A rapid and long-distance ranging system assisted by time-stretch and wavelength division

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***Abstract*—We propose and experimentally demonstrate an absolute distance measurement system based on dual-comb. The update rate can be 100 kHz, while the precision is approximately 97 nm with an averaging time of 5 ms. The non-ambiguity range is extended to 1.5 km theoretically.**

Keywords*— *Absolute distance measurement, dual-comb, the non-ambiguity range

I. Introduction

Precision measurement of long distance to an object is one of the core component in both scientific and industrial areas, such as multisatellite flying formation-based extraterrestrial planet searching, large-scale manufacturing and gravitational waves detection [1]. Laser based light detection and ranging (LiDAR) technology is always attractive in these applications, for it offers a long range, high precision and fast acquisition, which are key parameters for ranging system. In traditional LiDAR method, a continuous wave (cw) is used together with a Michelson interferometer to determine the distance difference of the reference and target arms, achieving sub-wavelength measurement resolution [2]. However, measurements are limited to relative range changes in distance as the non-ambiguity range (NAR) equals to half of the laser wavelength.

With the advent of optical frequency comb (OFC), it has led to revolutionary progress in absolute distance measurement benefits from its stability and coherence in both the temporal and frequency domains. Different comb-based approaches have been proposed take advantage of the superior characteristics of high repetition rate, large number of fine longitudinal modes and phase coherence of the comb laser, such as synthetic wavelength interferometry (SWI) [3], dispersive interferometry (DPI) [4], time-of-flight (Tof) method [5], and the dual-comb method. Each of the schemes has its own characteristics in practical applications, while there still exists trade-off between the NAR, precision and ranging speed. Particularly, the dual-comb ranging method has an outstanding overall performance in large dynamic range measurement of absolute distance, i.e. if the comb repetition rates vary from about 100 MHz to tens of GHz, the ambiguity range is typically on the order of a few meters to a few millimeters with sub-micron or even nanometer precision. Further, the NAR can be enlarged by interchanging the roles of the two combs during the measurement, which is not a real-time measurement. In addition, the repetition rate difference should satisfy $\Delta f_{rep} < f_{rep}^2/(2\Delta v_{opt})$ to avoid spectral aliasing, where Δv_{opt} represents the optical bandwidth of the dual-comb, which slows down the ranging speed [6]. In general, the interferometric systems own the ability to a high precision ranging, while the Tof method maintains a long distance and high-speed capabilities.

In this paper, we combine the two measurements principles, which bridges the gap between the precision, speed and NAR. An dual-comb based time-stretch ranging system is presented. Leveraging the frequency difference between the dual-comb, the reflected probe comb will encounter the local comb with precise temporal delay automatically. Additionally, a wavelength division scheme is performed in this work to enable the both of the two combs to act as probe so as to extend the NAR further. As a proof-of-principle demonstration of the ranging capability, we achieve a precision of 2.97 μm with an update time of 10 μs. With an averaging time of 5 ms, the Allen deviation reaches 97 nm, which can be more accurate for a longer averaging time.

II. Principle and Experimental Set-up

A. Principle

Based on our previous work [7], we combine the time-stretch and wavelength division technology with dual-comb to speed up the large NAR and high precision ranging measurements. The time-stretched pulses of dual-comb come across periodically with a slight time shift Δt = 1/frep2 − 1/frep1 (f_{rep1}/f_{rep2} represents the repetition frequency of dual-comb) due to the temporal Vernier effect. So that the beating frequency between each pair of the time-stretched pulses in different periods increases with the time shifts $t' = q\Delta t$ (q is integer), and can be expressed as $f_{beating} = t'{\cdot}\varphi$, where φ represents the dispersion-based chirped rate. Since the value

This work was supported by grants from the National Key Research and Development Program of China (Grant Nos. 2022YFF0705904) and the National Natural Science Foundation of China (Grant Nos. 62075072, and 61927817).

