High synchronization absolute distance measurement using a heterodyne and superheterodyne combined interferometer

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We propose an absolute distance measurement method that employs heterodyne and superheterodyne combined interferometers to achieve synchronous detection and demodulation of multiwavelengths. Coarse and fine synthetic wavelengths are generated by a dual-longitudinal-mode He–Ne laser and four acoustic optical frequency shifters. Further, to improve phase synchronization measurement for multiwavelengths, we analyze the demodulation characteristics of coarse and fine measurement signals and adopt a demodulation method suitable for both signals. Experimental results demonstrate that the proposed method can achieve high-precision synchronous demodulation of multiwavelengths, and standard deviation is 1.7 × 10^{-5} m in a range of 2 m.

Keywords: multiwavelength; absolute distance; superheterodyne interferometry; phase synchronization.
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1. Introduction

In recent years, research on large-scale, high-precision absolute distance measurement has become an important agenda item in fields such as aerospace fabrication, assembly of aviation modules, and general-purpose coordinate measurements[1,2]. Major techniques that overcome these challenges include time of flight (TOF), frequency (wavelength)-sweeping interferometry (FSI), and multiple-wavelength interferometry (MWI). However, the TOF method is limited to time detection accuracy, which is limited to millimeter scale, and FSI is limited by the frequency modulation, which cannot meet the real-time measurement requirement[3]. MWI achieves high resolution and a wide range[4,5]. However, as the need for real-time measurement grows, the accuracy and synchronization of MWI meet even-higher standards.

In 1977, C. R. Tiford first proposed the concept of synthetic wavelength and the analysis method of using multiple-wavelength fractional fringes to determine the measured length[6]. Theoretically, MWI can achieve the highest measurement accuracy by constructing a synthetic wavelength chain with multiple wavelengths. The Physikalisch Technische Bundesanstalt designed a three-wavelength diode laser interferometer, using light sources with wavelengths of 780, 823, and 825 nm to produce synthetic wavelengths of 15 and 29 μm for surface shape measurement[4]. This method can meet the high-precision measurement requirements at the nanometer level, but it is difficult to achieve a measurement range of tens of meters. It is because traditional light source synthesis technology can only synthesize wavelengths on the order of micrometers, and it is difficult to synthesize wavelengths larger than millimeters. To achieve a large measurement range, one way is to construct a three-stage synthetic wavelength chain (micrometer–millimeter–meter), but this will significantly increase the complexity of the optical path structure; the other way is to choose different optical frequency combs to construct synthetic wavelength chains. Yang *et al.* proposed a dual-comb-based multiwavelength absolute interferometer to achieve long distance measurement, realizing measurement uncertainty of 5.3 × 10^{-7} at 20 m[7]. The disadvantages of this method are its high cost and difficulty in achieving synchronous measurement with different optical combs. To improve the measurement synchronization of MWI, Yokoyama *et al.* proposed a superheterodyne interferometer that combined two He–Ne lasers at 633 and 612 nm with two acousto-optic frequency shifters (AOFSs) to generate dual-synthetic wavelengths, achieving high real-time measurement through synchronous demodulation of coarse and fine measurement signals[8]. Even though this method performs in real time and with high accuracy, the measurement range is only 18 μm. Furthermore, the synchronous demodulation technique is not appropriate for large-scale measurement requirements.

In this Letter, we proposed a heterodyne and superheterodyne combined interferometer for absolute distance measurement (HSADM). A dual-longitudinal-modes He–Ne laser with four AOFSs generates coarse and fine synthetic wavelengths. To keep high accuracy and high synchronization of multiwavelength measurement, the demodulation characteristics of coarse and fine measurement signals were analyzed, and a demodulation method suitable for both signals was proposed.

