Laser Ranging With Micrometer Precision and kHz Rate via Joint Frequency-Phase Measurement

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***Abstract*— A joint frequency-phase measurement is proposed for high-precision and fast laser ranging, in which a frequency-modulated continuous-wave (FMCW) method is used for coarse long-distance ranging, while a phase-shift method is used for high-precision ranging. Since a low-duty-cycle linear-frequency-modulated (LFM) signal is used, the precision of the FMCW method can be reduced to be smaller than the unambiguous distance of the phase-shift method. Therefore, fast phase unwrapping can be achieved for the phase-shift method using a small bandwidth LFM signal. In the experiment, a lightwave is simultaneously modulated by a 1-7 GHz low-duty-cycle LFM signal and a 15 GHz single-tone signal, which are frequency-separated so that the FMCW ranging and the phase-shift ranging can be simultaneously achieved. The measurement precision and measurement rate are 58μm and 1.7 kHz, respectively. The measurement range can be 300 m. Therefore, the proposed method can be used to achieve laser ranging with kHz rate and decades of μm precision at hundreds of meters distance.**

***Index Terms*— Laser ranging, frequency-modulated continuous-wave, phase-shift, phase unwrapping.**

I. Introduction

LASER ranging is widely used in remote sensing [1], [2], aerospace surveying [3], 3D mapping [4], and automatic driving [5]. Phase-shift ranging is one of the popular ranging methods [6], [7], [8], in which the lightwave is modulated by a continuous-wave RF signal. It obtains distances by calculating the phase differences between the local and the recovered RF signals. Therefore, the precision depends on the accuracy of the phase discriminators and the frequency of the RF signals [9]. However, since the measurement range of a phase discriminator is $[-\pi, \pi]$, the unambiguous distance is equal to the wavelength of the RF signal, which is rarely larger than several meters if a millimeter-level precision is required [10].

Manuscript received 10 August 2022; accepted 13 September 2022. Date of publication 19 September 2022; date of current version 5 October 2022. This work was supported in part by the National Natural Science Foundation of China under Grant 62171219 and in part by the National Key Research and Development Program of China under Grant 2018YFB2201803. *(Corresponding authors: Zhongyang Xu; Shilong Pan.)*

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Color versions of one or more figures in this letter are available at https://doi.org/10.1109/LPT.2022.3207810.

Digital Object Identifier 10.1109/LPT.2022.3207810

To achieve long-distance ranging, multi-tone signals are used [11], [12], [13], [14]. However, the phase shifts of multiple frequencies must be simultaneously extracted so that parallel phase discriminations are required. Although the phase shift can be extracted from the tone-power variations, the precision is only 0.75 cm [12], [13]. Moreover, frequency-stepped signals can also be used to achieve long-distance and high-precision phase-shift ranging. Since the phase discriminations are successively implemented at the stepped frequencies, the measurement rate is limited to below kHz [14], [15]. Besides, although phase-shift ranging with pseudo-random amplitude modulation has a large unambiguous distance, the sampling rate should be as high as 3 THz to achieve a precision of 100 μm. The sampling rate can be further reduced by the fitting algorithm [16], but the measurement rate is lowered.

Frequency-modulated continuous-wave (FMCW) ranging is another widely used method, in which distances are measured according to the frequency differences between the local and the recovered linear frequency-modulated (LFM) signals [17]. Compared with the phase-shift ranging, the FMCW method does not require a long accumulation time for phase discrimination. Although the precision is usually at the centimeter-level for an FMCW ranging system without calibration apparatus, it has a larger measurement range and a higher measurement rate [18], [19], [20]. Therefore, the FMCW method is always used for long-distance and fast ranging, while the phase-shift method is used for high-precision ranging.

