Optoelectronic polarimeter controlled by a graphical user interface of Matlab

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Abstract. We show the design and implementation of an optical polarimeter using electronic control. The polarimeter has a software with a graphical user interface (GUI) that controls the optoelectronic setup and captures the optical intensity measurement, and finally, this software evaluates the Stokes vector of a state of polarization (SOP) by means of the synchronous detection of optical waves. The proposed optoelectronic polarimeter can determine the Stokes vector of a SOP in a rapid and efficient way. Using the polarimeter proposed in this paper, the students will be able to observe (in an optical bench) and understand the different interactions of the SOP when the optical waves pass through to the linear polarizers and retarder waves plates. The polarimeter prototype could be used as a main tool for the students in order to learn the theory and experimental aspects of the SOP for optical waves via the Stokes vector measurement. The proposed polarimeter controlled by a GUI of Matlab is more attractive and suitable to teach and to learn the polarization of optical waves.

1. Introduction
In general, the state of polarization (SOP) for optical waves is described by using the Stokes vectors [1, 2]. These SOP for optical waves are: unpolared, partially polarized and completely polarized (linear, circular and elliptical) [1]. The optical polarization is very important in several areas of photonics, because a lot of optical devices, such as Faraday rotator, retarder plate, optical fiber sensors, fiber optic gyroscope, etc, are based on optical polarization. In order to use very well the previous optical devices, it is necessary to understand very well the theoretical concepts and experimentation related to the SOP for optical waves. Several practical applications are based on optical polarization, such as diffractive optical elements applied to ophthalmology [3], contrast microscopy [4], biomedicine [5], image processing [6, 7], among other.

In this paper, we present an optical polarimeter that it is controlled by using electronics and a graphical user interface (GUI) of MATLAB. The optical setup is divided in two system. The first and the second systems are used to generate and measure the SOP, respectively. The generation of the SOP is based on the Muller matrices of the linear polarizer (LP) and the quarter wave plate (QWP). The measurement of the SOP is based on the synchronous detection of optical waves in order to compute the Stoke vector. The GUI implemented in MATLAB can control the processes of the generation and measurement of the SOP. This GUI is more attractive and suitable to teach the polarization of optical waves. The proposed optical polarimeter could be used for optical sensing and testing.
The rest of the paper is organized as follow. Section 2 presents the optoelectronic devices that will be used to generate and measure the SOP. In sections 3, it is determined the transmission axis orientation of a LP. The fast axis orientation of a QWP is evaluated in section 4. Section 5 shows the generation and measurement of the SOP by computing the Stokes vector and using the synchronous detection of optical waves. Finally, the conclusions are outlined in section 6.

2. Optical setup to generate and measure the SOP

Figure 1 shows the experimental setup that it is used to generate and measure the SOP. The generation system of the SOP is composed by: one laser (with a wavelength of  \( \lambda = 633 \text{ nm} \) and linear vertical polarization), one LP and one QWP. The measurement system of the SOP is composed by: one QWP, one LP and one photodetector. The two LPs are mounted in two different mechanical rotation stages. We implement a GUI in MATLAB to control the generation and measurement systems of the SOP. The two QWPs are mounted in two different mechatronic rotation stages; these two stages are controlled by the GUI implemented in MATLAB. The acquisition process of the optical intensity values obtained from the photodetector is also controlled by the GUI implemented in MATLAB. The electronic control of the two mechatronic rotation stages and the acquisition process of the photodetector is implemented using a serial communication interface between the GUI, the data acquisition board connected to the photodetector, and the physical controller of the two mechatronic rotation stages. Before performing the generation and measurement of the SOP, it is necessary to determine the transmission and fast axis orientations of a LP and a QWP, respectively.