2. Design Model of HSADM

The schematic of the main configuration of the MWI based on the heterodyne and superheterodyne combined method is shown in Fig. 1. The dual-frequency He–Ne laser generates the beam with orthogonally polarized dual frequencies ν_1 and ν_2, respectively, and the frequency difference between them is 822 MHz. $\lambda_1 = c/\nu_1$ and $\lambda_2 = c/\nu_2$ are the corresponding wavelengths, where c indicates the speed of light in vacuum. The beam first passes through a half-wave plate (HWP) HWP1 and a polarized beam splitter (PBS) PBS1, split into two beams with equal light intensity. Each beam is transferred into a quarter-wave plate (QWP) and a PBS, generating two pairs of orthogonally polarized beams with the same frequency and light intensity. The beam with frequency ν_1 is divided by PBS2 as beam 1 and beam 2, which are a pair of orthotropically polarized beams. Similarly, the beam of frequency ν_2 is split into beam 3 and beam 4 by PBS5. Each beam is incident on AOFSs, and then beam 1 and beam 2 are recombined by PBS3 after the orthogonally polarized beams pass through HWP2 and HWP3, respectively. Beam 3 and beam 4 are recombined in the PBS4. The beam output from PBS3 reflected by mirror (M) M2 is transferred into a nonpolarized beam splitter (NPBS) NPBS1, split into a transmitted beam and a reflected beam. The reflected beam serves as the coarse measurement beam with heterodyne

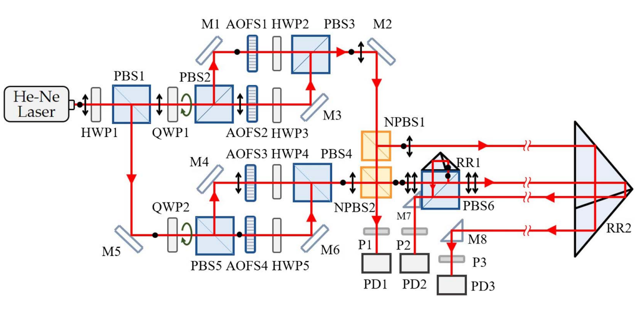

Fig. 1. Schematic diagram of the main composition of the MWI based on heterodyne and superheterodyne absolute distance measurement method with a He–Ne laser. HWP, half-wave plate; PBS, polarizing beam splitter; M, mirror; AOFS, acousto-optical frequency shifter; QWP, quarter-wave plate; NPBS, nonpolarizing beam splitter; RR, retroreflector; P, polarizer; PD, photodetector.

beat frequency $f_1 - f_2$, and the transmitted beam is combined with the beam output from PBS4 by NPBS2, whose frequencies are $\nu_1 + f_1$, $\nu_1 + f_2$, $\nu_2 + f_3$, and $\nu_2 + f_4$. Then the beam is divided into two parts: one is detected by the photodetector1 (PD1); the other is passing through PBS6 and split into two beams. The transmitted beam with frequencies $\nu_1 + f_1$ and $\nu_2 + f_3$ serves as the measurement arm of the fine measurement ruler, and the reflected beam with frequencies $\nu_1 + f_2$ and $\nu_2 + f_4$ serves as the reference arm of the fine measurement ruler. Two beams are reflected by retro-reflector (RR) RR2 and RR1, respectively; then they are recombined in PBS6 and detected by PD2.

3. High Synchronization Demodulation Method

As shown in Fig. 2, the signal with frequency difference $f_1 - f_2$ and phase $\phi_{s1} = 4\pi L/\lambda_{s1}$ is obtained after heterodyne interference of two light beams with frequencies $\nu_1 + f_1$ and $\nu_1 + f_2$, and the signal with frequency difference $f_3 - f_4$ is obtained as well. The combined signals of $f_1 - f_2$ and $f_3 - f_4$ are self-multiplied to obtain the phase signal $\phi_{s2} = 4\pi L/\lambda_{s2}$. The coarse and fine synthetic wavelengths are $\lambda_{s1} = c/(f_1 - f_2)$ and $\lambda_{s2} = c/(\nu_1 + f_1 - \nu_2 - f_3) \approx c/(\nu_1 - \nu_2) \approx 0.365\,\text{m}$, respectively. Assuming the phase measurement accuracy is 0.1°, the measurement uncertainty is $\Delta L_1 = (\lambda_{s1}/2)/3600$. To construct a synthetic wavelength chain, the order of synthetic wavelengths is required to satisfy the conditions for transition between adjacent orders as $\lambda_{si} > 4(\Delta L_{i-1} + \Delta L_i)$[9,10]. Considering the conditions for transition between adjacent orders, it can be calculated that

$$\begin{cases} \lambda_{s1} < 657\,\text{m} \\ f_1 - f_2 > 0.5\,\text{MHz} \end{cases}. \tag{1}$$

Take $f_1 - f_2 = 1\,\text{MHz}$, $f_1 = 81\,\text{MHz}$, $f_2 = 80\,\text{MHz}$, $f_3 = 81\,\text{MHz}$, and $f_4 = 80.01\,\text{MHz}$. Thus, the coarse and fine synthetic wavelengths are $\lambda_{s1} = 300\,\text{m}$ and $\lambda_{s2} = 0.365\,\text{m}$.