To achieve a long-distance, high-precision, and fast laser ranging, a joint frequency-phase measurement that simultaneously implements FMCW ranging and phase-shift ranging can be used. To ensure the phase unwrapping for the phase-shift method, the precision of the FMCW method must be smaller than the unambiguous distance of the phase-shift method, which always requires large bandwidth [17]. Recently, an FMCW method using a low-duty-cycle LFM signal is proposed to achieve high resolution with small bandwidth [21]. It provides an approach to the joint frequency-phase measurement without large bandwidth.

In this work, we demonstrate a laser ranging method based on the joint frequency-phase measurement. A low-duty-cycle LFM signal is used for high-precision FMCW laser ranging, while a single-tone RF signal is used for phase-shift laser ranging. Fast phase unwrapping is achieved for the phase-shift method according to the measured results of the FMCW method. In the experiment, an LFM signal and a single-tone

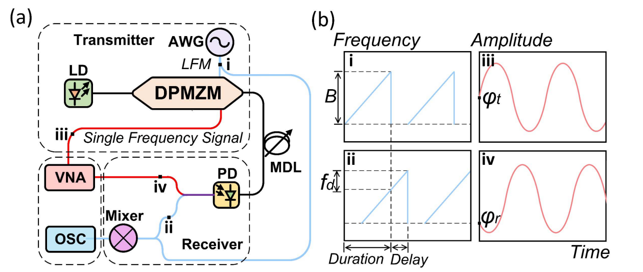

Fig. 1. Principle of the joint frequency-phase measurement. (a) Experimental setup. AWG: arbitrary waveform generator; LD: laser diode; DPMZM: dual-parallel Mach-Zehnder modulator; MDL: motorized variable optical delay line; PD: photodetector; VNA: vector network analyzer; OSC: oscilloscope. (b) Waveforms at different locations in the system.

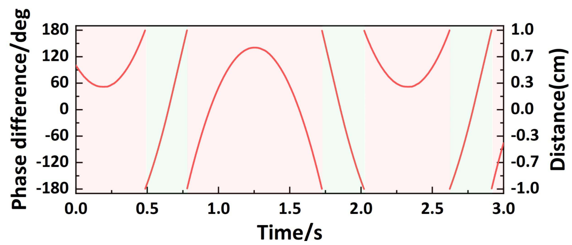

Fig. 2. Measurement results of the phase-shift method. The left and the right axes are the measured phase difference and the relative position of the MDL, respectively.

signal are simultaneously used to modulate the laser. The frequency of the single-tone signal is 15 GHz, while a 1-7 GHz LFM signal with a 0.1 duty cycle is used. The length of a variable optical delay line (MDL) is successfully measured in real-time with a precision of 58 μm and a rate of 1.7 kHz. The measurement range can be as large as 300 m.

II. Principle and System

The experimental setup of the proposed method is shown in Fig. 1(a). In the transmitter, a lightwave from a laser diode (LD) is modulated in a dual-parallel Mach-Zehnder modulator (DPMZM). A single-tone signal from a vector network analyzer (VNA) and an LFM signal from an arbitrary waveform generator (AWG) are simultaneously used to drive the DPMZM. Therefore, an RF mixer can be dispensable to enhance power efficiency. After an MDL, the optical signal is detected by a photodetector (PD). The photocurrent consists of two RF signals (a single-tone signal and an LFM signal), which are respectively used for the phase-shift and FMCW methods. The waveforms of the RF signal at different locations in the system are shown in Fig. 1(b). The de-chirped signal is obtained by mixing the local (i of Fig. 2(b)) and the recovered LFM signals (ii of Fig. 2(b)), which is recorded by an oscilloscope (OSC). Meanwhile, the VNA measures the phase difference between the local (iii of Fig. 2(b)) and the recovered single-tone signals (iv of Fig. 2(b)).

