Experimental evaluation of long path heterodyne interferometers with optical-frequency comb and continuous-wave laser

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An optical-frequency comb can be used directly as the light source of long-path interferometer. The interference happens only when a pair of optical comb pulse trains overlaps with each other. So the measurable distance is long, but is discrete in space. In this paper, a new heterodyne interference system is presented using an acoustic-optical modulator and a piezo-electric transducer to realize absolute long-distance measurement. Two optical combs and a laser diode with the same center wavelength are used as light sources to evaluate the stability of the system by measuring distances of 22.500 m and 22.909 m. The experimental results show that the measurement stability in 50 s of optical comb and laser diode interferometers is similar due to the effect of the new heterodyne phase-sensitive (lock-in) technique. The standard deviation of measurements decreases to several tens nanometers when the time constant of the lock-in amplifier increases to 10 s. The preliminary experiment has been done to measure the distance of 7.5 m using different time constants of the lock-in amplifier. The measurement reproducibility for one hour is 4.929 μm though the refractive index of air is not corrected.

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NOMENCLATURE

c = light velocity in vacuum
f_{ceo} = carrier envelop offset frequency of optical comb
f_h = heterodyne frequency
f_r = repetition rate of optical frequency comb
L = scanning range of piezo-electric transducer (PZT)
T = scanning period of PZT
t = time interval of the two measured peaks
Δ = shift frequency by the acoustic-optical modulator

1. Introduction

Various interferometers were proposed to realize long-distance measurement, which is required in many areas of industry for production and safety evaluation of high-accuracy large equipments. Recently, optical frequency comb has the possibility of being used in many systems because of its high frequency-stability and high accuracy, which is traceable to the definition of second. Therefore, it can be used not only as absolute measurement of the frequency standard but also as absolute measurement of distance directly.

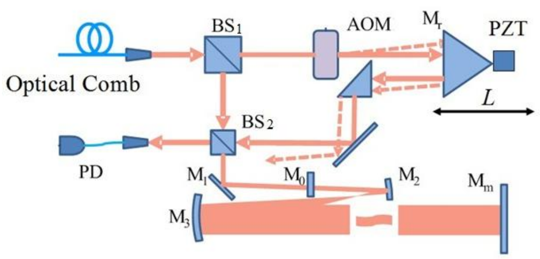
The frequency f of any mode within an optical comb can be expressed as $f = Nf_r + f_{ceo}$, where f_r is the repetition rate, f_{ceo} is the carrier envelop offset frequency and N is an integer. The frequency uncertainty can be traced with high precision to the frequency standard in use, so the optical comb is often used combining the continuous-wave laser diode (cw LD) to obtain higher frequency stability and smaller uncertainty [1]. The optical-frequency comb may also be used directly as the light source of long-path interferometers, which has prompted various efforts to investigate new possibilities of absolute distance measurements which were not possible with conventional light sources. Various experiments were proposed using high temporal coherence between a pair of pulse trains of the optical comb for absolute measurement of a long distance[2~4]. The availability of the optical comb laser with its high-stabilized repetition period can realize a high accuracy of micrometers for the measurement of several tens meters.

In this paper, we propose a long-distance measurement system using the optical comb with a new heterodyne technique and a phase-sensitive (lock-in) technique. The measurement stability is evaluated over distance of about 22.5 m, comparing with cw LD interferometer, and the experiment at a distance of 7.5 m is performed. The reproducibility is 4.929 μm though the experiment is done in atmospheric environment and the refractive index of air is not corrected.

