Research Article

Bin Sun*, Junfang Song, Chao Wang, Lanlan Li, and Linqiu Tan

Research on absolute ranging technology of resampling phase comparison method based on FMCW

https://doi.org/10.1515/phys-2023-0112
received May 23, 2023; accepted August 28, 2023

Abstract: As an advanced optical precision ranging method, FMCW (frequency-modulated continuous-wave) laser interferometric ranging technology can achieve a large-scale and high-precision absolute distance measurement, so it has high research and application value in the field of coordinate measurement in large space. How to improve the resolution and stability of laser interferometry is a research difficulty in this technology. Based on FMCW laser interferometry relative distance technology, a method for achieving absolute distance measurement through phase comparison after repeated sampling is proposed. Using the FMCW laser distance measuring system, two interference optical paths of measuring interferometer and auxiliary interferometer are constructed, respectively. Synchronous sampling is performed on two interference signals, and the phase ratio of the two interference signals is obtained through the extracted frequency information. The optical path difference of the unknown measurement interferometer is derived from the known auxiliary interferometer information. This method uses a triangular wave modulation laser to reduce the influence of Doppler frequency shift and eliminate quantization errors. By using the fixed-point repeated sampling, the optical path difference information is quickly extracted, and the nonlinear error of laser interference frequency modulation is effectively reduced.

Keywords: FMCW, absolute ranging, resampling, phase comparison method, laser interference

*** Corresponding author: Bin Sun,** School of Optoelectronics Engineering, Xi'an Technological University, Xi'an, 710021, China, e-mail: sun075634@163.com
Junfang Song: School of Information Engineering, Xizang Minzu University, Xianyang 712082, China
Chao Wang, Lanlan Li, Linqiu Tan: School of Optoelectronics Engineering, Xi'an Technological University, Xi'an, 710021, China

1 Introduction

Since the birth of laser, it has played an important role in the field of distance measurement with its unique multiple characteristics such as high collimation, high coherence, and modulability [1,2]. Frequency-modulated continuous-wave (FMCW) laser interferometric ranging is derived from light detection and ranging technology. This method has the advantages of large ranging range, high accuracy, searchability, and stability and reliability and has been widely applied in the fields of ultra-precision manufacturing and large-scale detection [3–5]. The basic principle of FMCW is to implement periodic continuous frequency modulation on the laser, and the modulated laser first loads the ranging information in the optical path system and then combines the beam to form interference. When the optical paths corresponding to the reference and signal optical paths of the interference system are not equal, there is a certain frequency difference between the combined two FMCW lasers, resulting in a dynamic beat frequency interference signal. By demodulating the initial phase change of the beat signal, the change of the measured light path difference can be obtained [6,7]. FMCW laser interferometry technology produces a dynamic beat interference signal, and it is easy to extract the phase subdivision, phase-moving direction resolution, and interference period count in the signal. Since the extracted phase can subdivide the wavelength of a laser, the FMCW laser interferometry technology can achieve high-precision distance measurement [8,9].

The measurement system uses a distributed feedback laser (DFB) semiconductor laser as the light source. The laser is equipped with an fiber grating filter, which ensures a stable output wavelength, extremely narrow linewidth, and excellent edge mode suppression ratio. Due to its small size and convenient installation, this device has been widely used. However, as a semiconductor device, it has defects such as poor temperature characteristics and easy noise generation [10–12]. In actual measurement, the laser is affected by factors such as modulation nonlinearity error, system calibration error, and Doppler frequency shift. These factors all greatly affect the ranging accuracy and stability of the FMCW ranging system, making it difficult to achieve stable and reliable engineering applications.

In order to solve the aforementioned problems, many scholars have put forward a lot of very effective methods, which mainly include early active compensation and late fitting treatment. Active compensation methods include pre-correction compensation and feedback frequency modulation technology and electro-optic phase-locked loop feedback correction technology [13–15]. Post-processing methods include signal frequency reference correction, optical frequency comb correction, and multi-optical path correction [16,17]. Naresh built an FMCW laser ranging optical path and designed a semiconductor laser source feedback control system with a ranging resolution of 1.5 mm [18]. Satyan *et al.* used a single-mode vertical cavity surface emitting laser to build a ranging system with a spatial ranging resolution of 250 μm and a range of 1 m [19]. Iiyama *et al.* improved the light source system using fiber optic self-mixing technology and measured targets at a distance of 1.5 m, achieving a ranging resolution of 31 μm [20]. Baumann used a frequency comb to correct the optical frequency of the laser, increasing the ranging resolution to 130 μm and the repetition accuracy to 6 nm [16]. The aforementioned method optimizes the signal extraction method and improves the measurement accuracy to a certain extent. However, the Doppler phase shift and nonlinear error caused by the large-scale laser frequency dynamic modulation are still a difficult problem that seriously affects the measurement accuracy and stability and has not been completely solved.

