Error analysis and Stokes parameter measurement of rotating quarter-wave plate polarimeter*

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In this paper, we present a simple Stokes parameter measurement method for a rotating quarter-wave plate polarimeter. This method is used to construct a model to describe the principle of how the magnitudes of errors influence the deviation of the output light Stokes parameter, on the basis of accuracy analysis of the retardance error of the quarter-wave plate, the misalignment of the analyzing polarizer, and the phase shift of the measured signals, which will help us to determine the magnitudes of these errors and then to acquire the correct results of Stokes parameters. The method is validated by the experiments on left-handed circularly polarized and linear horizontal polarization beams. With the improved method, the maximum measurement deviations of Stokes parameters for these two different polarized states are reduced from 2.72% to 2.68%, and from 3.83% to 1.06% respectively. Our results demonstrate that the proposed method can be used as a promising approach to Stokes parameter measurement for a rotating quarter-wave plate polarimeter.

Keywords: polarization, stokes parameter detection, polarimeter

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1. Introduction

Polarized light is used in various areas, such as circular dichroism spectroscopy,[1,2] quantum cryptography,[3] object surface characteristics recognition[4] and all-optical magnetization recording.[5,6] Polarization is characterized by the Stokes vector,[7] so accurate Stokes parameter measurement plays a key role for these applications.

In the remote sensing field,[8] the polarization imagers need accurately calibrating in the laboratory by a specific input polarized state. The measurement accuracy of this input polarized state will directly influence the quality of calibration. A lot of efforts have been made to set up flexible systems to obtain high-precision, high-accuracy polarization state of light.[9] All these techniques are divided into simultaneous polarization measurement technique and time modulated polarization measurement technique. Simultaneous polarization measurements in general lead to loss in intensity and degradation of the signal-to-noise ratio.[10] For example, multiple-detector polarimeter measurement technique is hard to manage in low-intensity conditions. Moreover, it would be too complex to perfectly calibrate the detectors to guarantee the spatial uniformity and relative placement of these detectors.[11] Time modulated polarization measurement technique makes use of only one detector and modulates the light intensity with rotating quarter-wave plate, Pockels cells, liquid crystal variable retarder or other modulators.[4] Because the light polarization component detection that is used for calibrating the imager in laboratory in this paper does not require much in immediacy, in the study reported here we use time modulated measurement technique in polarimetric arrangement for simplicity, precision, accuracy, and stability.[9] The setup has a moving quarter-wave plate and a static polarizer.

The rotating quarter-wave plate polarimeter is capable of measuring any polarization state of incident light. In the use of conventional measurement method we encounter the problems that how to correctly determinate the measurement errors on the Stokes vector elements and on the other parameters derived from them.[12] The error due to the deviation from a $\pi/2$ retardation of the quarter-wave plate and incorrectly oriented analyzing polarizer can be corrected with the known retardance and the misalignment.[9,13] However, these imperfections and misalignments in the optical components of the polarimeter are difficult to measure.

In this paper, we try to determine the misalignment of the analyzing polarizer by constructing a model. This model describes the principle of how the magnitude of alignment error influences the deviation of the output light Stokes parameter measurement. The use of this model could improve the polarization state measurement accuracy without harsh demand for the initial alignment which will free up operating personnel's time and energy to devote to their most pressing task. The

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method is validated by the experiments on left-handed circularly polarized and linear horizontal polarization beams. In order to avoid polarization state-difference-caused deviations which result from the imperfect polarimeter, the deviations of Stokes parameters measured values changing with polarized states are also simulated. This simulation shows the estimations of measurement error for various input polarized states.

The rest of this paper is organized as follows. In Section 2, the apparatus and experimental methodology are given in detail. Subsequently, data sampling and estimation are presented. In Section 3, the error source is investigated and its influence on parameter measurement is also estimated. In Section 4, the Stokes parameter measurement results with and without the proposed methodology are reviewed. Finally, some conclusions are drawn from the present study in Section 5.