![Figure 1](image)

**Figure 1.** The experimental setup of the optoelectronic polarimeter.

3. Determination of the transmission axis orientation for a LP

In order to determine the transmission axis orientation for a LP with respect to the vertical direction of the laboratory, we perform the following experimental steps: the laser beam with a linear vertical polarization is propagated through to the LP, this LP is rotated by an angle \( \theta_r \) with respect to the vertical direction of the laboratory. We do not know the transmission axis orientation of the LP. Therefore, the LP will be rotated by an angle \( \theta_r + \theta_0 \), where \( \theta_0 \) denotes the angle between the transmission axis of the LP and the vertical direction of the laboratory. At last, we capture the optical intensity value \( I(\theta_r + \theta_0) \) produced by the emergent laser beam of the LP using the photodetector. The emergent SOP \( \mathbf{S}_{\text{pol}} \) from the LP is given by the matrix multiplication between the Mueller matrix of a LP with its transmission axis rotated by an angle \( \theta_r + \theta_0 \) with respect to the vertical direction of the laboratory and the Stoke vector of a laser beam with a linear vertical polarization \[1\]

\[
\mathbf{S}_{\text{pol}} = \frac{1}{2} \begin{pmatrix}
1 & \cos(2\theta_r + \theta_0) & \sin(2\theta_r + \theta_0) & 0 \\
\cos(2\theta_r + \theta_0) & \cos^2(2\theta_r + \theta_0) & \sin(2\theta_r + \theta_0) \cos(2\theta_r + \theta_0) & 0 \\
\sin(2\theta_r + \theta_0) & \sin(2\theta_r + \theta_0) \cos(2\theta_r + \theta_0) & \sin^2(2\theta_r + \theta_0) & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}.
\]

The optical intensity captured by the photodetector \( I(\theta_r + \theta_0) \) will be equal to the parameter \( S_0 \) of \( \mathbf{S}_{\text{pol}} \)

\[
I(\theta_r + \theta_0) = S_0 = \frac{1}{2} \left[ 1 + \cos(2\theta_r + \theta_0) \right] = \frac{1}{2} \left[ 1 + \cos(2\theta_0) \cos(2\theta_r) - \sin(2\theta_0) \sin(2\theta_r) \right].
\]
The transmission axis orientation of a LP given by the angle $\theta_0$, it can be determined by using the synchronous detection of optical waves. We captured the optical intensity $I(\theta_r + \theta_0)$ for the following angles:

$$\theta_r = \frac{2\pi(r-1)}{N}$$

with $r = 1, ..., N$. Then, if every $I(\theta_r + \theta_0)$ is multiplied by the terms $\sin(2\theta_r)$ or $\cos(2\theta_r)$, and finally, when these $N$ products are added, we obtain

$$2\sum_{r=1}^{N} I(\theta_r + \theta_0)\sin(2\theta_r) = -\frac{N}{2}\sin(2\theta_0), \quad 2\sum_{r=1}^{N} I(\theta_r + \theta_0)\cos(2\theta_r) = \frac{N}{2}\cos(2\theta_0).$$

(3)

Using the equation (3), the angle $\theta_0$ is

$$\theta_0 = \frac{1}{2}\arctan \left( \frac{-\sum_{r=1}^{N} I(\theta_r + \theta_0)\sin(2\theta_r)}{\sum_{r=1}^{N} I(\theta_r + \theta_0)\cos(2\theta_r)} \right).$$

(4)

The experimental procedure denotes by equation (4) was applied to each LP of the generation and measurement systems of figure 1. The optical intensity measurements $I(\theta_r + \theta_0)$ were captured for the angles $\theta_r$ between $0^\circ$ and $355^\circ$ with an incremental step of $5^\circ$. The GUI of figures 2(a) and 2(b) show that the transmission axis orientations of the LPs for the generation and measurement systems of the SOP with respect to the vertical direction of the laboratory are: $\theta_{01} \approx 17^\circ$ and $\theta_{02} \approx -11^\circ$, respectively.

![Figure 2](image)

(a) (b)

Figure 2. Determination of the angle $\theta_0$ for the LP located in the system of: (a) generation and (b) measurement, of the SOP.

4. Determination of the fast axis orientation for a QWP

We use an optical system composed by two LP and one QWP, in order to evaluate the fast axis orientation for a QWP. This optical system is called $LP_1 - QWP - LP_2$, and this name represents the location of the two LPs and the QWP. The transmission axis of the LPs $LP_1$ and $LP_2$ are oriented along the vertical direction of the laboratory. The emergent SOP from the LP $LP_1$ is linear vertically polarized, this SOP is propagated through to the rotated QWP with an angle $\theta_r$ with respect to the vertical direction of the laboratory. We do not know the fast axis orientation of the QWP. Therefore, the QWP will be rotated by an angle $\theta_r + \theta_l$ where $\theta_l$ represents the angle between the fast axis of the QWP and the vertical direction of the laboratory. Using the Mueller matrix of a QWP with its fast axis rotated by an angle $\theta_r + \theta_l$ with respect to the vertical direction of the laboratory and the Stoke vector of the emergent SOP from the LP $LP_1$, which is linear vertically polarized, the emergent SOP $S_{LR}$ from the QWP will be [1]