In a joint frequency-phase measurement, the distance is precisely measured according to the phase difference (φ_r-φ_t) between the recovered and the local single-tone signals. The unambiguous range of the phase-shift method is limited by

$$R_{ua} = \frac{c}{f_S} \tag{1}$$

where f_S is the frequency of the single-tone signal, c is the speed of light in vacuum. The distance longer than R_{ua} has to be determined by the FMCW method as

$$R = \frac{cTf_d}{B} \tag{2}$$

where T and B are the duration and bandwidth of the LFM signal, f_d is the frequency of the de-chirped signal. The key to the joint frequency-phase measurement is to ensure that the ranging precision of the FMCW method is smaller than the unambiguous range of the phase-shift method. If the frequency of single-tone is set to 15 GHz, the unambiguous range is 2 cm. For the traditional FMCW laser ranging, the 2-cm precision requires a bandwidth of 15 GHz. However, it is not easy to generate a high-performance LFM RF signal with large bandwidth. Meanwhile, the spectra of the LFM and the single-tone signals are always overlapped.

To solve these problems, a small-bandwidth and low-duty-cycle LFM signal is used for high-precision FMCW ranging. As a result, all-optical zero-filling can be achieved without complicated digital processing so that the de-chirped signal shows a higher spectral density than the full-duty-cycle signal. The ranging precision is calculated from the frequency interval between the spectral lines in the high-precision FMCW ranging method, which can be expressed by [21]

$$\delta R = \frac{c\alpha}{B} \tag{3}$$

where α is the duty cycle of the LFM signal. Theoretically, if the duty cycle is set to 0.1, a 1-GHz bandwidth is sufficient to achieve a 3-cm precision, which enables the phase unwrapping in the phase-shift method using a 10-GHz RF signal.

Finally, the distance can be calculated from the unwrapped phase and the de-chirped frequency, which is given by

$$R = R_{ua}\left(\text{floor}\left[\frac{cTf_d}{BR_{ua}}\right] + \frac{\Delta\varphi}{2\pi}\right) \tag{4}$$

where floor$[x]$ is the integer no greater than x, $\Delta\varphi$ is the wrapped phase differences measured by phase discriminators. The measured range is determined by the duration of the LFM signal, which can be as large as hundreds of meters. The measurement rate is limited by the phase discriminator. Since no frequency-stepped signal is used in the phase-shift method, the measurement rate can be enhanced to more than 1 kHz.

III. Experiment Results And Discussions

A demonstrated experiment is implemented. In the transmitter, a 15-GHz single-tone signal and a 1-7 GHz LFM signal are used to drive the DPMZM (Fujitsu FTM7961). The duration and the duty cycle of the LFM signal are 1 μs and 10%, respectively. In the receiver, a 40-GHz PD (Finisar XPDV2120RA) is used. The phase difference between the recovered and the local single-tone signals is recorded by the VNA (R&S ZVA67), in which the measurement rate is 1.7 kHz. The relative position of an MDL (General Photonics MDL-002) is real-time measured by the phase-shift method, which is shown in Fig. 2. During the measurement, the phase difference varies from $-\pi$ to π, and five 2π phase jumps

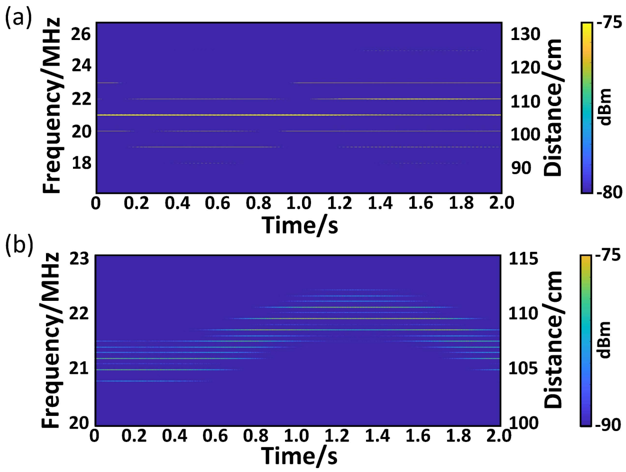

Fig. 3. Time-frequency diagrams of de-chirped signal using a (a) 10% duty-cycle, (b) full duty-cycle LFM signal. The right axis is the corresponding distance.

appear. It indicates that the unambiguous range of the phase-shift method is 2 cm, which is equal to the wavelength of the single-tone signal.