2. Apparatus and methodology

Stokes vector components are measured with a rotating quarter-wave plate polarimeter depicted in Fig. 1. A titanium-doped-sapphire laser MBR110 and an optical parametric oscillator are used to generate a laser source. Laser wavelength stability is about ± 0.001 nm with a linewidth less than 2.7×10^{-7} nm. Polarization generator system is composed of a vertical polarizer, P_1, followed by a quarter-wave plate, W_1, whose fast axis makes an angle θ with respect to the x axis. The polarimeter has two optical elements: a quarter-wave plate, W_2, and a linear polarizer, P_2. The P_1 and P_2 both have an extinction ratio of 10^5:1. Modulated signal passes through the analyzer and is recorded by a trap detector.

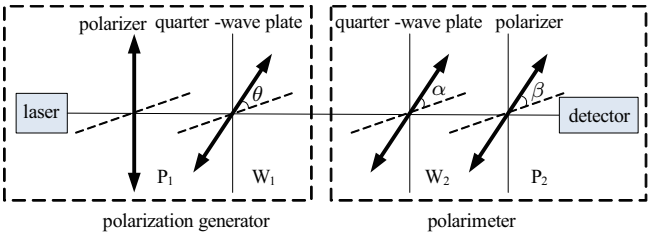


Fig. 1. (color online) Schematic layout of the rotating quarter-wave plate polarimeter.

The Stokes vectors that are incident on and exit from the polarimeter system are $\boldsymbol{S}_{\rm in} = [S_0, S_1, S_2, S_3]^{\rm T}$ and $\boldsymbol{S}_{\rm out} = [S_0', S_1', S_2', S_3']^{\rm T}$, respectively. The Muller matrix of W_2 with retardance δ and rotating azimuthal angle α is $\boldsymbol{M}_1(\delta, \alpha)$. The Muller matrix of P_2 whose transmission axis makes an angle β with respect to the $x-$axis is $\boldsymbol{M}_2(\beta)$. The Stokes vector emerging from P_2 can be expressed as

$$S_{\rm out} = M_2(\beta)M_1(\delta,\alpha)S_{\rm in}. \tag{1}$$

The measurable intensity is enclosed in the first term of the output Stokes vector $\boldsymbol{S}_{\rm out}$, and can be expressed as a function of δ, α, and β:

$$\begin{aligned} S_0' = {} & \frac{S_0}{2} + \frac{S_3}{2}\sin\delta\sin 2(\beta-\alpha) \\ & + \frac{1}{4}(S_1\cos 2\beta + S_2\sin 2\beta)(1+\cos\delta) \\ & + \frac{1}{4}(1-\cos\delta)[(S_1\sin 2\beta + S_2\cos 2\beta)\sin 4\alpha \\ & + \cos 4\alpha(S_1\cos 2\beta - S_2\sin 2\beta)]. \end{aligned} \tag{2}$$

The corresponding set up is shown in Fig. 2. Light from the laser passes through an attenuator and enters into a pupil. An attenuator is used to control the intensity on the trap detector. A pupil is added in order to block the deflected beam. The PBS splits the light into two beams, one is reference signal and is checked by power and wave meter (check whether the laser intensity and wavelength are sufficiently stable), and the other is test signal. Intensity variations are corrected by means of the reference signal. Test signal passes through the polarization generator system (various polarization states can be acquired from different rotating angles of W_1) and is then modulated and detected by the polarimeter system. The W_1, W_2 and P_2 are all mounted in the step motors (step 6° with a resolution of 0.05°) which are controlled by step motor controller. For the trap detector to be insensitive to the polarization incoming light,[14] nor to temperature (less than 0.02%/K), we use such a detector to measure modulated signals.

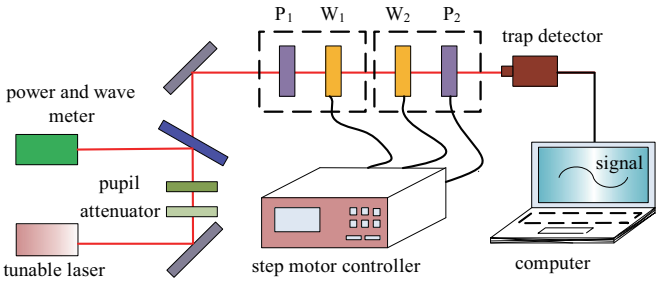


Fig. 2. (color online) Set up of the rotating quarter-wave plate polarimeter.

