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Central fringe identification by phase quadrature interferometric technique and tunable laser-diode

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Abstract

When the optical path difference is not zero, the phase of the interferogram is strongly influenced by the wavelength variation of the light source. Under this condition, the phase variation can be estimated with a phase quadrature interferometric technique. And the central fringe of the interferogram can be identified as the phase variation remains unchanged. Based on this fact, an improved method to identify the central fringe is presented. It has some merits, such as simple optical setup, easier operation in real time, inexpensive, ability to judge which arm of interferometer is longer, etc. The feasibility is demonstrated with 10 nm resolution. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Central fringe; Quadrature interferometry; White-light interferometry

1. Introduction

White-light interferometry has many applications, such as, the measurements of displacement, pressure, temperature, strain, etc. When it is applied to these applications, it is necessary to identify the central fringe (zeroth order) of the interferogram. Because of the very short coherence length of the white-light source, it is difficult to identify the central fringe. To improve this drawback, the introduction of a source with two or more wavelengths has been presented [1–3]. The full-width-half-maximum (FWHM) value of the central fringe is increased, and it is easier to identify the central fringe. However, the multi-wavelength system usually means relative complex, difficult to align and high cost. Moreover, the misalignment, optical dispersion and distortion will induce the fringe beating effect [4]. Consequently, the output fringe pattern suffers a substantial degree of asymmetry and the central fringe may be confused [5]. In addition, some electronic circuits have been proposed to square the intensity of the interferogram such that the contrast of the central fringe can be enhanced [6,7]. But it cannot be operated in real time.

We had previously proposed two methods for the central fringe identification by use of a heterodyne interferometric technique [8,9]. They are very useful to the white-light interferometry, but they may be some expensive owing to the

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introduction of an electro-optic modulator. In this paper, an improved method for central fringe identification by use of a phase quadrature interferometric technique and a tunable laser-diode is presented. Although its 10 nm resolution capability is between the two previous methods, it has almost all of their advantages. Moreover, it is inexpensive and easier to align the optical system. The feasibility is demonstrated.

2. Principle

The schematic diagram of this method is shown in Fig. 1. The linearly polarized light from a tunable laser-diode LD passing through a beam-splitter BS_1 enters a Michelson interferometer, in which the light is divided into two beams by a polarization beam-splitter PBS_1. The paths of these two beams are $PBS_1 \rightarrow M_1 \rightarrow PBS_1 \rightarrow BS_1 \rightarrow$ PDS (for the reflected s-polarization light) and $PBS_1 \rightarrow M_2 \rightarrow PBS_1 \rightarrow BS_1 \rightarrow$ PDS (for the transmitted p-polarization light). Here PDS is the phase detection system and it consists of a quarter wave plate Q, a beam-splitter BS_2, two polarization beam-splitters $PBS_{2,3}$, four photodetectors $D_{1\text{–}4}$, two difference amplifiers $DA_{1,2}$, an analog-to-digital converter ADC, and a personal computer PC. There are four optical paths in PDS. They are (1) $Q \rightarrow BS_2 \rightarrow PBS_2(45°) \rightarrow D_1$, (2) $Q \rightarrow BS_2 \rightarrow PBS_2(-45°) \rightarrow D_3$, (3) $Q \rightarrow BS_2 \rightarrow PBS_3(0°) \rightarrow D_4$, and (4) $Q \rightarrow BS_2 \rightarrow PBS_3(90°) \rightarrow D_2$, respectively. If the amplitude of the light detected by D_n is E_n $(n = 1, 2, 3, 4)$, then the intensity measured by the photodetector D_n is $I_n = |E_n|^2$. Next, the two signals $P = I_4 - I_2$ and $Q = I_1 - I_3$ can be obtained from the difference amplifiers DA_2 and DA_1, respectively. Finally, these two signals P and Q are sent to an analog-to-digital converter ADC and a personal computer PC. And the central fringe of the Michelson interferometer will be identified.