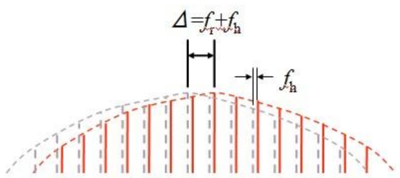
2. Principle

2.1 Heterodyne Interference of Optical Comb

Figure 1 shows the schematic of the heterodyne interference system with optical comb which is based on an unbalanced optical-path Michelso interferometer. An acoustic-optical modulator (AOM) is set in reference arm to generate the frequency shift Δ, which is can be written as $\Delta=f_r+f_h$, where f_r is the repetition rate, which is tens of megahertz and f_h is tens of kilohertz. The light beam is separated by a beam splitter (BS_1) and one of the beams passes through the AOM. The original (k+1)-th mode of the optical comb will interfere with shifted k-th mode, so the heterodyne frequency is f_h (Figure 1(b)). A spherical mirror (M_2) and a parabolic mirror (M_3) are used to expand the beam's diameter. The beams are combined by the other beam splitter (BS_2). The interference fringes generated are detected by a photo detector (PD).



(a)



(b)

Fig. 1 (a) the schematic of the heterodyne interference system using optical comb; (b) the frequency shift of optical comb and the heterodyne frequency f_h.

The heterodyne signals are generated when the temporal coherence interference happens. So the optical path difference (OPD) between the two arms of the interferometer should be

$$OPD = m \cdot c / f,$$

where m is an integer, c is the light velocity in vacuum. The corner reflector of the measurement arm (M_m) is moveable to change the value of m. The position of M_0 is at the OPD = 0, and the distance between M_m and M_0 is OPD/2.

The corner reflector of reference arm (M_r) is moved back and forth by using a piezo-electric transducer (PZT) to realize the scanning measurement. The movable range is hundreds micrometers, which is larger than the temporal coherence length. So the appearance and disappearance of interference will be observed and the peak of the interference fringe signal is found to determine the exact distance. When the scan period is long enough, two peaks are recorded (Figure 2), one is the interference signal at OPD=0. Here, the scan period of PZT is T, the scan distance is L, and the time interval between two peaks is t. The distance, l, under measurement is calculated as:

$$l = (m \cdot c / f \pm L \cdot t / T) / 2.$$

The integer m will be determined by other conventional method, and the sign before L is determined by the scan direction of the PZT and the sequence of the two peaks.

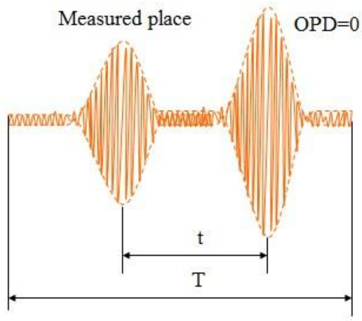
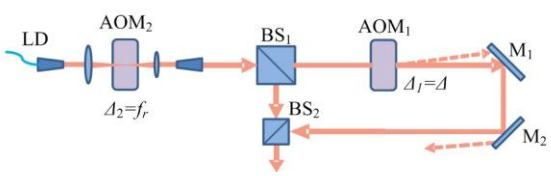


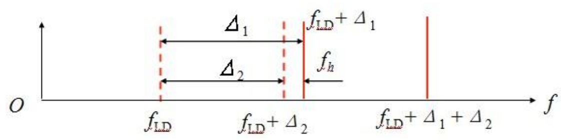
Fig. 2 The detected signal when the PZT is scanned.

2.2 Heterodyne Interference of Continue-Wave LD

To evaluate the stability of this heterodyne interference system using the optical comb, the cw LD is also used as the light source and the experimental condition will keep the same. The shift frequency by AOM and the reference frequency of the lock-in amplifier should be the same with those when the optical comb is used. Two acoustic-optical modulators are used (Figure 3(a)). AOM_1 is set in the reference arm, and the shift frequency is $\Delta_1 =f_r+f_h$. AOM_2 is set before BS_1 to generate a frequency shift Δ_2, $\Delta_2=f_r$. The frequency of LD, f, nearly equals to the center frequency of the optical comb. A set of confocal lenses allows that both the light beams of optical frequencies f and $f + \Delta_2$ enter the heterodyne interferometer, so the light beam of the reference arm consists of $f + \Delta_1$, $f + \Delta_2$ and $f+\Delta_1+\Delta_2$, while the light beam of the measurement arm consists of the frequencies f and $f +\Delta_1$ (figure 3(b)). As a result, the heterodyne frequency is $| \Delta_1-\Delta_2 |$, which still equals to f_h, and the reference frequency of the lock-in amplifier also remains the same.



