Modeling of Photonic-Integrated FMCW Doppler LiDAR System with Onchip Dynamic Frequency Stabilizer

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ABSTRACT

We propose a model that can simulate the performance of a photonic-integrated FMCW Doppler LiDAR system with various target and system settings. The well-rounded system model can predict the measured target speed and velocity, system axial resolution, beat signal SNR, frequency modulation nonlinearity induced system error, with a new concept for swept-source laser frequency stabilization. Two sets of autonomous driving scenarios are simulated. Simulations confirm that our model yield system performance consistent with the theoretical calculations.

Keywords: LiDAR, FMCW, Laser Frequency Stabilization

1. INTRODUCTION

Light Detection and Ranging (LiDAR) system have been considered as a promising high-resolution distance sensing solution for the future advanced driving assistance system (ADAS). Camera-based AI pattern recognition pseudo-LiDAR [1] and Radar system [2] have been used for real-time target distance measurement and obstacle recognition. Since LiDAR can provide much higher range and angular resolution while being largely immune to inter-channel interference and environmental noise, its system robustness overwhelms the other solutions in the mid-range 3D imaging task. However, the development of a commercialized LiDAR system often costs a tremendous amount of budget [3]. It is also difficult to predict product performance without a sophisticated system modeling that covers every aspect of system setting and performance metrics.

Several models for the FMCW LiDAR system have been researched in the past [4-6]. However, the focus is mainly on one aspect of the system performance. The laser frequency tuning linearization and the sampled data post-processing have been studied to address the issue of modulation nonlinearity induced detection error [7-8]. To our knowledge, there is no model specific for the onchip FMCW Doppler LiDAR system, which covers the coupling of light in and out of the PIC and the onchip laser frequency stabilization system.

This report presents a system model for the FMCW Doppler LiDAR system, including target sensing simulation, beat signal SNR estimation, and an onchip dynamic frequency stabilizer modeling. The model has been used for a system design of an onchip line-scan FMCW Doppler LiDAR functioning at a 10m working distance.

2. DOPPLER FMCW LIDAR SYSTEM WITH TRIANGULAR WAVE LASER FREQUENCY MODULATION

FMCW Doppler LiDAR utilizes a frequency-chirped laser source and coherent detection. The reflected light from the target is mixed with the local oscillator signal in a balanced photodetector, the round-trip travel time of reflected light can be calculated from the beat note frequency. Fig. 1. shows the system diagram of the triangular wave modulated photonic integrated FMCW Doppler LiDAR system. The CW laser is frequency modulated with a triangular wave current signal. As can be seen in Fig. 1(a), 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

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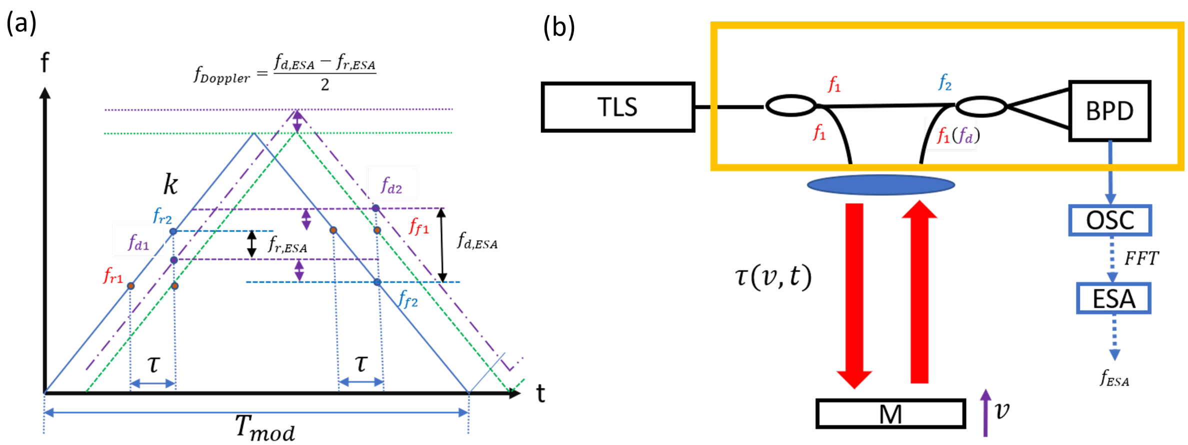

