Generation of the Rotating Linearly Polarized Light Using the Triangular Cyclic Interferometer

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Abstract—This paper presents the linearly light generator using triangular cyclic interferometer. The Jones calculus was used for investigating the potential of the setup to generate the rotating linearly polarized light. The output from the interferometer could be adjusted to a designed angular position. The experimental results were compared to the simulation ones from mathematical analysis. It showed that the rotating linearly polarized light from this scheme was found to be in a good agreement with expected theoretical outcome. Also, it yielded the decent degree of polarization of 96.82 \pm 3.5%. Thus, the proposed system is suitable for verifying characteristics of materials by way of non-contact measurement.

Keywords—Cyclic interferometer; rotating linearly polarized light; Jones calculus

I. INTRODUCTION

The interferometry is an important and well-known optical technique not only in the phase measurement, but also in the sample investigation [1]. This method is widely used in applications because it offers a non-contact many measurement. The production of rotating linearly polarized light also plays a vital role in the thin film measurement. Some conventional interferometers were reported to be used to generate such a polarized light for characterizing thin-film [2,3]. However, conventional schemes such as Michelson and Mach-Zehnder interferometers require several optical devices in order to create linearly polarized light. In contrast, cyclic interferometer uses less number of equipment than others but it still can deliver good results [4]. Results from the cyclic interferometer are stable and can be well applied to rug surfaces [5]. Cyclic interferometer is widely used in both laboratories and industries to determine optical sample quality for surface and phase characteristics [6]. Cyclic interferometer can be configured in two forms: triangular and rectangular patterns [7]. However, triangular arrangement was proved to be easy to implement.

In mathematical treatments, the Jones calculus is generally employed to analyze polarization-based optical systems [8,9]. The mathematical outcome from the Jones calculus can be easily used to verify whether the light is the rotating linearly polarized light or not.

In this work, we present an alternative approach to produce the linearly polarized light using triangular cyclic interferometer. Jones calculus is used to characterize the interferometry schematic setup and to verify the generated output light. The paper is organized as follow: Section 2 introduces related theories and backgrounds; Section 3 and 4 present an experimental setup and results, respectively. Finally, conclusion and discussion can be found in section 5.

II. THEORETICAL BACKGROUNDS

The schematic setup of the triangular cyclic interferometer is depicted in Fig. 1. The input beam to the cyclic interferometer is the linear polarized light. The beam is aligned by adjusting a half wave plate (HWP) to be 45° with respect to the axis of a polarizing beam splitter (PBS). From Fig. 1, the Jones vector representing an electric field for light going into the PBS after passing through HWP can be expressed as

$$V_a = \frac{1}{\sqrt{2}} \begin{bmatrix} 1\\1 \end{bmatrix} e^{i(\Delta_o - \omega_o t)} \tag{1}$$

where Δ_0 and ω_0 are initial phase and angular frequency of an incident light, respectively. The polarizing beam splitter separates the input light into orthogonally linear components. The

This research is supported by A New Researcher Scholarship of Coordinating Center for Thai Government Science and Technology Scholarship Students (CSTS), National Science and Technology Development Agency (NSTDA).

Jones matrix of the polarizing beam splitter can be described with two transformation matrixes as

$$T_{PBT} = \begin{bmatrix} 1 & 0\\ 0 & 0 \end{bmatrix}$$
(2a)

and

$$T_{PBR} = \begin{bmatrix} 0 & 0\\ 0 & 1 \end{bmatrix}$$
(2b)

where T_{PBT} and T_{PBR} refer to transmission and reflection components, respectively. Therefore, the electric field of transmitted light, V_{aT} , out of the PBS can be found by

$$V_{aT} = T_{PBT} \bullet V_a = \frac{1}{\sqrt{2}} \begin{bmatrix} 1\\0 \end{bmatrix} e^{j(\omega_o - \omega_o I)}$$
(3a)

and the reflected light electric field V_{aR} can be written as

$$V_{aR} = T_{PBR} \cdot V_a = \frac{1}{\sqrt{2}} \begin{bmatrix} 0\\1 \end{bmatrix} e^{j(\omega_o - \omega_o t)}$$
(3b)

From (3a) and (3b), it is evident that V_{aT} and V_{aR} are linearly parallel and perpendicular with respect to the axis of the PBS, respectively. Then, both beams will experience different additional phase retardation corresponding to their propagating routes. A piezoelectric transducer (PZT), attached to a mirror1 (M1), is used to modulate the light with frequency Ω . The transmitted light travels through a mirror 2 (M2) and PZT(M1) before being incident on the PBS once again. The electric field of light in this path (path 1 in Fig. 1) can be found by $V_{aT'} = PBS \cdot M2 \cdot PZT(M1) \cdot V_{aT}$ and this yields

$$V_{aT'} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1\\0 \end{bmatrix} e^{i[(\Delta_0 + \Delta_2 + \Delta_1) - (\omega_0 + \Omega)t]}$$
(4a)

where Δ_1 and Δ_2 are phase shifts introduced from the beam propagation through PZT(M1) and M2, respectively. On the other hand, the electric field of reflected light, which propagates along path 2 shown in Fig. 1, can be determined by $V_{abc} = PBS \cdot PZT(M1) \cdot M2 \cdot V_{abc}$. It can be rewritten as

$$V_{aR} = \frac{1}{\sqrt{2}} \begin{bmatrix} 0\\1 \end{bmatrix} e^{i[(\Delta_0 + \Delta_1 + \Delta_2) - (\omega_0 + \Omega)t]}$$
(4b)