This manuscript proposes a method of fixed-point repeated sampling and phase comparison based on the correction technique of two optical paths to eliminate the nonlinear effects caused by laser modulation. The fixed-point repeated sampling algorithm is derived in detail. The correctness of the formula is verified by simulation analysis, and the corresponding auxiliary measurement optical path based on optical fiber is built by combining the algorithm. The experimental results show that the system can calculate the accuracy and reliability of the optical path difference and realize the high-precision and large-size measurement engineering application of FMCW laser interferometry absolute ranging.

2 FMCW ranging principle

As shown in Figure 1, the FMCW laser is collimated by a collimating lens and then divided by a coupler. The optical path where the fixed reflector is located is the reference beam, and the OPD (optical path difference) will not change. The optical path where the movable reflector is located is a signal beam. When the reflected beam from the movable reflector and the fixed reflector meets at the coupler, the two beams will interfere to generate a dynamic interference signal. The displacement of the movable reflector is calculated by the frequency and phase of the interference signal.

When these two waves interfere, the interference signal light intensity, the OPD between the reference wave and the signal wave in one modulation period, is as follows:

$$I(\mathrm{OPD}, t) = I_0[1 + V\cos(\omega t + \phi_0)],$$

$$I(\mathrm{OPD},t) = I_0\left[1 + V\cos\left(\frac{2\pi\Delta\nu\nu_m \mathrm{OPD}}{c}t + \frac{2\pi}{\lambda_0}\mathrm{OPD}\right)\right]$$
$$= I_0[1 + V\cos(2\pi\nu_b t + \varphi_{b0})], \quad (1)$$

where $\Delta\nu$ is the optical frequency modulation excursion, ν_m is the frequency the modulation signal, c is the speed of light in free pace, λ_0 is the central optical wavelength, and ν_b and φ_{b0} are the frequency and the initial phase of the beat signal, respectively.

Then, the absolute ranging based on frequency is as follows:

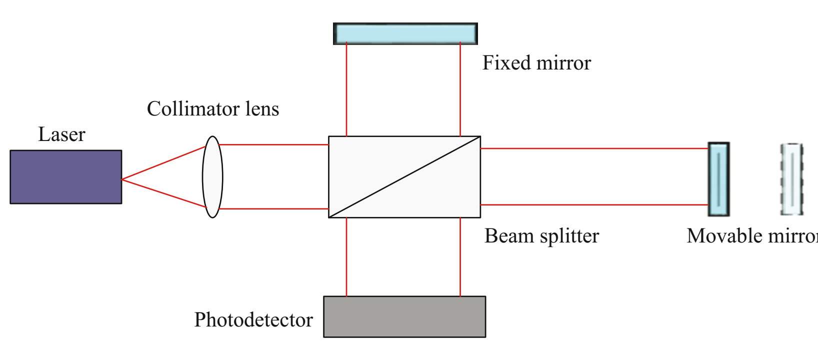

Figure 1: FMCW optical system diagram.

$$\nu_b = \frac{\Delta\nu\nu_m \mathrm{OPD}}{c}, \tag{2}$$

$$L = \mathrm{OPD}/2 = \frac{1}{2}\frac{c}{\Delta\nu\nu_m}\nu_b \tag{3}$$

3 Resampling phase comparison method for absolute ranging

In order to improve the accuracy of absolute distance measurement in large range and eliminate the quantization error caused by nonlinear frequency modulation and experimental calibration, a dual-optical path-measuring device based on a single-mode fiber is proposed. As shown in Figure 2, the basic structure of the dual optical path-ranging system is mainly composed of two parallel interference devices: one is the measuring interference device and the other is the auxiliary interference device. The DFB laser emits a triangular wave signal with the wavelength of 1,550 nm, which is divided into two parts according to the ratio of 1:1 by the coupler. The emitted light entering the measuring interference device is emitted through the circulator and collimating lens. The light reflected by the measuring target mirror and the light reflected by the half lens of the collimator form Michelson interference in the loop. The beat frequency signal formed by the interference is collected by photoelectric detector 1 through circulator 3. The laser entering the auxiliary interference device is divided into two parts by the coupler, enters the optical fiber with different optical path difference, and then combines the beams to form the Mach–Zehnder interferometer. The interference signal is collected by photodetector 2.