(a)



(b)

Fig. 3 (a) the schematic of the heterodyne interference system using a LD; (b) the frequency shift of LD and the heterodyne frequency.

2.3 Heterodyne Interference System

Figure 4 shows the schematic of the whole interference system, and Figure 5 shows the photograph of the experiment setup. A switch is used to select the light source, a 30-meter-long optical fiber connects the light source to the interferometer, and an optical power amplifier is used to increase the light power of the LD. The phases of the interference signal are measured by the lock-in amplifier and are recorded by a digital oscilloscope.

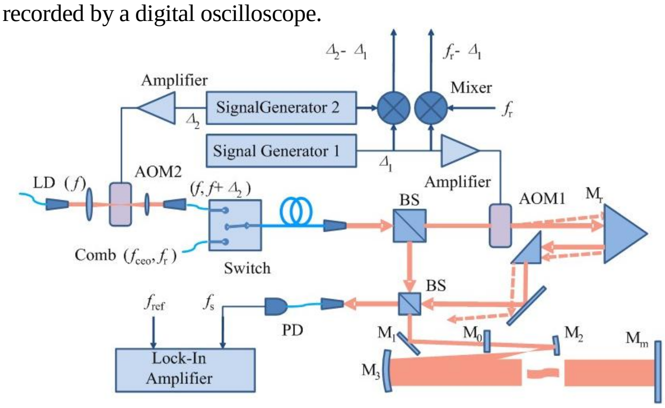


Fig. 4 The schematic of the whole interference system.

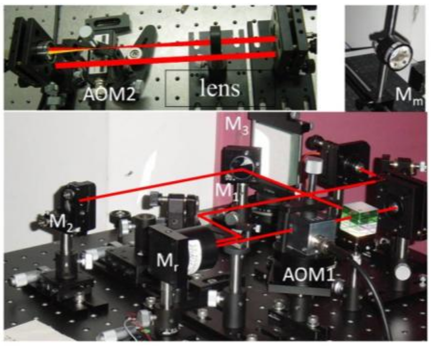


Fig. 5 The photograph of the interference system.

3. Experiment and Results

3.1 Stability Evaluation

Two optical combs (Comb1 and Comb2) are used as the laser source. Comb1 (Menlosystems C-Fiber Femtosecond Laser, f_r = 100.0000 MHz, output power is 10 mw) is stabilized to a Rb frequency standard and the stability is10^{-10} order. Comb 2 (NEOARK Co., f_r = 58.9286 MHz, output power is 2 mw and the amplified power is about 10 mw) is stabilized to a GPS frequency standard. To evaluating the measurement stability of the two optical combs, two groups of experiments have been done. One is to compare Comb1 with the LD (RIO Inc., the center wavelength; 1.560 μm, wavelength stability is about 3 kHz, output power is 4.5 mw) at the distance of 22.5 m. In this case, the integer m=15, the frequency shifts Δ_1 = 99.9 MHz and Δ_2 = 100 MHz, and then the generated heterodyne frequency f_s is 100 kHz. The other is to compare Comb2 with the LD at the distance of 22.909 m, where m = 9, Δ_1=59.0000 MHz, Δ_2 = 58.9286 MHz, and f_s= 71.4 kHz. The time constant of the lock-in amplifier is changed from 1 ms to 10 s and the PZT is not scanned in this case.

Figure 6 shows the phase of interference fringe signal for 50 s, and the time constant is 3 s. The maximum variation of measured distance is about 116 nm (Comb1), and about 24 nm (Comb2).

Figure 7 shows the measurement standard deviation when the time constant is changed from 1ms to 10 s. The measurement stabilities are similar when the light sources are optical comb and LD. The maximum differences are 44.33 nm (Comb1) and 96.89 (Comb2), and when the time constant is 3 s, the differences are only 13.14 nm (Comb1) and 1.53 nm (Comb2). In the experiments of measuring the distance of 22.909 m, the standard deviation is no more than 30 nm when the time constant is longer than 100 ms, and it is less than 10 nm when the time constant is longer than 1 s. The difference between two groups dues to the different conditions of experiments is found.