Eventually, two optical beams recombine at the PBS and then travel through a quarter-wave plate (QWP) oriented at 45° with respect to the axis of the PBS. Jones vector of the output light out of QWP can be described as



Fig. 1.Schematic diagram of the triangular cyclic interferometer setup.

$$V_o = Q \bullet V_{aT'} + Q \bullet V_{aR'} \tag{5}$$

where Q is the Jones matrix of the quarter wave retarder. The matrix Q is given by

$$Q = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & i \\ i & 1 \end{bmatrix}$$
(6)

By substituting (4a), (4b), and (6) into (5), the Jones vector V_0 can be rewritten as

$$V_0 = \frac{1}{2} \begin{bmatrix} 1+i\\ 1+i \end{bmatrix} e^{i[(\Delta_0 + \Delta_1 + \Delta_2) - (\omega_o + \Omega)t]}$$
(7)

This process produces the left- and right-circular polarized lights. The recombination of both circular polarizations results in the generation of the rotating linearly polarized light. The expression of the output in (7) clearly corresponds to the state of light, and its oscillation is dependent on the modulation frequency Ω . The output light intensity *I* is found to be stable as $I = V_0 \cdot V_0^* = 1$ or constant.

Practically, the existence of the rotating linearly polarized light can be proved by putting light through an analyzer set at angle θ and observe the light intensity profile. In mathematical model, it can be done by using (7) along with an analyzer's Jones matrix, $P(\theta)$, to find Jones component for output electric field V_d expressed in (9).

$$P_{\theta} = \begin{bmatrix} \cos^2 \theta & \sin \theta \cos \theta \\ \sin \theta \cos \theta & \sin^2 \theta \end{bmatrix}$$
(8)

$$V_{\theta} = P(\theta) \bullet V_{\theta} \tag{9}$$

Thus, light intensity can be found by

$$I = V_{\theta} \cdot V_{\theta}^* = \frac{1}{2} \left[1 + \sin(\Omega t + 2\theta) \right]$$
(10)

Equation (10) shows the intensity of rotating linearly polarized light as a function of an angle θ set at an analyzer and frequency Ω from the modulation with PZT. The intensity profile, simulated from theoretical analysis, can be illustrated as shown in Fig. 2.



Fig. 2.The simulation of theoretical intensity profile from the rotating linearly polarized light corresponding to setting of analyzer and modulation frequency.

The quality of the output can be stated in terms of the degree of polarization or DOP as

$$DOP = \frac{I_{\max}}{I_{\max} + I_{\min}} \times 100\%$$
(11)

where *I_{max}* and *I_{min}* are maximum and minimum light intensity, respectively.

III. EXPERIMENTAL SETUP

The experimental setup shown in Fig. 3 was arranged according to the schematic diagram depicted in Fig. 1. A linearly polarized He-Ne laser with $\lambda = 633$ nm was used as a light source. With the help of a HWP, the light polarization can be rotated to any desired orientation. To obtain a linear polarized beam oriented at 45° with respect to the axis of the PBS, the HWP was adjusted at 22.5° with respect to the axis direction of the PBS.



Fig. 3.The experimental setup of triangular cyclic interferometer.

The incident light then was equally divided into two orthogonal linear polarized light beams by the PBS. Both polarized beams reflected twice with PZT(M1) and M2 and then recombined at the PBS. The state of the polarized beam along the path PBS \rightarrow PZT(M1) \rightarrow M2 \rightarrow PBS was linear perpendicular to the plane of the interferometer, while the state of the other one along the path PBS \rightarrow M2 \rightarrow PZT(M1) \rightarrow PBS was linear parallel to the plane of the interferometer. The QWP, oriented at 45°, with respect to the axis of the PBS, transformed the two linear polarized light beams into left- and right-circular polarized lights. Subsequently, the controllable linearly polarized light was achieved. The azimuth angle of this output linear polarized beam can be controlled by the modulation of M1 with PZT.

IV. EXPERIMENTAL RESULTS

The production of the rotating linearly polarized light was achieved and visually observed as a unique waveform on the oscilloscope. The obtained result shown in Fig. 4(a) was in a good agreement with the mathematical prediction illustrated in Fig. 2.The fringe pattern was displayed in Fig. 4(b). The results showed the maximum and minimum light intensity as 6.10 ± 0.11 V and 0.20 ± 0.07 V, respectively. This yielded the DOP of $96.82\pm 3.5\%$. In addition, the polarization state of the output light was clearly linearly polarized light and its orientation could be controlled by the modulation frequency from a PZT.



(a)



(b)

Fig. 4. Experimental results of the rotating linearly polarized light generator. (a) Light intensity profile. (b) Fringe pattern from light interference.

V. CONCLUSION AND DISCUSSION

In this report, the generator of rotating linearly polarized light using triangular cyclic interferometer were simulated and tested. Jones calculus was employed in mathematical analysis. The experimental results were consistent with simulation outcomes. It yielded a respectable DOP of $96.82\pm3.5\%$. The cyclic interferometer was insensitive to external vibration and, hence, a high quality of rotating linearly polarized light was generated and observed. With a minor improvement of the DOP, the system can certainly be applied for the phase retardation measurement for transparent and thin film samples. All of these findings have an implication that our proposed scheme could be used as a reliable system for generating linearly polarized beam.

ACKNOWLEDGEMENT

R.Keawon would like to express his gratitude to the Royal Thai Government for granting Thai Government Science and Technology Scholarship.

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