However, phase information of coarse and fine synthetic wavelengths cannot be strictly acquired at the same time. Thus, it is important to apply an appropriate analog signal demodulation method to achieve highly simultaneous acquisition. It is best to demodulate the signals in the same way and obtain demodulated signals with the same frequency. An electronic system is designed for synchronous detection and demodulation.

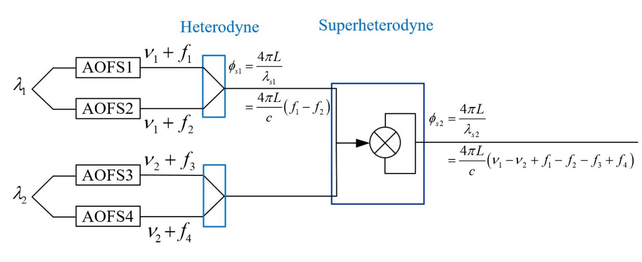

Fig. 2. Generation principle of multiwavelengths.

3.1. Demodulation method for the fine synthetic wavelength

The intensity of measurement signal I_m detected by PD2 can be written as

$$\begin{aligned}&I_m(t)\\&\propto \mathrm{Re}[(E_{1m}+E_{2m})\cdot(E_{1m}+E_{2m})^*]+\mathrm{Re}[(E_{3m}+E_{4m})\cdot(E_{2m}+E_{4m})^*]\\&\propto I_{0m}+2|A_1||A_2|\cos\left[2\pi(f_1-f_2)t+4\pi\frac{\nu_1+f_1}{c}L_m-4\pi\frac{\nu_1+f_2}{c}L_r\right]\\&\quad+2|A_3||A_4|\cos\left[2\pi(f_3-f_4)t+4\pi\frac{\nu_2+f_3}{c}L_m-4\pi\frac{\nu_2+f_4}{c}L_r\right],\end{aligned}\tag{2}$$

where I_{0m} is the DC component, $E_{1m}=A_1e^{-i[2\pi(\nu_1+f_1)t-2\pi\frac{\nu_1+f_1}{c}L_m]}$, $E_{2m}=A_2e^{-i[2\pi(\nu_1+f_2)t-2\pi\frac{\nu_1+f_2}{c}L_r]}$, $E_{3m}=A_3e^{-i[2\pi(\nu_2+f_3)t-2\pi\frac{\nu_2+f_3}{c}L_m]}$, and $E_{4m}=A_4e^{-i[2\pi(\nu_2+f_4)t-2\pi\frac{\nu_2+f_4}{c}L_r]}$; A_1, A_2, A_3, and A_4 are the amplitudes of four beams, and L_m and L_r correspond to the optical path lengths of measurement and reference arms, respectively. To simplify the analysis, assume $A_1=A_2=A_3=A_4=A$.

To obtain the phase information of fine measurement wavelength, one common method is using superheterodyne detection, which self-multiplies $I_m(t)$ by an analog mixer or multiplier. The resultant signal I_m^2 can be expressed as

$$\begin{aligned}&I_m^2(t)\\&\propto 4A^4\left\{\frac{1}{2}\cos[4\pi(f_1-f_2)t+2\phi_{1m}+2\phi_{2m}]\right.\\&\quad+\frac{1}{2}\cos[4\pi(f_3-f_4)t+2\phi_{3m}+2\phi_{4m}]\\&\quad+\cos[2\pi(f_1-f_2+f_3-f_4)t+\phi_{1m}+\phi_{2m}+\phi_{3m}+\phi_{4m}]\\&\quad\left.+\cos[2\pi(f_1-f_2-f_3+f_4)t+\phi_{1m}+\phi_{2m}-\phi_{3m}-\phi_{4m}]+1\right\},\end{aligned}\tag{3}$$

where $\phi_{1m}=4\pi(\nu_1+f_1)L_m/c$, $\phi_{2m}=4\pi(\nu_1+f_2)L_r/c$, $\phi_{3m}=4\pi(\nu_2+f_3)L_m/c$, and $\phi_{4m}=4\pi(\nu_2+f_4)L_r/c$. The frequency component $f_1-f_2-f_3+f_4$ is extracted from the resultant signal using the low-pass filter; then the signal is given by

$$\begin{aligned}i_m(t)\propto i_{0m}&+\cos[2\pi(f_1-f_2-f_3+f_4)t\\&+\phi_{1m}-\phi_{2m}-\phi_{3m}+\phi_{4m}].\end{aligned}\tag{4}$$

