A Frequency Digital Pre-distortion Compensation Method for FMCW LiDAR System

Ting-Hui Chen[1]*, Chien-Ying Huang[1], Tim Kuei Shia[2], Sin-Jhu Wun[1], Ching-Hsiang Hsu[1], Kai-Ning Ku[1], Chi-Sen Lee[1], Chen-Yu Lin[1], Po-Chih Chang[1], Chung-Chih Wang[1], Shang-Chun Chen[1], Chien-Chung Lin[1,3] and Chih-I Wu[1,4]

[1]*Electronic and Optoelectronic System Research Laboratories, Industrial Technology Research Institute, Hsinchu 310, Taiwan*
[2]*Information and Communications Research Laboratories, Industrial Technology Research Institute, Hsinchu 310, Taiwan*
[3]*Institute of Photonic System, College of Photonics, National Chiao Tung University, Tainan 711, Taiwan*
[4]*Graduate Institute of Photonics and Optoelectronics, National Taiwan University, Taipei, 106, Taiwan*
**Tinghui@itri.org.tw*

Abstract: We propose a digital pre-distortion (DPD) compensation method for FMCW LiDAR system and demonstrate that the proposed method can enhance the ranging accuracy more than three times in our FMCW ranging experiment.

1. Introduction

Light detection and ranging (LiDAR) has been extensively studied in recent years, and it has been used for a wide range of applications, such as 3D mapping [1,2], autonomous vehicles [3], and robotics [4]. Frequency modulated continuous wave (FMCW) LiDAR has several advantages over time-of-flight LiDAR, including cost-effective implementation, robustness to background noises. FMCW LiDAR utilizes a triangularly frequency-swept laser to extract distance and velocity information of the target simultaneously [5,6]. Higher modulation speed of frequency-swept laser enables us to detect and range a target within a shorter timeframe. However the increase of laser scanning frequency leads to the distortion of frequency ramp and optical bandwidth, which limits the sensitivity of systems [7]. In this work, we propose a novel method to compensate the distortion of triangular frequency sweep due to high speed modulation. We first model the transfer function of laser with different modulation speeds and develop a digital pre-distortion (DPD) compensation method to predict the frequency response of frequency tuning distortion [8,9]. We then pre-distort a driving signal to compensate the nonlinear laser frequency chirp caused by the high speed modulation. In our proof-of-concept ranging experiment, we demonstrate that the proposed method can increase the ranging accuracy more than three times. The proposed DPD compensation method could provide an effective way to enhance the linearity of chirp rate and modulation optical bandwidth, and improve the effective sampling rate and range sensitivity of FMCW LiDAR system.

2. Digital Pre-distortion (DPD) Compensation Method

One of the key component in this study is the current driver which can initiate the frequency sweep of the laser, as shown in the block diagram of Fig. 1(a). The diagram also includes our DPD frequency compensation module to provide the necessary modification in driving currents. A distributed feedback (DFB) laser with linewidth of 320 KHz, working at temperature of 25°C and wavelength of 1550 nm, is used in our FMCW LiDAR experiment.

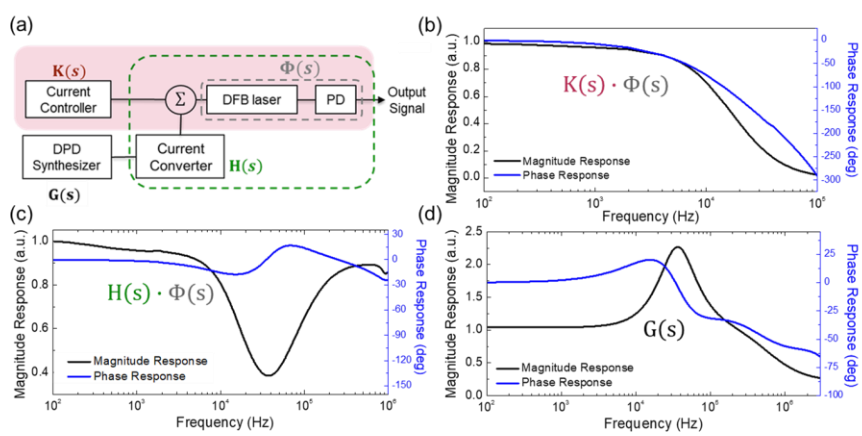

Fig. 1. (a) Block diagram of the DPD frequency compensation method. (b) Frequency response of $K(s) \cdot \Phi(s)$. (c) Frequency response of $H(s) \cdot \Phi(s)$. (d) DPD synthesizer frequency response $G(s)$.

