Birefringence Measurements by a Zeeman Laser and a New Scheme

林俊鋒 羅裕龍

遠東科技大學電腦應用工程系 成功大學機械系

jacklin@cc.feu.edu.tw loyl@mail.ncku.edu.tw

Abstract

This paper presents a new optical configuration for measuring the principal axis angle and phase retardation of optical linear birefringent materials. A heterodyne light source, which is generated by a Zeeman laser, and a new scheme measure the principal axis angle and phase retardation. The measurement system has advantages as a simple optical setup, high stability, small size, and portable owing to the use of a Zeeman laser and the configuration. Using the amplitudes from two measured heterodyne signals and a referenced heterodyne signal, a simple derived algorithm can obtain the principal axis angle and phase retardation directly and easily. According to the algorithm, the principal axis angle is limited in the range from 0^0 to 90^0 while the phase retardation in the range from 0^0 to 180^0 is available. Moreover, we can extend dynamic range of the phase retardation measurement to be 180^0 successfully. According to the experimental results, the average absolute errors for the principal axis angle and the phase retardation of $\lambda/4$ -wave plate with principal axis angle set on 90^0 are determined to be 1.47^0 and 2.9 % respectively. The error for the phase retardation is within uncertainty range 5 % or more of commercial quarter-wave plates.

Keywords: Birefringence, Phase retardation, Zeeman laser.

1. Introduction

More than twenty years ago, Serreze and Goldner [1] used an electro-optic modulator (EOM) as the modulating source to measure the properties of birefringent materials. However, it is difficult to post-process the measurement signals, and the precision of measurement is deeply influenced. Lo and Hsu [2] proposed a new heterodyne scheme for birefringence measurements using an EOM droved by a sine-wave signal in a compact common-path interferometer.

Several researchers have proposed methods to simultaneously measure the principal axis direction and various phase retardation levels of birefringent materials [3-4]. Wang and Oakberg [3] developed a novel instrument for measuring both the magnitude and the phase angle of low-level linear birefringence in optical materials. This instrument employed a photo-elastic modulator (PEM) to modulate a He-Ne laser beam, and proved capable of measuring different low-level linear birefringence with a high sensitivity. However, this system has an upper retardation limit of 90^0.

Recently, Lee *et al.* [4] also proposed a new method modulated by an EOM with a saw-tooth signal, and used only a lock-in amplifier to demodulate the changes in the principal axis angle and birefringence by the phase- and intensity-locked signal process. However, this circular heterodyne interferometer also suffered a drawback as a restricted phase retardation range of just 90^0. In order to overcome this disadvantage, we further present a new simplified heterodyne interferometer with three intensity measurements for measuring the principal axis angle and phase retardation easily and extending the range of phase retardation to be 180^0 in this paper.

2. Methodology

2.1 Optical Configuration

The configuration of optical setups in the proposed method is illustrated in Fig. 1. A Zeeman laser (HP 5519A) that includes two orthogonal linearly polarized waves in different temporal frequencies was used as the light source. Two orthogonal linearly polarized waves, one *p* polarized and the other *s* polarized, passed through a Glan-Thompson polarizer in which the azimuth angle was set at 45^0. Subsequently, the light beam passes through the first beam splitter, resulting in a transmitted beam and a reflected beam. The reflected beam is polarized and detected as the referenced signal. The transmitted beam transmits through the sample, and the second beam splitter. Finally the two splitting beams are polarized through an analyzer and detected by a photodetector respectively, to produce two measured signals.