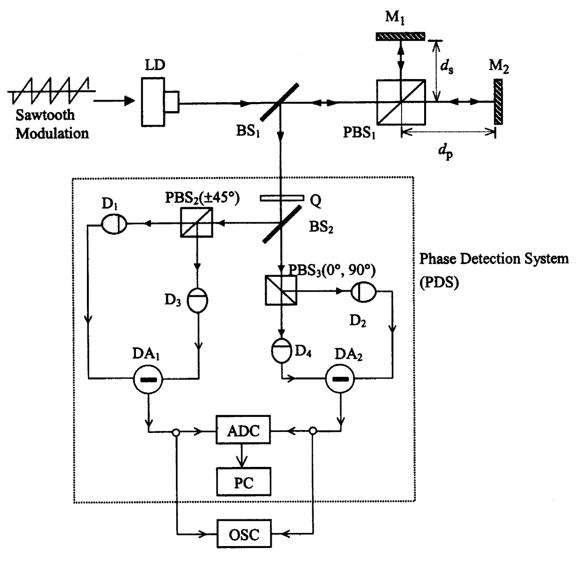

Fig. 1. Schematic diagram of an improved method to identify the central fringe of an interferometer. LD: laser-diode, BS: beam-splitter, PBS: polarization beam-splitter, M: mirror, Q: quarter wave plate, D: photodetector, DA: difference amplifier, ADC: analog-to-digital converter, PC: personal computer, and OSC: oscilloscope.

2.1. The phase quadrature interferometric technique with a tunable laser-diode

For convenience, the z-axis is chosen along the propagation direction and the y-axis is along the vertical direction. Let the output light of the laser-diode be linearly polarized at 45° with respect to the x-axis, then the Jones vector [10,11] of the light returning from the Michelson interferometer can be written as

$$E = \frac{1}{\sqrt{2}}\begin{bmatrix}\exp(i\phi_p)\\ \exp(i\phi_s)\end{bmatrix}, \tag{1}$$

where $\phi_{p,s} = 4\pi d_{p,s}/\lambda$, $d_{p,s}$ are the lengths of two arms of the Michelson interferometer and λ is the wavelength. If the fast axis of the quarter wave plate Q is at 45° with respect to the x-axis, then the amplitude of the light detected by photodetector D_1 is

$$\begin{aligned} E_1 &= PBS_2(45°)\,Q(45°)\,E \\ &= \frac{1}{2}\begin{bmatrix}1 & 1\\ 1 & 1\end{bmatrix}\frac{1}{\sqrt{2}}\begin{bmatrix}1 & i\\ i & 1\end{bmatrix}\frac{1}{\sqrt{2}}\begin{bmatrix}\exp(i\phi_p)\\ \exp(i\phi_s)\end{bmatrix} \\ &= \frac{1+i}{4}\begin{bmatrix}1\\ 1\end{bmatrix}[\exp(i\phi_p) + \exp(i\phi_s)]. \end{aligned} \tag{2}$$

Its intensity is

$$I_1 = |E_1|^2 = \tfrac{1}{2}(1 + \cos\phi), \tag{3}$$

where $\phi = \phi_p - \phi_s = 4\pi d/\lambda$ and $d = d_p - d_s$. Based on similar derivations, the output signals of the four photodetectors D_{1-4} can be written, respectively, as

$$I_n = S\left\{A_n + B_n \cos\left[\phi + (n-1)\frac{\pi}{2}\right]\right\}, \quad (4)$$

where the subscript n is an integer from 1 to 4. A_n and B_n are the mean intensity and interference visibility, respectively. The factor S relates with the power variation of the laser-diode [11]. In this optical system, the conditions of $A_4 = A_2$, $A_1 = A_3$, and $B_4 + B_2 = B_1 + B_3 = B$ can be achieved. Then two signals $P = I_4 - I_2$ and $Q = I_1 - I_3$ are obtained from the difference amplifiers DA_1 and DA_2, respectively. And they can be written as

$$\begin{aligned} P &= I_4 - I_2 \\ &= S[A_4 - A_2 + (B_4 + B_2)\sin\phi] = SB\sin\phi \end{aligned} \quad (5)$$

and

$$\begin{aligned} Q &= I_1 - I_3 \\ &= S[A_1 - A_3 + (B_1 + B_3)\cos\phi] = SB\cos\phi. \end{aligned} \quad (6)$$

So the phase difference ϕ between p- and s-polarizations can be given as

$$\phi = \frac{4\pi d}{\lambda} = \tan^{-1}\left(\frac{P}{Q}\right). \quad (7)$$

2.2. Identification of central fringe

If the wavelength of the laser-diode has a small variation $\Delta\lambda$, then Eqs. (5) and (6) are changed to

$$P = SB\sin\left(\phi - \frac{4\pi d}{\lambda^2}\Delta\lambda\right) \quad (8)$$

and

$$Q = SB\cos\left(\phi - \frac{4\pi d}{\lambda^2}\Delta\lambda\right). \quad (9)$$

From Eqs. (7)–(9), the phase difference variation is given as

$$\Delta\phi = \frac{4\pi d}{\lambda + \Delta\lambda} - \frac{4\pi d}{\lambda} \cong -\frac{4\pi d}{\lambda^2}\Delta\lambda. \quad (10)$$

