1 November 1998

ELSEVIER

Optics Communications 156 (1998) 1–4

OPTICS COMMUNICATIONS

High resolution central fringe identification

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Received 12 June 1998; revised 1 August 1998; accepted 6 August 1998

Abstract

A high resolution central fringe identification by using the heterodyne interferometry with a tunable laser-diode and a fixed wavelength laser is presented. It can be operated easily and can be used to judge which arm of the Michelson interferometer is longer. The feasibility is demonstrated and it has 0.2 nm resolution. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Central fringe; Heterodyne interferometry

1. Introduction

White-light interferometry has been applied for the measurement of displacement or other quantities that can be converted into displacement. When it is applied to these measurements it is necessary to identify the central fringe [1–3]. We had previously proposed a novel method for the central fringe identification by using the heterodyne interferometry and a tunable laser-diode [4]. Although it is very useful to the white-light interferometry, it has only 0.2 μm resolution and it can not meet the requirements for high precision measurements [5,6]. In this paper, we modify our previous method by adding a laser. So, it becomes a two-laser source optical configuration. It has all advantages of our previous method. Besides, its resolution is enhanced to 0.2 nm.

2. Principle

The schematic diagram of this method is shown in Fig. 1. A linearly polarized light being polarized at 45° with respect to the horizontal axis passes through an electro-optic modulator (EO). Let the fast axis of EO be along the horizontal axis, and an external sawtooth voltage signal with angular frequency ω and amplitude $V_{\lambda/2}$, the half-wave voltage of EO, is applied to EO. Then the light is incident on a beam-splitter BS_2, and is divided into two parts, the reflected light and the transmitted light. The reflected light passes through an analyzer AN_r with the transmission axis being at 45° with respect to the horizontal axis and enters into a photodetector D_r. The intensity measured by D_r is the reference signal. On the other hand, the transmitted light enters a Michelson interferometer, in which the light is divided into two beams by a polarization beam-splitter PBS. The paths of these two beams are $PBS \to M_1 \to PBS \to BS_2 \to AN_t \to D_t$ (for the reflected s-polarization light) and $PBS \to M_2 \to PBS \to BS_2 \to AN_t \to D_t$ (for the transmitted p-polarization light), respectively. Finally, both these two beams pass the analyzer AN_t with the transmission axis being at 45° with respect to the horizontal axis and enter the photodector D_t. The interference intensity measured by D_t is the test signal. Based on the same derivations as in Ref. [4], the intensities of the reference signal and the test signal are

$$I_r = 1 + \cos \omega t, \tag{1}$$

and

$$I_t = 1 + \cos\left(\omega t - \frac{4\pi d}{\lambda}\right), \tag{2}$$

respectively. Where λ is the light wavelength, $d = (d_p - d_s)$, d_p and d_s are the lengths of two arms of the Michelson interferometer.

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PII: S0030-4018(98)00430-1

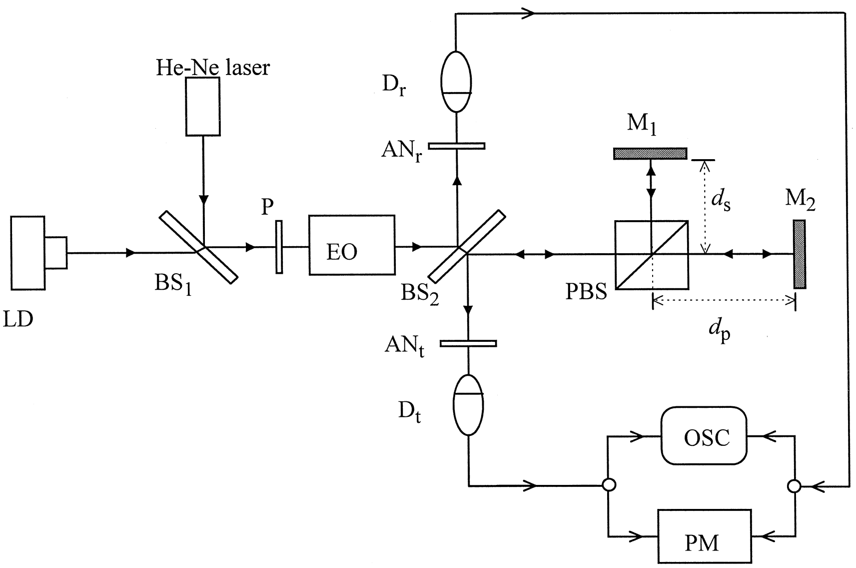

Fig. 1. Schematic diagram of our method for identifying the central fringe of an interferometer. LD: laser-diode, EO: electro-optic modulator, AN: analyzer, M: mirror, OSC: oscilloscope, BS: beam-splitter, P: polarizer, PBS: polarization beam-splitter, D: photodetector, PM: phase meter.