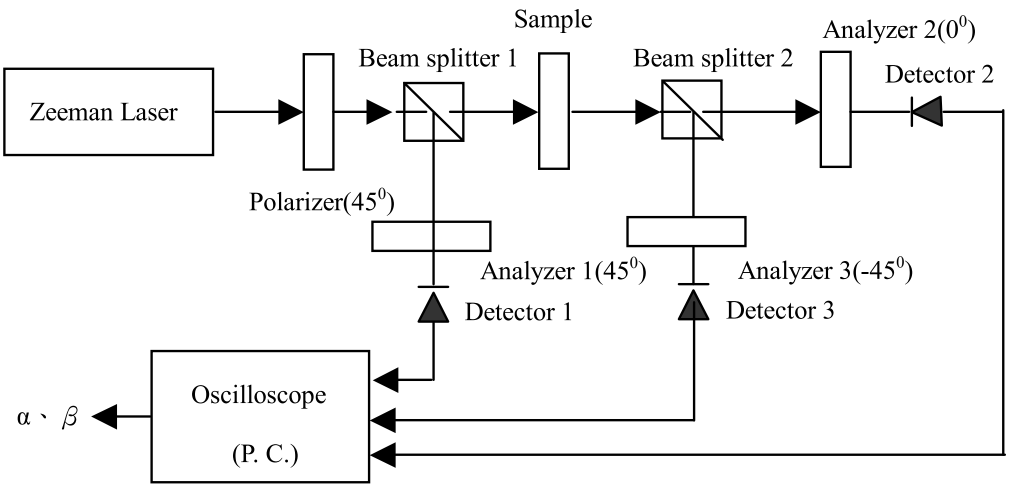


Fig. 1 The optical setup.

2.2 Working Principle

According to the Jones matrix formalism, the intensities for the reflected referenced light and transmitted measurement lights are expressed as

$$I_1 = \frac{1}{4}\left(a_p^2 + 2a_p a_s\left[\left(\omega_p - \omega_s\right)t\right] + a_s^2\right) \tag{1}$$

and

$$I_2 = \left(\frac{1}{16} + \frac{1}{32}\sin 4\alpha(1-\cos(\beta))\right)\left(a_p^2 + 2a_p a_s\left[\left(\omega_p - \omega_s\right)t\right] + a_s^2\right) \tag{2}$$

and

$$I_3 = \left(\frac{1}{32}(1+\cos 4\alpha)(1-\cos(\beta))\right)\left(a_p^2 + 2a_p a_s\left[\left(\omega_p - \omega_s\right)t\right] + a_s^2\right) \tag{3}$$

where the incident electric field, orthogonal linear polarization states, whose amplitudes and angular frequencies are (a_p, ω_p) and (a_s, ω_s), respectively, and α is the principal angle of the sample, β is the phase retardation of the sample.

An oscilloscope is employed to achieve the ac component of the referenced intensity and the two measured output intensities at the beat frequency. Consequently, the principal axis angle of the optical sample, α, and its phase retardation, β, can be derived as:

$$\alpha = \frac{1}{2}\tan^{-1}\left(\frac{4I_2 - I_1}{4I_3}\right) \tag{4}$$

and

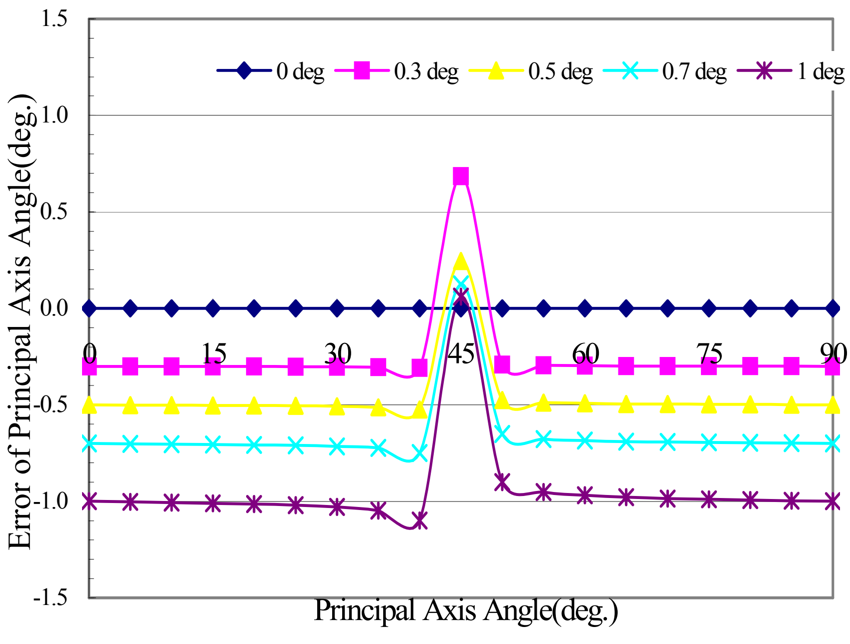
$$\beta = 2\sin^{-1}\left(\sqrt{\frac{(4I_2 - I_1)^2 + (4I_3)^2}{8I_1I_3}}\right) \qquad (5)$$

According to Eq. (4), the principal axis angle is determined without ambiguity in the range from 0^0 to 90^0. The phase retardation, β, is determined in a range from 0^0 to 180^0 following Eq. (5).