Figure 1. System diagram of the triangular-wave modulated FMCW doppler LiDAR system.

and serves as a target probing signal. When the target is moving toward the laser source, the reflected light frequency is higher than the transmitted signal frequency. The doppler effect results in two peaks in the beat signal spectrum. As can be seen in Fig. 1(b), the peak frequency average is used to calculate the delay time and the frequency difference can be used for target velocity measurement. The light that goes to the target is delayed by

$$\tau = \frac{f_{r,ESA} + f_{d,ESA}}{2k}, \tag{1}$$

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

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

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

$$D = \frac{\tau c}{2n} = \frac{(f_{r,ESA} + f_{d,ESA})T_{mod}c}{8\Delta f n}, \tag{3}$$

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

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

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

$$D_{max} = min(\frac{c}{2\Delta v}, \frac{cT_{mod}}{4n}, \frac{cT_{mod}(f_{sample} - 2f_{Doppler})}{8\Delta f n}), \tag{5}$$

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

$$D_{res} = max(\frac{cT_{mod}}{4\Delta f n T_{frame}}, \frac{2ln2c}{\pi\Delta f}, \frac{T_{mod}c\Delta v}{2\Delta f n}), \tag{6}$$

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

3. 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 cancels all the non-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

$$SNR(R) = \frac{\int_{\frac{-B}{2}}^{\frac{+B}{2}} P_{las}\sqrt{LOSS_{LO}LOSS_{Delay(R)}}T_{frame}sinc^2(\frac{T_{frame}\omega_s}{2})e^{-\frac{2\tau}{\tau_c}}\,d\omega}{hvB + \int_{\frac{-B}{2}}^{\frac{+B}{2}} P_{las}\sqrt{LOSS_{LO}LOSS_{Delay(R)}}\frac{4\tau_c}{4+(\omega_s\tau_c)^2}\{1-e^{-\frac{2\tau}{\tau_c}}[\cos(\omega_s\tau)]+\frac{2}{\omega_s\tau_c}\sin(\omega_s\tau)\}\,d\omega}, \quad (7)$$

Where the B is the bandwidth of the electronic filter, R is the target distance, $\omega_s = -k\tau$ 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

$$LOSS_{LO} = T_{edge}T_{star}C_{star}T_{trans-forward}T_{coupler}T_wL_{LO}\,, \quad (8)$$

$$LOSS_{Delay} = T_{edge}T_{star}C_{star}T_{trans-up}T_{rec}T_{atm}^2\frac{\rho_R(\theta)}{\pi}\frac{A_{rec}cos^2(\theta)}{R^2}\eta_{coh}(R)T_{coupler}T_wL_{delay}\,, \quad (9)$$

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 is 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 an FFT sampling time of $10\mu s$, the beat signal SNR is calculated for different linewidth and electronic filters 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 [9]. This requirement for minimum beat signal SNR poses a limit on the maximum working distance of the FMCW LiDAR.

4. ONCHIP LASER FREQUENCY MODULATION LINEARIZATION SYSTEM

The ideal tunable laser source for the FMCW LiDAR system should provide a constant output power and a central frequency that follows a perfect triangular wave pattern. Many factors from the laser frequency modulator and laser gain medium can contribute to the distortion and non-linearity of the modulation pattern. The laser frequency modulation is done by applying a triangular wave modulated electrical current signal to the laser gain medium. The current source, which is the arbitrary wave generator, can be modeled as a digital-analog converter (DAC) connected to a low-pass electronic filter. It filtered out the high-frequency component of the triangular wave, which flatten the peak and bent the waist of the modulation pattern. The laser gain medium has a nonlinear current-frequency response, which will bend the triangular modulation pattern into a non-linear quasi-sin wave pattern. The frequency modulation through current injection also induces residual amplitude modulation (RAM), which will be added directly on top of the photodiode current of the light signal from the frequency discriminator. If the intensity of light after passing frequency reference is used to characterize the signal frequency directly, the RAM will be added on top of the detected signal intensity and lead to distorted frequency reference. To address this issue, an adapted Pound-Drever-Hall (PDH) technique with a transmission pattern modulated MZI as the dynamic frequency reference is proposed.