$$S_{LR} = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos^2(2(\theta_r + \theta_l)) & \sin(2(\theta_r + \theta_l))\cos(2(\theta_r + \theta_l)) & -\sin(2(\theta_r + \theta_l)) \\
0 & \sin(2(\theta_r + \theta_l))\cos(2(\theta_r + \theta_l)) & \sin^2(2(\theta_r + \theta_l)) & \cos(2(\theta_r + \theta_l)) \\
0 & \sin(2(\theta_r + \theta_l)) & -\cos(2(\theta_r + \theta_l)) & 0
\end{bmatrix}. \quad (5)$$

$$\begin{bmatrix}
1 \\
1 \\
0 \\
0
\end{bmatrix}$$
The emergent SOP $S_{P2}$ form the system $LP_1$-$QWP$-$LP_2$ is given by the matrix multiplication between the Stoke vector $S_{LR}$ and the Mueller matrix of the LP $LP_2$ with its transmission axis oriented along the vertical direction of the laboratory

$$S_{P2} = \frac{1}{2} \begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} S_{LR}. \quad (6)$$

The optical intensity captured by the photodetector $I(\theta_r + \theta_l)$ will be equal to the parameter $S_0$ of $S_{P2}$

$$I(\theta_r + \theta_l) = S_0 = \frac{1}{2} \left[ 1 + \cos^2 \left( 2(\theta_r + \theta_l) \right) \right] = \frac{1}{4} \left[ 3 + \cos(4\theta_r) \cos(4\theta_l) - \sin(4\theta_r) \sin(4\theta_l) \right]. \quad (7)$$

The fast axis orientation of a QWP given by the angle $\theta_l$, it can be evaluated by using the synchronous detection of optical waves. We captured the optical intensity $I(\theta_r + \theta_l)$ for the following angles: $\theta_r = 2\pi (r - 1)/N$ with $r = 1, \ldots, N$. Then, if every $I(\theta_r + \theta_l)$ is multiplied by the terms $\sin(4\theta_r)$ or $\cos(4\theta_r)$, and finally, when these $N$ products are added, we obtain

$$4 \sum_{r=1}^{N} I(\theta_r + \theta_l) \sin(4\theta_r) = -\frac{N}{2} \sin(4\theta_l), \quad 4 \sum_{r=1}^{N} I(\theta_r + \theta_l) \cos(4\theta_r) = \frac{N}{2} \cos(4\theta_l). \quad (8)$$

Using the equation (8), the angle $\theta_l$ is

$$\theta_l = \frac{1}{4} \arctan \left( \frac{-\sum_{r=1}^{N} I(\theta_r + \theta_l) \sin(4\theta_r)}{\sum_{r=1}^{N} I(\theta_r + \theta_l) \cos(4\theta_r)} \right). \quad (9)$$

The experimental procedure given by equation (9) was applied to each QWP of the generation and measurement systems of figure 1. The optical intensity measurements $I(\theta_r + \theta_l)$ were captured for the angles $\theta_r$ between $0^\circ$ and $355^\circ$ with an incremental step of $5^\circ$; these measurements and rotations of the QWPs are controlled by the GUI. Figures 3(a) and 3(b) show that the fast axis orientations of the QWPs for the generation and measurement systems of the SOP with respect to the vertical direction of the laboratory are: $\theta_{l1} \approx -24^\circ$ and $\theta_{l2} \approx -31^\circ$, respectively.