For easier experimental observation, signals P and Q are sent to the horizontal and the vertical inputs of an oscilloscope, respectively. Eq. (10) shows that the phase difference variation $\Delta\phi$, being proportional to the optical path difference *2d* in the Michelson interferometer, will appear as the wavelength of LD is changed slightly. Since the laser power and its wavelength are proportional to the injection current, hence as the injection current of the laser-diode increases, both the factor S and the wavelength variation $\Delta\lambda$ also increase. Then, the curve traced by a point with position components (P, Q) can be observed on the oscilloscope. This curve can be depicted with a polar coordinate $(S, \Delta\phi)$. Here, we have

(i) if $d > 0$, then $\Delta\phi < 0$. Hence, the curve is a spiral pattern with a counterclockwise direction;
(ii) if $d < 0$, then $\Delta\phi > 0$. Hence, the curve is a spiral pattern with a clockwise direction;
(iii) if $d = 0$, then $\Delta\phi = 0$. Hence, the curve is a straight line.

So, if mirror M_1 or M_2 is adjusted so that the rotational angle equal to zero, that is, the curve becomes a straight line, then the central fringe is identified. For enhancing the resolution, an analog-to-digital converter and personal computer are introduced to estimate the phase difference variation. When the phase difference variation remains unchanged, the phase detection system indicates the central fringe of the interferogram. Under this condition, the lengths of the two arms of the Michelson interferometer are exactly equivalent.

3. Experiments and results

In order to show the feasibility, a laser-diode (PS020-00) manufactured by Blue Sky Research Inc. is used. The relation curve between the wavelength and the injection current is measured, as shown in Fig. 2. The laser-diode has a central wavelength of 634.27 nm and its wavelength variation is proportional to the injection current with a rate 0.01 nm/mA before mode hopping. Its output power is a function of the injection current, too. The mode hop occurs in the interval between 44 and 45 mA, and its wavelength jumps a step of 0.56 nm.

Firstly, a sawtooth injection current, which varies between 40 and 44 mA with a 1 kHz frequency, is

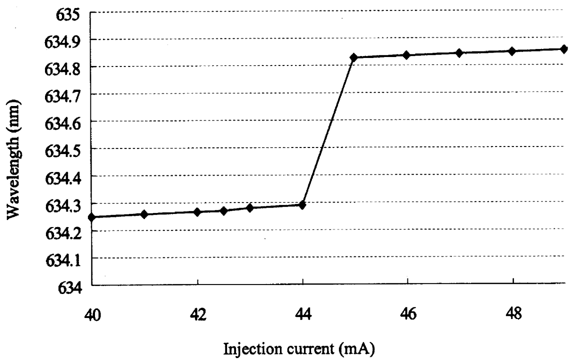

Fig. 2. Experimental curve of the wavelength versus the injection current for the laser-diode.

applied to modulate the laser-diode. From Fig. 2, it is seen that the wavelength variation is about $\Delta\lambda = 0.04$ nm. When $d \approx -6.78$ mm $(d_s > d_p)$, the P and Q signals form a clockwise spiral pattern, as shown in Fig. 3(a). The sweeping angle or the phase difference variation is about 485°. If $d \approx 2.03$ mm $(d_p > d_s)$, then the P and Q signals form an counterclockwise spiral pattern, as shown in Fig. 3(b). The sweeping angle or the phase difference variation is about 145°. It is clear that we can judge which arm of an interferometer is longer according to the spiral direction.

To increase the wavelength variation, the characteristic of the mode hop is used. The sawtooth injection current varied between 43 and 47 mA with the same frequency is applied to modulate the laser-diode. And $\Delta\lambda \approx 0.56$ nm is obtained in this condition. According to the phase difference variation and the direction of the spiral pattern shown in Fig. 3(c), we can get $d \approx 24$ μm from Eq. (10). Then, the position of mirror M_2 is so modified until a straight line like Fig. 3(d) has been achieved. Under this condition, the optical path difference exactly equals to zero.

