Method for gauge block measurement with the heterodyne central fringe identification technique

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In a modified Michelson interferometer, the top face of the wringing platen is first identified using the heterodyne central fringe identification technique. Then the reference mirror located in the other arm is moved by a precision translation stage until the top face of the tested gauge block is also identified with the same technique. The displacement of the mirror is exactly equivalent to the length of the tested gauge block. The measurable range of the interferometer relates to the maximum travel range of the translation stage and its uncertainty depends on the uncertainty of the heterodyne central fringe identification method and the resolution of the translation stage. © 2010 Optical Society of America

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1. Introduction

A gauge block is usually used as a standard for accurate length measurement. Accurate techniques are necessary for calibrating the length of a gauge block. Generally, the length of a gauge block is determined by using the excess fraction method [1,2]. Although this method has high measurement accuracy, it still requires prior information about the nominal length of the gauge block. To solve this problem, Bitou and Seta [3] used a wavelength scanning interferometer to measure the length of a gauge block without the nominal length information and good results were obtained. However, the uncertainties of these two methods are affected by the wavelength stability of the laser source. As an alternative, Lee *et al.* [4] proposed a central fringe identification technique for identifying the central fringe of an interferogram by using heterodyne interferometry [5,6] with a tunable laser. This method can locate the zero optical path difference position accurately in a modified Michelson interferometer, and is not affected by the wavelength stability of the laser source. Both a commercial translation stage and a laser interferometer for displacement measurement have very high resolutions. But it is very difficult to make two faces of the tested gauge block to superpose on their starting and stopping points. They cannot be directly applied for measuring a gauge block.

To solve this drawback, a simple method for measuring a gauge block is presented with the heterodyne central fringe identification technique and a precision translation stage. In a modified Michelson interferometer, the gauge block wrung on a wringing platen is located in one arm and a reference mirror is located in the other arm. The reference mirror can be accurately positioned using the heterodyne central fringe identification technique such that the optical path lengths of two arms of the interferometer are absolutely equivalent. Then, the position of the mirror can be identified as the corresponding position of the tested object surface. First, the corresponding position of the wringing platen is identified. Next, the

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mirror is displaced to the position corresponding to the top face of the gauge block. The displacement of the mirror can be obtained by the readouts of the translation stage and is equal to the length of the gauge block being measured. Comparing with white light interferometry [7], this method can distinguish the zero optical path difference position that is before or behind the reference mirror. The necessary displacement of the reference mirror can be determined from the phase meter or from the moving direction and wave numbers of the sine-wave signals displayed on an oscilloscope. The measurable range relates to the maximum travel range of the translation stage and its uncertainty depends on the uncertainty of the heterodyne central fringe identification method and the resolution of the translation stage. The validity of this method is proved. It has several merits, such as simple optical structure, easy operation, high measurement accuracy, and long measuring range.

2. Principle

The schematic diagram of this method is shown in Fig. 1. It consists of two beam splitters (BS), a prism (PR), a polarization beam splitter (PBS), two mirrors (M), a translation stage (TS), a gauge block (G), a wringing platen (W), two analyzers (AN), three photodetectors (D), a phase meter (PM), a function generator (FG), and an oscilloscope (OSC). The gauge block is wrung on the wringing platen, and M_1 is a reference mirror translated by the translation stage. For convenience, the $+z$ axis is chosen to be along the light propagation direction and the $+y$ axis is the direction pointing out of the paper. A heterodyne light source composed of a tunable diode laser and a modulated electro-optic modulator (EO) is used in this method. There is an angular frequency difference ω between the p- and the s-polarizations of the output. The light beam passes through the BS_1 and the PR, and is divided into two parallel light beams, Ray-1 and Ray-2. Then they enter into a modified Michelson interferometer. The optical paths of Ray-1 are PBS → W → PBS → BS_2 → AN_1 → D_1 (s-polarization) and PBS → M_1 → PBS → BS_2 → AN_1 → D_1 (p-polarization). The optical paths of Ray-2 are PBS → G → PBS → BS_2 → AN_1 → D_2 (s-polarization and PBS → M_1 → PBS → BS_2 → AN_1 → D_2 p-polarization). If the transmission axis of the AN_1 is at 45° to the x axis, the light intensity received by the $D_{i(i=1,2)}$ can be written as