If the light wavelength is switched from λ to λ' (the amplitude of the external sawtooth voltage signal applied to EO should be varied from $V_{\lambda/2}$ to $V_{\lambda'/2}$), then the reference signal remains unchanged and the test signal is changed to

$$I_t' = 1 + \cos\left(\omega t - \frac{4\pi d}{\lambda'}\right). \tag{3}$$

Comparing Eqs. (2) and (3), the phase variation is given as

$$\begin{aligned} \Delta\phi &= \frac{-4\pi d}{\lambda'} - \frac{-4\pi d}{\lambda} = \frac{4\pi d(\lambda' - \lambda)}{\lambda\lambda'} \\ &= \frac{4\pi d}{\Lambda} \end{aligned} \tag{4}$$

where

$$\frac{1}{\Lambda} = \frac{1}{\lambda} - \frac{1}{\lambda'} = \frac{\lambda' - \lambda}{\lambda\lambda'} = \frac{\Delta\lambda}{\lambda\lambda'}, \tag{5}$$

and Λ is the effective wavelength. So Eq. (3) can be rewritten as

$$I_t' = 1 + \cos\left(\omega t - \frac{4\pi d}{\lambda} + \Delta\phi\right). \tag{6}$$

From Eq. (4), it is seen that the phase variation $\Delta\phi$ is proportional to the optical path difference d and inversely proportional to the effective wavelength Λ. If the lengths of the two arms of the Michelson interferometer are equal, i.e., $d = 0$, then $\Delta\phi$ equals zero despite of the wavelength variation. From Eq. (5), the effective wavelength Λ is inversely proportional to the wavelength variation $\Delta\lambda$. In general, the wavelength tuning range of a laser-diode which is obtained by controlling the injection current is very small. So its effective wavelength is long enough to avoid the phase ambiguity. Hence, a tunable laser-diode is used firstly to identify the central fringe approximately. Then, we can judge which arm in the Michelson interferometer is longer according to the sign relation between $\Delta\phi$ and Λ. Finally, a laser of different wavelength is added, the wavelength difference between the additional laser and the laser-diode is very large. Because the effective wavelength is very short, the central fringe identification can be achieved with high resolution.

3. Experiments and results

In order to show the feasibility, a laser-diode(HL6720G) manufactured by Hitachi and a He–Ne laser are used. The electro-optic modulator EO is PC100/2 manufactured by Electro-Optics Developments. The central wavelength of the laser-diode is 671 nm and its wavelength variation is proportional to the injection current. In one longitudinal mode, the maximum wavelength variation is 0.04 nm. At first, the wavelengths 671.02 nm (λ_1) and 670.98 nm (λ_2) of the tunable laser-diode are used to identify the central fringe approximately. This is achieved without phase ambiguity. Next, the wavelength 632.8 nm (λ_3) of the He–Ne laser is introduced to identify the central fringe with high resolution. The half-voltages of EO for the laser-diode and a He–Ne laser are 220 V and 207.5 V, respectively. The frequency of the external sawtooth voltage signal which is applied to EO is 900 Hz.

For easier observation, the signals detected by photodetectors D$_r$ and D$_t$ are filtered to removed the d.c. bias and