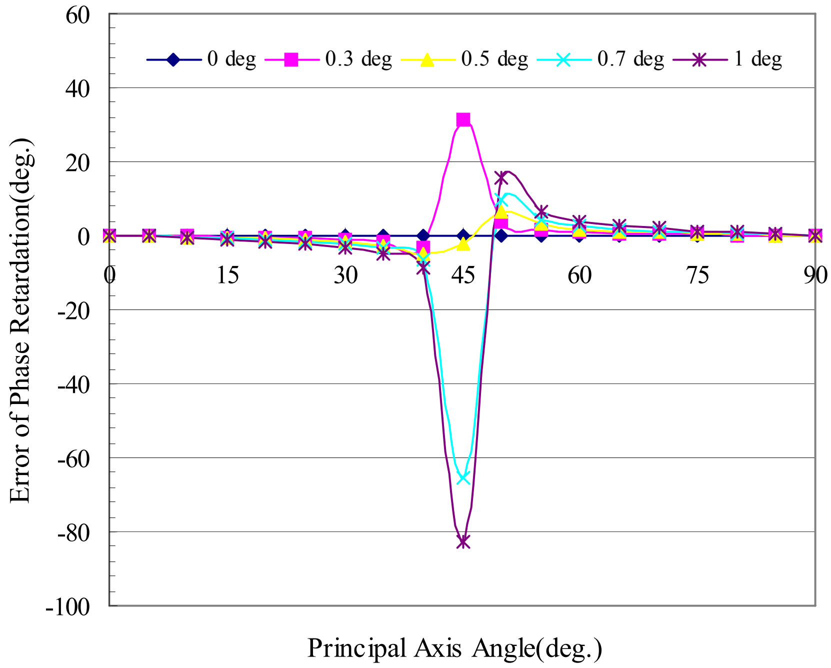
2.3 Error Analysis

In this optical setup, the feature of intensity ratio in this setup result in better accuracy. The measurement errors are induced by elliptical polarization of the incident laser beam, the error of rotation and the imperfect polarizer in this setup. The error analysis in elliptical polarization of the incident Zeeman laser could be cited [5]. Residual ellipticity of linearly polarized components of commercial available Zeeman lasers is not specified by the manufacture. Because it determines the amplitude of the background signal in the absence of a sample, to bring the background signal to a small value as possible a wave plate can be used after laser to compensate for residual ellipticity. A typical value of ellipticity (ratio of minor axis to major axis) for a commercial Zeeman laser is 0.08 [6]. If a higher extinction ration of a polarizer such as Glan-Thomposon polarizer is used, the error of birefringence measurement due to imperfect polarizer can be neglected. The present study restricts its attention to the measurement errors induced by the error of rotation angle [7].

Fig. 2 presents the simulated absolute principal axis angle and phase retardation errors, respectively, for the case of a quarter-wave plate sample and the rotation of inclination angle has a value of 0^0, 0.3^0, 0.5^0, 0.7^0, and 1^0. Fig. 2 (a) indicates that the maximum absolute principal axis angle error occurs when principal axis angle is equal to 45^0. The values of the absolute error are seen to be $0.^0$, 0.686^0, 0.245^0, 0.124^0, and 0.060^0 for the rotation of inclination angle has a value of 0^0, 0.3^0, 0.5^0, 0.7^0, and 1^0. Fig. 2 (b) indicates that the maximum absolute phase retardation error occurs when principal axis angle is close to 45^0. Moreover, it is noted that when the rotation of inclination angle exceeds 0.5^0, the magnitudes of the non-linearity errors increase.



(a)



(b)

Fig. 2 Non-linear errors caused by the rotation of inclination angle (a) Error in principal angle α and (b) error in phase retardation β.