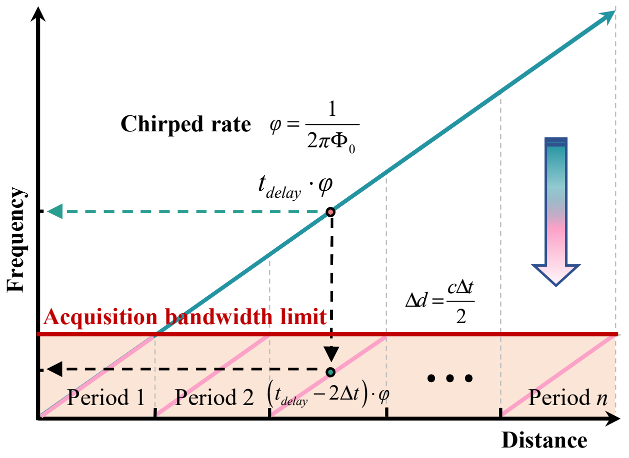

Fig. 1. Principle of the rapid long-distance ranging system.

of n is given by $f_{rep1}/(f_{rep1} - f_{rep2})$. Moreover, by setting the analog acquisition bandwidth of oscilloscope or using a bandwidth-limited photodiode so as to filter out the high frequency component, the frequency threshold can be given by $\Delta t/2\pi\Phi_0$, where Φ_0 denotes to a total group delay dispersion (GDD, ps^2). As a result, the large-distance-induced delay $t_{delay} = n\Delta t + \delta t$ ($\delta t < \Delta t$) is segmented by the time shift Δt corresponding to a segmental distance $\Delta d = c\cdot\Delta t/2$, as shown in Fig. 1. Thus, the measured result can be expressed as:

$$d = n\Delta d + \frac{c\cdot\delta t}{2} \tag{1}$$

where the n can be calculated by the time interval of reference and target fringes and δt can be extracted by the frequency of fringes. To extend the NAR, we interchange the role of the two combs simultaneously by wavelength division. The distance D is given by

$$D = (d_2 - d_1)\cdot\frac{f_{rep2,or1}}{\Delta f_{rep}} + d_{1,or2} \tag{2}$$

where $d_1$and d_2 denote to the results of the two probe, respectively. Thus, the NAR can be described as $c/(2\Delta f_{rep})$, which reaches 1.5 kilometers with a 100 kHz update rate in this work.

B. Experimental set-up

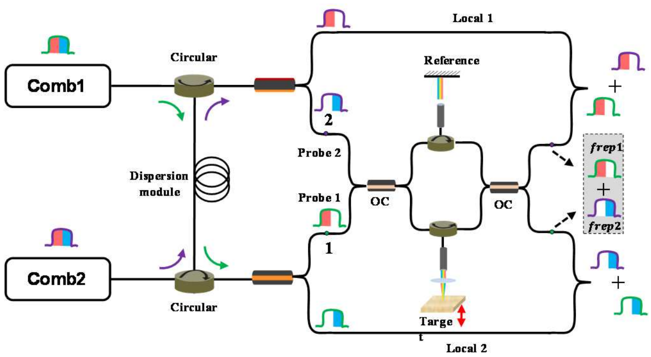

Fig. 2. Experimental set-up. Dispersion module: the dispersion module is combined of 3.3 km dispersion compensate fiber. OC: optical coupler.

As shown in Fig. 2, dual-comb sources consist of two mode-locked fiber lasers (f_{rep1} = 100 MHz and f_{rep2} = 100.1 MHz) based on nonlinear polarization rotation and phase-locked through a digital phase-locked loop (DPLL). Dual-comb sources are launched into the same dispersion module (about 3.3-km dispersion compensating fiber) in opposite directions. The time-stretched pulses are then divided into two parts with different center wavelength (1530~1548 nm and 1549~1567nm), which acts as probe and local signal separately. The probe1 and probe2 with different repetition rates are coupled into the target and reference arm by a 50/50 optical coupler. The reflected signals from the two arms are combined with the two local signals from the different combs, and acquired by a 40-GHz photodiode (Finisar XPDV2120RA) and a 33-GHz oscilloscope (KEYSIGHT DSZA594A).

