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 interferometer to achieve synchronous detection and demodulation of multi-wavelengths. Coarse and fine synthetic wavelengths are generated by a dual-longitudinal-mode He-Ne laser and four acoustic optical frequency shifters (AOFS). Further, to improve phase synchronization measurement for multi-wavelengths, 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 multi-wavelengths, and standard deviation (STD) is $1.7 \times 10^{-5}$ m in a range of 2 m.

Keywords: multi-wavelength, absolute distance, superheterodyne, phase synchronization

1. Introduction

In recent years, researches on large-scale, high-precision absolute distance measurement have become an important agenda in the field 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, 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 ever-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 highest measurement accuracy by constructing a synthetic wavelength with multiple wavelengths. The Physikalisch Technische Bundesanstalt designed three-wavelength diode laser interferometer, using light sources with wavelengths of 780 nm, 823 nm, and 825 nm to produce synthetic wavelengths of 16 μm and 29 μm for surface shape measurement [4]. This method can meet the high-precision measurement requirements at the nm 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 μm, and it is difficult to synthesize synthesized wavelengths larger than millimeters. To achieve a large measurement range, one way is to construct a three-stage synthetic wavelength chain (μm-mm-m), 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 proposed a dual-comb-based multiwavelength absolute interferometer to achieve long distance measurement, realizing measurement uncertainty of $5.3 \times 10^{-5}$ 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, Shuko Yokoyama proposed a superheterodyne interferometer that combines two He-Ne lasers at 633 nm and 612 nm with two acoustic optic frequency shifters (AOFS) 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 multi-wavelength 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

Fig. 1. Schematic diagram of the main composition of the MWI based on heterodyne and superheterodyne absolute distance measurement method with He-Ne laser. HWP: half-wave plate; PBS: polarizing beam splitter; M: mirror; A0FS: acousto-optical frequency shifter; QWP: quarter-wave plate; NPBS: non-polarizing beam splitter; RR: retro reflector; P: polarizer; PD: photodetector.

The schematic of the main configuration of the MWI based on heterodyne and superheterodyne combined method is shown in Fig. 1. The dual-frequency He-Ne laser generates the beam with orthogonal polarized dual frequencies \( v_1 \) and \( v_2 \), respectively, and the frequency difference between them is 822 MHz. \( \lambda_1 = c/v_1 \) and \( \lambda_2 = c/v_2 \) are the corresponding wavelengths, where \( c \) indicates the speed of light in vacuum. The beam first passes through a half-wave plate (HWP) HPW1 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 orthogonal polarized beams with same frequency and light intensity. The beam with frequency \( v_1 \) is divided by PBS2 as beam 1 and beam 2, which are a pair of orthotropic polarized beams. Similarly, the beam of frequency \( v_2 \) is split into beam 3 and beam 4 by PBS5. Each beam is incident on acousto-optic frequency shifters (A0FS), and then beam 1 and beam 2 are recomposed by PBS3 after the orthogonal polarized beams passing through HWP2 and HWP3 respectively. Beam 3 and beam 4 are recomposed in the PBS4. The beam output from PBS3 reflected by mirror M2 is transferred into non-polarized beam splitter (NPBS) NPBS1, split into a transmitted beam and a reflected beam. The reflected beam serves as the coarse measurement beam with heterodyne beat frequency \( f_c = f_1 - f_2 \), the transmitted beam is combined with the beam output from PBS4 by NPBS2, whose frequencies are \( v_1f_1 \) and \( v_2f_2 \). Then the beam is divided into two parts: one is detected by the photodetector (PD1), the other is passing through PBS6 and split into two beams. The transmitted beam with frequencies \( v_1f_1 \) and \( v_2f_2 \) serves as the measurement arm of the fine measurement ruler, and the reflected beam with frequencies \( v_1f_3 \) and \( v_2f_4 \) serves as the reference arm of the fine measurement ruler. Two beams are reflected by retro reflector RR3 RR2 and RR1, respectively, then they are recomposed in PBS6 and detected by PD2.