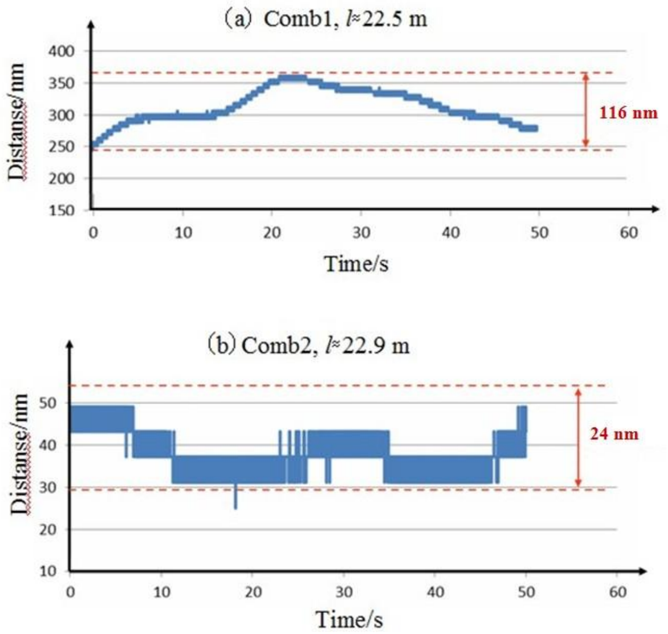


Fig. 6 Standard deviation of the measurement results using different combs (time constants =3 s).

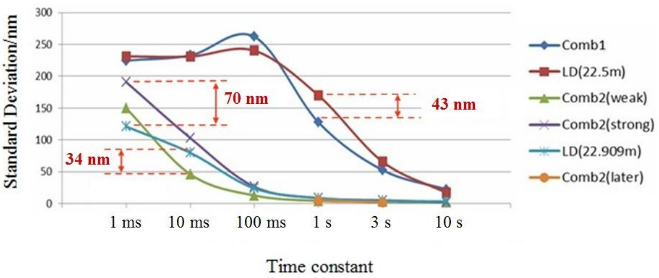


Fig. 7 Standard deviations of measurement results with different time constants of lock-in amplifier.

3.2 Distance Measurement at 7.5 m using Comb1

The distance measurements at 7.5 m using Comb1 as the light source have been done and 23 groups of data measured for about one hour were recorded. The driving voltage of the PZT is from 8.6 V to 105.6 V and the scanning range is 221 μm. The scanning frequency is changed from 5 mHz to 35 mHz when the time constant of lock-in amplifier is 10 ms (7 groups), 30 ms (5 groups) and 100 ms (11 groups). The air temperature is 22.245 degrees, and the air pressure is 998.5 kPa.

Figure 8 shows the driving signal of the PZT and the measured signal of the lock-in amplifier when the time constant is 10 ms and the scan frequency is 25 mHz. The red-color curve is the fitted curve of the measured data and the two peaks happens at 10.54 s and 34.61 s, so the time interval between them is 24.07 s. Since the scanning direction is opposite to the light source and the peak of OPD=15 m leads the peak of OPD=0, the measured distance should be (7.5 m -

	PZT scanning length of the first peak (OPD=15 m)	PZT scanning length of the second peak (OPD=0)	Corresponding OPD between two peaks
Average value/μm	44.72	154.42	111.30
Standard deviation/μm	5.55	1.62	4.93

Table. 1 Experimental result of the 23 groups of measurements.

54.4 μm). The measurement reproducibility is 3.85 μm.