Following the diagram in Fig. 1(a), we can define the frequency-response of different testing blocks. For example, the frequency response $\mathrm{K(s)}$ of the current controller and the response $\Phi(s)$ of laser and photodetector can be combined together $\mathrm{K(s)} \cdot \Phi(s)$ as the transfer function of the uncompensated system. The addition of DPD synthesizer can bring two extra functions into the system: one for synthesizer itself ($G(s)$) and the other is for modulation current converter ($H(s)$). Our interest of the modulation speed is within 100 Hz to 100 KHz, which is the comment range of FMCW laser sweep. These transfer functions in Fig.1 (b) to (d) can be approximated numerically for the purpose of compensation calculation later. The deviation from low frequency when the driving frequency approaches 100 KHz can be observed both in amplitude and phase in Fig. 1(b), and this phenomenon has to be considered during the compensation stage. Since we can design (or control) the $G(s)$, our purpose is to maintain the amplitude and phase especially at higher frequency to alleviate the distortion. The "pre-distorted" signal can flatten the deviation in the frequency domain and provide a nearly perfect triangular sweep in linear frequency. The measured frequency response of modulation current converter $\mathrm{H(s)} \cdot \Phi(s)$ is shown in Fig. 1(c). The measured $\mathrm{H(s)} \cdot \Phi(s)$ has a magnitude response dip and zero phase crossing near 36 KHz. The designed DPD synthesizer frequency response $\mathrm{G(s)}$ is numerically approximated by fitting the cascaded frequency response of $G(s) \cdot \mathrm{H(s)}$ to a 1^{st} order 400 KHz Bessel low pass filter as shown in Fig. 1(d).

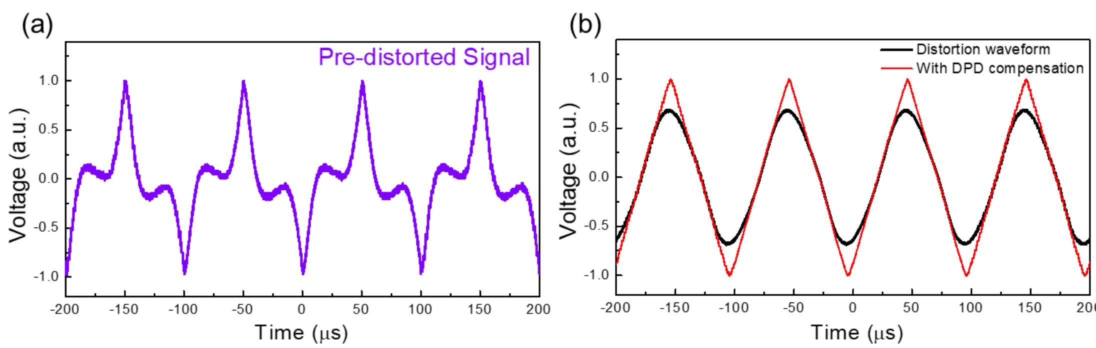

Fig. 2. (a) Designed pre-distorted signal for 10 KHz distorted triangular waveform. (b) Measured signals with and without DPD compensation.

Here $G(s) \cdot \mathrm{H(s)}$ pre-distorted signal to compensate a 10 KHz distorted triangular waveform is shown in Fig. 2(a). After both the sweep signals from the current controller $\mathrm{K(s)}$ and pre-distorted signal $G(s) \cdot \mathrm{H(s)}$ are aligned and combined, the measured signal with DPD compensation is compared to the uncompensated one solely by the current controller in Fig. 2(b). The improvement can be clearly demonstrated.

3. FMCW LiDAR Ranging

The next step is to implement our design into an actual FMCW LiDAR system. Fig. 3(a) demonstrates the concept of linear triangular modulation scheme of laser optical frequency versus time for FMCW LiDAR system. Due to the time delay mismatch between transmitted signal (TX) and received signal (RX), a beat frequency f_{beat} is proportional to the distance to the target. In our experiment, the period time (T) of DFB laser is 100 μs and frequency modulation bandwidth (BW) is 5.5 GHz.

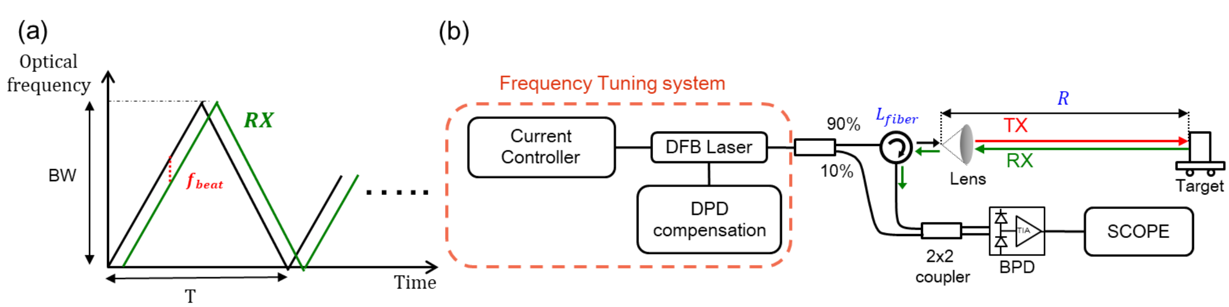

Fig. 3. (a) Concept of FMCW LiDAR with triangular modulation. (b) The measurement setup of FMCW LiDAR ranging system.

