Improving the frequency chirp linearity of a frequency-modulated continuous-wave laser

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Abstract: We propose a novel driving signal pre-distortion method to improve the frequency chirp linearity of an InP/Si_3N_4 hybrid-integrated external cavity laser. The measured chirp linearity is increased from 87.3% to 99.7%. The ranging resolution reaches 10.3 cm.

1. Introduction

Light detection and ranging (LiDAR) technology has attracted widespread attention in both scientific research and industry, which plays a key role in many applications ranging from geographic surveying and 3D-mapping to autonomous driving and robotics [1, 2]. Compared to the conventional pulsed time-of-flight (ToF) method, the frequency-modulated continuous-wave (FMCW) technology eliminates the need for high peak power laser, optical filters for interference rejection, and especially fast electronics for precise timing. For the FMCW LiDAR system, the detection resolution is directly affected by the linearity of the frequency chirp, and the coherence-limited detection range is determined by the linewidth of the laser [3, 4]. Unfortunately, for most lasers, there is essentially no linear mapping between the chirp frequency and the driving voltage. Moreover, when the detection range reaches 150 m and the obversion window is 10 μs, the linewidth of the laser is required to be at sub-MHz level [5], which is quite challenging for most tunable lasers such as DFB lasers.

In this work, we propose a novel driving signal pre-distortion method to improve the frequency chirp linearity of an InP/Si_3N_4 hybrid-integrated external cavity laser (ECL) with a narrow linewidth [6]. We first non-uniformly sample the driving signal waveform according to the chirp. Then we adopt the linear update iteration method with an adaptive correction coefficient, which can effectively avoid over-compensation. We demonstrate that the proposed method can enhance the linearity of the optical frequency chirp from 87.31% to 99.77%. With the corrected driving signal, high accuracy detection is achieved in our proof-of-concept ranging experiment without real-time feedback control or heavy post-processing.

2. Driving Signal Pre-distortion Method

Figure 1(a) and (b) show the experimental configuration of the driving signal pre-distortion system and the structure of the InP/Si_3N_4 hybrid-integrated ECL [7], respectively. The ECL is connected to a Mach-Zehnder Interferometer (MZI) with a fixed optical delay (τ) between the two arms. The interference output is then recorded by a pair of balanced photodetectors (BPD). The beating of the original chirped signal and the delayed version generates an RF signal. The RF signal frequency $f_b(t)$ is equal to the difference between the frequencies of the original chirped signal $v(t)$ and the delayed version $v(t-\tau)$, *i.e.*, $f_b(t) = v(t) - v(t-\tau) = \gamma \cdot \tau$, where γ is the chirp slope. If τ is sufficiently small, then $f_b(t)$ can be approximated by the first term in the Taylor series, i.e., $f_b(t) \approx v'(t) \cdot \tau$. Since the instantaneous phase is related to the laser frequency chirp as $\varphi_b(t) = 2\pi \int f_b(t)dt = 2\pi\tau \int v'(t)dt = 2\pi\tau \cdot v(t)$, the frequency chirp of the ECL can be directly calculated from the beat signal phase extracted by adopting the Hilbert Huang Transform (HHT). The linearity of laser frequency chirp is defined as $R = 1 - \Delta v_{max}/BW \times 100\%$, where Δv_{max} represents the maximum deviation of the measured chirp from the linear chirp and BW is the chirp bandwidth.

After reconstructing the frequency chirp of the ECL, we can perform chirp nonlinearity correction by using a pre-distorted driving signal. First, the original triangular driving signal is re-sampled with a non-uniform interval dependent on the measured chirp nonlinearity, as shown in Fig. 1(b). The purpose of the non-uniform sampling is to ensure the laser frequency is linearly increased/decreased so that the frequency-time mapping curve is linearized with a modified driving signal. In this process, we set the error signal as the difference between the measured chirp slope and the desired linear chirp. When the measured frequency change rate is greater than that of the desired one, the corresponding time interval is reduced. Conversely, the sampling interval increases when the frequency change rate is less than the required one. The major advantage of this process is that we can quickly obtain the approximate shape of the final pre-distorted driving signal when the original chirp nonlinearity is small. However, it suffers from a limited parameter scope and can lead to instability and over-compensation, inhibiting the chirp linearity from further improvement. To solve this issue in the non-uniform sampling process, we adopt the linear update algorithm to continuously improve the chirp linearity. In this process, we set the objective function as the frequency difference between the measured and the desired one. The iterative formula of the linear update process can be expressed as $u_{n+1}(t) = u_n(t) + p \cdot e_k(t)$, where p is a correction coefficient and $e_k(t)$ represents the difference between the obtained chirp and the desired one. With the correction coefficient p decreases over the iterations, the obtained chirp $v(t)$ gradually converges to the linear chirp $v_d(t)$ [8], and hence the optimal driving signal is obtained. Nevertheless, it should be noted that the convergence speed slows down with a smaller correction coefficient, leading to unnecessary waste of computing resources and susceptibility to environmental interference due to the prolonged optimization. Therefore, we introduce an adaptive correction coefficient in the linear update process to break this trade-off. By changing the value of the correction coefficient according to the chirp linearity, convergence can be speed up as long as the chirp linearity is still continuously improved. Figure 1(c) illustrates the 10 kHz triangular driving signal waveforms with and without correction. The improvement of the chirp linearity is demonstrated through the subsequent proof-of-concept ranging experiment.

