A sensitive method of determining optic axis azimuth based on laser feedback*

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(Received 22 February 2013; revised manuscript received 4 July 2013)

A sensitive method to determine the optic axis azimuth of the birefringence element is presented, which is based on laser feedback. The phase difference between the two intensities in birefringence feedback changes with the angle between the optic axis of the birefringence element and laser original polarization. The phase difference is highly sensitive to the relative position of the optic axis and the laser original polarization. This method is used to highly precisely determine the optic axis azimuth, and is able to distinguish between the fast axis and the slow axis of the birefringence element. Theoretical analysis and experimental results are both demonstrated.

Keywords: laser feedback, optic axis, differential method, phase difference

PACS: 42.62.Eh, 42.62.–b, 78.20.Fm **DOI:** 10.1088/1674-1056/22/12/124205

1. Introduction

The birefringence effect exists in many kinds of materials, such as wave plates, photomask windows, fiber, liquid crystal, etc. Birefringence elements are widely used and play important roles in optical systems. Optic axis orientation influences the performances of birefringence elements and also affects the accuracy of optical systems. For the wave plate used in an interferometer, the optic axis must be accurately tuned to avoid polarization cross coupling (PCC), because PCC leads to a serious nonlinear effect and affects the accuracy of resolution and measurement. Hence, it is important to determine the optic axis azimuth precisely in birefringence elements.

Some methods have shown how to identify the optic axis, including the system utilizing a photo-elastic modulator,[1] by using an infrared spectrometer,[2] reflection perpendicular-incidence ellipsometry (PIE),[3] heterodyne interferometric technique, and discrimination technique of using two light beams with different wavelengths.[4]

Among the above-mentioned methods of determining the optic axis azimuth determination, some are complicated and expensive in systems, and some do not exhibit the high performances in measurement accuracy and resolution required by industry and science.

In this paper, a sensitive method of determining the optic axis based on birefringence laser feedback is demonstrated. Laser intensity can be modulated by reflecting part of the output light into the laser cavity by a mirror, which is called feedback effect, first reported by King and Steward[5] in the 1960s. The feedback system has the advantages of simplicity and self-alignment, and lots of interest has been aroused in optical feedback. Feedback phenomenon has been widely used in the fields of displacement,[6,7] Doppler velocity,[8–10] absolute distance[11–13] and retardation measurement.[14]

In our experiment, we chose a quarter wave plate, which is made of quartz, as the measurement sample. Quartz is a positive uniaxial crystal. Quartz crystal is cut to make the optic axis parallel to the surface when being used as a phase retardation element as shown in Fig. 1.

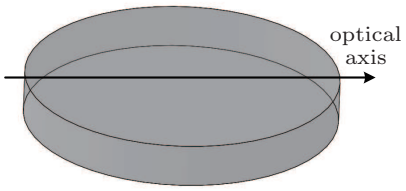


Fig. 1. Optic axis azimuth of quartz quarter-wave plate.

2. Experimental setup

The layout of experimental setup is shown in Fig. 2, which has a simple linear configuration. The setup consists of three parts: laser, feedback part, and detection part.

The laser is an intra-cavity HeNe laser which operates in a single longitudinal mode with linear polarization and its working wavelength is 632.8 nm. The ratios between gaseous pressures in the laser tube are He:Ne = 9:1 and Ne_{20}:Ne_{22} = 1:1. The reflectivity values of cavity mirrors M_1 and M_2 are 99.5% and 99%, respectively. The cavity length is 140 mm.

The feedback part is made of wave plate (WP), feedback mirror (M_3) and piezoelectric transducer (PZT). M_3 moves back and forth pulled by PZT which is driven by a triangular wave voltage. The triangular wave voltage is generated by PZT driven circuit AMP. M_3 is an ordinary glass plate without

*Project supported by the Natural Science Foundation of Beijing, China (Grant No. 3091002).

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any coating. The feedback cavity is formed by M_3 and M_2. WP is placed in the light path, thus forming a birefringence feedback cavity. The angle between the original polarization direction and the optic axis of WP can be tuned conveniently.