Fig. 3(b) shows the schematic diagram of the FMCW LiDAR ranging system. The frequency tuning system includes a DFB laser, the current controller, the modulation current converter and the DPD synthesizer. First, the optical light generated by the frequency tuning system is split by a 90:10 coupler for transmitted signal and reference one respectively. The TX signal is collimated by a lens and incident on a target at distance R. The RX signal is mixed with reference signal to obtain the beat frequency using balance photodetector (BPD) with bandwidth of 75MHz. The RF output signal is observed by real-time scope and spectrum analyzer (SA).The detected distance R and the beat frequency, f_{beat}, are numerically given by

$$f_{beat} = \frac{BW}{0.5T} \times \left(\frac{n_{fiber}}{c} L_{fiber} + \frac{n_{air}}{c} 2R\right) = 3.23 + 0.73 \times (R[m])\ [MHz], \qquad (1)$$

where c is the speed of light in the air, n_{fiber} is 1.47, and n_{air} is 1. Here the optical path difference includes the optical path delay in the air of 2R, and the fiber delay, L_{fiber} , of 6 m.

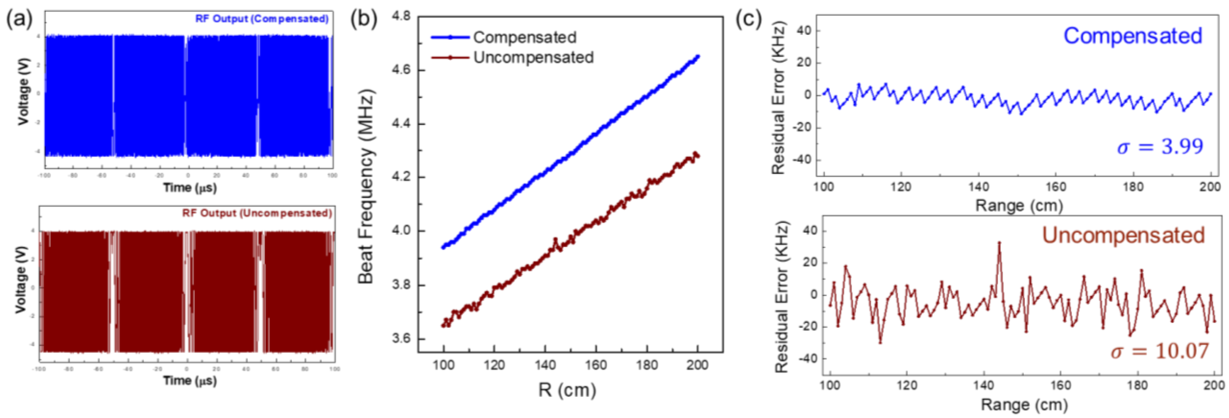

Fig. 4. FMCW LiDAR ranging experiment results for compensated and uncompensated frequency modulation. (a) Images of RF output signal from real-time scope. (b) Beat frequency for the distance from 1 m to 2 m in air. (c) The beat frequency residual error.

Fig. 4(a) shows the RF output signal of compensated and uncompensated frequency modulation from real-time scope, and the sampling rate has been increased by the proposed DPD compensation. In Fig. 4(b), the measured beat frequency is plotted against distance R, and the linear feature of Eq. (1) can be observed between 1 m to 2 m. The response of beat frequency becomes more linear and less wavy so that the sensitivity of ranging resolution have been enhanced as well. As shown in Fig. 4(c), the standard deviation of the beat frequency residual error with DPD compensation has been reduced by 2.52 times. Moreover, the range of residual error decreases from 62.5 KHz (the uncompensated case) to 18.3 KHz with DPD compensation, which implies the improvement of the ranging accuracy by 3.41 times.

4. Conclusions

In this work, we propose a DPD compensation method for FMCW LiDAR system. In our proof-of-concept ranging experiment, we demonstrate that the proposed method can increase the ranging accuracy more than three times. This method could provide a novel way to enhance the linearity of chirp rate and modulation optical bandwidth, and improve the effective sampling rate and range sensitivity of FMCW ranging system.

5. References

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