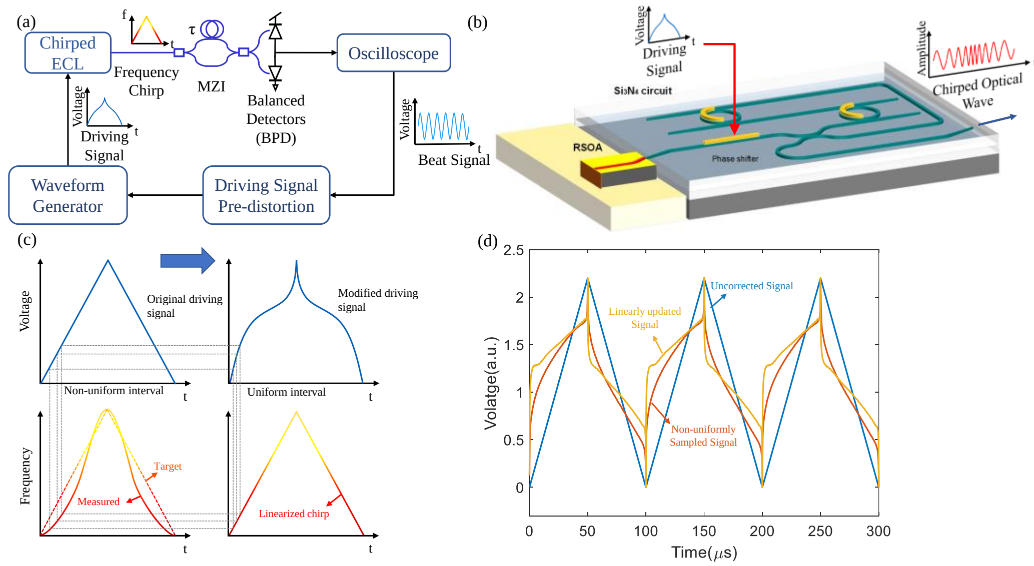

Fig. 1. (a) Driving signal pre-distortion scheme to increase chirp linearity. (b) Structure of the Si_3N_4 hybrid-integrated ECL. (c) Diagram of the Non-uniform Sampling. (d) Driving electrical signal with and without pre-distortion.

3. FMCW LiDAR Experimental Results

Figure 2 (a) and (b) show the system configuration of the proof-of-concept ranging experiment. The experiment consists of two parts: the chirp linearity verification and the ranging measurement. Before the ranging experiment, we adopt the aforementioned non-uniform sampling and linear update method to generate the optimal pre-distorted driving signal. In the chirp linearity verification part, we use the heterodyne detection method to measure the laser chirp. As shown in Fig. 2(a), the output of the chirped ECL is mixed with a fixed laser operating near the start frequency of the chirp to generate a down-converted beat signal measurable to the oscilloscope. The resulted RF beat signal has the same chirp rate γ and bandwidth with those of the ECL. Thus, the time-frequency distribution of the chirp can be obtained by adopting the short-time Fourier transform. Finally, we verify the ranging performance of the FMCW system by transmission through optical fibers of different lengths, as illustrated in Fig. 2(g)-(j). The chirp period (T) is 100 µs, the chirp bandwidth (BW) is 1.55 GHz and the ranging distance varies from 1m to 50m.

Figure 2 (c) and (d) show the improvement of linearity after performing driving signal pre-distortion. The original linearity is 87.3% when a triangular driving signal is applied. With the introduction of non-uniform sampling and the adaptive linear update algorithm, the chirp linearity is increased to 99.7% after 26 iterations. Figure 2 (e) and (f) show the time-frequency distribution of the heterodyne beat signal before and after the correction. The chirp linearity of the laser has been significantly improved after correction.

