ELSEVIER

1 April 1999

Optics Communications 162 (1999) 7–10

OPTICS
COMMUNICATIONS

Common-path heterodyne interferometric detection scheme for measuring wavelength shift

Ju-Yi Lee, Der-Chin Su *

Institute of Electro-Optical Engineering, National Chiao Tung University, 1001 Ta-Hsueh Road, Hsin-Chu, Taiwan

Received 7 April 1998; received in revised form 5 January 1999; accepted 2 February 1999

Abstract

When a linearly polarized light passes through a uniaxial crystal, small wavelength shifts will introduce phase difference variations between s- and p-polarizations. These phase difference variations can be measured accurately by heterodyne interferometry. Based on these facts, a common-path heterodyne interferometric detection scheme for measuring wavelength shift is proposed. This scheme has the advantages of both common-path interferometry and heterodyne interferometry. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Wavelength shift; Heterodyne interferometry

1. Introduction

An optical interferometric sensor using wavelength changes as the measurand is becoming important [1–3]. Its resolution mainly depends on how small wavelength shift can be detected. In order to increase the resolution, Ning et al. [4] developed an interferometric detection scheme for measuring the small wavelength shift. In Ning's unbalanced interferometric configuration, the small wavelength shift was converted into interference phase variation. To stabilize the optical path difference (OPD), an additional stabilized light source and a feedback control system were used to lock the average OPD at the designated value. Thus, the optical structure becomes very complex and is difficult to operate.

In this paper, a novel method for measuring small wavelength shifts is presented, based on the similar consideration of Shyu et al. [5] who developed the technique for measuring the retardation of a wave plate with heterodyne interferometry. When a linearly polarized light passes through a uniaxial crystal, the small wavelength shifts will introduce phase difference variations between s- and p-polarizations; these phase difference variations can be measured accurately by heterodyne interferometry. Because of its common-path heterodyne interferometric configuration, it has both the advantages of common-path interferometry and heterodyne interferometry, such as simple optical structure, easy operation, high stability against air turbulence, and high measurement accuracy.

2. Principle

For convenience, the $+z$ axis is chosen along the propagation direction and the x axis is along the horizontal direction. Let the incident light be linearly polarized at 45° with respect to the x axis.

2.1. Phase difference variations resulting from wavelength shifts

As shown in Fig. 1, when linearly polarized light passes through the uniaxial crystal (UC) whose optical axis

---

[*] Corresponding author. E-mail: t7503@cc.nctu.edu.tw

PII: S0030-4018(99)00074-7

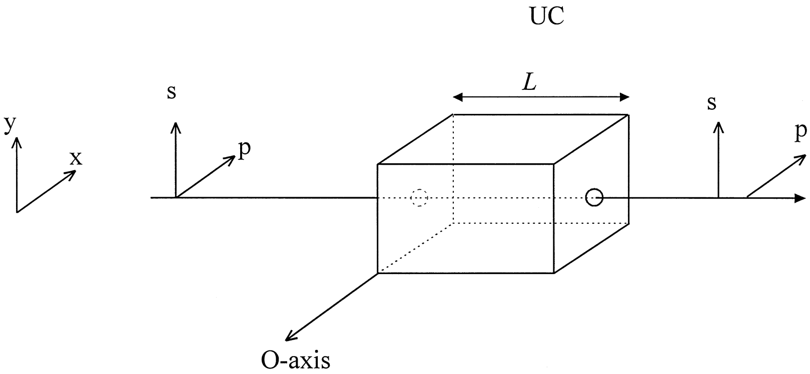

Fig. 1. Linearly polarized light passes through a uniaxial crystal.

is along the x-axis, the phase difference of s-polarization relative to p-polarization is [6]

$$\phi = \frac{2\pi}{\lambda} nL, \tag{1}$$

where λ is the wavelength of light, n is the birefringence index difference and L is the thickness of the uniaxial crystal. If the wavelength has a small variation $\Delta\lambda$, then the variation in phase difference is

$$\Delta\phi \cong -\frac{2\pi nL}{\lambda^2}\Delta\lambda. \tag{2}$$

Eq. (2) can be rewritten as

$$\Delta\lambda \cong -\frac{\lambda^2}{2\pi nL}\Delta\phi. \tag{3}$$

2.2. Phase difference variation measurement with heterodyne interferometry

Shyu et al. [5] proposed a method for measuring the phase retardation of a wave plate by using a heterodyne interferometric technique. The schematic diagram of the optical arrangement of our method, which is based on a similar principle, is designed and shown in Fig. 2. The linearly polarized light passing through an electrooptic modulator EO is incident on a beam splitter BS and divided into two parts: the reference beam and the test beam. The reference beam, which is reflected from BS, passes through an analyzer AN_r, then enters the photodetector D_r. Here the intensity I_r measured by D_r is the reference signal. On the other hand, the test beam is transmitted through BS, a uniaxial crystal UC and an analyzer AN_t. Finally, it is detected by another photodetec-

