Photonic Reservoir Computing Enabled Time-Domain Demodulation for Frequency Modulated LiDAR

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***Abstract*— A novel frequency modulated continuous wave LiDAR system, utilizing photonic reservoir computing for Fourier-free time-domain signal analysis, achieves robust distance measurement with improved computing efficiency and eliminates Fourier spectrum broadening issues due to inherent nonlinear optical wavelength sweeping. Experimental results show 100% signal classification accuracy.**

***Keywords*— LiDAR, reservoir computing, microwave photonics, semiconductor laser, optical injection, frequency modulation**

I. Introduction

Frequency modulated continuous-wave (FMCW) light detection and ranging (LiDAR) offers robust anti-interference capabilities, high resolution, a superior signal-to-noise ratio (SNR) and demands minimal optical power. It has found wide applications in ranging, remote sensing and three-dimensional imaging [1]. FMCW LiDAR adopts optical heterodyne coherence detection, where the signal light is coupled with the reference light to generate an intermedia frequency (IF) signal carrying target distance and speed information.

Fourier analysis of the received IF signal is always required to extract target distance and velocity information from narrow peaks in the power spectrum. However, Fourier transform calculations are computationally intensive and time-consuming. In addition, practical implementations of FMCW LiDAR often encounter challenges due to non-ideal frequency sweeping of wavelength swept light sources, which can significantly distort and broaden the power spectrum peaks. This leads to reduced ranging resolution and poor SNR [2]. Existing approaches primarily rely on correcting and compensating nonlinear frequency sweeping through resampling before Fourier analysis [3], however at the expense of increased signal processing times.

In this work, we report a novel alternative demodulation solution for FMCW LiDAR, offering direct signal analysis in the time-domain without relying on computationally demanding Fourier analysis and remaining fully immune to nonlinear optical wavelength sweeping, thereby eliminating the need for digital resampling and correction. Our approach leverages the efficiency of temporal signal analysis, specially reservoir computing (RC) [4]. The system operates by employing the RC algorithm to classify the IF signal over time to determine the target distance information. In addition, we develop a delay-based photonic RC system is developed to physically implement the RC model, utilizing optical injection within a semiconductor laser. The photonic RC demonstrates a 100% accuracy in time-domain signal classification.

II. Principle

Figure 1 illustrates the proposed FMCW LiDAR system incorporating an RC model to perform direct temporal signal analysis for real-time distance measurement. The top part of figure shows the developed FMCW LiDAR system. A wavelength-swept light source produces a continuous wave optical carrier with its instantaneous wavelength sweeping over time. Interference between the echoed signal from target and the reference signal at a photodetector (PD) generates an IF signal with its frequency indicating the target distance. The detected IF signal is then sent to RC for time-domain data analysis. In this system, distinct target distance information produce distinct IF waveforms, which can be classified using the RC module. Consequently, target distance information is determined from the classification outcomes, eliminating the need for computationally intensive Fourier analysis and complex nonlinearity correction operations.

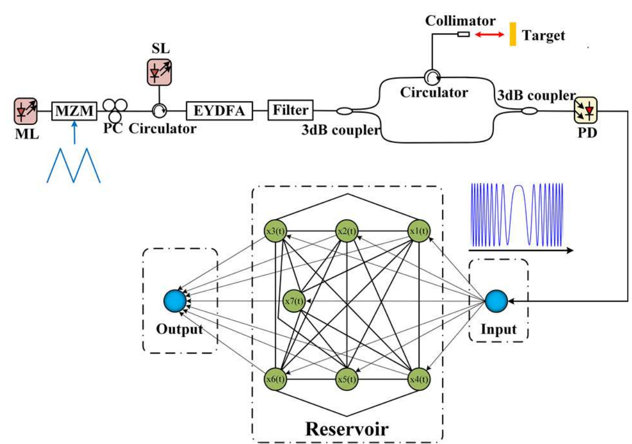

Fig. 1. Schematic diagram of the developed FMCW LiDAR system incoporating time-domain demodulation based on RC algorithm.

III. Results

Experiments are carried out to verify the proposed approach. We first construct a FMCW LiDAR system to produce experimental data for the RC-assisted signal processing model. At the core of a FMCW LiDAR system is an optical wavelength swept source. In our implementation, this source is developed using an optically injected semiconductor laser [5], chosen for its advantages of simple structure and adjustable sweeping rate, which allows facilitating convenient reconfiguration in LiDAR applications. We measure the beating signal between the wavelength swept sideband and the fixed optical carrier (subsequently removed using an optical bandpass filter in the LiDAR system) and its instantaneous frequency is shown in Fig. 2(a). Notably, nonlinear frequency sweeping is observed. A FMCW LiDAR system employing the developed optical source is constructed. Fig. 2(b) shows the IF signal waveforms within one scanning period. Pronounced frequency chirp is evident.