The spectrum of the beat signal narrows with the increased chirp linearity. Figure 2 (g) and (h) show the measured beat signal power density spectra before and after driving signal pre-distortion when the length of the fiber is changed from 1 m to 50 m. Through comparison, we can see that a single narrow peak is present in the beat signal spectrum after driving signal pre-distortion, indicating that the ranging resolution is improved accordingly. As shown in Fig. 2(i), the ranging resolution is improved to 9.87 cm at 10 m distance and 29.6 cm at 40 m distance with the proposed pre-distortion method, which is close to the range resolution limit of 9.6 cm under the 1.55 GHz chirp bandwidth. Fig. 2 (j) demonstrates the measured ranging result with or without the pre-distortion method, the deviation in the estimated range have improved to 43 cm at 40 m distance, which can be reduced by subsequent calibration.

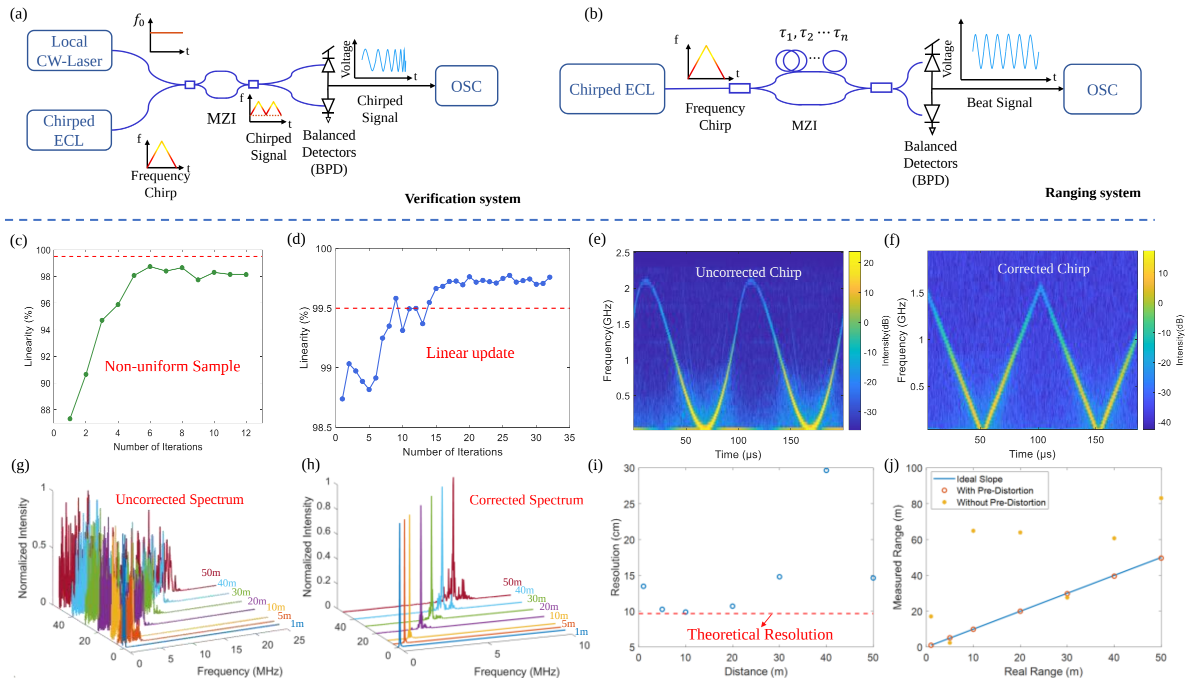

Fig. 2. Experimental systems for (a) chirp linearity verification and (b) ranging measurement. (c) and (d) Increment of chirp linearity after two correction processes. Short-time Fourier Transform of the beat signal (e) before and (f) after correction. Measured ranging results of the FMCW system (g) before and (h) after pre-distortion. (i) Resolution and (j) measured range for different fiber distances of the FMCW ranging system.

4. Conclusions

We proposed a novel frequency chirp nonlinearity pre-distortion method for an InP/Si_3N_4 hybrid-integrated ECL. The chirp linearity is increased from 87.31% to 99.77% without any prior knowledge of the dynamic behavior of the laser. This method improves the chirp linearity and increases the accuracy of the FMCW detection system without complex phase-locked loops or complicated post-processing, making it useful to improve the ranging resolution in LiDAR systems.

5. References

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