Here, the Stokes parameters of left-handed circularly polarized (LCP) and linear horizontal polarization (LHP) input beams at a wavelength of 870.3 nm are measured. Two necessary conditions need satisfying to generate the left-handed circularly polarized light: a phase difference of 90° and a unit amplitude ratio.[15] One way to achieve these is to set the angle θ to be 45° as shown in Fig. 1. By substituting normalized Stokes vector $[1, 0, 0, -1]^{\rm T}$ into Eq. (2), theoretically, intensity modulation function can be simplified into the following expression:

$$S_{\rm LCP}' = 1/2 + 1/2\sin(2\alpha). \tag{3}$$

The detector responds to the S_0 component of $\boldsymbol{S}_{\rm out}$ vector and generates a sinusoidal output as a function of angle α. Similarly, for LHP input beam, the normalized Stokes vector

is $[1, 1, 0, 0]^{\mathrm{T}}$, and intensity modulation function can be simplified as follows:

$$S'_{\mathrm{LHP}} = 3/4 + 1/4\cos(4\alpha). \tag{4}$$

The simulated data and the measured intensity (S'_0 component) are plotted in Fig. 3 for LCP and LHP light for one full rotation period of the quarter-wave plate.

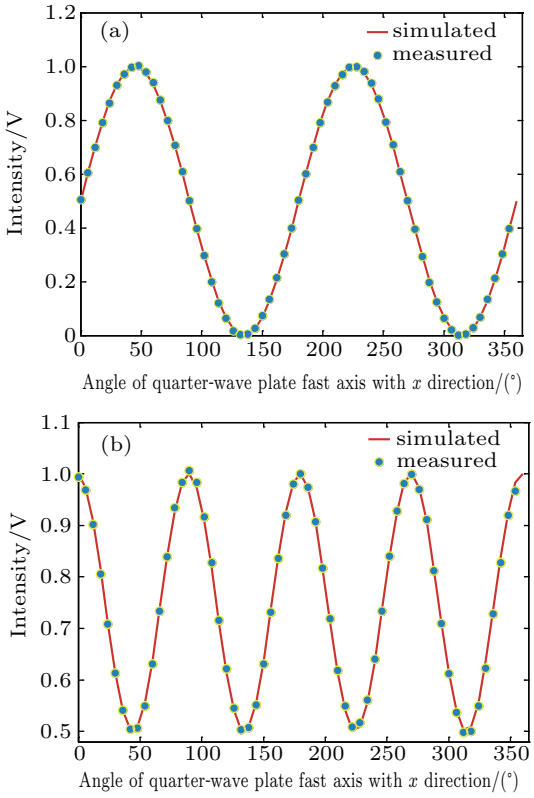


Fig. 3. (color online) Variations of simulated (solid curve) and measured intensity (solid circles) with angle of quarter-wave plate fast axis with respect to x direction for input beams of (a) LCP and (b) LHP.

3. Error analysis

Corresponding measures that could reduce the error of Stokes parameter measurement are proposed. Before experiment, the laser, the optical parametric oscillator and the trap detector are run for more than half an hour to reach the thermal equilibrium state with the environment. To reduce the effect of stray light and temperature fluctuations on optical elements, the experiments are conducted in dark environments and the laboratory temperature is controlled within $22\pm0.5^{\circ}$. Modulated intensity signals are corrected by subtracting the total noise variance from the measured signals. For linear polarizer, the extinction ratio is 10^5:1, making measurement relatively precise. A more profound analysis of the analyzer misalignment, retardance error and phase shift are presented in following subsections.

3.1. Phase shift

Equation (2) can be considered as a truncated Fourier series of a function of the angle α.[16] The coefficients of Fourier series are obtained by integrating the intensity Eq. (2) over one rotation period. Then the Stokes parameters are calculated as follows:

$$\begin{aligned}
S_0 &= \frac{1}{\pi}\int_0^{2\pi} S'_0(\alpha)\,\mathrm{d}a - \frac{2}{\pi}\int_0^{2\pi} S'_0(\alpha)\cos(4\alpha)\,\mathrm{d}\alpha,\\
S_1 &= \frac{4}{\pi}\int_0^{2\pi} S'_0(\alpha)\cos(4\alpha)\,\mathrm{d}\alpha,\\
S_2 &= \frac{4}{\pi}\int_0^{2\pi} S'_0(\alpha)\sin(4\alpha)\,\mathrm{d}\alpha,\\
S_3 &= -\frac{2}{\pi}\int_0^{2\pi} S'_0(\alpha)\sin(2\alpha)\,\mathrm{d}\alpha.
\end{aligned} \tag{5}$$