III. Results and Conclusion

For the proof-of-principle, we place a static mirror at a distance of 5.6 m away from the reference arm. After an initial dispersion calibration, the results of about 18 ms are illustrated in Fig. 3(a) .

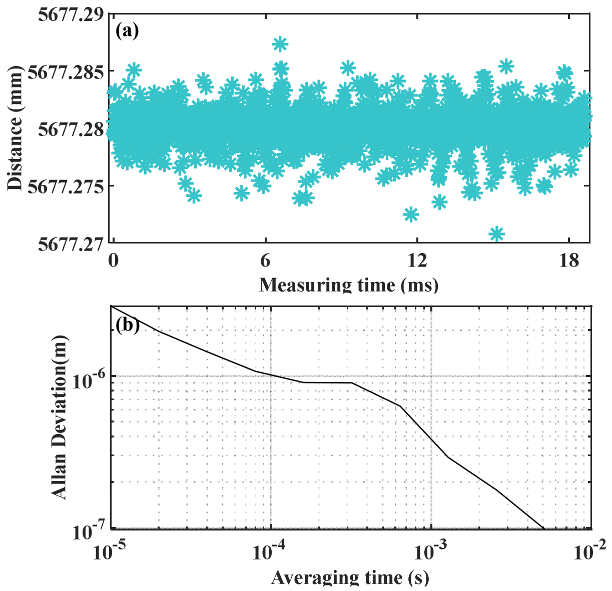

Fig. 3. (a)Results measured during a 18 ms time-window. (b) Allan deviation with different averaging time.

According to the equation (2), the distance can be extracted to 5.6772801 m, with a standard deviation of 2.97 µm. The Allen deviation reaches 97 nm with an averaging time of 5 ms, which can be more accurate for a longer average time as shown in Fig. 3(b).

In this work, we demonstrate a Lidar system with a large NAR and high ranging speed. The NAR and frame rate can be easily adjusted by detuning the frequency difference between the dual-comb, which is promising for a wide range of applications, such as optical coherence tomography system and automatic pilot for both scientific and industrial applications.

Acknowledgment

We thank the Wuhan National Laboratory for Optoelectronics of Huazhong University of Science and Technology for the support in device fabrication.

REFERENCES

[1] W. Cash, A. Shipley, S. Osterman, and M. Joy, "Laboratory detection of X-ray fringes with a grazing-incidence interferometer," Nature, vol. 407, pp. 160-162, September 2000.

[2] R. Pierce, J. Leitch, M. Stephens, P. Bender, and R. Nerem, "Intersatellite range monitoring using optical interferometry," Appl. Opt., vol. 47, pp. 5007-5019, September 2008.

[3] Z. Zhu, G. Xu, K. Ni, Q. Zhou, and G. Wu, "Synthetic-wavelength-based dual-comb interferometry for fast and precise absolute distance measurement," Opt. Express, vol. 26, pp. 5747-5757, March 2018.

[4] S. A. van den Berg, S. van Eldik, and N. Bhattacharya, "Mode-resolved frequency comb interferometry for high-accuracy long distance measurement," Sci. Rep., vol. 5, p. 14661, September 2015.

[5] J. Lee, Y.-J. Kim, K. Lee, S. Lee, and S.-W. Kim, "Time-of-flight measurement with femtosecond light pulses," Nat. Photonics, vol. 4, pp. 716-720, October 2010.

[6] S. L. Camenzind, J. F. Fricke, J. Kellner *et al.*, "Dynamic and precise long-distance ranging using a free-running dual-comb laser," Opt. Express, vol. 30, pp. 37245-37260, October 2022.

[7] L. Xu, L. Zhang, K. Wang *et al.*, "Dual-comb based time-stretch optical coherence tomography for large and segmental imaging depth," Opt. Express, vol. 30, pp. 39014-39024, October 2022.