Polarizing Triangular Cyclic Interferometer for Characterizing Optical Samples with Birefringent Properties

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ABSTRACT

This paper presents the polarizing triangular cyclic interferometer (pTCi) for characterizing optical samples with birefringent properties such as half- and quarter-wave plates. The interferometric system was set up to analyze the phase retardation of wave retarders in both qualitative and quantitative aspects. For the qualitative aspect, the distinct signal outputs from the inspected birefringent components oriented at particular angles are employed to distinguish different types of optical devices. For the quantitative aspect, the same arrangement could determine the phase difference (γ) of unknown retarders, so that it could be used to characterize types of samples. The experimental results showed the corresponding results obtained from both mentioned aspects where γ were measured to be 89.62° and 177.17° for half- and quarter-wave plates, respectively. The pTCi has been proved to be a proper scheme to characterize optical samples with birefringent properties.

Keywords: Polarizing triangular cyclic interferometer, Birefringent material, Jones calculus

1. INTRODUCTION

The interferometry is an important and well-known optical technique that can be used to determine an optical phase shift introduced by a sample such as wave retarders [1-5]. For a particular interferometer technique, a rotating linear polarized light is created and used as a probing beam to characterize polarizing samples. In addition, a mathematical treatment known as Jones calculus is employed to confirm the experimental results from the interferometer [6-7].

In this study, the polarizing triangular cyclic interferometer (pTCi) is proposed to characterize optical samples with different properties. Also, the Jones calculus is formulated according to the arrangement so as to verify the operation of the setup theoretically. Two samples composed of half- and quarter-wave retarders are chosen because of their common usage in optics experiments and research. The investigation is divided into two parts. In the first part, unique distinctions of the output waveform patterns are utilized as an indicator to notify types of wave retarders under examination. The method is purely based on a visual comparison and, therefore, this is called the qualitative aspect. In the second part, the information of intensities can also be extracted from the output signals. With a simple mathematical expression, a quantity of the phase shift introduced by a particular wave retarder is revealed. The numerical outcome can be used to confirm the conclusion from the qualitative aspect. This part of the study is called the quantitative aspect.

2. THEORETICAL BACKGROUND AND PRINCIPLE OF OPERATION

The schematic diagram of the pTCi is illustrated in Fig. 1. In this interferometer, a HWP is aligned at 22.5° with respect to a reference axis which is defined by the optical plane of the setup. The beam out of HWP travels into a polarizing beam splitter (PBS) and is divided into two orthogonal linear polarized lights. Each beam follows a separate path as shown in

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Fig. 1. According to the Jones matrix formalism, the vector of a light beam output, emerging from the setup and captured by the photodetector, is given by [8]

$$V_{out} = P(45^o)QWP(45^o)PBS \bullet \left[V_{aT'sample} + V_{aR'sample} \right] \quad (1)$$

$$V_{out} = P(45^o)QWP(45^o)PBS \bullet [\underbrace{M1 \bullet Sample(\gamma,\psi) \bullet PZT(M2) \bullet V_{aT}}_{V_{aT'sample}} + \underbrace{PZT(M2) \bullet Sample(\gamma,\psi) \bullet M1 \bullet V_{aR}}_{V_{aR'sample}}] \quad (2)$$

where *P, QWP, PBS, M1, Sample* and *PZT(M2)* represent Jones matrices for polarizer, quarter wave plate, polarizing beam splitter, mirror *M1*, optical sample under investigation and mirror *M2* attached to a piezoelectric transducer (PZT), respectively. V_{aT} and V_{aR} are the Jones vectors for transmitted and reflected beams with initial phase Δ_0 and angular frequency ω_0 from a light source.