Integral expressions of Eq. (5) can be effectively calculated with Simpson algorithm. However, it is unavoidable that the placement of plates presents spatial offset from the appropriate location, which will result in a phase shift between the expected and the recorded test curves. The initial angular position of the quarter-wave plate will cause variations in the parameters calculation of Eq. (5). In order to obtain an accurate numerical calculation, first, phase shift, is determined by using a sine or cosine curve fit method around null intensities of the LCP and LHP signals. After non-linear curve fitting of sampling data, the phase shifts for LCP and LHP sampling signals are -1.02° and -3.87°, respectively. Second, error reduction algorithm is introduced by substituting phase shift into Simpson algorithm, which refers to plugging phase shift into Eq. (5) and then turning the integrals into sums to calculate the Stokes parameters, this algorithm is better than rectangle and parabolic method when the sampling number is small in one rotating period. A detailed introduction of this algorithm is given in Ref. [17].

3.2. Wave plate retardance

Note that for a perfect quarter-wave ($\lambda/4$) plate, the retardance angle $\delta = \pi/2$, where λ is the wavelength of light considered.[18] In fact, the uncertainties caused by multiple reflections, refraction and other physical effects dominate the uncertainties of retardance. Thus the retardance must be estimated prior to experiment because the measured intensity in Eq. (2) is sensitive to them.

The retardance of the rotating quarter-wave plate is determined with the crossed polarizer method suggested by Goldstein.[19] The mean of ten independent measurement values and the corresponding standard deviation based on this method are presented in Table 1. The W_{LCP} and W_{LHP} are the corrected quarter-wave plate retardance for measuring the LCP and LHP light.

Table 1. Values of corrected retardance δ for quarter-wave plate.

	Mean value δ/(°)	Standard deviation $\Delta\delta$/(°)
W_{LCP}	89.89	0.50
W_{LHP}	91.05	0.12

3.3. Analyzer misalignment

We expect that analyzer transmission axis can be oriented along the x axis. Actually, because of various errors on the analyzing polarizer, the angle with respect to the x axis is not equal to zero. The effect on Stokes parameters due to δ and β (as indicated in Eq. (6)) can be analytically introduced to determine the misalignment of the analyzer.

$$\begin{aligned} S_0(\beta,\delta) &= S_0 + S_1\cos\delta\cos 2\beta + S_2\sin 2\beta,\\ S_1(\beta,\delta) &= (1-\cos\delta)(S_1\cos 2\beta - S_2\sin 2\beta),\\ S_2(\beta,\delta) &= (1-\cos\delta)(S_1\sin 2\beta + S_2\cos 2\beta),\\ S_3(\beta,\delta) &= S_3\cos 2\beta\sin\delta. \end{aligned} \tag{6}$$

In Eq. (7), δ and β are substituted by $\delta = 90^\circ + a$ and $\beta = 0^\circ + b$. Subsequently, the measurement values are subtracted by the corresponding simulated values, then we obtain the reconstructed model in the following form:

$$\begin{aligned} \Delta S_0 &= -S_1\sin a\cos(2b) + S_2\sin(2b),\\ \Delta S_1 &= S_1[(1+\sin a)\cos(2b) - 1] - S_2(1+\sin a)\sin 2b,\\ \Delta S_2 &= S_2[(1+\sin a)\cos(2b) - 1] + S_1(1+\sin a)\sin 2b.\\ \Delta S_3 &= S_3[\cos(2b)\cos a - 1]. \end{aligned} \tag{7}$$

By substituting normalized Stokes vector $[1, 1, 0, 0]^{\mathrm{T}}$ into Eq. (7), the differences ΔS_i (between measurement and simulation), where $i = \{0, 1, 2, 3\}$, versus the angle of quarter-wave plate fast axis with respect to x direction are presented in Fig. 4 for LHP (using the same method for LCP) incident light. In this case, the domain of the retardance error a is defined in the interval: $-5^\circ \le a \le 5^\circ$ and the domain of analyzer misalignment b is defined in the interval: $-6^\circ \le b \le 6^\circ$.