As can be seen in Fig. 2, the traditional PDH technique converts the frequency mismatch between reference locking frequency and the laser output frequency to an error signal. The zeros-crossing of the error function is sensitive only to the frequency shift induced power fluctuation and not the RAM. To apply this technique to the frequency-modulated laser source, the transmission pattern of the onchip MZI reference will be modulated by

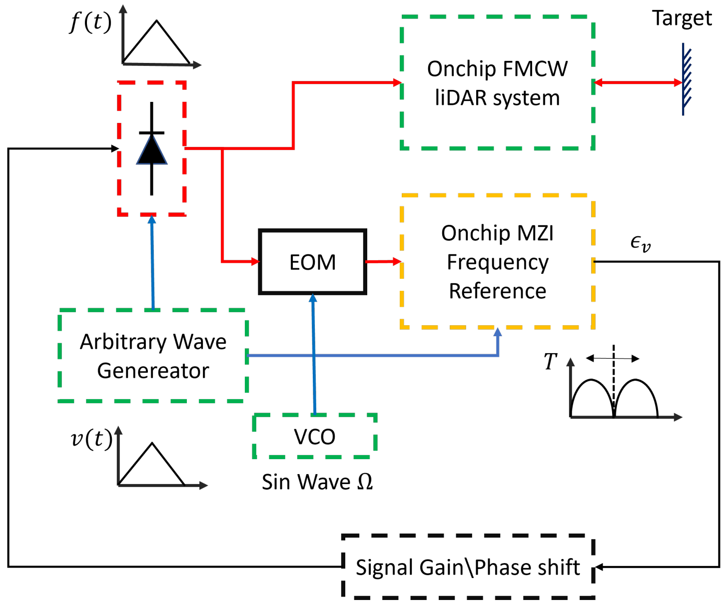

Figure 2. System diagram of the onchip frequency stabilizer for a swept-source laser.

the laser frequency modulation signal. The reference modulation signal will be amplified and phased shifted to sync the laser instantaneous frequency and the reference locking frequency. The reference modulation signal will be amplified and phased shifted to sync the laser instantaneous frequency and the reference locking frequency. The beat optical signal power in the PDH loop can be expressed as [10]

$$P_{PDH} = 2P_s - 4\sqrt{P_s P_c} Im(T(\omega)) sin(\Omega t) + (2\Omega terms)\,, \tag{10}$$

Where $P_c = J_0^2(\beta)P_0$ and $P_s = J_1^2(\beta)P_0$ are the power of the carrier and the first-order sideband of sine-wave modulated laser. β is the modulation depth of the electro-optical phase modulator (EOM) and P_0 is the laser power going into the frequency stabilizer. $T(\omega)$ is the optical power transmission coefficient of the onchip MZI, of which the peak served as the laser frequency reference. Ω is the modulation frequency of the electrical signal applied on the EOM. The error signal power after mixing the optical beat signal power with the VCO modulation signal is given by

$$\epsilon_f = -2\sqrt{P_c P_s} Im(T(\omega)) \approx -\frac{2}{\pi}\sqrt{P_c P_s}\frac{\delta\omega}{FSR},\,, \tag{11}$$