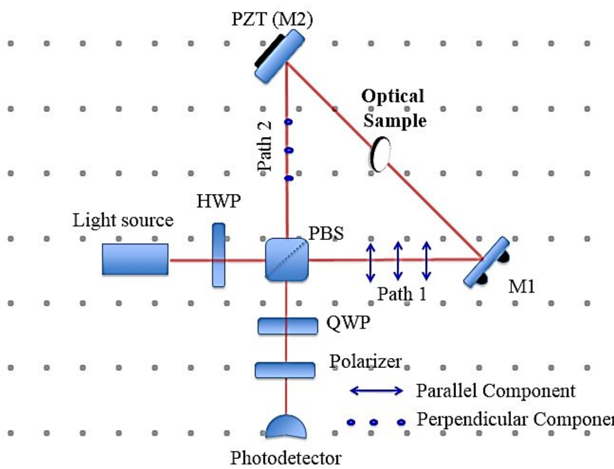


Figure 1. The schematic diagram of the polarizing triangular cyclic interferometer setup

Both beams travel through an optical sample oriented with its fast axis at an angle relative to a reference axis. As a result, the intensity of the emerging beam perceived by the photodetector ($I = V_{out} \bullet V^*_{out}$) can be formulated as Eqs. (3), (4), and (5) depending on the sample retardance (γ) and orientation (ψ). In this study, HWP and QWP are chosen to be examined samples and each sample is oriented at $\psi = 0^o$, 45^o and 90^o with respect to the reference. Therefore, the intensity outputs corresponding to any phase retardation and chosen orientations of the sample are written as

$$I_{\text{sample}}(\gamma, \psi = 0^\circ) = V_o^2 \cos^2(\Omega t) \quad (3)$$

$$I_{\text{sample}}(\gamma, \psi = 45^\circ) = 4V_o^2 \cos^2[\frac{\gamma}{2} + \Omega t] \quad (4)$$

$$I_{\text{sample}}(\gamma, \psi = 90^\circ) = V_o^2 \cos^2(\Omega t) \quad (5)$$

where V_o is the amplitude of the incident beam and Ω is the modulating frequency introduced by PZT.

Determination of the phase retardation by intensity signal waveform

Eq.(4) is the key expression to determine the phase retardation of inspected optical samples for both qualitative and quantitative aspects. In terms of the qualitative aspect, the optical samples, such as HWP and QWP, introduce different waveforms due to the beam propagation within the cyclic path, so that the distinction can be clearly observed when the sample oriented at 45° to the reference. To verify the characterization, the output light intensity signals, $I_{\text{sample}}(\gamma, \psi = 0°)$, $I_{sample}(\gamma, \psi = 45°)$, and $I_{\text{sample}}(\gamma, \psi = 90°)$ described as in Fig. 2 are used in the calculation for quantitative part.

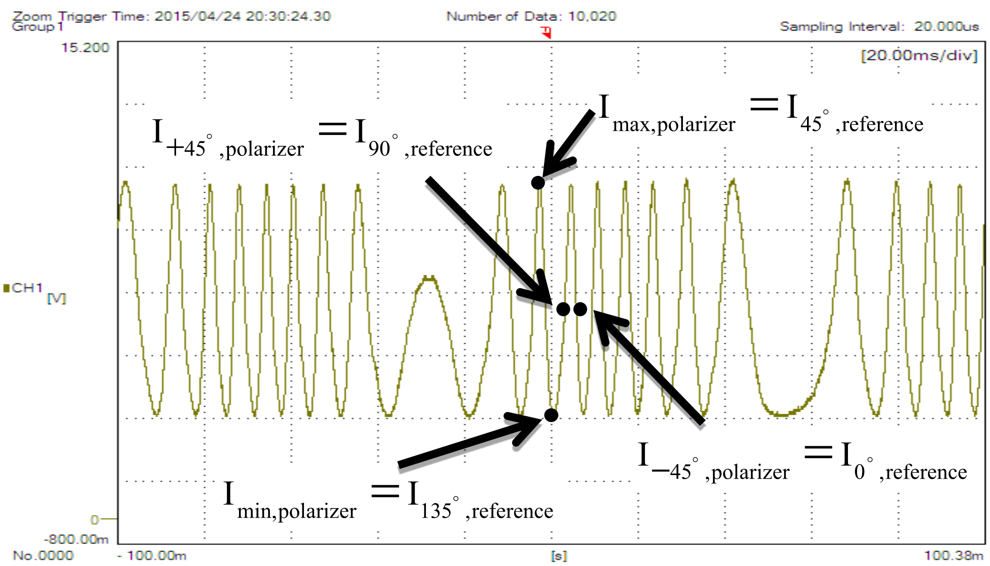
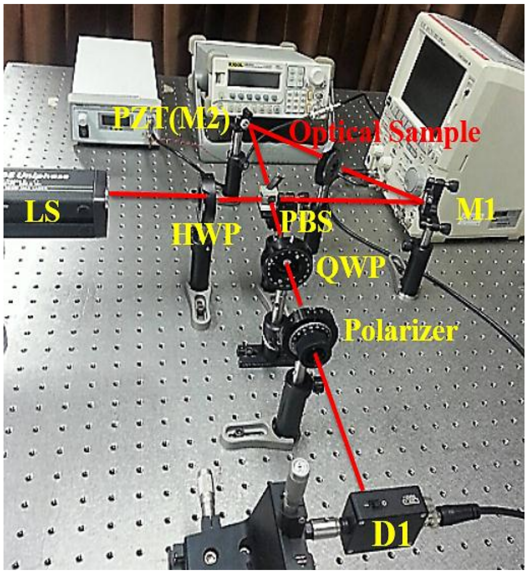