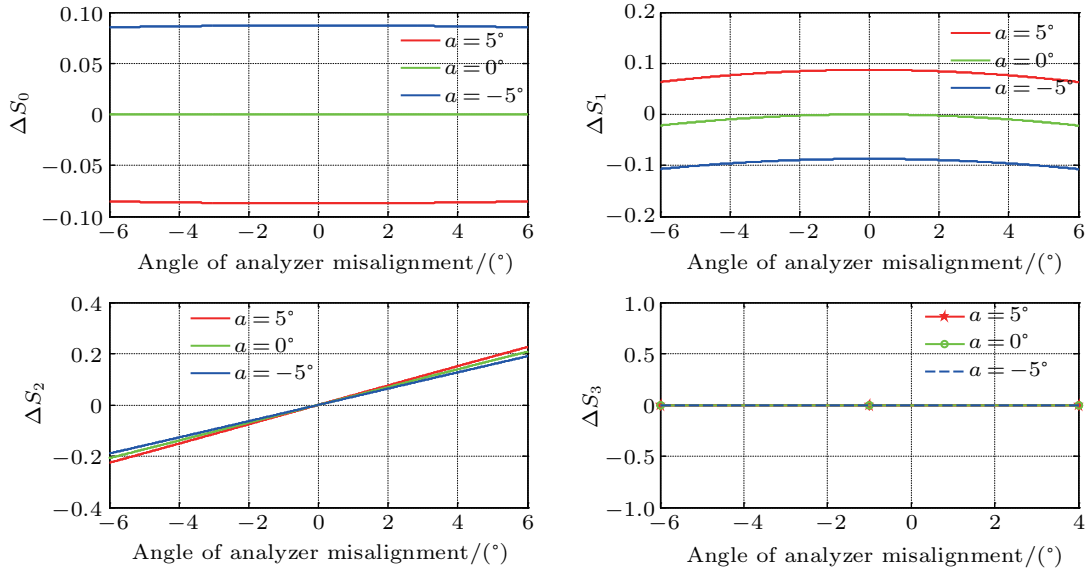


Fig. 4. (color online) Simulation results describing the dependency of the values $\Delta S_i(a,b)$, where $i = \{0,1,2,3\}$, versus the angle of analyzer misalignment and retardance error for LHP incident light.

As shown in Fig. 4, analyzer misalignment b and quarter-wave plate retardance error a do not cause ΔS_3 change. The ΔS_0, ΔS_1, and ΔS_2 follow a roughly linear variation trend across the error of retardance. The ΔS_1 changes with b in the cosine form. It is clear that ΔS_0, ΔS_1, and ΔS_2 are sensitive to a and b, and change as a and b change. Thus, for the upper bound on the errors of parameter measurement to be minimized, a and b must be as small as possible.

Both figure 4 and the above analysis are used for determining the misalignment of analyzer. The specific procedure is as follows. Step 1: the measurement and simulation results listed in Table 3 are normalized to obtain the differences ΔS_i. Step 2: we find out the corresponding numerical point of ΔS_i from Fig. 4. Step 3: we locate analyzer misalignment b combining with retardance error. (Because the retardance of the quarter-wave plate have been determined with the crossed polarizer method, the retardance error is available for us). The estimation of analyzer misalignment is $b = -1.04^\circ$ for LHP measurement by this model. By using the same method, we obtain $b = -0.45^\circ$ for LCP incident light.

3.4. Instrument error influences on different input polarization states

The effects of errors in the two optical elements of polarimeter (the values of a and b) on the measurement accuracy vary with input polarization state. Hence to establish the accuracy of our polarimeter measurement, we simulate the variations in the measured values of Stokes parameters for different incident light. This simulation presents the estimation of parameter measurement error. Poincaré sphere is introduced to characterize the polarization state and polarization behavior. The relevant angles are the ellipticity angle χ (the domain of χ is defined in the interval $-45^\circ \le \chi \le 45^\circ$), and the angle of polarization ψ (the domain of ψ is defined in the interval

$0^\circ \le \psi \le 180^\circ$).

$$\begin{bmatrix} S_0(\chi,\psi) \\ S_1(\chi,\psi) \\ S_2(\chi,\psi) \\ S_3(\chi,\psi) \end{bmatrix} = \begin{bmatrix} 1 \\ \cos 2\chi \cos 2\psi \\ \cos 2\chi \sin 2\psi \\ \sin 2\chi \end{bmatrix}. \quad (8)$$

Substituting the normalized Stokes vector given in Eq. (8) into Eq. (6) and simplifying the resulting equation yield the equations $\Delta S_i(\chi,\psi)/S_i$ ($i = 1, 2, 3, 4$), which represent the measurement differences for each normalized Stokes vector component with and without polarimeter error. Figure 5 illustrates the variations in $\Delta S_i(\chi,\psi)/S_i$ with ellipticity angle χ and the angle of polarization ψ for fixed a and b.