Where $\delta\omega$ is the deviation of laser frequency from the MZI transmission peak and FSR is the free spectral range of the onchip MZI reference. The approximation is good when $\delta\omega \ll FSR$. Since the MZI transmission profile is being modulated with the same triangular waveform as the diode laser frequency, the laser instantaneous frequency is being locked to the dynamic MZI transmission peak. As the modulation linearity of EOM is much better than the linearity of laser current response, The modulated MZI transmission profile can be used as a dynamic frequency reference. Fig. 3. shows the dynamic frequency reference based on the tunable MZI transmission profile. Fig. 3(a). and Fig. 3(b). shows the zoomed-in and zoomed-out dynamic frequency reference based on an MZI with $10cm$ onchip delay line. All the parameters used in this simulation can be found in Appendix A.1. As can be seen from Fig. 3(c), when the error signal is turned down to zero by a negative feedback control loop, the laser frequency is locked to the peak of the MZI transmission profile. Fig. 4. shows the dynamic frequency locking of the swept-source laser through linear iterative control. The error signal from every period of the triangular-wave function is collected by processing electronics and feedback to the AC drive current of the laser diode. After 100 iterations or $100\mu s$, the laser instantaneous frequency is aligned to the peak of the MZI transmission profile. Fig. 4. shows the FMCW LiDAR beat frequency before and after frequency locking to the dynamic MZI transmission peak. Without the modulation nonlinearity compensation, the beat signal frequency

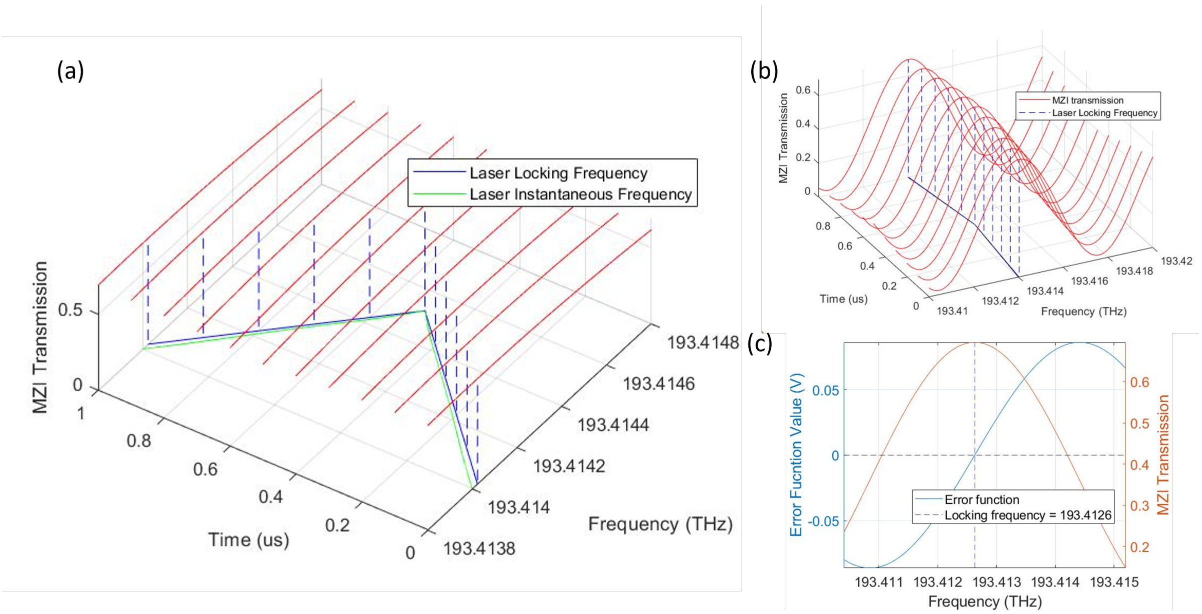

Figure 3. Dynamic frequency reference based on MZI transmission profile.