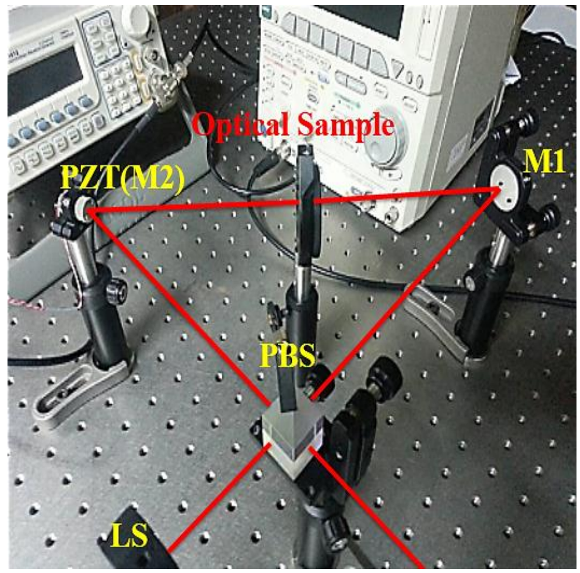
Figure 2. The experimental waveform signal taken from the oscilloscope and the intensity components at various output light orientations.

After a sample is inserted in the interferometer, the polarization state of the signal output is still the rotating linearly polarized light [1]. The signal intensity, when the output beam orientation being parallel to the transmission axis of the polarizer at the end setup, is obviously maximum. Because this output orientation is actually at 45° with respect to the reference, the intensity is then assigned as $I_{45°,reference}$. For the same reason, the rotating linearly polarized light oriented at 45° with respect to the transmission axis of the polarization is given as $I_{90°,reference}$. Similarly, when the rotating linearly polarized light oriented perpendicular and -45° with respect to the transmission axis, the intensities are assigned as $I_{135°,reference}$ and $I_{0°,reference}$, respectively. The required intensities $I_{\text{sample}}(\gamma, \psi)$ can be achieved from experimental data acquisition by MATLAB program [10]. By using Eq. (3) and (4) and aforementioned intensities, γ can be determined by

$$\gamma = 2\cos^{-1}\left[\frac{1}{2}\sqrt{\frac{I_{sample}(\gamma, \psi = 45^o)}{I_{sample}(\gamma, \psi = 0^o)}}\right] \tag{6}$$

3. THE EXPERIMENTAL SETUP





(a) (b)

Figure 3. The photograph of (a) the complete arrangement of the polarizing triangular cyclic interferometer (b) the triangular cyclic part with inserted optical sample.