Analyzing the characteristics of measurement systems using frequency characteristics and decoupling important information hidden in physical phenomena is one of the important methods in signal processing technology [21–23]. In order to explain in detail, the working principle of resampling phase comparison absolute ranging, the acquisition method, is mathematically deduced. When the modulation frequency of the laser signal is ν_m and the frequency modulation range is $\Delta\upsilon$, the measuring interference device and the auxiliary interference device have the same light source.

Auxiliary interferometer distance:

$$L_r = \mathrm{OPD}/2 = \frac{1}{2}\frac{c}{\Delta\nu\nu_m}\nu_{br} \tag{4}$$

Measuring interferometer distance:

$$L_m = \mathrm{OPD}/2 = \frac{1}{2}\frac{c}{\Delta\nu\nu_m}\nu_{bm} \tag{5}$$

Then,

$$\frac{L_m}{L_r} = \frac{\nu_{bm}}{\nu_{br}} = \frac{\omega_m}{\omega_r},$$

$$L_m = \frac{\nu_{bm}}{\nu_{br}}L_r \tag{6}$$

The absolute ranging calculation method based on beat frequency is adopted. Obviously, the measurement accuracy is restricted by frequency. Since the phase can subdivide the beat frequency signal frequency and improve the measurement accuracy, the absolute ranging calculation can be realized based on the sum of phases within the time window Δt.

Auxiliary interferometer distance:

$$L_r = \frac{\mathrm{OPD}}{2} = \frac{1}{2}\frac{c}{2\pi\Delta\nu\nu_m}\frac{\Delta\phi_r}{\Delta t} = K\frac{\Delta\phi_r}{\Delta t} \tag{7}$$

Measuring interferometer distance:

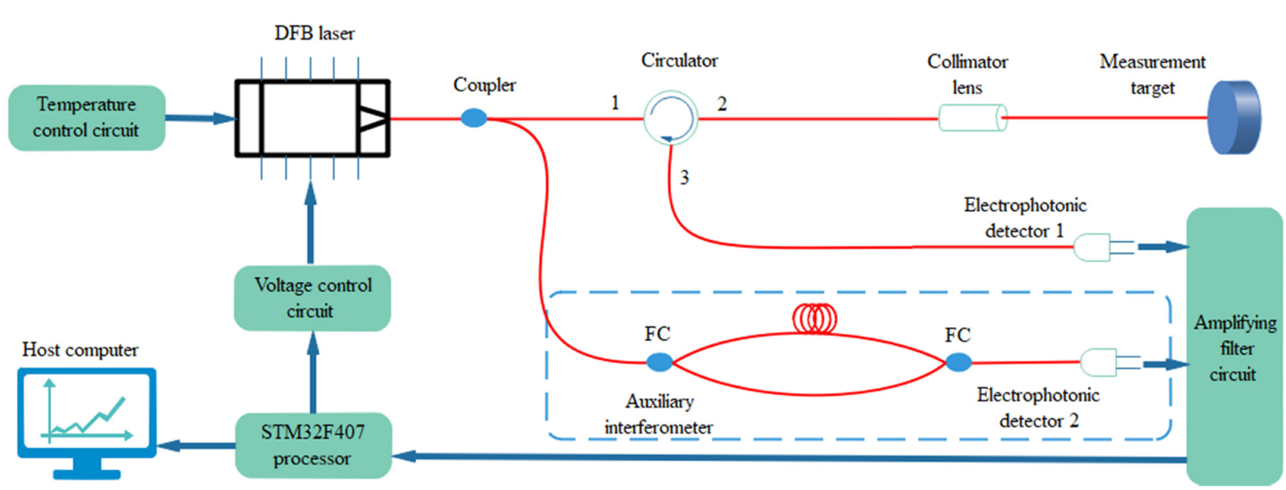

Figure 2: Schematic diagram of light path.

$$L_m = \frac{\text{OPD}}{2} = \frac{1}{2}\frac{c}{2\pi\Delta\nu\nu_m}\frac{\Delta\phi_m}{\Delta t} = K\frac{\Delta\phi_m}{\Delta t}. \quad (8)$$