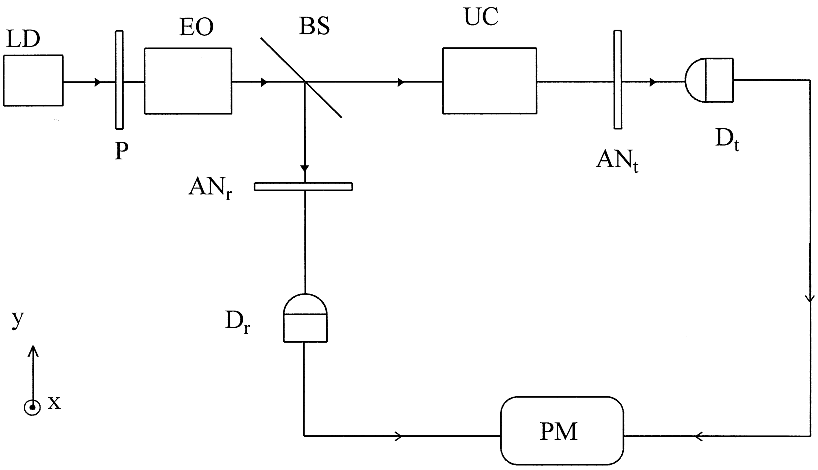

Fig. 2. Schematic diagram for measuring the phase difference variations; LD: laser diode; P: polarizer; EO: electrooptic modulator; BS: beam splitter; UC: uniaxial crystal; AN: analyzer; D: photodetector; PM: phase meter.

tor D_t, and the intensity I_t measured by D_t is the test signal.

If the fast axis of EO is in the x-axis, and a sawtooth signal of angular frequency ω and amplitude $V_{\lambda/2}$, the half-wave voltage of EO, is applied to EO, then using the Jones calculus we can get

$$I_r = \frac{1}{2}[1 + \cos(\omega t + \phi_r)], \tag{4}$$

and

$$I_{t1} = \frac{I_0}{2}[1 + \cos(\omega t + \phi_1)]. \tag{5}$$

In Eqs. (4) and (5), ϕ_r and ϕ_1 are the phase differences between s- and p-polarizations owing to the reflection at BS and the passage of UC, respectively; I_0 is the intensity of the test beam relative to the reference beam. These two sinusoidal signals are sent to the phase meter PM as shown in Fig. 2. The phase difference between the reference signal and the test signal,

$$\phi_1' = \phi_1 - \phi_r, \tag{6}$$

can be obtained. In the second measurement let the wavelength be changed to $\lambda + \Delta\lambda$, the test signal has the form

$$I_{t2} = \frac{1_0}{2}[1 + \cos(\omega t + \phi_2)]. \tag{7}$$

Therefore, the phase meter at this time represents

$$\phi_2' = \phi_2 - \phi_r. \tag{8}$$

Subtracting Eq. (6) from Eq. (8), we get a phase difference variation

$$\Delta\phi = (\phi_2 - \phi_r) - (\phi_1 - \phi_r) = \phi_2 - \phi_1. \tag{9}$$

Finally, by substituting Eq. (9) into Eq. (3), we can evaluate the wavelength shift with high accuracy.

3. Experiments and results

To show the feasibility of this technique, the small wavelength shifts of a laser diode (Model HL 6720G, manufactured by Hitachi Ltd.) were measured. It has a central wavelength of 672 nm and its wavelength variation is proportional to the injection current. An electrooptic modulator (Model PC200/2, manufactured by England Electro-Optics Developments Ltd.) with a half-wave voltage of 220 V was used in this test. The frequency of the externally modulated sawtooth signal was 2 kHz. And a uniaxial crystal made of quartz with birefringence index difference $n = 0.009$ and thickness $L = 10.00$ mm was used. Both the electrooptic modulator and the uniaxial crystal were in contact with a temperature stabilizer which had been fixed at 25.0°C. First, we measured the phase difference variations as the injection currents were varied and the laser diode temperature was fixed at 10.0°C by a temperature controller. Second, the data of the phase difference variation were substituted into Eq. (3) to calculate the corresponding wavelength shifts. The experimental results between the wavelength shift and the wavelength versus the injection current are shown in Fig. 3. In this figure, the symbols □ and ○ represent the values measured with this method and an optical spectrum analyzer, respectively.