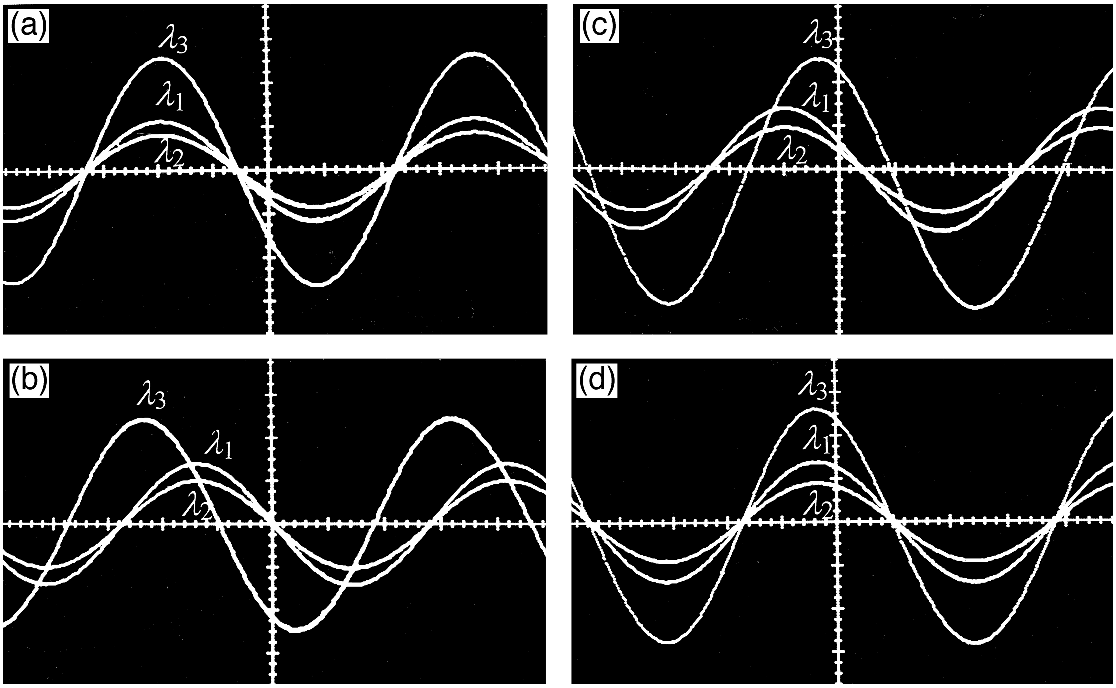

Fig. 2. The variations of waveforms of (a) the reference signals, (b) the test signals for $d \cong -1$ μm, (c) the test signals for $d \cong 0.5$ μm, (d) the test signals for $d \cong 0$, as the light wavelengths 671.02 nm (labelled λ_1), 670.98 nm (labelled λ_2), and 632.8 nm (labelled λ_3) are used, respectively.

then monitored by an oscilloscope (OSC). The results are shown in Fig. 2. The amplitudes of these signals are different because of the different laser power. The largest one corresponds to 632.8 nm (labelled λ_3), the smallest one corresponds to 670.98 nm (labelled λ_2), and the middle one corresponds 671.02 nm (labelled λ_1). Fig. 2a represents the reference signals of these three wavelengths, and there is no phase difference between them. Figs. 2b and c represent the test signals of these three wavelengths for $d \cong -1$ μm and $d \cong 0.5$ μm, respectively. From these two figures, it is clear that the phase difference between the signals of λ_1 and λ_2 is very small and it is hardly to distinguish between them. However the phase difference between the signals of λ_1 (or λ_2) and λ_3 is very obvious. The waveform of λ_3 in Fig. 2b is ahead of the other two waveforms, and in Fig. 2c the situation is opposite. The amount of the phase difference in Fig. 2b is almost twice that of Fig. 2c. Fig. 2d represents the case of $d \cong 0$. There is no phase difference between them, and this means the photodetector D_t detects the central fringe of the interferogram.

4. Discussion

The wavelength of a laser diode varies with injection current and temperature. The wavelength increases when the injection current or the temperature increases. Generally the rates of increasing are ~0.005 nm/mA and ~0.04 nm/°C, respectively. In our experiment, the laser diode is mounted on a copper block, which is thermally coupled to a thermoelectric cooler to control the temperature. The temperature of the cooler block is stabilized at 10°C within 0.1°C. So the wavelength stability of the laser diode is about 0.004 nm. According to Eq. (4), when the lengths of the two arms of the Michelson interferometer are equal, the phase variation $\Delta\phi$ equals zero despite of the wavelength variation. Hence, this stability of the wavelength does not influence the phase variation when the central fringe is identified.

From Eq. (4), the resolution is given as

$$|d| = \frac{\Delta\phi}{4\pi}|\Lambda|. \tag{7}$$

The angular resolution of the phase meter is 0.01° in our experiment. By using the single laser-diode method, if its central wavelength is 671 nm, and the wavelength difference $\Delta\lambda$ is 0.04 nm, then the effective wavelength Λ is about 11.256 mm. After substituting these data into Eq. (7), a resolution of 0.2 μm is obtained. On the other hand, as is proposed in this paper, if a He–Ne laser and a laser-diode are used, then the effective wavelength Λ is about 11.177 μm. And a resolution of 0.2 nm is obtained.

5. Conclusion

In this paper, we have modified our previous method by adding a laser to the optical configuration, so it can identify the central fringe with high resolution. It not only has the same merits of the previous method, but also has high resolution. The main merits are as follows.

(i) Easier operation because a laser-diode has a longer coherence length than a white light source.

(ii) According to the direction of the waveform shift, it is very easy to judge which arm of the Michelson interferometer is longer.

The feasibility is demonstrated and it has 0.2 nm resolution.

Acknowledgements

This study was supported in part by National Science Council, ROC, under the contract number: NSC 86-2215-E-009-013.

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