To resolve the range ambiguity, the FMCW ranging is simultaneously implemented, in which the OSC (Tektronix DSA72004B) is used to record the de-chirped signal. Fig. 3(a) shows the time-frequency diagram of the de-chirped signals for the full-duty-cycle LFM signal, in which the vibration of the MDL is not clearly shown. The ranging precision is limited to 5 cm. In Fig. 3(b), a 10% duty-cycle LFM signal is used so that the spectral precision is reduced to 100 kHz. Theoretically, the ranging precision can be enhanced to 0.5 cm, which is finer than the unambiguous range of the phase-shift method. Hence, the vibration can be clearly seen. In addition, the window length for the discrete Fourier transformation (DFT) is 64 μs, which promises a measurement rate higher than 10 kHz.

Fig. 4 shows the measured results of the length of the vibrating MDL. In a vibration period, the MDL moves from 0 cm to 2.4 cm (Stage I), then to 0.6 cm (Stage III), and back to 0 cm (Stage V). In Stages II and IV, the MDL is static. The results in 2 seconds are recorded, in which the beginning time is at Stage II. Fig. 4 (a) shows the results of the phase-shift method, in which the unambiguous distance is 2 cm. In Fig. 4(b), the result of the FMCW method is calculated from the peak frequency. It should be noted that the peak frequencies vary in different peaks due to the low signal-to-noise ratio and power fluctuations. As a result, the ranging precision is 2 cm which is 4 times larger than the theoretical values. The total length can be calculated according to Equation (4) since the distance finer than 2 cm is determined by the phase-shift method. The results are shown in Fig. 4(c). The length continuously varies and is consistent with the actual value, which verifies the feasibility of the proposed method.

As a comparison, Fig. 4(d) shows the measured results of the traditional FMCW method using a full-duty-cycle LFM signal. Since the range precision is 5 cm (shown in Fig. 4(d)), the phase ambiguity cannot be resolved so the measured length is incorrect, which is shown in Fig. 4(e). It should be noted that the measurement rates of the phase-shift method and the

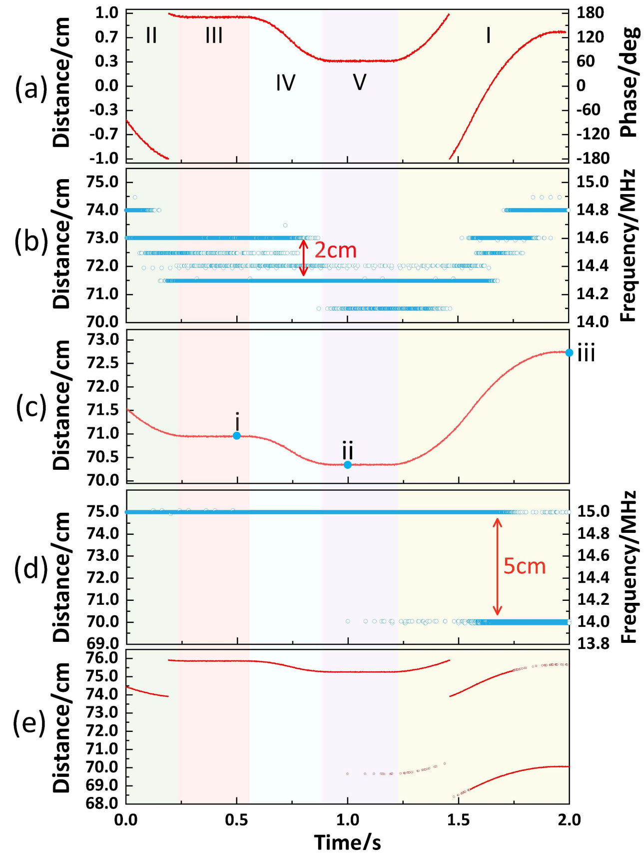

Fig. 4. Results of the joint frequency-phase measurement in 2 seconds. (a) The distance measured by the phase-shift method. (b) and (d) are the distances respectively measured by the FMCW method using 10% and full duty-cycle LFM signals. (c) and (e) are the calculated distances according to the results in (b) and (d).