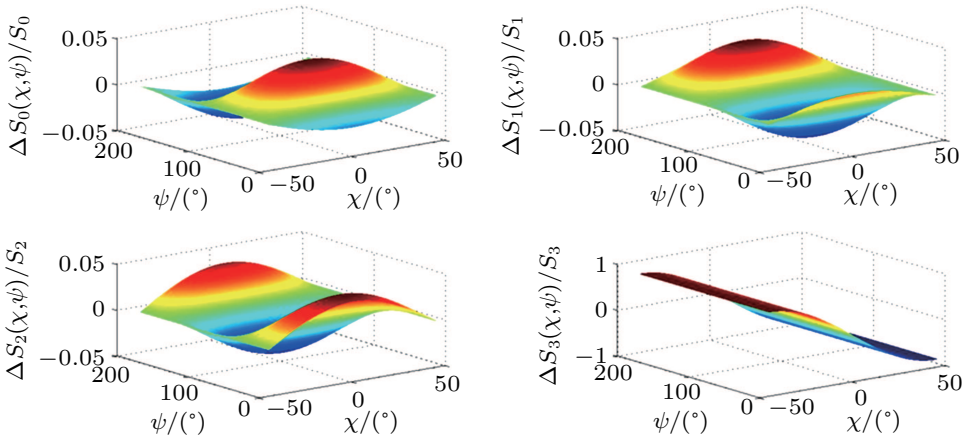


Fig. 5. (color online) Simulation results describing the dependence of the measurement differences $\Delta S_i(\chi,\psi)/S_i$ on the polarization and ellipticity angle.

For the LCP, where $\chi = -\pi/4$ and ψ for some arbitrary value, the measurement differences for each normalized Stokes vector component with perfect and imperfect polarimeter are equal to zero except $\Delta S_3(\chi,\psi)/S_0$. For the LHP, where $\chi = 0$ and $\psi = 0$, the components are non-zero except $\Delta S_3(\chi,\psi)/S_0$. All these non-null values are due to polarimeter error, but the disparity stems from the diverse polarization and ellipticity angle. So the errors of polarimeter are certain to affect the precision of one polarization state differently.

Table 2. Simulated parameter measurements errors for LCP and LHP input beam.

	LHP	LCP
$\Delta S_0(\chi,\psi)/S_0$	–1.83%	0
$\Delta S_1(\chi,\psi)/S_0$	1.77%	0
$\Delta S_2(\chi,\psi)/S_0$	–3.70%	0
$\Delta S_3(\chi,\psi)/S_0$	0	0.01%

We simulate the influences exerted by the ellipticity and polarization angles for LCP and LHP input beams as shown in Table 2. As mentioned previously, this simulation is based on the above error analysis, i.e., on the assumption that the errors of polarimeter are known. Simulated results show that the deviation caused by imperfect polarimeter on LCP is less than those on LHP beams.

4. Results

4.1. Results from traditional method

The mean of ten independent Stokes parameter measurement results and the relative measurement deviations are listed in Table 3 for LCP and LHP input beams. These results are calculated with the traditional method, in other words, experiments are conducted under carefully alignment. In this case, P refers the degree of polarization (DOP), and the relative measurement deviation is calculated from $\Delta \boldsymbol{S}_{\mathrm{Rela}} = (\boldsymbol{S}_{\mathrm{Meas}} - \boldsymbol{S}_{\mathrm{Simu}})/\boldsymbol{S}_{\mathrm{Simu}}$, where $\boldsymbol{S}_{\mathrm{Meas}}$ and $\boldsymbol{S}_{\mathrm{Simu}}$ are the Stokes vectors of measurement and simulation. Here, the quantities with the subscripts Simul. and Meas. refer to measurement and simulation results. Stokes parameters are measured by voltage sizes (V).