$$I_i = \frac{1}{2}[1 + \cos(\omega t + \phi_i)], \qquad (i = 1, 2), \tag{1}$$

where the phase is

$$\phi_i = \frac{4\pi d_i}{\lambda}. \tag{2}$$

Here, λ is the wavelength of the light, $d_i (d_i \equiv d_{pi} - d_{si})$ is the optical path difference between two arms, d_{pi} and d_{si} are optical path lengths of two arms in the interferometer, and the subscript $i (i = 1, 2)$ refers to Ray-1 and Ray-2, respectively.

Also, another heterodyne light beam reflected by the BS_2 passes through the AN_0 with the transmission axis at 45° to the x axis and enters the D_0. Its intensity acts as a reference signal and can be expressed as

$$I_r = |E_r| = \frac{1}{2}[1 + \cos(\omega t)]. \tag{3}$$

Both I_r and I_i are sent into the PM, from which the phase ϕ_i can be obtained.

When the wavelength of the light is changed from λ_1 to λ_2, there is a phase variation $\Delta\phi_i$, which can be derived from Eq. (2) and written as

$$\Delta\phi_i = \phi_{i,\lambda_2} - \phi_{i,\lambda_1} = \frac{4\pi d_i \Delta\lambda}{\lambda_1 \lambda_2}, \tag{4}$$

where $\Delta\lambda \equiv \lambda_2 - \lambda_1$. From Eq. (4), it is obvious that, only if the optical lengths of the two arms in the interferometer are equivalent, i.e., $d_i = 0$, will $\Delta\phi_i$ equal zero despite the wavelength variation. This is the core concept of the heterodyne central fringe identification technique. Consequently, M_1 can be accurately positioned where the optical paths of two arms of the interferometer are absolutely equivalent with the heterodyne central fringe identification technique. If Ray-1 is considered first, then the position of M_1 is identified as the corresponding position of the W and it is denoted as W′. The M_1 is displaced by the TS along the optical axis until it is positioned at the exact position where the optical paths of two arms of the interferometer are absolutely equivalent again for Ray-2 with the same technique. Here, this position of M_1 is identified as the corresponding position of the G and it is denoted as G′. The displacement of the M from W′ to G′ can be obtained by reading the data of the TS, and it is equal to the length of the gauge block L.

3. Experiments

To show the validity of this method, a tunable diode laser (Model 6304, New Focus) with a wavelength tuning range of 632.60–637.96 nm and a tuning resolution of 0.02 nm is used to measure a gauge block of grade 0 [8] of 1.03 mm (Mitutoyo, 516-402-26). The M_1 is displaced by a precision translation stage (Chuo Precision, ALS-510-H1P) and its position is read with an optical meter (Sony, BL57-NE). The stage has a minimum incremental motion of 1 nm and a maximum travel range of 100 mm. The EO (Model 4002, New Focus) driven by the sawtooth signal with a frequency of 500 Hz and a phase meter with a uncertainty of 0.036° is also introduced. The reading of the phase meter and the direction and wave numbers of the sine-wave signals displayed on the oscilloscope (OSC) are used to identify the position of M_1. That is, as $\Delta\phi_i > 0$, it means M_1