Then, there is:

$$\frac{L_m}{L_r} = \frac{\Delta\phi_m}{\Delta\phi_r} \quad (9)$$

$$L_m = \frac{\Delta\phi_m}{\Delta\phi_r}L_r \quad (10)$$

It can be seen from the aforementioned formula that if the optical path difference of the auxiliary interferometer is known in advance and the interference signals of the two interferometers are sampled synchronously, the optical path difference of the measuring interferometer can be obtained only by determining the ratio of the phase changes of the two interference signals in the same time period.

4 Experimental verification and analysis

In order to verify the correctness of the aforementioned methods, an absolute ranging experiment with a length of 2 m was designed in the standard vertebra laboratory environment. As shown in Figure 3, the distance between the precision electric drive guide rail and the collimating lens is 2 m on the Thorlabs optical platform. The measuring target mirror is installed on the electric driver, and the movable range is 0–1 m. The measuring beam is emitted from the collimator and reflected by the measuring target

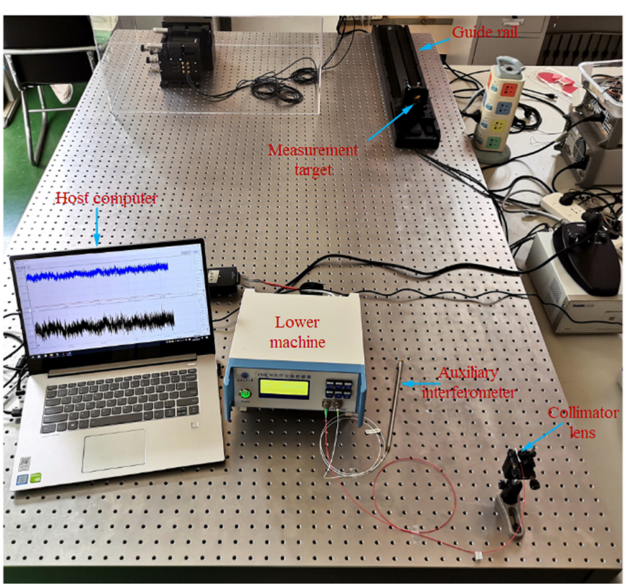

Figure 3: Measurement experiment.

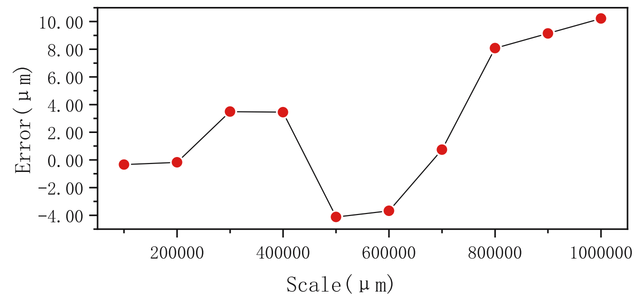

Figure 4: Linear error curve of interferometer.

mirror and then combined with the half lens in the collimator to form the beat frequency signal of the measurement interferometer. Through channel 1 of the lower machine, the measurement signal is collected by the processor, and the moving distance of the target mirror is modulated and demodulated. It can be seen from the figure that the self-made auxiliary interferometer has a fixed cavity length, and the stable beat signal is collected and processed by channel 2 of the lower machine. The notebook computer is used as the host computer to collect two interferometer signals processed by the lower computer, and the results are statistically analyzed.

During the measurement, the modulation frequency of DFB laser is 100Hz, the amplitude of modulation voltage is 1.23 V, and the modulation current range is 39.9–83.1 mA. The average change rate of laser output light frequency with current is about 0.4 Ghz/mA, and the frequency modulation range (bandwidth) is about 18 GHz. During the experiment, the micro-displacement platform was controlled to drive the measurement target mirror to move at a uniform speed, and the position of the guide rail and the measurement results of the interferometer were recorded