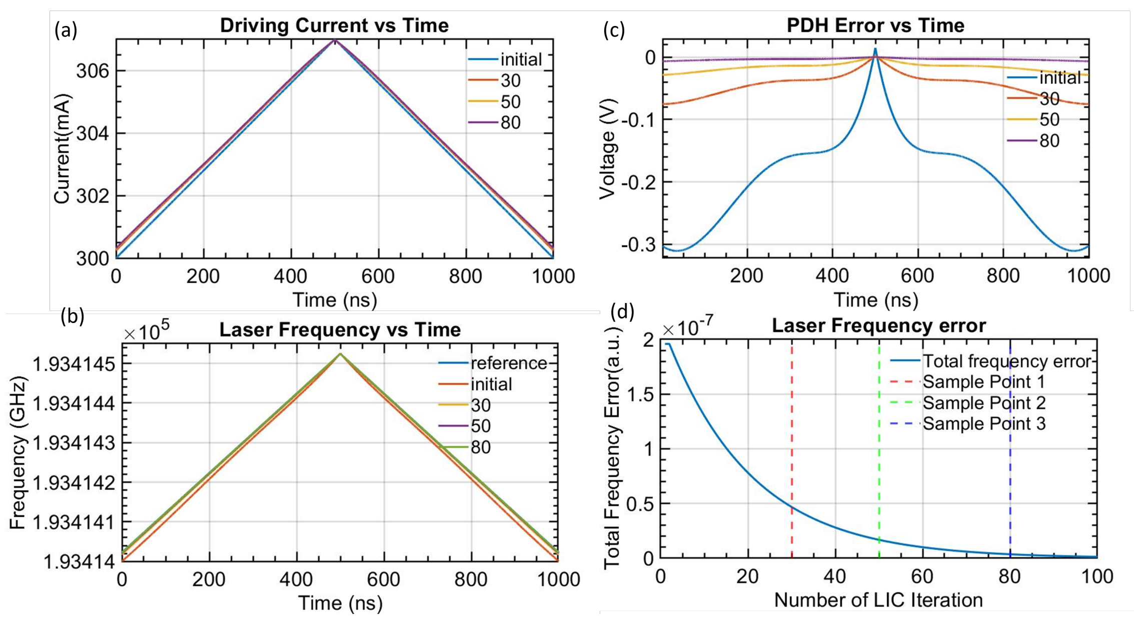

Figure 4. Dynamic swept-source laser frequency locking through linear iterative control.

fluctuated around the theoretical value and the oscillation depends on the type of laser FM nonlinearity. The non-linearity gives a distance measurement error of $0.47m$ while the theoretical range resolution is $0.26m$.

5. LIDAR PERFORMANCE SIMULATION

The parameter used for the LiDAR performance can be found in Appendix A.2. Two sets of simulations are performed. One with a target distance of $10m$ and the target velocity of $10km/h$, the other one with a set static target distance of $10, 30, 60$, and $80m$. As can be seen in Fig. 6(a), the doppler effect causes the beat signal to have different frequencies along with the rise and falling ramp of laser frequency modulation. The calculated

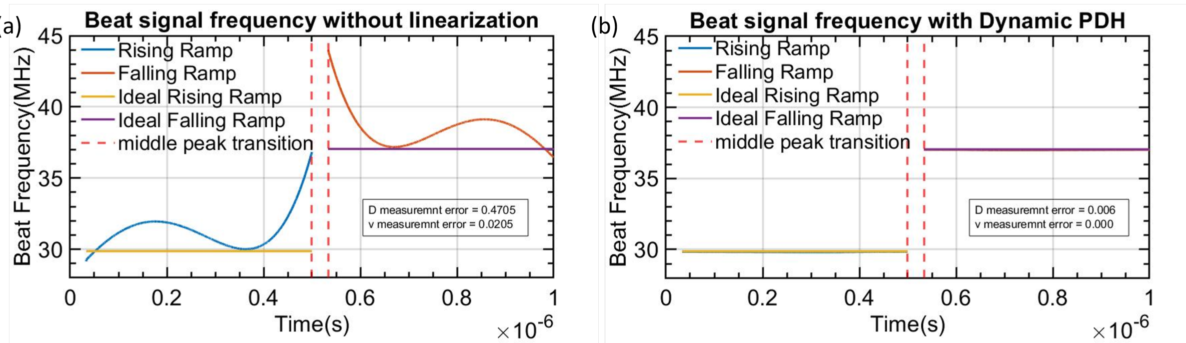

Figure 5. LiDAR beat signal frequency before and after dynamic PDH technique.