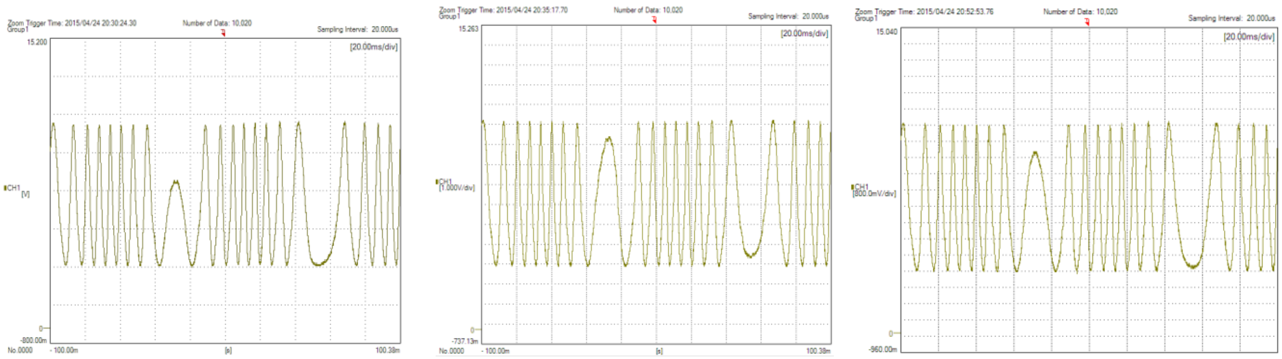
The experimental setup of the proposed pTCi is depicted in Fig 3(a). The triangular path of the cyclic interferometer is formed by polarizing beam splitter (PBS) and the mirrors (M1 and M2) as illustrated in Fig 3(b). A 632.8 nm HeNe laser is used as a light source. The amplitude of an expanded and collimated laser beam polarized at 45^o with respect to the reference is split equally by a PBS. The transmitted and reflected optical beam components from two exit faces of the PBS consist of two orthogonal linearly polarized light beams. A transparent phase sample (e.g. half- or quarter-wave retarder) is inserted in between M1 and M2, as shown in Fig. 3(b). The M2 is attached to the PZT so that the propagation beams can be modulated. A quarter-wave plate is placed at the output of the interferometer with one of its principle direction equally inclined to 45^o, so that the two linear polarized beams are transformed into two circularly polarized beams with opposite orientations and then combine to give a rotating linearly polarized light. Then, a linear polarizer P(θ), oriented at 45^o to the reference, facilitates the discovery of the polarization phase shifting. With the optical axis of the sample chosen to be 0^o, 45^o and 90^o, the interference fringes represented by output intensity waveform can be seen on the oscilloscope.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

A set of known wave plates were used as inspected samples to evaluate the performance of the pTCi system. The experimental results were investigated in qualitative and quantitative aspects. The description and results for each aspect is presented as follows.