3. Experimental Setup and Results

3.1 Experimental Setup

In Figure 1, the experimental setup employs a Zeeman laser (Hewlett-Packard Hp 5519A) with a beam composed of two orthogonal linearly polarized states, *p* and *s* waves, with different temporal frequencies was used. The output power of the laser beam was 1mw, the wavelength of the Zeeman laser was 632.8 nm, the difference frequency of the two orthogonal polarization modes was 2.6 MHz, and short-term (1 hour) wavelength stability is ± 0.002 ppm typical. Optics temperature must be stabilized to $\pm 2^0 C$ to achieve accuracy specifications. The optical arrangement also includes four Glan-Thompson type polarizers with extinction ratio of 5 x 10^{-6} and three photodetectors (NEW FOCUS Model 1801 DC-version type). Digitization of reference and measurement signals is performed by a four-channel digital storage oscilloscope (Tektronix TDS 5054), which provides 500 MHz and sampling rate of 5 GS/s.

3.2 Experimental Results

After conducting the careful alignment and calibration procedures, we perform a series of experiments. First, a $\lambda/4$-wave plate is used as a sample and measurements are taken as the principal angle is 90^0. As shown in Fig. 3, the average absolute error for the principal axis angle of $\lambda/4$-wave plate is determined to be 1.47^0. The standard deviation of this measurement is 0.19^0. As shown in Fig. 4, the average absolute error for the phase retardation of $\lambda/4$-wave plate is determined to be 2.9 % with standard deviation 0.22^0.

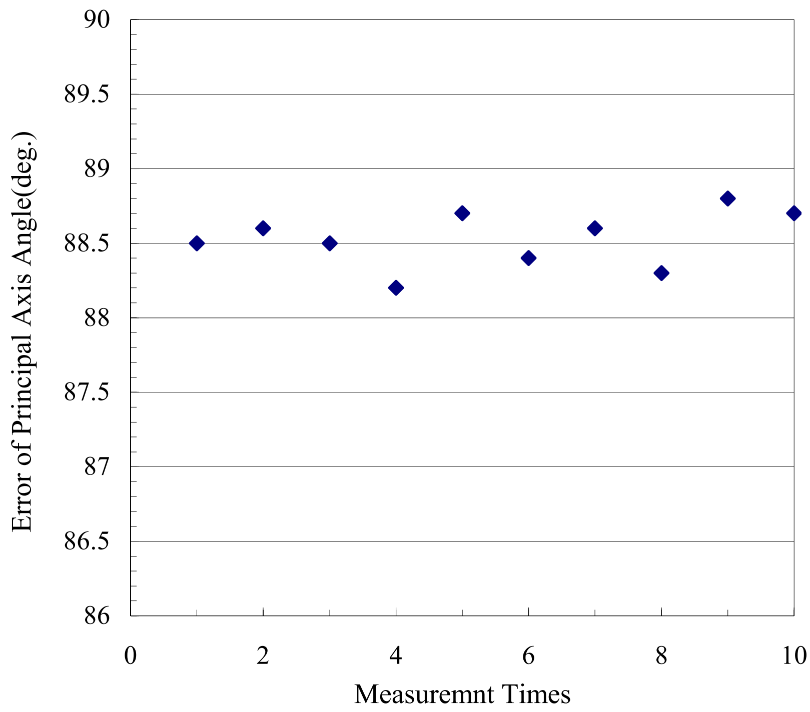


Fig. 3 Experimental results of principal axis ($\lambda/4$ -wave plate sample).