target distance and velocity are $9.9988m$ and $10.0022km/h$. Fig. 6(b). shows the measured distances for the four targets are $[10.0011, 19.9977, 60.0020, 79.9996]m$ respectively. The calculated target distance demonstrates mm measurement accuracy. Balanced photon detection significantly increases the SNR of the beat signal by canceling the non-interference terms in the beat signal and the environmental noise. Fig. 7. shows the SNR

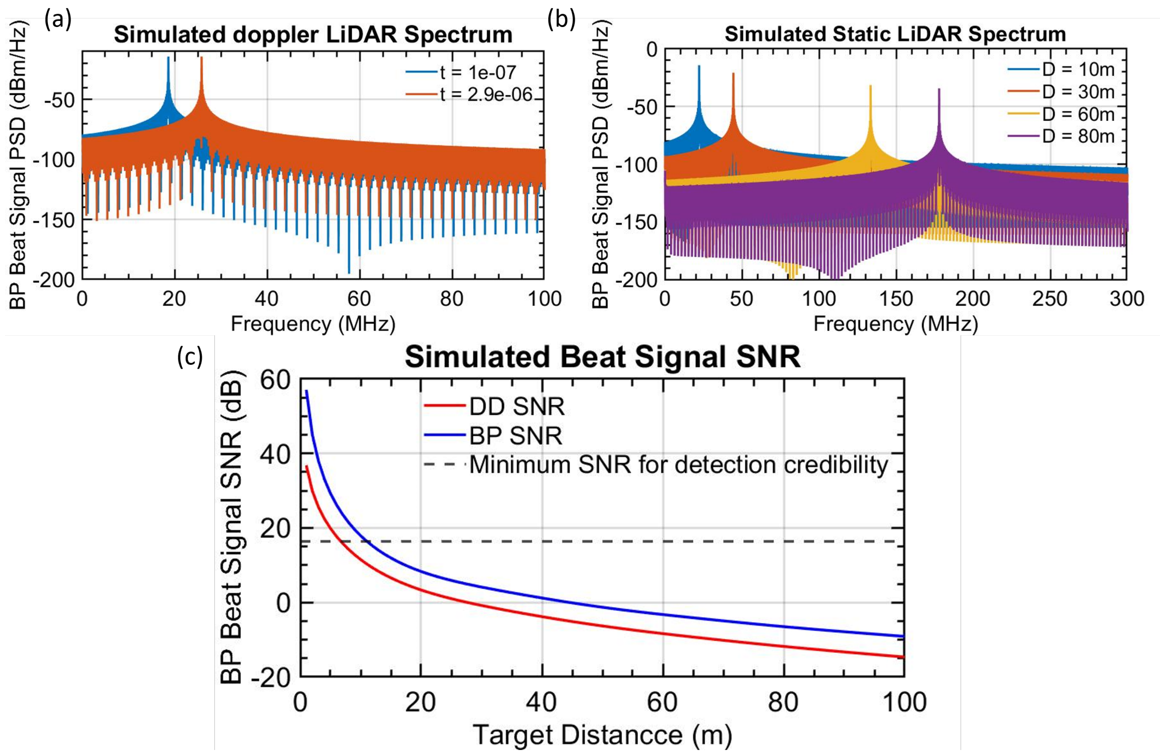

Figure 6. Simulated FMCW LiDAR spectrum and SNR.

with different laser and system settings. It is shown that the BP SNR is sensitive to the laser linewidth and the electronic filter bandwidth, which determines the phase noise in the spectrum. The beat signal SNR degrades with a longer working distance, which means a narrow linewidth laser source and smaller bandwidth electronic bandwidth filter needs to be used for mid-range LiDAR design.