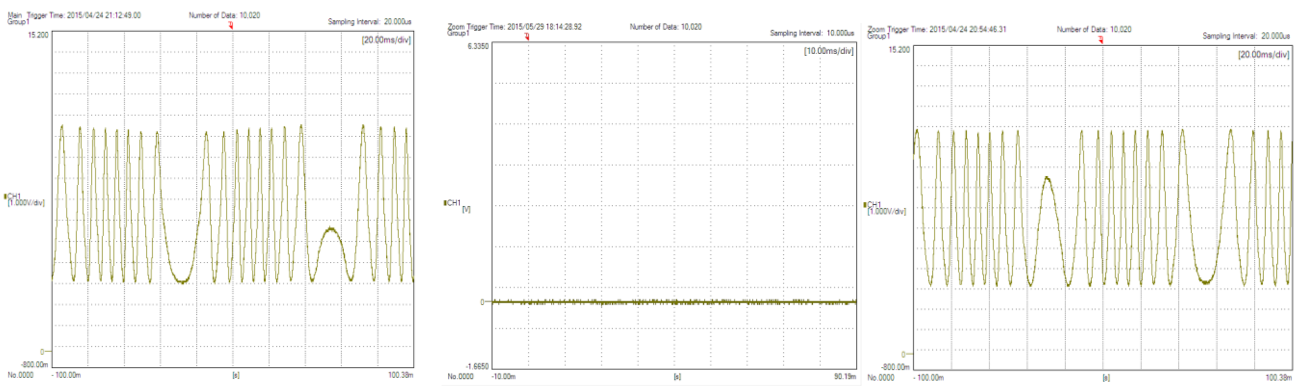
The qualitative aspect

For the qualitative aspect, two known wave plate retarders were examined so as to check the performance of the triangular cyclic interferometer. In brief, the specimens under investigation were composed of two fixed phase shift devices; i.e., quarter- and half-wave plates. The wave plate sample was inserted between M1 and M2. The optics axis of the sample was selectively oriented to proper orientations including 0º, 45º and 90º with respect to the reference. The waveforms of the output signals corresponding to the retardance at particular orientation were shown in Fig. 4 and Fig. 5. Due to the phase retardation difference as shown in Fig. 4 and Fig. 5, output signals from the two samples were clearly distinguishable.



$I_{0°,reference}$ = 3.48±0.14% $I_{45°,reference}$ = 7.01±0.04% $I_{90°,reference}$ = 3.69±0.10%

Figure 4. The intensity waveforms taken from an oscilloscope when QWP is oriented at 0º, 45º and 90º.



$I_{0°,reference}$ = 3.43±0.07% $I_{45°,reference}$ = 0.008±0.04% $I_{90°,reference}$ = 3.80±0.12%

Figure 5. The intensity waveforms taken from an oscilloscope when HWP is oriented at 0º, 45º and 90º.

The dissimilar waveforms suggest that the output signals from the inserted birefringence components, oriented at particular angles become a simple indicator to separate types of samples. The matter of distinction becomes very obvious at a particular orientation when comparing waveforms from QWP and HWP. Under all chosen orientations, the waveforms due to the introduction of the QWP are exactly the same as the reference. This suggests that the insertion of the QWP oriented at specific directions has no effect on the operation of the pTCi. This is because the insertion of QWP is just equivalent to an introduction of a phase shifter between two orthogonal circular polarized light beams. The recombination of the circular polarized light beams still gives a rotating linear polarized light beam. The same explanation can also be applied to the two orientations, i.e. 0º and 90º, of the HWP. The waveform from the HWP at 45º becomes a clear notification which can be used to separate the insertion of the HWP from QWP. The output magnitude is roughly nil because the HWP at 45º simply diverts the two linear polarized beams propagating to the PBS and they are screened out by property of PBS. The output waveforms from the pTCi have already been proved to be a valuable tool for separating different types of polarizing components under investigation. This method provides a fast and effective means to detect and identify different waveform patterns of the output signals from the pTCi.

The quantitative aspect

By monitoring the intensities of the output signals, mentioned in Eqs.(3), (4) and (5), the numerical value of the phase shift γ introduced by the sample could be calculated using Eq.(6), the γ can be determined. Figs. 4 and 5 show corresponding intensities and their numerical values were extracted by a MATLAB program. The measured intensity data from Fig. 4 yielded $I_{0°,reference}$ = 3.48±0.14%, $I_{45°,reference}$ = 7.01±0.04%, and $I_{90°,reference}$ = 3.69±0.10%. Therefore, γ = 89.6º ± 0.3º for the QWP. Similarly, Fig. 5 showed the measured data of $I_{0°,reference}$ = 3.43±0.07%, $I_{45°,reference}$ = 0.008±0.04%, and $I_{90°,reference}$ = 3.80±0.12%, thus, this yielded γ = 177.2 º ± 0.4º for the HWP. These achieved numerical values strongly confirm the conclusion obtained from the qualitative aspect in the earlier part.

5. CONCLUSIONS

The polarizing triangular cyclic interferometer for describing birefringent optical samples is proposed in this paper. The experiments were carried out to verify the samples from both qualitative and quantitative characteristics. For quantitative aspect, the distinct light outputs from investigated samples oriented at certain angles were used to distinguish types of optical retarders. The experimental results from the qualitative aspect were consistent with the ones from the quantitative aspect as γ were measured to be 89.62° and 177.17° for HWP and QWP, respectively. From the theoretical analysis and experimental results presented here, it is obvious that pTCi can be used as a fast and simple method to distinguish and evaluate phase retardation introduced by optically transmissive samples.

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