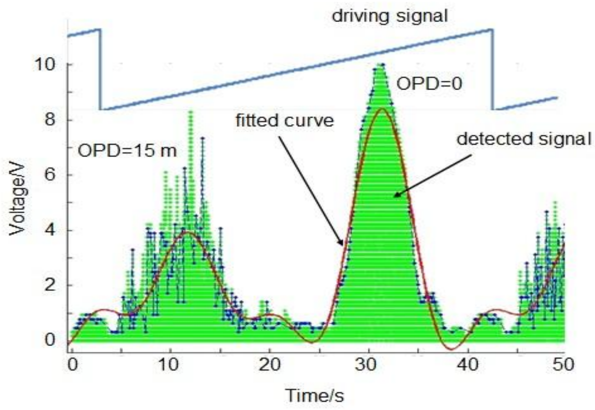


Fig.8 The measurement result and the fitted curve; the time constant of the lock-in amplifier is 10 ms and the scanning frequency of the PZT is 25 mHz.

The results of all the groups of data are showed in Figure 9 and Table 1. The reproducibility for one hour is 4.93 μm. The variation tendencies of three curves in Figure 9 are similar, but the standard deviation of the PZT scanning distance where the second peak appears is only 1/3 of the value of the corresponding OPD between two peaks. The experimental results shows that the influence of the air fluctuation is reduced by measuring the OPD between the target mirror and the mirror at OPD=0.

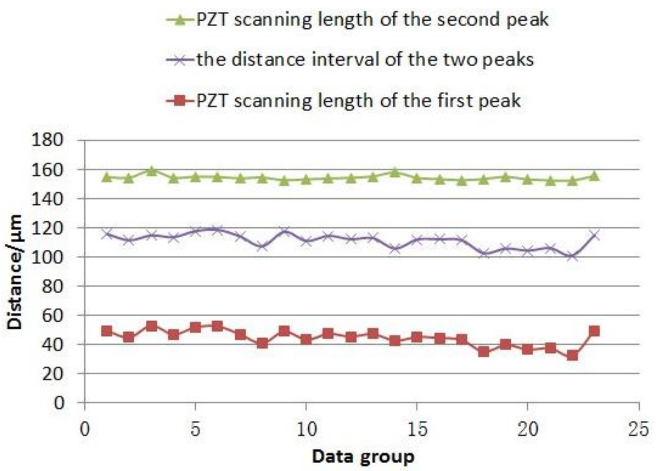


Fig. 9 The 23 group measurement data with different time constants and scanning frequencies.

Table 2 shows the average value and the standard deviation of the distance interval between two peaks with different time constants, which are ordered in chronological sequence. The result shows that the average value and the standard deviation are both increased. It means that the corresponding OPD is decreased, which is due to the change of the environment condition. We may correct the measurement condition data for the measured distance for improving the measurement accuracy. Both the scanning precision of the PZT and the poor resolution of the digital oscilloscope are known to influence the accuracy of the measurements.

Order	1	2	3	4
Time constant/ms	100	10	30	100
Average /μm	105.85	109.31	111.37	114.28
Standard deviation /μm	2.68	3.85	4.62	5.89

Table. 2 The corresponding OPD between two peaks with different time constants.

4. Conclusions

The new heterodyne interferometer of optical comb is developed using an AOM and a PZT and is evaluated, and realizes the absolute distance measurement of 7.5 m.

The stability of the interference system at the distances of 22.5 m and 22.909 m for 50 s is similar in the case of optical comb and laser diode. The measurement standard deviation of the optical comb (Menlosystems) is about 115 nm when the time constant of lock-in amplifier is 3 s, and decreases to several tens nanometers when the time constant increases to 10 s. The influence of environmental condition, such as air fluctuation, is reduced by lock-in technique (phase sensitive technique).

The experiments at the distance of 7.5 m have been done using different time constants of the loch-in amplifier. When the time constant is too short or the scanning period is too long, the detected signal of OPD=0 will be weak and the resolution of measurement will decrease. The time constant is too long or the scanning period is to short, the detected signal at long distance will be weak. These two parameters need to be suitable to each other to get good data and higher accuracy. The measurement reproducibility for one hour is 4.93 μm. The influence of the environmental condition such as the fluctuation on the experimental table, is reduced by measuring the scanning distance of OPD=0.

The measurement interference system is under improvement, such as using of optical fibers system to realize the interferometer and improving the fixedness of mechanism for obtaining the measurement accuracy of sub-micrometers, at present.

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