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Free-running dual optical comb high-precision ranging technology

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Abstract: Dual comb absolute ranging technology is characterized by high-precision, and fast absolute distance measurement. However, the complicated system structure limited its use. In this paper, a free-running dual comb high-precision ranging system is proposed. The ranging precision is improved through software algorithms processing, such as adaptive filtering and cross-ambiguity function. Therefore, the system is simplified a lot. The experiments show that the range precision of 4.8 μm can be achieved when the target distance is about 1 m, laser repetition is about 180 MHz, frequency difference between two combs is about 587 Hz. The work in this paper is meaningful to the field application of the free running dual comb ranging system.

1. Introduction

Fast, real-time, high-precision distance measurement has important applications in scientific research, advanced equipment manufacturing and space exploration. The femtosecond optical comb has the characteristics of ultra-wide spectral range, ultra-narrow pulse width and ultra-stable pulse sequence interval, and the dual optical comb ranging system makes full use of the characteristics of the optical comb light source, which can realize the absolute distance measurement with large range, high precision and fast speed. The current high-precision practical measurement applications, generally require ranging accuracy to the micron level [1-3]. The current research team is mainly devoted to improving the measurement precision from the hardware aspect. In this paper, starting from software algorithm, a free-running dual optical comb high-precision ranging technique (hereinafter referred to as DCR) is proposed, which can effectively improve the ranging accuracy by dealing with the phase noise introduced by the carrier envelope offset frequency and repetition frequency fluctuation on the IGMs signals through the methods such as adaptive filtering and mutual ambiguity function [4]. The ranging accuracy of the free-running DCR system is about 4.8 um with a pulse repetition rate of about 180 MHz and a re-frequency difference of about 587 Hz, which meets the requirements of most of the high-precision measurements in practical applications, and provides a new idea for free-running double optical comb ranging.

2. Principles

2.1 DCR Measurement Model

The schematic diagram of the structure of the DCR system based on the TOF method is shown in Fig. 1 [5].

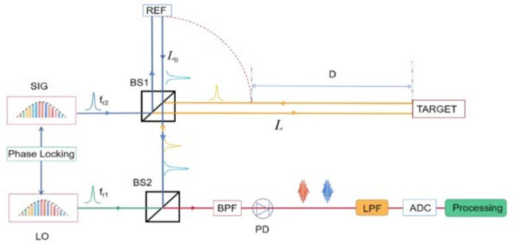

Fig 1. DCR measurement schematic diagram

L_0 and SIG are signal lasers with frequencies f_{r1} and f_{r2}. The output of SIG is divided into two beams by beam splitter BS1, one beam is emitted to the reference reflector REF, and the other beam is emitted to the target reflector TARGET. The reflected light from REF and TARGET is confluent by BS1 and then intersected with L_0 respectively, resulting in two interferograms (one generated by the reflected light of REF and L_0, and the other generated by the reflected light of TARGET and L_0). The time interval between the peak positions of the envelopes of the two interferograms is proportional to the distance difference between the target and reference mirrors, $D = L - L_0$ This implies that the optical range difference, L can be obtained from the time interval between the two interferograms, and then the target distance D, in the time of flight (TOF) [6] based DCR system can be calculated by the following equation (1):

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$$D = \frac{c\Delta\tau}{2n_g}\frac{\Delta f_r}{f_{r1}} \quad (1)$$

c is the speed of light， $\Delta\tau$ is the time delay between the measurement letter and the reference signal, and Δf_r is the frequency difference between f_{r1} and f_{r2}.

2.2 Calibration principle

Since the light source used in this paper is a free-running and an unlocked comb pair, the acquired IGMs contain more noise. We roughly categorize the noise as phase noise caused by Δfr and $fceo$ fluctuations on the IGMs signals, repeated as $\delta\Delta f_r(t)$ and $\delta f_{ceo}^{RF}(t)$ Jitter in the $fceo$ causes an overall flattening of the spectrum, resulting in an absolute frequency misalignment, while jitter in the repetition frequency directly destroys the fixed comb spacing [7]. Therefore, before calculating the target distance using the time-of-flight algorithm, proper signal processing of the IGMs is required, aiming at eliminating the phase noise caused by Δfr and $\Delta fceo$ fluctuations on the signals of the IGMs through digital signal processing. Before correcting RF $fceo$ jitter, adaptive filtering is adopted firstly to eliminate the noise out the signal frequency.