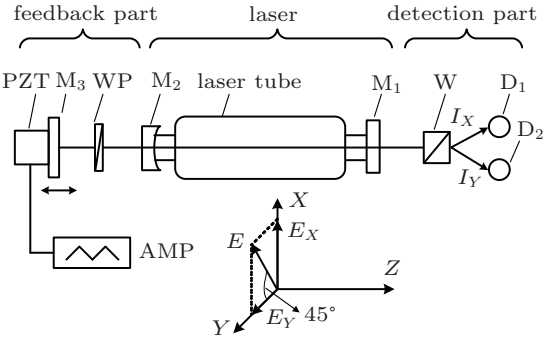


Fig. 2. Schematic diagram of experimental setup and original coordinates. PZT: piezoelectric transducer, M_3: feedback mirror, WP: wave plate, M_1 and M_2: cavity mirrors, W: Wollaston prism, D_1 and D_2: photoelectric detectors, AMP and PZT: driven circuits.

The detection part consists of Wollaston prism W and photoelectric detectors D_1, D_2. Wollaston prism (W) is adjusted to make the angle between the original polarization direction and optic axes of W reach 45°. The laser outputs linear polarization light without feedback. The light E which outputs from M_1 is split by W into two beams in the orthogonally polarized directions, the X direction and Y direction, and their intensities (I_X and I_Y) are detected by D_1 and D_2, respectively.

In experiment, when WP is removed, the feedback cavity is isotropic, and the laser still outputs linear polarization. I_X and I_Y are in-phase. Then we place WP into the experimental system, and the feedback cavity becomes anisotropic. When WP rolls around the laser axis, the laser will output elliptical polarization in most cases. Then, there will be phase difference between I_X and I_Y. But, when either fast axis or slow axis of WP is parallel to the original polarization, the laser still outputs linear polarization. I_X and I_Y are also in-phase. Then we can determine the direction of either fast axis or slow axis of WP. This is a kind of method with high sensitivity, which will be discussed in detail later.

3. Theoretical analysis

Various theories based on the model of equivalent cavity of Fabry–Perot interferometer have been developed and used primarily for explaining the feedback phenomenon. In our study here, a theory model with considering the birefringence feedback cavity is presented.

We consider the simplest feedback case first, by using M_3 as feedback mirror directly, in the absence of WP. The light beam can be divided into two parts. One is reflected by cavity mirror M_2, traveling in resonant cavity. The other part transmits through M_2, and part of it is reflected into the resonant cavity again. These two parts are superposed in the resonant cavity, and the feedback effect is generated. We denote the electric vector in front of M_2 with feedback as $E_0(t)$, and as mentioned above, $E_0(t)$ is divided into two parts and when these two parts come back to the same location, they combine together to form $E_0(t)$ again. Hence, we can obtain that

$$\begin{aligned} E_0(t) &= r_1 r_2 \exp(\mathrm{i}2knL_0 + 2gL_0)E_0(t) \\ &\quad + t_2^2 r_3 r_1 \xi \exp[\mathrm{i}wk(l+nL_0) + 2gL_0]E_0(t), \end{aligned} \tag{1}$$

where r_1, r_2, and r_3 are the reflection coefficients of M_1, M_2, and M_3, respectively. Also, t_2 is the transmission coefficient of M_2, ξ is the feedback coupling factor when the laser beam is reflected back into the resonant cavity which is a constant when the laser and M_3 is chosen, k is the wave number, L_0 and l are the resonant cavity and feedback cavity length, respectively, g is the linear gain per unit length due to the simulated emission inside the resonant cavity in the presence of feedback, and n is the refractive index of the laser gas.

Equation (1) can be expressed as

$$1 = r_1 r_2 \exp(\mathrm{i}2knL_0 + 2gL_0[1 + \beta \exp(\mathrm{i}2kl)], \tag{2}$$

where $\beta = t_2^2 r_3 \xi / r_2$, equation (2) is solved as

$$g = -\frac{1}{2L_0}[\ln(r_1 r_2) + \beta \cos(2kl)]. \tag{3}$$

If there is no feedback in the absence of M_3, and $\beta = 0$, the linear gain per unit length without feedback is

$$g = -\frac{1}{2L_0}\ln(r_1 r_2). \tag{4}$$

So the excess gain g with optical feedback can be expressed as

$$\Delta g = -\frac{1}{2L_0}\beta \cos(2kl). \tag{5}$$

Then we consider the birefringence feedback with wave plate WP set in the feedback cavity. Owing to the wave plate, the feedback cavity becomes a birefringence one. To make it easy to understand, we assume that either the fast axis or the slow axis is parallel to the coordinate axis (X direction or Y direction) initially. Hence, the angle between $E_0(t)$ and the fast axis (or slow axis) of WP is 45°. The electric vector in the feedback cavity can be divided into two parts whose directions are parallel to the X and Y directions, respectively. Correspondingly, we also divide $E_0(t)$ into $E_{0X}(t)$ and $E_{0Y}(t)$ along the X and Y directions. Feedback effects are generated in the two directions. With a similar analysis method to that used for Eqs. (1)–(5), we can obtain the excess gain with birefringence feedback along the two directions as

$$\begin{aligned} \Delta gX &= -\frac{1}{2L_0}\beta \cos(2kl_X), \\ \Delta gY &= -\frac{1}{2L_0}\beta \cos(2kl_Y). \end{aligned} \tag{6}$$