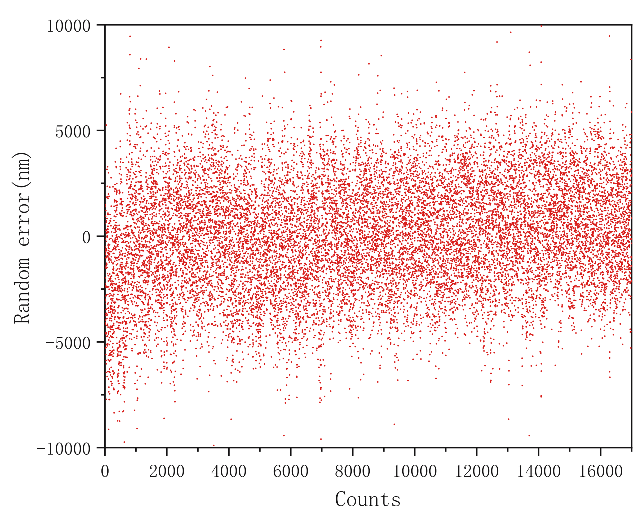

Figure 5: Scatter diagram of interferometer stability.

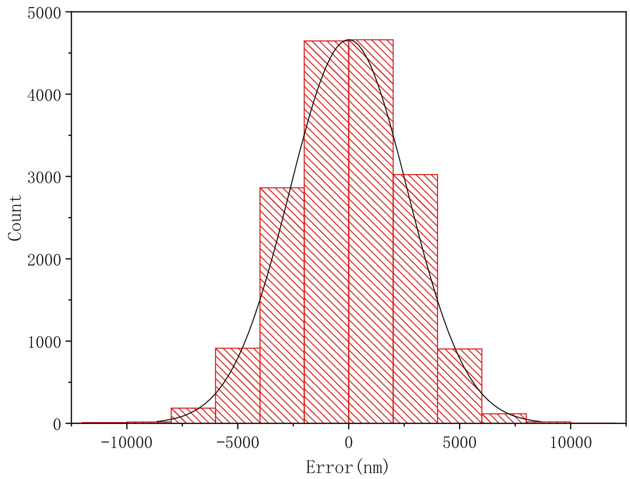

Figure 6: Normal distribution.

every 100 mm (1,000,000 μm). In the experiment, ten measurements were taken within the range of 1–2 m, using the position of the guide rail as a reference. The results recorded and obtained are shown in the measurement error curve of the laser interferometer as shown in Figure 6. It can be seen from Figure 4. that the error is ≤10 μm.

In a laboratory environment, adjust the range of the distance between the collimator and the measurement target mirror to be 1.3 m, and continuously collect 17,000 data in a static state. The stability scatter diagram is shown in Figure 5. Perform normal distribution processing on the scatter plot; as shown in Figure 6, within the 95% confidence interval, the maximum standard deviation is 2.656 μm.

It can be seen through experiments that this method can eliminate the influence of the quantization error substituted by the experimental calibration and realize the ranging resolution of 1 nm, and the measurement standard deviation exceeds 3 μm, which proves that the method has a high resolution and measurement repeatability. However, because the system has not been accurately calibrated, there are still systematic errors in the ranging results. Since the distance measurement experiment is implemented on a vibration isolation optical platform, external vibration and temperature changes have little effect on the experimental results. However, the system is more sensitive to vibration and temperature, and the impact of vibration and temperature must be considered in actual measurement, and vibration isolation design and temperature control are required.

5 Conclusion

FMCW laser interferometry ranging technology is to linearly modulate the frequency of the emitted laser, and the local oscillator signal interferes with the echo signal to form a beat frequency signal. The measurement distance is calculated by extracting the frequency information of the beat frequency signal. In the actual measurement, the laser has the problem of modulation nonlinearity, which causes the spectrum broadening of the measured signal seriously, which limits the ranging accuracy of the FMCW ranging system. In order to solve these problems, this study proposes an absolute ranging method based on the resampling phase comparison. Two signals of measuring interferometer and auxiliary interferometer are constructed by using dual optical path FMCW laser-ranging system. If two interferometers are sampled synchronously, the optical path difference can be obtained only by calculating the phase ratio of the two interferometers. The experimental results show that the nonlinear frequency modulation error of the laser is reduced by using fixed-point sampling because the quantization error caused by experimental calibration is eliminated, and this method effectively improves the accuracy and stability of measurement.

Funding information: This work was supported by the National Natural Science Foundation of China (No. 62263028) and Shaanxi Natural Science Foundation of China (No. 2023-JC-YB-592/2023-JC-QN-0633).

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Conflict of interest: The authors state no conflict of interest.

Data availability statement: The data used to support the findings of this study are available from the corresponding author upon request.

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