2.2.1 Calibration $\delta f_{ceo}^{RF}(t)$

Mutual ambiguity function. The mutual ambiguity function is a variant of the correlation function used to calculate the time delay and frequency shift of two similar waveforms with the following expression:

$$\chi_{1,\mathrm{k}}(\tau, f_o) = \int_{-\infty}^{\infty} A_1(t)A_2^*(t+\tau)\exp(2\pi i f_o t)dt \quad (2)$$

where $A1\,(t)$ and $A2\,(t)$ are the two waveforms to be computed; * denotes the complex conjugate, and f_o and τ denote the frequency offset and time delay to be retrieved. The corresponding τ when $|\chi_{1,k}(\tau, f_0)|$ is maximized is the period interval between the two IGMs, and f_o is the spectral offset between the two IGMs. The actual center pulse position of each IGMs is obtained by τ, and the phase sequence obtained by unwrapping and interpolating the instantaneous phase at the center pulse of each IGM can be used to compensate for the carrier envelope offset $\delta f_{ceo}^{RF}(t)$.

2.2.2 Calibration $\delta\Delta f_r(t)$

After the $fceo$ jitter correction, we also need to correct for the pulse repetition frequency difference between the two combs. It is known that the IGMs generated by the DCR system of a mode-locked laser are periodic pulsed signals, and it can be known that the peak spacing of the time-domain signals with different periods can usually be considered as $T = 1/\Delta fr$. Therefore it is possible to using the adjusted frequency result in Eq(1) to calculate the distance

3. experimental verification

In this paper, a set of 1550 nm free-running DCR system is used to process the experimental data using the chapter 2 signal correction method, and the correction results are shown in Fig 2.

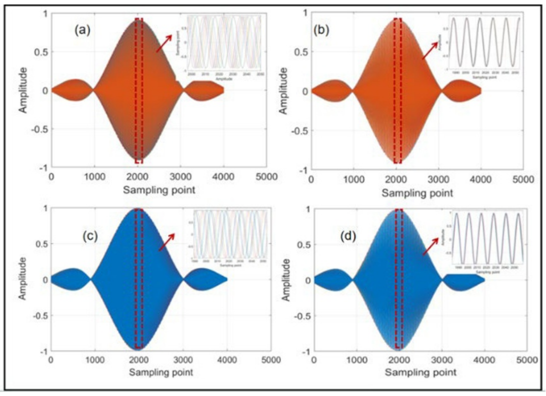

Figure 2. (a) Reference IGM RF $fceo$ jitter uncorrected, (b) reference IGM RF $fceo$ jitter corrected, (c) signal IGM RF $fceo$ jitter uncorrected, (d) signal IGM RF $fceo$ jitter corrected

As can be seen from the envelope amplification plot, there is a slip in the carrier envelope signal (a)(c) before the $\delta f_{ceo}^{RF}(t)$ is corrected. After the $\delta f_{ceo}^{RF}(t)$ is corrected, it's obvious that the slip in the carrier envelope signal (b)(d) is eliminated by the mutual ambiguity function process.

In the experimental process we set the starting value of VDL as 20 mm, change the VDL in the range [20 mm, 24 mm] with a step of 1mm by manual micrometer. The range is about 1m. Adaptive filtering and mutual ambiguity function are utilized to process the experimental data, and the results are shown in Table 1 and Fig 3.

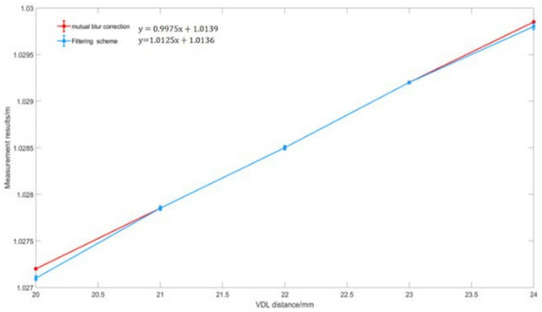

Fig 3. Measurement results by two different algorithms

Table 1. Parameters of DCR system

VDL	Filtering (mean/variance)	Filtering+ ambiguity function (mean/variance)
20 mm	1.027 m/25.0 um	1.027 m/3.13 um
21 mm	1.028 m/24.6 um	1.028 m/3.32 um
22 mm	1.029 m/24.8 um	1.029 m/3.50 um
23 mm	1.029 m/23.7 um	1.029 m/6.57 um
24 mm	1.030 m/31.5 um	1.030 m/7.39 um

The measurement results of both filtering methods can be stabilized to increase linearly with the increase of the VDL setting value. From the linear fitting line in Fig. 3, the linearity between the ranging results and the VDL readings is good, and the average ranging results obtained by the two correction schemes are highly consistent. It's obvious that the range precession after correction is greatly improved. The average precession of the adaptive filtering scheme is about 23.9 um, and that of the mutual ambiguity function correction method is about 4.8 um. The slope of the fitted curve is about 0.9975. Theoretically, the slope should be 1, and this error may be caused by the manual reading of VDL.

4. Conclusion

This experiment verifies that through software process, DCR can realize um-level range accuracy when the laser works in a free-running condition. The results show promise for the free-running DCR system to be used in the field application. In addition, DCR technology can be easily expanded to dual comb spectroscopy, and time-frequency transfer technology. It is foreseeable that DCR systems will be useful in many fields such as LiDAR, environmental monitoring, and bioimaging.

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