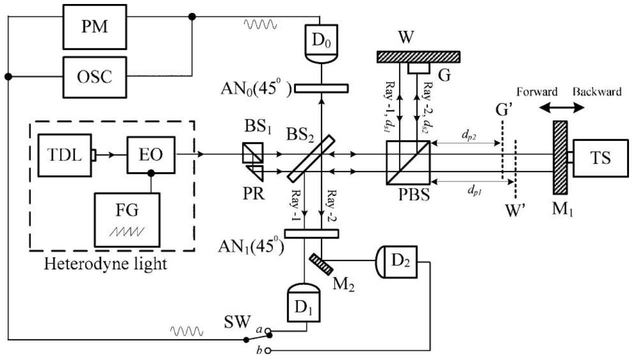

Fig. 1. Schematic diagram of this method. TDL, tunable diode laser; EO, electro-optic modulator; FG, function generator; BS, beam splitter; PR, prism; PBS, polarizing beam splitter; G, gauge block; W, wringing platen; M, mirror; TS, translation stage; AN, analyzer; D, photodetector; SW, switch; OSC, oscilloscope; PM, phase meter.

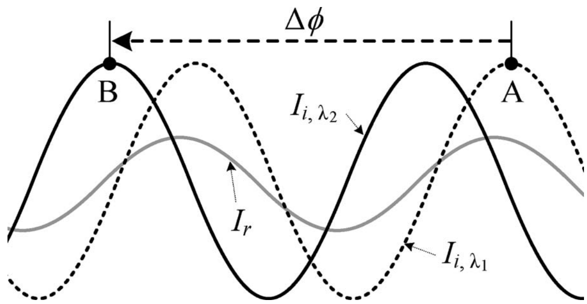

Fig. 2. Signals display on the oscilloscope. The peak of the sine-wave signal shifts over one period from point A to point B, as the wavelength scans from λ_1 to λ_2.

does not reach the zero optical path difference position yet; as $\Delta\phi_i < 0$, it means M_1 already exceeds the zero optical path difference position. Moreover, the corresponding optical path difference d_i can be estimated by using Eq. (4). To determine the zero optical path difference position W′ of the wringing platen, first, M_1 is slightly located behind W′ (see Fig. 1) by a ruler for a convenient measurement, and the switch (SW) is turned to the position a for Ray-1. The following procedures are operated and the associated data in our tests are listed in Table 1.

I. Let the wavelength of the light scan from λ_1 to λ_2; then we can see that point A of signal I_1 shifts to point B on the OSC, in which I_r is the reference signal, as shown in Fig. 2. At the same time, the phase variation $\Delta\phi_i$ displayed on the PM is also recorded. The data of $\Delta\phi_1$ should be modified with the integral number of periods between A and B of the signal. In our test, $\Delta\phi_1$ must be modified from 18.09° to 378.09°. The data of d_i is derived from Eq. (4), and the translation stage was displaced forward by 10.5 mm.

II. Increase the amount of $\Delta\lambda$, and repeat step I. The data of $|\Delta\phi_1|$ becomes small and this means M_1 is approaching W′.

III. Increase the amount of $\Delta\lambda$ to be a maximum and repeat step I. If the data $\Delta\phi_1$ still remains positive, this means M_1 has not reached W′, and the TS should be moved forward again. On the other hand, if $\Delta\phi_1$ becomes negative, which means the position of M_1 has exceeded W′, then the TS should be moved back.

IV. The TS is moved back and forth until the condition $\Delta\phi_1 = 0$ is achieved as $\Delta\lambda$ remains maximized. Here, M_1 is exactly positioned at W′ and the readout of the translation stage is recorded.

Next, to determine the zero optical path difference position G′ of the top surface of the gauge block, the switch is turned to the position b for Ray-2 and M_1 should be displaced slightly behind G′ for fast measurement (without wasting time for calculating the number of periods); but this displacement needs to be recorded. In our test, because the length of the gauge block is smaller than the maximum effective wavelength, it can be tested without changing its position. Then, the following procedures are similar to steps I–IV, and they are denoted steps V–VIII. The associated data in our tests are also listed in Table 1. The difference of the readouts of the translation stage at steps IV and VIII is equal to the length of the gauge block, and is 1,030,009 nm in our test.