Here, l_X and l_Y are the lengths of feedback cavity along the X direction and Y direction, respectively. They are different because of birefringence feedback due to WP. The laser intensity can be expressed as[15]

$$I = I_0(1 - K\Delta g), \tag{7}$$

where K is a constant and I_0 is the initial intensity without feedback. Considering Eqs. (6) and (7) simultaneously, the laser output intensity with birefringence feedback can be expressed as

$$I_X = I_{0X}[1+\eta\cos(\varphi)],$$
$$I_Y = I_{0Y}[1+\eta\cos(\varphi+2\delta)]. \quad (8)$$

Here, $\eta = K\beta/2L_0$, and $\varphi = 2klx$. From Eq. (8), we can see that there is a phase difference of between I_X and I_Y. δ can be expressed as

$$\delta = d(n_Y - n_X)\cdot 2\pi/\lambda, \quad (9)$$

where d is the thickness of WP, λ is wavelength of laser, n_X and n_Y are refractive indices of WP along the X and Y directions, respectively. When the slow axis is parallel to the Y direction, $n_Y - n_X$ equals $n_e - n_o$, where n_e and n_o are the refractive indices of WP along the slow axis and fast axis, respectively, because quartz is a positive uniaxial crystal. Also, we know that $n_e > n_o$. δ equals retardation of WP at the special direction, and phase difference is twice the retardation of WP. When the fast axis is parallel to the Y direction, $n_Y - n_X$ equals $n_o - n_e$, which means that the phase difference between I_X and I_Y may be either positive or negative when WP is rolling around the laser axis. When the phase difference is zero, the fast axis or slow axis is parallel to the original laser polarization. Next, we will explain how to distinguish between the fast axis and slow axis in experiment.

The optic axis of WP is parallel to its surface. Hence, the cross section of the refractive index ellipsoid of WP in the X–Y plane is an ellipse. As shown in Fig. 3(a), when the slow axis is parallel to the Y direction initially, the phase difference between I_X and I_Y is positive, because n_e is larger than n_o. Then we rotate the WP anticlockwise, n_Y decreases while n_X increases. Phase difference 2δ also decreases to zero and then becomes negative. As shown in Fig. 3(b), when the fast axis is parallel to the Y direction initially, and then we rotate the WP anticlockwise, the phase difference 2δ which is negative originally increases to zero and then becomes positive. According to the difference mentioned above, we are able to distinguish between the fast axis and the slow axis of WP. For the same reason, the method is of high sensitivity.

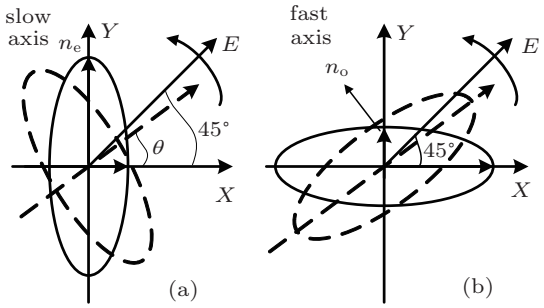


Fig. 3. Refractive index ellipsoid of WP in X–Y plane.

4. Experimental results

We take a quarter wave plate in our experiment for example. We place the WP into the feedback cavity and rotate it anticlockwise. When I_Y tends toward I_X as shown in Fig. 4(a), phase difference 2δ is positive. We continue to rotate WP anticlockwise, then we can obtain zero and negative phase difference sequentially. The results are shown in Figs. 4(b) and 4(c). When the zero phase difference is reached, the fast axis of WP is parallel to the original polarization at this moment. For quartz, which is a positive uniaxial crystal, the fast axis is the optic axis. Then we can determine the azimuth of the optic axis of WP.