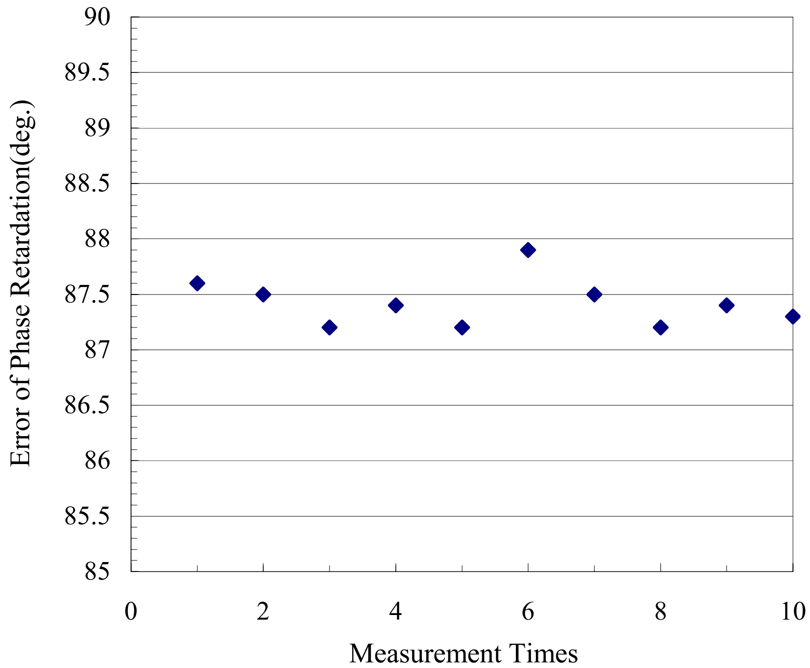


Fig. 4 Experimental results of phase retardaton ($\lambda/4$ -wave plate sample).

4. Discussion and Conclusions

This paper presents a new simplified optical system for the measurement the principal axis angle and phase retardation of optical linear birefringent materials. A Zeeman laser used in this new optical setup can make the measurement system to have advantages as simple configuration, small size, portable, and high stability. Using the amplitudes from two measured heterodyne signals and a referenced heterodyne signal, a simple derived algorithm can obtain the principal axis angle and phase retardation directly. From Eqs. (4)

and (5), the principal axis angle is limited in the range from 0^0 to 90^0 while the phase retardation in the range from 0^0 to 180^0 is available. Moreover, we can extend the dynamic range of phase retardation measurement to be 180^0 successfully.

Experimental results show that the average absolute errors for the principal axis angle and the phase retardation of $\lambda/4$-wave plate with principal axis angle set on 90^0 are determined to be 1.47^0 and 2.9 % respectively. The absolute average error, 2.9 %, in this paper is lower than 4.8 % measured by normalized intensity in [4], and is higher than 0.23 % by phase-locked measurement in [8]. The error for the phase retardation is within uncertainty range 5 % or more of commercial quarter-wave plates [9].

5. References

[1] Serreze,H.B.,& Goldner,R.B. (1974) A Phase-Sensitive Technique for Measuring Small Birefringence Changes. *Rev. Sci. Instrum*. 45, 1613-1614.

[2] Lo,Y.L.,& Hsu,P.F. (2002) Birefringence Measurements by an Electro-Optic Modulator Using a New Heterodyne Scheme. *Opt. Eng.* 41, 2764-2767.

[3] Wang,B.,& Oakberg,T.C. (1999) A New Instrument for Measuring Both the Magnitude and Angle of Low Level Birefringence. *Rev. Sci. Instrum*. 70(10), 3847-3854.

[4] Lee,S.Y.,Lin,J.F.,& Lo,Y.L. (2004) A Compact Circular Heterodyne Interferometer for the Simultaneous Measurement of Variation in the Magnitude of Phase Retardation and the Principal Angle. *Meas. Sci. Technol.* 15(5), 978-982.

[5] Wu,Y.Z.,& Xie,Y. (1989) Elliptical Polarization and Nonorthogonality of Stabilized Zeeman Laser Output. *Appl. Opt*. 28(11), 2043-2046.

[6] Wu,C.M.,& Deslattes,R.D. (1998) Analytical Modeling of the Periodical Nonlinearity in Heterodyne Interferometry. *Appl. Opt*. 37(28), 6696-6700.

[7] Liu,Z.,Lin,D.,Jiang,H.,& Yin,C. (2003) Roll Angle Interferometer by Means of Wave Plates. *Sen. and Actu. A*. l04, 127-131.

[8] Lo,Y.L.,Lee,S.Y.,& Lin,J.F. (2004) The New Circular Polariscope and the Senarmont Setup With Electro-Optic Modulation for Measuring the Optical Linear Birefringent Media Properties. *Opt. Commun*. 237, 267-273.

[9] Rochford,K.B.,Rose,A.H.,& Wang,C.M. (1997) NIST Study Investigates Retardance Uncertainty. *Laser Focus World.*, 223-227.

6. Acknowledgment

This research was partially supported by National Science Council of Taiwan Republic of China through contract number 94-2212-E-269-005.