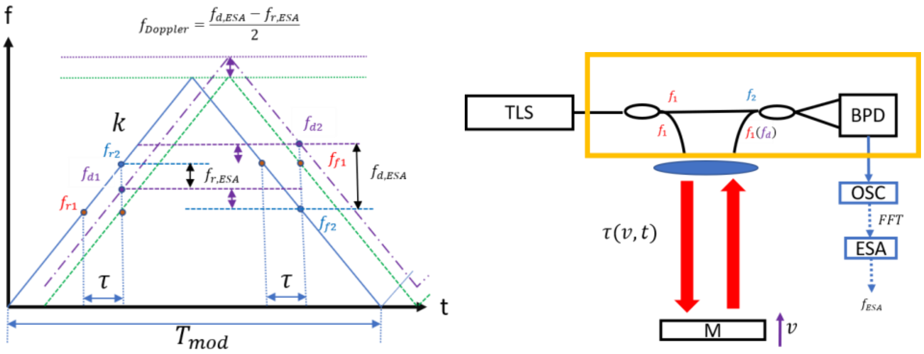

Figure 1 System diagram of triangular-wave modulated FMCW doppler LiDAR system.

Fig.1. shows the system diagram of the triangular wave modulated photonic integrated FMCW LiDAR system. The CW laser is frequency modulated with a triangular wave current signal. The light is split into two paths by an optical power splitter. One part serves as the local oscillator signal and the other part is coupled to a collimating lens and serve as target probing signal. When the target is moving toward the laser source, the reflected light frequency is higher than the transmitted signal frequency, which result in two peaks in the beat signal spectrum. The peak frequency average is used to calculated the delay time and the frequency difference can be used for target velocity calculation. The light that goes to the target is delayed by

$$\tau == \frac{f_{r,ESA} + f_{d,ESA}}{2k}$$

Where τ is the delay time from the light propagation in free space, $f_{r,ESA}$ and $f_{d,ESA}$ represent the beat signal frequency between the local oscillator signal and the reflected signal on the rising and falling edge. k stands for the slope of the laser frequency modulation, which is given by

$$k = \frac{2\Delta f}{T_{mod}}$$

Where Δf is the laser chirping frequency and T_{mod} is the modulation period. The target distance can be calculated as

$$D = \frac{\tau c}{2n} = \frac{(f_{r,ESA} + f_{d,ESA})T_{mod}c}{8\Delta f n}$$

Where c is the speed of light and n is the refractive index of air. The speed of the target can be extracted from doppler frequency

$$v = \frac{\lambda}{2} f_{doppler} = \frac{|f_{d,ESA} - f_{r,ESA}|}{4}\lambda$$

Where λ is the central wavelength of the laser. The modulation period, sampling frequency of photodiode and processing electronics limit the maximum working distance.

$$D_{max} = \min\left(\frac{cT_{mod}}{4n}, \frac{T_{mod}c(f_{sample} - 2f_{doppler})}{8\Delta f n}\right)$$

The ranging resolution of the FMCW LiDAR system is limited by the sampling time of FFT and the coherence length and the linewidth of the tunable laser.

$$D_{res} = \max\left(\frac{T_{mod}c}{4\Delta f n T_{frame}}, \frac{2ln2c}{\pi\Delta f}, \frac{T_{mod}c\Delta v}{2\Delta f n}\right)$$

Where Δv is the linewidth of laser and T_{frame} is the sampling time of FFT.

SNR and LiDAR Performance Metrics

The SNR of the beat signal is determined by the laser power, optical signal attenuation during propagation and the noise contribution from various factors. The balanced photodetection cancel all the none-phase related terms in the spectrum and only phase noise contribution and fundamental quantum noise is presented. The SNR of the beat signal can be calculated by

$$SNR(R) = \frac{\int_{-\frac{B}{2}}^{+\frac{B}{2}} P_{las}\sqrt{LOSS_{LO} * LOSS_{Delay}(R)}\, T_{frame} sinc^2\left(\frac{T_{frame}\omega_s}{2}\right) e^{-\frac{2\tau}{\tau_c}} d\omega}{hvB + \int_{-\frac{B}{2}}^{+\frac{B}{2}} P_{las}\sqrt{LOSS_{LO} * LOSS_{Delay}(R)}\, \frac{\tau_c}{1+\left(\frac{\omega_s\tau_c}{2}\right)^2}\left\{1 - e^{-\frac{2\tau}{\tau_c}}\left[\cos(\omega_s\tau) + \frac{2}{\omega_s\tau_c}\sin(\omega_s\tau)\right]\right\} d\omega}$$