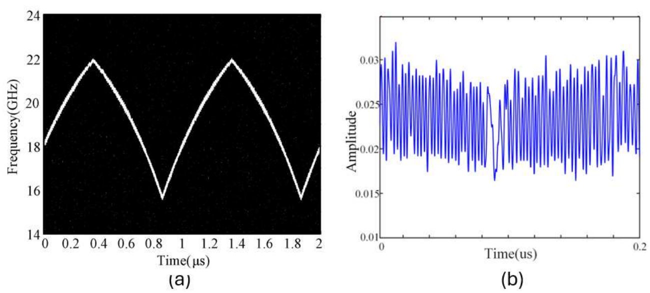

Fig. 2. Experiment results from the developed FMCW LiDAR system. (a) the beating signal between the wavelength-swept sideband and the fixed optical cearrir, indicating nonlinear optical wavelength sweeping; (b) the measured IF signal at the output of LiDAR system.

A RC model has been developed to analyze the captured IF waveforms for signal classification [6]. This approach exploits the distinctive characteristics of time-domain waveforms of beat signals following nonlinear frequency sweeps, enabling precise distance measurements, not only mitigating the adverse effects of frequency sweeping nonlinearity in the optical source, but also enhancing distance resolution through comprehensive model training.

Implementing the RC model using a digital processing unit still faces challenges such as limited computational throughput and low energy efficiency. In this study, we construct a delay-based photonic RC system utilizing an optically injected semiconductor laser [7], and exploit its utility in FMCW LiDAR signal analysis. In the input layer, the captured IF waveforms is mixed with an input mask function and then modulates a continuous wave optical carrier. The reservoir layer is essentially an optical fibre feedback loop incorporating an optically injected semiconductor laser serving as the single nonlinear activation node. By adjusting injection parameters such as detuning frequency, injection power, feedback power, and polarization states, the semiconductor laser operates in an injection-locked state, ensuring the consistency and memory capacity of the photonic RC system.

Time-domain signal classification employing the photonic RF is carried out for FMCW LiDAR. The simulated IF waveforms corresponding to different target distances are reproduced using an arbitrary waveform generator (AWG) and modulate the optical carrier in photonic RC. The reservoir outputs are measured using an oscilloscope. Two different target distances are shown in Fig. 3. Top row are IF waveforms and bottom row are reservoir outputs. The read-out weights are then trained according to the reservoir state information alongside its corresponding labels (distances). 360 data samples corresponding to 9 different target distances have been selected. 70% is allocated for training, while the remaining 30% is set aside for evaluating the photonic RC's identification performance. Our results show that he developed photonic RC demonstrates a 100% accuracy in time-domain signal classification.

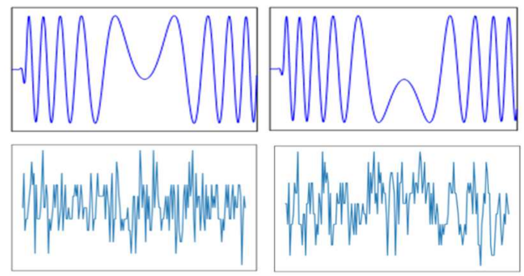

Fig. 3. Signal analysis using the photonic RC. Top row: simulated IF waveforms for two different target distances; bottom row: the corresponding reservoir outputs.

IV. Conclusion

We demonstrate a novel time-domain demodulation solution for FMCW LiDAR, using a photonic reservoir computing approach, which offers advantages of reduced computational complexity and lower energy consumption. Limitations associated with conventional Fourier analysis techniques are overcome, particularly in addressing nonlinear frequency sweeping issues in FMCW LiDAR systems.

References

[1] D. Jeong, H. Jang, M. U. Jung, T. Jeong, H. Kim, S. Yang, J. Lee, and C. S. Kim, "Spatio-spectral 4D coherent ranging using a flutter-wavelength-swept laser," Nat Commun, vol. 15, no. 1, p. 1110, February 2024.

[2] D. F. Pierrottet, F. Amzajerdian, L. Petway, B. Barnes, G. Lockard and M. Rubio, "Linear FMCW laser radar for precision range and vector velocity measurements," MRS Proceedings, 10760406, August 2008.

[3] S. Vergnole, D. Lévesque, and G. Lamouche, "Experimental validation of an optimized signal processing method to handle non-linearity in swept-source optical coherence tomography," Optics Express, vol. 18, no. 10, pp. 10446-10461, May 2010.

[4] L. Larger, M. C. Soriano, D. Brunner, L. Appeltant, J. M. Gutierrez, L. Pesquera, C. R. Mirasso, and I. Fischer, "Photonic information processing beyond Turing: an optoelectronic implementation of reservoir computing," Opt. Express, vol. 20, no. 3, pp. 3241-3249, January 2012.

[5] S. Li, Z. Liu, A. Zhang, H. Pan, R. Stancu, Y. Yue, R. Zhang, and C. Wang, "High-speed and high-resolution optical fiber sensor interrogation based on optical injection in semiconductor laser and microwave filtering," J. Lightwave Technol., vol. 40, no. 20, pp. 6805-6812, October 2022.

[6] T. Luan, R. Zhang, Y. Yue, S. Liu, A. Zhang, and C. Wang, "A Frequency Modulated Continuous Wave LiDAR System Based on Reservoir Computing," in 2023 International Topical Meeting on Microwave Photonics (MWP), 15-18 October 2023.

[7] G. Tanaka, T. Yamane, J. B. Héroux, R. Nakane, N. Kanazawa, S. Takeda, H. Numata, D. Nakano, and A. Hirose, "Recent advances in physical reservoir computing: A review," Neural Networks, vol. 115, pp. 100-123, March 2019.