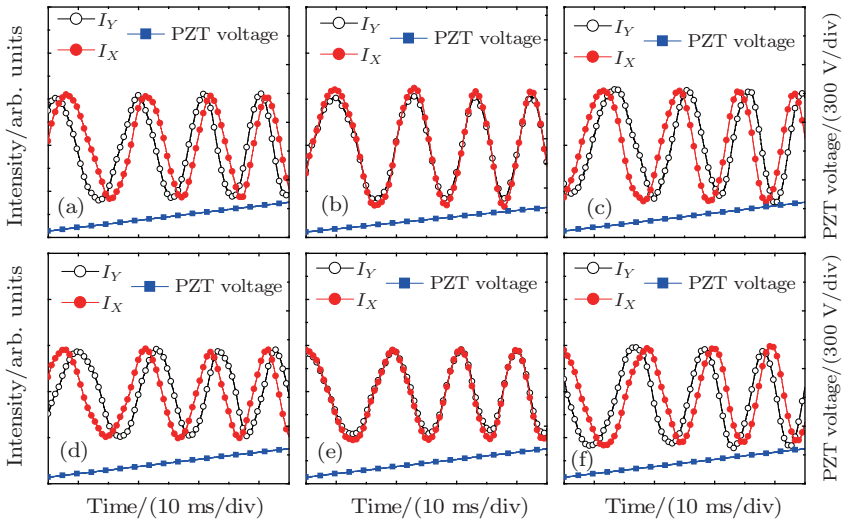


Fig. 4. (color online) Experimental results when WP is placed in feedback cavity and rotated anticlockwise.

If the negative phase difference is first obtained, then the zero and positive phase difference are obtained when rotating WP anticlockwise. The results are shown in Figs. 4(d)–4(f). When the zero phase difference is obtained, the slow axis of WP is parallel to the original polarization at this moment. So we can determine the azimuth of the fast axis and slow axis simultaneously.

5. Discussion

The analyses and experiments mentioned above are based on the fact that the length of the feedback cavity is increasing under the action by PZT. We also observe the phase differences between I_X and I_Y when the length of the feedback cavity is increasing and decreasing subsequently, which is tuned by PZT. Experimental curve is shown in Fig. 5.

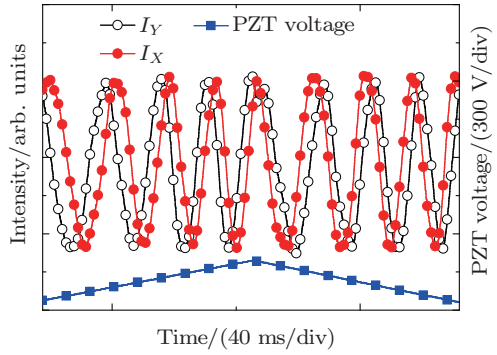


Fig. 5. (color online) Experimental results when PZT driven voltage increases and decreases.

From Fig. 5 it follows that the phase differences between I_X and I_Y appear oppositely in signs when PZT driven voltage increases and decreases. When PZT driven voltage increases, the laser intensity I_Y tends toward I_X. While PZT driven voltage decreases, I_X tends toward I_Y. This offers an effective method to improve the phase sensitivity when judging whether phase difference between I_X and I_Y is zero. By simultaneously observing the phase differences when PZT driven voltage increases and decreases, the sensitivity of phase detection increases twice. This is the second reason why the method is highly sensitive.

As shown in Fig. 3, θ is the angle between the fast axis (optic axis) and the X direction. According to analytical geometry, n_X and n_Y can be expressed as

$$n_X = n_e n_o / \sqrt{(n_o \sin\theta)^2 (n_e \cos\theta)^2},$$
$$n_Y = n_e n_o / \sqrt{(n_o \cos\theta)^2 (n_e \sin\theta)^2}. \quad (10)$$

The phase difference detection resolution is superior to 0.2°, according to Eqs. (8)–(10), the resolution of determination on optic axis azimuth is superior to 0.03° for a quarter wave plate.

If the wave plate is made of negative uniaxial crystal, the method still works. But the phase difference is opposite to that of positive uniaxial crystal in the same condition.

6. Conclusion

In this paper, we present a sensitive method to determine the optic axis azimuth of the birefringence element based on the laser feedback effect. The experiment is carried out on a linear, compact, low cost, and on-line system. Theoretical analysis and experimental results are in good agreement with each other. The phase difference between intensity signals of the two orthogonal polarizations is highly sensitive to the relative position of the optic axis and the laser original polarization. The resolution of determination on the optic axis azimuth is superior to 0.03° for the quarter wave plate.

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