The superheterodyne process not only introduces a significant DC bias, but it also minimizes the signal amplitude. As a result, the differential filtering circuit shown in Fig. 3 is used to eliminate the DC component while amplifying the desired signal. Thus, the demodulated reference signal and measurement signal are as follows:

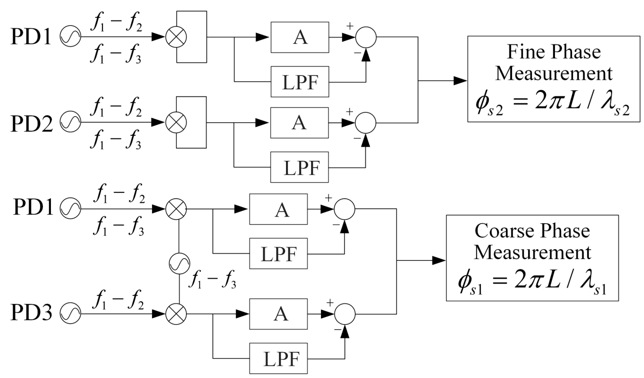

Fig. 3. Schematic setup for the synchronous detection and demodulation. A, amplifier; LPF, low-pass filter.

$$\begin{cases}i_r(t)\propto\cos[2\pi(f_1-f_2-f_3+f_4)t+\phi_{1r}-\phi_{2r}-\phi_{3r}+\phi_{4r}]\\ i_m(t)\propto\cos[2\pi(f_1-f_2-f_3+f_4)t+\phi_{1m}-\phi_{2m}-\phi_{3m}+\phi_{4m}]\end{cases},\tag{5}$$

where $\phi_{1r}=4\pi(\nu_1+f_1)L_0/c$, $\phi_{2r}=4\pi(\nu_1+f_2)L_0/c$, $\phi_{3r}=4\pi(\nu_2+f_3)L_0/c$, $\phi_{4r}=4\pi(\nu_2+f_4)L_0/c$, and L_0 is the reference optical path length. By calculating the phase difference between two signals, we get $\phi_{s2}=2\pi L/\lambda_{s2}$.

3.2 Demodulation method for the coarse synthetic wavelength

The demodulation technique and demodulated frequency of the coarse synthetic wavelength should be the same as for the fine synthetic wavelength in order to achieve synchronous detection and demodulation.

The measurement signal of coarse measurement is obtained by PD3, and the reference signal is obtained by PD1, which includes two heterodyne signals. To separate two heterodyne signals and extract the signal with frequency f_1-f_2, the local oscillator signal is selected as f_3-f_4, as shown in Fig. 3. Thus, the signals after mixed can be expressed as

$$\begin{cases}I_r'(t)=I_0'+\cos\left[2\pi(f_1-f_2-f_3+f_4)t+4\pi\frac{f_1-f_2}{c}L\right]\\ I_m'(t)=\cos\left[2\pi(f_1-f_2-f_3+f_4)t+4\pi\frac{f_1-f_2}{c}L\right]\end{cases},\tag{6}$$

where I_0' is the DC bias. The demodulated signal frequency of the coarse synthetic wavelength is the same as the fine synthetic wavelength $f_2-f_1-f_3+f_4=10\,\mathrm{kHz}$. I_0' can be eliminated by the differential filtering circuit. Thus, by calculating the phase difference between two signals, we get $\phi_{s1}=2\pi L/\lambda_{s1}$. The four signals' amplitudes can be made nearly equal by modifying the amplifier's gain, which increases the precision of phase measurement.