4. Discussion

From Eq. (10), the resolution is given as

$$|d| = \frac{|\Delta\phi|\lambda^2}{4\pi|\Delta\lambda|}. \tag{11}$$

In our experiments, a 16 bit analog-to-digital converter and a personal computer are used to

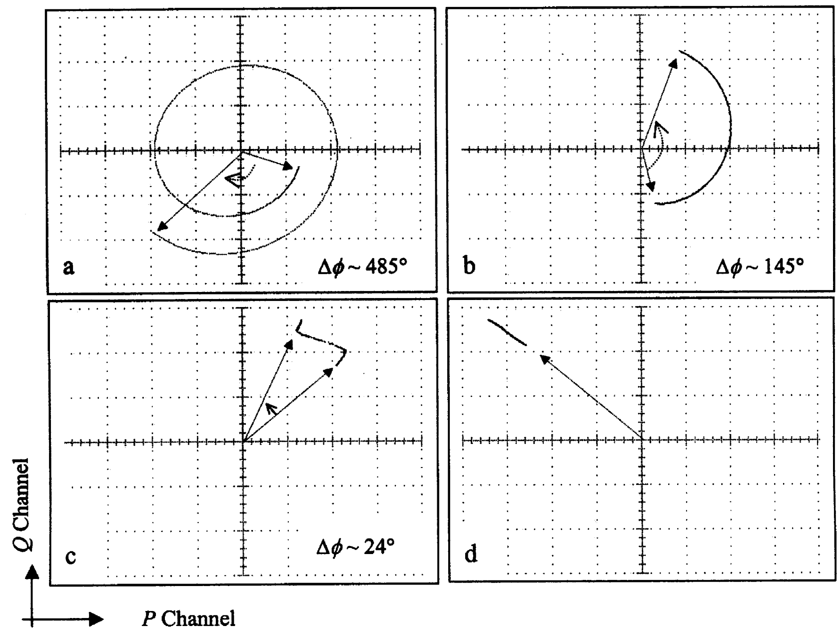

Fig. 3. Experimental spiral patterns for (a) $d \approx -6.78$ mm, (b) $d \approx 2.03$ mm as $\Delta\lambda = 0.04$ nm, (c) $d \approx 24$ μm, and (d) $d \approx 0$ as $\Delta\lambda = 0.56$ nm.

estimate the phase difference variation. Its effective bit rate is reduced to 14 bit because of noise. So this ADC card has a $\Delta\phi = 180°/2^{14} \approx 0.01°$ phase resolution. After substituting the experimental data ($\Delta\phi = 0.01°$, $\lambda = 634.5$ nm, and $\Delta\lambda = 0.56$ nm) into Eq. (11), the resolution of 10 nm is obtained.

5. Conclusion

When the optical path difference is not zero, the phase of the interferogram is strongly influenced by the wavelength variation of the light source. Under this condition, the phase variation can be estimated with a phase quadrature interferometric technique. And the central fringe of the interferogram can be identified as the phase variation remains unchanged. Based on this fact, an improved method to identify the central fringe has been presented in this paper. To demonstrate its feasibility, we use a tunable laser-diode as a light source. An analog-to-digital converter and a personal computer have been used to estimate the phase difference variation of the interferogram, and an oscilloscope has been used for easy observation and understanding. In order to increase its resolution, the characteristic of laser mode hopping is used such that 10 nm resolution can be obtained. It has some merits, such as simple optical setup, easier operation in real time, inexpensive, and the ability to judge which arm of interferometer is longer, etc.

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References

[1] D.N. Wang, Y.N. Ning, K.T.V. Grattan, A.W. Palmer, K. Weir, IEEE Photon. Technol. Lett. 5 (1993) 1350–1352.
[2] Y.J. Rao, D.A. Jackson, Electron. Lett. 30 (1994) 1440–1441.
[3] B.K. Ward, K. Seta, Appl. Opt. 30 (1991) 66–71.
[4] Y.N. Ning, K.T.V. Grattan, A.W. Palmer, Meas. Sci. Technol. 7 (1996) 700–705.
[5] D.N. Wang, K.T.V. Grattan, A.W. Palmer, Opt. Commun. 127 (1996) 19–24.
[6] D.N. Wang, C. Shu, Opt. Commun. 162 (1999) 187–190.
[7] Q. Wang, Y.N. Ning, A.W. Palmer, K.T.V. Grattan, Opt. Commun. 117 (1995) 241–244.
[8] J.Y. Lee, M.H. Chiu, D.C. Su, Opt. Commun. 128 (1996) 193–196.
[9] J.Y. Lee, D.C. Su, Opt. Commun. 156 (1998) 1–4.
[10] C.K. Lee, G.Y. Wu, C.T. Teng, W.J. Wu, C.T. Lin, W.H. Hsiao, H.C. Shih, J.S. Wang, S.C. Lin, C.C. Lin, C.F. Lee, Y.C. Lin, Jpn. J. Appl. Phys. 38 (1999) 1730–1741.
[11] V. Greco, G. Molesini, F. Quercioli, Rev. Sci. Instrum. 66 (1995) 3729–3734.