4. Discussions

A data acquisition card (NI, PCI-6110) is installed in the phase meter to acquire the sine-wave signals of two photodetectors. The phases can be obtained with the three-parameter sine-wave fitting (least-squares fitting) technique [9]. The acquisition

Table 1. Experimental Condition and its Associated Data at Each Step (at 20°C)[a]

	λ_1[nm]	λ_2[nm]	$\Delta\lambda$[nm]	$\Delta\phi_1$(deg.)	$d_1 = \Delta\phi_1 \frac{\lambda_1\lambda_2}{4\pi\Delta\lambda}$	Stage Displacement
I	633.00	633.02	0.02	378.09	$1.0521E+07$ nm	+10,500,000 nm
II	633.00	634.00	1.00	37.46	$2.0880E+04$ nm	+20,900 nm
III	632.60	637.96	5.36	−0.17	$-1.7778E+01$ nm	−18 nm
IV	632.60	637.96	5.36	0.00	$0.0000E+00$ nm	
	λ_1[nm]	λ_2[nm]	$\Delta\lambda$[nm]	$\Delta\phi_2$(deg.)	$d_2 = \Delta\phi_2 \frac{\lambda_1\lambda_2}{4\pi\Delta\lambda}$	Stage Displacement
V	633.00	633.02	0.02	37.02	$1.0301E+06$ nm	+1,000,000 nm
VI	633.00	634.00	1.00	53.84	$3.0010E+04$ nm	+30,000 nm
VII	632.60	637.96	5.36	0.09	$9.4117E+00$ nm	+9 nm
VIII	632.60	637.96	5.36	0.00	$0.0000E+00$ nm	

[a]The length of the gauge block is 1,030,009 nm.

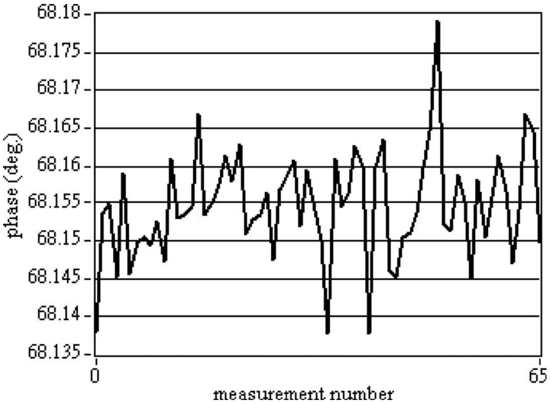

Fig. 3. Result of a data acquisition test of the phase meter.

frequency of the card and the frequency difference of the heterodyne light source are 5 MHz and 500 Hz, respectively, so the theoretical phase uncertainty is 0.036° [10]. Figure 3 shows the results of repeated phase measurements at a fixed experimental condition. Thus, the experimental phase repeatability is about ±0.02°. The main two origins of the phase repeatability come from the instability of the laser power and the quantization noise. Because the phase measurement in this method is used only for identifying the absolute optical path difference position, the measurable range of this method is not limited by the coherence length of the light source. Although the displacement of the precision translation stage can be read with an optical meter inside the stage, its accuracy becomes worse for long distance measurements. It may have an error of 45 nm in a measured displacement of 100 mm. If a commercial laser interferometer, such as Agilent 5529A, is applied to directly measure the displacement of the reference mirror, then the measurement accuracy will be enhanced.

The measurement results reported in [11] show that the Abbe errors for reproducible wringing can be very small (less than 1 nm) for a high-quality 5 mm gauge block (Mitutoyo Company). If the displacement direction of the translation stage does not lie along the normal of the top surface of the gauge block, there is a guiding error of the translation stage. This error can be minimized ($<1.2\times 10^{-9}$ L) when a goniometric cradle and a rotation stage with resolution of 10 arc sec are applied in this system. If there is a parallelism error between Ray-1 and Ray-2 (30 arc sec here), it will induce optical path errors in both arms of the interferometer. Because the central fringe technique is used to identify zero optical path difference positions, these optical path errors can eliminate each other. Thus, the accuracy of the measurement result is not affected by the parallelism error. In addition, both the platen and the gauge block are made of steel, so there is no additional phase difference. If they are made of different materials, it may introduce an additional phase difference between the reflected lights from the platen and the gauge block face. It will affect the measurement results.