5. Generation and measurement of the SOP

The transmission and fast axis orientations of the LPs and the QWPs, respectively, of figure 1 are oriented along the vertical direction of the laboratory. The transmission axis orientations of the LPs of figure 1 are always fixed. The fast axis orientations of the QWPs of figure 1 can be rotated with the purpose of generating or measuring the SOP. The emergent SOP $S_{gen}$ from the generation system of figure 1 can be described by [1]
Figure 3. Determination of the angle $\theta$ for the QWP located in the system of: (a) generation and (b) measurement, of the SOP.

\[
\mathbf{S}_{\text{gen}} = \begin{pmatrix}
S_0 \\
S_1 \\
S_2 \\
S_3
\end{pmatrix} = \begin{pmatrix}
1 \\
\cos^2(2\theta) \\
\sin(2\theta)\cos(2\theta) \\
\sin(2\theta)
\end{pmatrix},
\]

where $\theta$ is the rotation angle of the QWP located in the generation system of the SOP and its possible values are between $-90^\circ < \theta < 90^\circ$. The generated SOP for the different angle $\theta$ are: linear vertical for $\theta = 0^\circ$, right-circular and left-circular when $\theta = 45^\circ$ and $\theta = -45^\circ$, respectively, and elliptical for all other cases of $\theta$.

In the measurement system, we evaluate the incident SOP by computing its Stoke vector ($S_0, S_1, S_2$ and $S_3$). The emergent SOP $S_{\text{out}}$ from the measurement system of figure 1 is given by [1]

\[
S_{\text{out}} = \frac{1}{2} \begin{pmatrix}
1 & 1 & 0 & 0 \\
1 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{pmatrix} \begin{pmatrix}
1 \\
\cos^2(2\theta_r) \\
\sin(2\theta_r)\cos(2\theta_r) \\
\sin(2\theta_r)
\end{pmatrix} = \begin{pmatrix}
S_0 \\
S_1 \\
S_2 \\
S_3
\end{pmatrix},
\]

where $\theta_r$ is the rotation angle of the QWP located in the measurement system of the SOP. The optical intensity captured by the photodetector $I(\theta_r)$ will be equal to the parameter $S_0$ of $S_{\text{out}}$

\[
I(\theta_r) = S_0 = \frac{1}{2} \left[ S_0 + S_1\cos^2(2\theta_r) + S_2\sin(2\theta_r)\cos(2\theta_r) - S_3\sin(2\theta_r) \right]
= \frac{1}{4} \left[ 2S_0 + S_1 + S_2\cos(4\theta_r) + S_2\sin(4\theta_r) - 2S_3\sin(2\theta_r) \right].
\]

We apply the synchronous detection of optical waves. We captured the optical intensity $I(\theta_r)$ for the following angles: $\theta_r = 2\pi(r - 1)/N$ with $r = 1, ..., N$. Then, if every $I(\theta_r)$ is added and if every $I(\theta_r)$ is multiplied by the terms $\sin(2\theta_r), \sin(4\theta_r)$ or $\cos(4\theta_r)$, and finally, when these $N$ products are added, we obtain the four parameters of the Stoke vector to be measured

\[
\mathbf{S} = \begin{pmatrix}
S_0 \\
S_1 \\
S_2 \\
S_3
\end{pmatrix} = \frac{1}{N} \begin{pmatrix}
2\sum_{r=1}^{N} I(\theta_r) - 4\sum_{r=1}^{N} I(\theta_r)\cos(4\theta_r) \\
8\sum_{r=1}^{N} I(\theta_r)\cos(4\theta_r) \\
8\sum_{r=1}^{N} I(\theta_r)\sin(4\theta_r) \\
-4\sum_{r=1}^{N} I(\theta_r)\sin(2\theta_r)
\end{pmatrix}.
\]
The optical intensity measurements $I(\theta_r)$ were captured for the angles $\theta_r$ between $0^\circ$ and $356^\circ$ with an incremental step of $4^\circ$. Figures 4(a) and 4(b) show the generation and measurement of the following SOP: linear vertical ($\theta = 0^\circ$) and left-circular ($\theta = -45^\circ$), respectively.

Figure 4. Generation and measurement of the SOP: (a) linear vertical and, (b) left-circular.

6. Conclusions
The design and implementation of an optoelectronic polarimeter has been presented. We have determined theoretically and experimentally the transmission and fast axis orientations for a LP and a QWP, respectively, by using the synchronous detection of optical waves. We generated completely polarized light in a controlled manner by means of a GUI implemented in MATLAB. We evaluated theoretically and experimentally the Stokes vector of a SOP by using the synchronous detection of optical waves and an optoelectronic system controlled by a GUI. Finally, the proposed optoelectronic polarimeter can be used to teach and to learn the polarization of optical waves, and to determine the Stokes vector of a SOP in a quick and efficient manner.

Acknowledgments
This research has been funded by the Universidad Popular del Cesar and the Universidad de La Guajira.

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