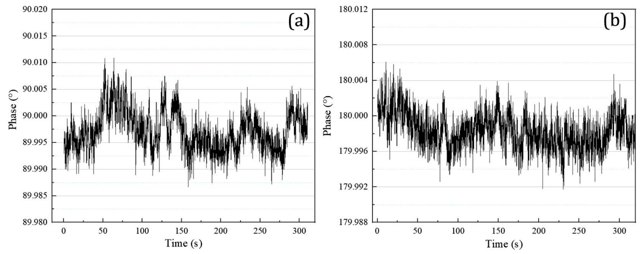

Fig. 4. Phase measurement data when the phase difference was set to (a) 90° and (b) 180°.

4. Experiments and Results

To verify the accuracy of phase measurement, we use Tektronix AWG5012C, producing two simulated mixed heterodyne signals; phase detection results are shown in Fig. 4. The measured phase accuracy reached 0.001°, and the phase fluctuation was ±0.008° and ±0.005° when the phase difference was set to 90° and 180°. The four AOFSs were developed by the 26th Research Institute of China Electronics Technology Group Corporation, and their first-order diffraction efficiency is beyond 85%. Experiments verify the high measurement accuracy and synchronization.

Figure 5(a) shows the experimental setup of heterodyne and superheterodyne combined interferometry for absolute distance measurement. The ranging experiment was performed on a 10 m granite rail system. We set the target mirror RR2 at 2 m; the measurement results are shown in Fig. 5(b). The distance L drifted 1.2×10^{-4} m, and the standard deviation (STD) was 1.7×10^{-5} m. For actual measurement accuracy, it is difficult to achieve the simulation results because of the issue of polarization cross talk in dual-longitudinal modes of the He–Ne laser. Therefore, if the error caused by polarization cross talk is adequately compensated, it will further improve the measurement accuracy.

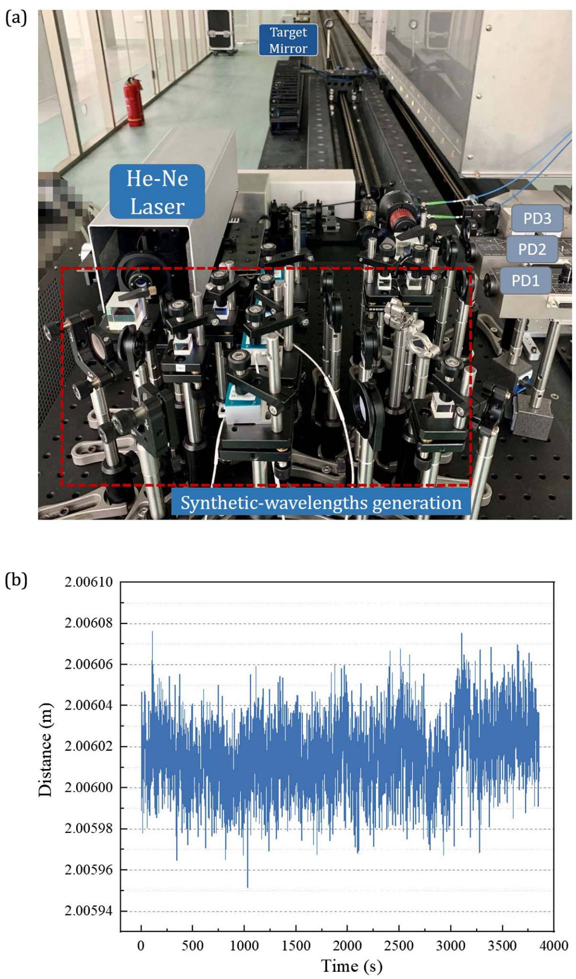

Fig. 5. (a) Experimental setup for absolute distance measurement based on heterodyne and superheterodyne combined absolute distance interferometry. (b) Experimental results of distance measurement at 2 m.

5. Conclusions

In conclusion, a heterodyne and superheterodyne combined interferometer is proposed for absolute distance measurement. A dual-longitudinal-mode He–Ne laser is employed to generate fine synthetic wavelengths, and when combined with four AOFSs, two heterodyne signals are generated, one of which is chosen as the coarse measurement wavelength. To improve the phase synchronization measurement for multiwavelengths, we analyze the demodulation characteristics of coarse and fine measurement signals and adopt a demodulation method suitable for both signals. Experiments verify the feasibility of this method, and results indicate that the proposed method can achieve high-precision synchronous demodulation of multiwavelengths, and STD is 1.7×10^{-5} m in a range of 2 m.

Acknowledgements

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