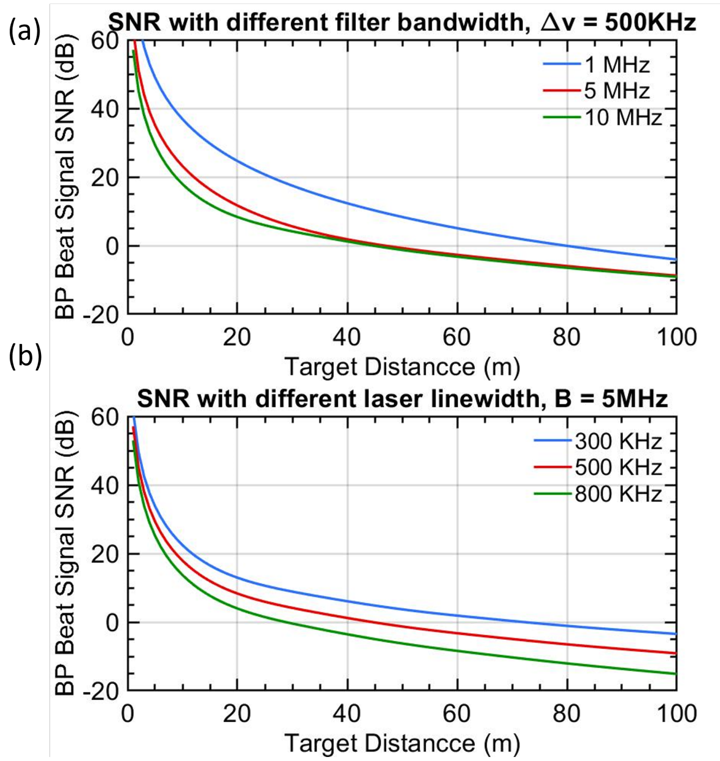

Figure 7. Simuated LiDAR SNR with different linewidth and electronic filter bandwidth.

6. CONCLUSION AND FUTURE WORK

A model for a triangular wave modulated coherent FMCW LiDAR system is presented, which includes the calculation of theoretical beat signal frequency, the beat signal SNR, the LiDAR work distance, and the ranging resolution. A dynamic PDH technique has been proposed for the frequency modulation linearization of the swept-source laser. The model has been used for the prototyping of an onchip FMCW LiDAR system with various laser and target position settings. In the future, we will compare the measurement result from a calibrated FMCW LiDAR chip with the simulation result.

APPENDIX A. SIMULATION PARAMETER SETTING

A.1 Dynamic PDH technical for swept-source laser frequency stabilization based on MZI transmission

Table 1. Parameter setting for the onchip laser frequency stabilizer.

Parameters	Description	Simulation Value
P_0	Laser power going into the frequency stabilizer	10mW
f_0	Laser central frequency	193.4128THz
β	EOM modulation depth	0.7
Ω	modulation frequency for EOM	1GHz
Δf	laser frequence excursion	501.5MHz
T_{mod}	modulation period	1000ns

A.2 FMCW LiDAR spectrum and SNR simulation

Table 2. Parameter setting for LiDAR spectrum and SNR simulatiom.

Parameters	Description	Simulation Value
P_{las}	Laser power	50mW
T_{edge}	edge coupler insertion loss	-3dB
T_{star}	star coupler insertion loss	-1dB
C_{star}	star coupler power splitting ratio	1
$T_{trans-forward}$	on-chip transmitter forward coupling efficiency	20%
T_w	propagation loss per cm in the waveguide	0.6dB/cm
$T_{trans-up}$	on-chip transmitter upward coupling efficiency	33%
T_{rec}	on-chip receiver coupling efficiency	-3dB
$T_{coupler}$	2×2 coupler trasmission coefficient	-1dB
$\eta_{coh}(R)$	coherence and focusing efficacy	Calculated
L_{delay}, L_{LO}	waveguide path length for delay and LO path	5 and 6 cm
R	target distance	Variable
T_{atm}	atmospheric transmission	Calculated
θ	angle of target position with respect to the normal	0
$_{R}(\theta)$	target reflectivity	0.9
A_{rec}	effective receiver area	$20cm^2$
B	Electronic filter bandwidth	5MHz
T_{fft}	FFT time window	10e-6s
Δf	laser frequence excursion	500MHz
T_{mod}	modulation period	3000ns
k	slope of laser frequency modulation	3.33e15

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