Where the B is the bandwidth of electronic filter, R is the target distance, $\omega_s = \omega - k\tau$ is the beat signal angular frequency, τ_c is the coherence time and τ is the delay time. The model is used to simulate the beat signal SNR for a photonic integrated line-scan FMCW LiDAR system [6]. The loss of light propagation in the LO path and delay line path is calculated by

$$LOSS_{LO} = T_{edge}T_{star}C_{star}T_{trans-forward}T_{coupler}T_w L_{LO}$$

$$LOSS_{Delay}(R) = T_{edge}T_{star}C_{star}T_{trans-up}T_{rec}T_{atm}^2 \frac{\rho_R(\theta)}{\pi}\frac{A_{rec}\cos^2(\theta)}{R^2}\eta_{coh}(R)T_{coupler}T_w L_{delay}$$

In the $LOSS_{LO}$ calculation, the transmission of onchip edge coupler, power splitting star coupler, the transmission of output grating coupler and the insertion loss of the MMI coupler are being considered. In the $LOSS_{Delay}$ calculation, the coherence length of the laser line, the coupling efficiency and the area of collimating lens, the distance of the target and the coupling efficiency of grating coupled are taken into consideration. Using a 10mW CW laser source with 400KHz linewidth and a FFT sampling time of $10\mu s$, the beat signal SNR is calculated for different linewidth and electronic filter with different bandwidth. The spectrums of the beat signal for three different target distances are simulated. As can be seen in Fig.2, narrow laser linewidth and smaller electronic filter bandwidth give higher beat signal SNR. The beat signal SNR has to be higher than $16.5dB$ to achieve a detection probability with thresholding of 90% and false alarm rate probability of 10^{-5} for a semi-diffused target [7]. This requirement for minimum beat signal SNR poses a limit on maximum working distance of the FMCW LiDAR.

Conclusion and Future Work

A model for triangular-wave modulated coherent FMCW LiDAR system is presented, which include the calculation of theoretical beat signal frequency, the beat signal SNR,

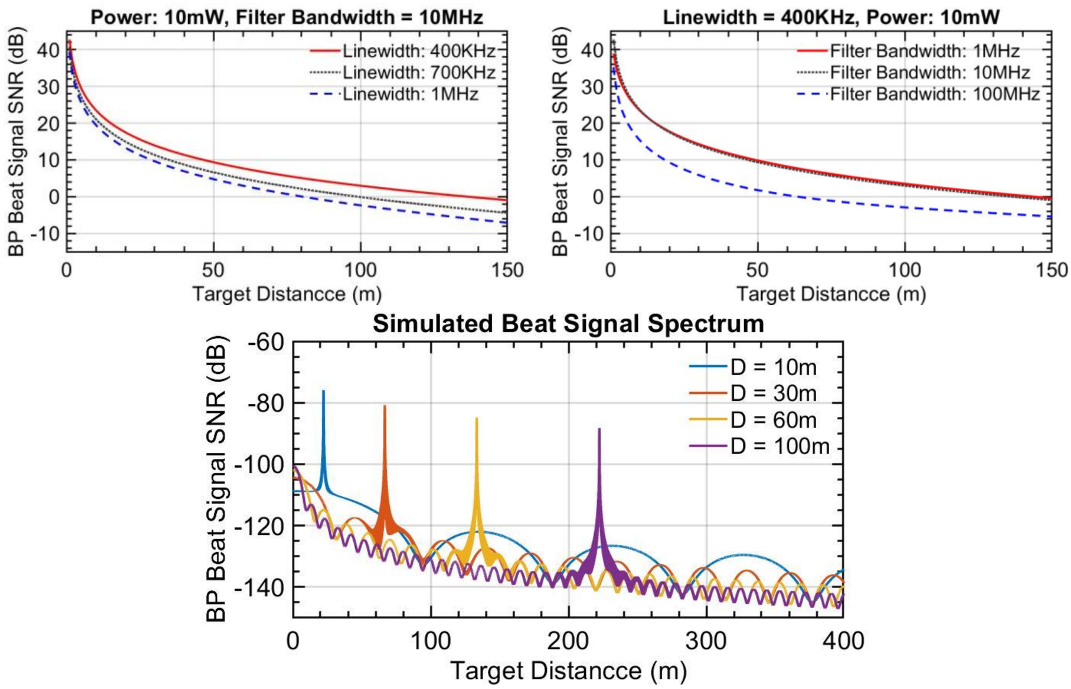

Figure 2 (top) FMCW LiDAR beat signal SNR for laser power of 10mW and FFT time frame of $10\mu s$. (bottom) Simulated beat signal spectrum for target distance of 10,30,60 and 100m.

the LiDAR work distance and the ranging resolution. The model has been used for the prototyping of an onchip FMCW LiDAR system with various laser and target position setting. In the future, we will include the modelling of an onchip wavelength stabilization system using a MZI with long delay line as a frequency reference. The simulation result will be compared with the experimental measurement.

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