It is obvious that S_2 is the largest influence on accurate parameter measurement, with maximum errors of 2.72% and 3.83%, respectively, for LCP and LHP input beams. The other components also have larger measurement errors especially for the DOP of LHP beam reaching to 3.59%. Although we try to align the optical elements, the outcome is not positive. In the process of polarization imagers calibration in the laboratory by a specific input polarized state, we expect that the Stokes parameter measurement errors should not exceed 2% for LHP input beams and 5% for LCP input beams, respectively. Therefore, we need to readjust the analyzer based on the analysis in Section 3 and re-measure the input beams to obtain the better parameter measurement results. It is worth noting that relative deviations in Table 3 agree well with the simulated error values especially for LHP input beam as shown in Table 2. In addition, the measurement deviations of LCP are also less than those of LHP light in general. The consistence between the experimental data and the simulated results shows that the analyzer misalignment estimation by modeling in this paper is reliable.

Table 3. Stokes parameter measurements for LCP and LHP input beams.

	LCP			LHP		
	Simu./V	Meas./V	Rela. Devi./V	Simu./V	Meas./V	Rela. Devi./V
S_0	6.4550	6.4506	–0.07%	1.4232	1.3967	–1.87%
S_1	0	0.0155	0.24%	1.4232	1.4457	1.58%
S_2	0	–0.1758	–2.72%	0	–0.0546	–3.83%
S_3	–6.4550	–6.4482	0.11%	0	–0.0064	–0.45%
P	1	1.0000	0.00%	1	1.0359	3.59%

4.2. Results from proposed method

In this experiment, initial analyzer in each of azimuth and fast axis direction of the quarter-wave plate is conducted under rough alignment. As previously mentioned, the retardance of quarter-wave plate and that of the phase shift are respectively obtained by using the crossed polarizer method and a sine or cosine curve fit method, and analyzer misalignment is obtained by the use of the constructed model. This study, along with the availability of these known errors, permits a realization of polarimeter optimization. By readjusting the analyzer, we measure the polarized states again. In Table 4 listed are the corrected Stokes parameters values (Corr. value), relative deviations, and the improved precisions (Impr. prec.) for the corrected case.

Table 4. Results of Stokes parameter measurement after correcting δ, β, and ϕ.

	LCP			LHP		
	Corr. Value/V	Rela. devi./V	Impr. Prec.	Corr. Value/V	Rela. devi./V	Impr. Prec.
S_0	6.4555	0.01%	0.06%	1.4217	–0.11%	1.76%
S_1	0.0121	0.19%	0.05%	1.4214	–0.13%	1.45%
S_2	–0.1729	–2.68%	0.04%	0.0151	1.06%	2.77%
S_3	–6.4523	0.04%	0.07%	–0.0060	–0.42%	0.03%
P	0.9999	–0.01%	–0.01%	0.9999	–0.01%	3.58%

The relative measurement deviations of Stokes parameters are $(0.01\%, 0.19\%, -2.68\%, 0.04\%)^{\mathrm{T}}$, and DOP deviation is -0.01% for LCP light. Comparing with the uncorrected results, measurement precision is improved generally. In analogy to the LCP light, for the LHP incident beam the relative measurement deviations of Stokes parameters are $(-0.11\%, -0.13\%, 1.06\%, 0.42\%)^{\mathrm{T}}$. The value of DOP is 0.9999, with a measurement error of 0.01%. After retardance, analyzer azimuth and phase shift are corrected, the maximum measurement deviations decrease from 2.72% to 2.68% and from 3.83% to 1.06% for LCP and LHP input beams, respectively. The measurement error of parameter S_2 is reduced by almost 2.77% and the measurement error of DOP is reduced by almost 3.58% for LHP incident light. Others parameter measurement errors are reduced to different degrees.

5. Conclusions

In this study, we propose a simple method to measure the polarization state of light through using a rotating quarter-wave plate polarimeter. This method could accurately measure the polarization state of light based on the proposed model, and the measurement is carried out under the condition of coarse alignment. This method imposes no harsh demand for the initial alignment accuracy for the operating personnel, allowing them to save time and effort. This simple method allows the maximum deviations to decrease from 2.72% to 2.68% and from 3.83% to 1.06% for LCP and LHP measurements, respectively. The results indicate that the proposed model can be used as a promising approach to Stokes parameter measurement for a rotating quarter-wave plate polarimeter.

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