FMCW method in Figs. 4(a) and (b) are respectively 1.7 kHz and 15.6 kHz. The measurement rate of the phase-shift method is limited by the phase discrimination using the VNA. On the other hand, the measurement rate of the FMCW method is limited by the time length of the DFT window. Since phase discrimination always requires a longer time than DFT, the measurement rate of the proposed method is mainly limited by the phase-shift method, which can be higher than 1 kHz. As a comparison, since the phase discrimination must be implemented for every frequency, the measuring time using frequency-stepped signals is much longer than the single-tone phase-shift ranging.

Moreover, the measurement precisions of the proposed method at long distances are analyzed and shown in Fig. 5. The MDL connected with a fiber spool moves with a 0.15-cm step. 50 successive measurements are implemented at each position. The redline is the exact length of the MDL. The standard deviations of the measured results are shown as the error bars. At the positions of 0.15 cm and 2.4 cm, the standard deviation is 58 μm and 95 μm, respectively, which indicates that the precision of the proposed laser ranging method can be finer than 100 μm. Since the precision of the phase discriminator is 1 degree, the theoretical ranging precision is 55 μm. As a comparison, a bandwidth larger than 100 THz is required to achieve a 100-μm precision if traditional FMCW is used.

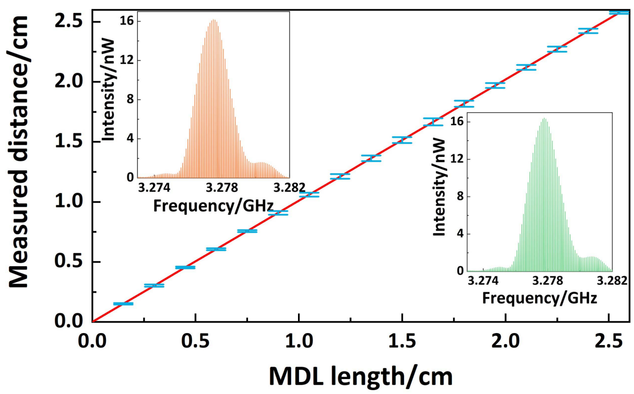

Fig. 5. Measurement precision of the proposed system at different positions of the MDL. Inset: the spectrums of the FMCW method when the MDL are set at 0.75 cm and 2.25 cm.

In addition, the inset in Fig. 5 shows the spectrums of the FMCW method when the MDL is set at 0.75 cm and 2.25 cm, respectively. The absolute length is 163.88758 m and 163.88121 m, which indicates that a micrometer-level precision can be achieved at the distance longer than 150 m. Theoretically, the measurement range of the system can be 300 m. Although laser ranging using a soliton microcomb can achieve longer distance and higher precision than our method, the microcomb is not practical and require a sophisticated system at present [22]. Therefore, the method based on microcomb is a promising approach, while our method is more practical.

IV. Conclusion

We propose a joint frequency-phase measurement method for high-precision and fast laser ranging. The FMCW ranging with is used to achieve long-distance and coarse ranging, while the phase-shift ranging is used for high-precision ranging. A high-precision FMCW method using low-duty-cycle signals is used to resolve the phase ambiguity in the phase-shift method. As a result, a 1-7 GHz LFM signal is sufficient to unwrap the phase in the phase-shift ranging with a 15-GHz RF signal. In the experiment, the total length of an MDL and a long fiber spool is measured. The measured precision can be as high as 58 μm. The measurement rate and the measurement range are 1.7 kHz and 300 m, respectively. The proposed method can be used to implement laser ranging with kHz rate and micrometer-level precision at hundreds of meters distance.

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