The uncertainty of this method mainly depends on the resolution $\delta d_t (\delta d_t = 1\ \text{nm})$) of the TS and the uncertainty δd_c of the heterodyne central fringe identification technique. From Eq. (4), we have

$$\delta d_c = \frac{1}{4\pi\Delta\lambda}\left[\delta(\Delta\phi)\lambda_1\lambda_2 + \Delta\phi(\lambda_1\delta\lambda_2 + \lambda_2\delta\lambda_1) + \Delta\phi\lambda_1\lambda_2\frac{\delta(\Delta\lambda)}{\Delta\lambda}\right], \tag{5}$$

where $\delta(\Delta\phi)$ is the phase uncertainty of the PM, $\delta\lambda_i$ is the wavelength stability ($\delta\lambda_1 = \delta\lambda_2$), and $\delta(\Delta\lambda)$ is the resolution of the wavelength change. The first term represents the effect of phase uncertainty; the second and third terms are the effects of wavelength uncertainty. Because $\delta\lambda_i$ is much smaller than either λ_i or λ_2, $\delta(\Delta\lambda)$ is also much smaller than $\Delta\lambda$, and $\Delta\phi$ can approach to $\delta(\Delta\phi)$; as d_i is nearly equivalent to 0, the second and the third terms can be neglected. Thus Eq. (5) can be simplified as

$$\delta d_c = \frac{\delta(\Delta\phi)\lambda_1\lambda_2}{4\pi\Delta\lambda}. \tag{6}$$

It can be seen that the effect of wavelength uncertainty can be ignored. By substituting the experimental conditions $\delta(\Delta\phi) = 0.036°$, $\lambda_1 = 632.6$ nm, $\lambda_2 = 637.96$ nm, and $\Delta\lambda = 5.36$ nm into Eq. (6), $\delta d_c \approx 3.8$ nm can be obtained. Therefore, the uncertainty of this method can be calculated as $\delta d_T = (\delta d_t^{\,2} + \delta d_c^{\,2})^{1/2} \approx 4$ nm.

From Eq. (6), it is obvious that the increment of the tunable wavelength range will improve the accuracy of this method. The half-wave voltage of the EO needs to be adjusted for larger wavelength variations. In addition, the refraction index of air, thermal expansion, and the uncertainty of surface roughness of the gauge block should be considered in precise measurement [12–14].

5. Conclusions

A simple method for measuring a gauge block that uses the heterodyne central fringe identification technique and a precision translation stage has been presented. In a modified Michelson interferometer, the gauge block being measured is wrung on a wringing platen located in one arm and a reference mirror is located in the other arm. The mirror can be accurately positioned using the heterodyne central fringe identification technique such that the optical path lengths of two arms of the interferometer are absolutely equivalent. Then, the position of the mirror can be identified with the corresponding position of the tested object surface. First, the corresponding position of the wringing platen is identified. Next, the mirror is displaced to the position corresponding to the top face of the gauge block. The displacement of the mirror can be obtained by the readouts of the translation stage and is equal to the length of the gauge block. The feasibility of the technique has been demonstrated. The measurable range is not limited by the coherence length of the light source and relates to the maximum travel range of the translation stage. The measurement resolution depends on the resolutions of the heterodyne central fringe identification method and the translation stage. In our experiments, we obtained a 100 mm measurable range and a 4 nm uncertainty. The wavelength stability has a minor effect. Moreover, our technique has potential for application to the quality inspection of high-aspect-ratio MEMS/NEMS.

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