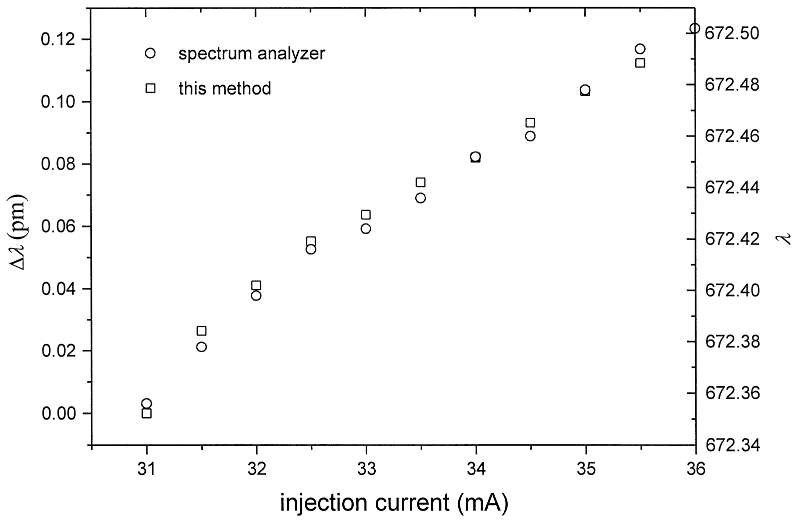

Fig. 3. Experimental results of the small wavelength shift and the wavelength versus the injection current.

4. Discussions

From Eq. (3), we can get

$$\Delta\lambda_{\mathrm{err}} = \Delta\lambda\left(\left|\frac{L_{\mathrm{err}}}{L}\right| + \left|\frac{n_{\mathrm{err}}}{n}\right| + \left|\frac{\Delta\phi_{\mathrm{err}}}{\Delta\phi}\right|\right), \qquad (10)$$

where $\Delta\lambda_{\mathrm{err}}$, L_{err}, n_{err} and $\Delta\phi_{\mathrm{err}}$ are the errors in the wavelength shift, crystal thickness, birefringence index difference, and phase difference, respectively. $|L_{\mathrm{err}}/L|$ is equal to $|\alpha T_{\mathrm{err}}|$, where α is the coefficient of linear expansion of UC and T_{err} is the temperature drift of the temperature stabilizer. In our experiment, they are 1.22×10^{-5}°C^{-1} and 0.1°C, respectively. Under the condition $T_{\mathrm{err}} = 0.1$°C, n_{err} nearly equals zero. To evaluate $\Delta\phi_{\mathrm{err}}$, a He–Ne laser was introduced into the setup shown in Fig. 2 to replace LD. We found that the phase difference varied 0.03° within 1 min, i.e., $\Delta\phi_{\mathrm{err}} = 0.03°$. Assuming the measured wavelength shift range $\Delta\lambda$ is 0.1 nm, then the phase difference variation $\Delta\phi$ is about 7.2° according to Eq. (2). Therefore, by substituting these experimental data into Eq. (10) a resolution $\Delta\lambda_{\mathrm{err}}$ of 4.2×10^{-4} nm can be obtained.

Owing to its common-path configuration, our system has high stability against air turbulence and environmental vibrations. And because it measures the phase difference instead of the light intensity, it is free of influences from the instability of a light source. Furthermore, it has a better resolution.

5. Conclusion

In this paper, a novel method for measuring a small wavelength shift is presented. If a linearly polarized light passes through a uniaxial crystal, then there is a phase difference variation between s- and p-polarizations as the light has a small wavelength shift. This phase difference variation is proportional to the product of the wavelength shift, the birefringence index difference and the thickness of uniaxial crystal. We have measured the phase difference variation by using a heterodyne interferometric technique. By using Eq. (3), the corresponding wavelength shift is obtained. This method has both the merits of common-path interferometry and heterodyne interferometry, such as simple optical structure, easy operation, high stability against air turbulence, and high measurement accuracy.

Acknowledgements

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

References

[1] B.T. Meggit, White light interferometric sensors, in: K.T.V. Grattan, B.T. Meggitt (Eds.), Optical Fiber Sensor Technology, Chapman & Hall, London, UK, 1995, p. 269.

[2] X.Q. Jiang, J. Kemp, Y.N. Ning, A.W. Palmer, K.T.V. Grattan, IEEE Photon. Technol. Lett. 8 (1996) 1055.

[3] X.Q. Jiang, J. Kemp, Y.N. Ning, A.W. Palmer, K.T.V. Grattan, Appl. Opt. 36 (1997) 4907.

[4] Y.N. Ning, W.J. Shi, K.T.V. Grattan, A.W. Palmer, B.T. Meggitt, Opt. Commun. 138 (1997) 27.

[5] L.H. Shyu, C.L. Chen, D.C. Su, Appl. Opt. 32 (1993) 4228.

[6] Yariv, P. Yeh, Optical Waves in Crystal, Wiley, New York, 1984, p. 136.