3. High synchronization demodulation method

As shown in Fig. 2, The signal with frequency difference \( f_c - f_1 \) and phase \( \phi_1 = 4\pi L/\lambda_1 \) are obtained after heterodyne interference of two light beams with frequencies \( v_1f_1 \) and \( v_2f_2 \); and the signal with frequency difference \( f_2 - f_1 \) is obtained as well. Self-multiply the combined signals of \( f_1 - f_2 \) and \( f_2 - f_1 \) to obtain the phase signal \( \phi_2 = 4\pi L/\lambda_2 \), the synthetic wavelengths is generated by heterodyne processing and superheterodyne processing method. The coarse and fine synthetic wavelengths are \( \lambda_1 = c/(f_1 - f_2) \), \( \lambda_2 = c/(v_1 + f_1 - v_2 - f_2) = c/(v_1 - v_2) \times 0.365m \), respectively.

Assuming the phase measurement accuracy is 0.1°, the measurement uncertainty is \( \Delta \phi = \phi_1/2 \times 3600 \)°. To construct a synthetic-wavelength chain, the order of synthetic wavelengths is required to satisfy the conditions for transition between adjacent orders as \( \lambda_1 > 4(\Delta L_1 + \Delta L_2) \) \[9, 10\]. Considering the conditions for transition between adjacent orders, it can be calculated that

\[
\begin{align*}
\Delta L_1 &< 657m \\
\Delta L_2 &> 0.5MHz
\end{align*}
\]

Take \( f_1 - f_2 = 1MHz, f_1 = 81MHz, f_2 = 80MHz \), \( \lambda_1 = 81MHz, \lambda_2 = 80MHz \), \( \lambda_3 = 0.365m \).

Fig. 2. Generation principle of multi-wavelength.

However, phase information of course and fine synthetic wavelengths cannot be strictly acquired at the same time. Thus, it is important to apply 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.

3.1 Demodulation method for the fine synthetic wavelength

The intensity of measurement signal \( I_0 \) detected by PD2 can be written as
4. Experiments and results

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 \( f - f_L \), the local oscillator signal is selected as \( f_0 \), as shown in Fig. 3. Thus, the signals after mixed can be expressed as

\[
I_2(t) = I_0 + \cos \left[ 2\pi \left( f - f_L - f_1 + f_L \right) t + \phi_0 - \phi_o - \phi_s \right]
\]

\[
I_2(t) = I_0 + \cos \left[ 2\pi \left( f - f_L - f_1 + f_L \right) t + \phi_0 - \phi_o - \phi_s \right]
\]

where \( I_0 \) is the DC bias. The demodulated signal frequency of the coarse synthetic wavelength is the same as the fine synthetic wavelength \( f - f_L + f_1 = 10kHz \). \( I'_c \) can be eliminate by the differential filtering circuit. Thus, by calculating the phase difference between two signals, we get \( \phi_s = 2\pi L / \lambda_s \). The four signals' amplitudes can be made nearly equal by modifying the amplifier's gain, which increases the precision of phase measurement.
To verify the accuracy of phase measurement, we use Tektronix AWG5012C producing simulated two mixed heterodyne signals, and 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 are developed by the 26th Research Institute of China Electronics Technology Group Corporation, and their first-order diffraction efficiency are beyond 85%. Experiments verify the high measurement accuracy and synchronization.

![Fig. 4. Phase measurement data when the phase difference was set to (a) 90°, (b) 180°.](image)

In conclusion, a heterodyne and superheterodyne combined interferometry 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 multi-wavelengths, we analyze the demodulation characteristics of coarse and fine measurement signals and adopts 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 multi-wavelengths, and standard deviation (STD) is $1.7 \times 10^{-5}$ m in a range of 2 m.

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