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Automated, low-cost and simple polarimeter based on intensity measurements by an LDR

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Dedicated to Professor Wolfgang Osten

This paper presents an automated, low-cost and simple polarimeter based on intensity measurements using a photoresistor (LDR). The polarization states are determined by sensing the intensity variations of an input beam as it passes through a polarizer mounted on a stage and rotates at a constant speed. We use a USB Data Acquisition system and LabVIEW to automate and analyze the data. The main advantage of this proposal lies in the fact that the polarization state obtained is shown by its polarization ellipse as well as its inclination (with a simple methodology of data acquisition and processing). In addition, the device can be activated remotely, and the results can be sent via email. The results will be validated by comparing them with a commercial polarimeter. © Anita Publications. All rights reserved.

Keywords: Polarization, Polarimetry, Automation, Sensors, Remote-controlling.

1 Introduction

It is possible to represent an optical field with elliptical polarization as an oscillating wave in the x-y plane. This wave travels in the z-direction and can be expressed in a vector form: $\mathbf{E} = (iE_x + jE_y e^{i\delta}) e^{i\phi}$. The components of the amplitude, E_x and E_y , together with the phase difference δ , describe the shape and orientation of the path traced by the electric field [1]. ϕ , on the other hand, is related to the phase of the wave. For example, if $\delta = \pm m\pi$ with m being an integer number, the resulting wave will be linearly polarized. If any other set of amplitudes and relative phases is used, an elliptical polarization will occur, including circular polarization when $E_x = E_y$ [2,3]. Depending on the sign of δ , the tip of the field can rotate either clockwise (right-hand) or counterclockwise (left-hand) as it propagates. The electric field vector of the propagating laser beam can be graphically described by its orthogonal components, as shown in Fig 1(a). If an observer looks perpendicularly to the x-y plane, the tip of the total $\mathbf{E}$ field vector will trace a curve of the polarization ellipse (Fig 1(b)); in such a way that this is one method to visualize the polarization state of an incident beam. The propagation of the electric field components, as well as the traced polarization ellipse, can be observed in a simulation provided by Rivera-Ortega and Dirckx [3].

The relationship between the magnitudes of the components and their phase difference defines the ellipticity and orientation. For example, Fig 2 depicts the resulting polarization ellipses when the amplitude of the components is equal and with a phase difference from 0 to π .

The main parameters of a polarization ellipse are represented in Fig 3. This polarization ellipse is bounded by a rectangle whose sides are equal to twice the amplitudes of the E_x and E_y components.

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The angle θ is measured between the horizontal axis and the major axis of the ellipse. These parameters are important since one of the main features of the proposed system is the graphical representation of the polarization ellipse.

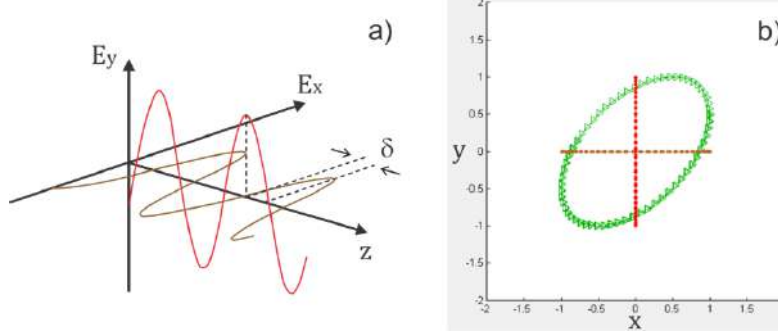


Fig 1(a). The two orthogonal components of the electric field, (b) the ellipse formed when observed perpendicularly to the x-y plane.

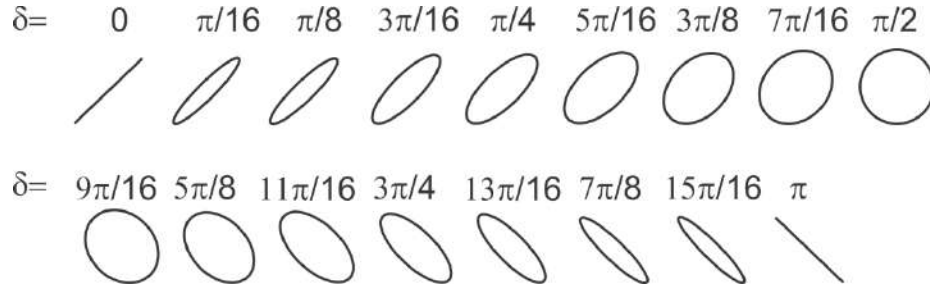


Fig 2. Some examples of polarization ellipses that are formed when the magnitudes of the components are equal and with a phase difference from 0 to π .

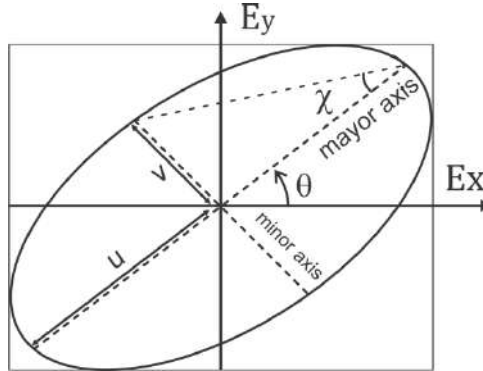


Fig 3. A polarization ellipse is described by its main parameters.

The polarization effect has many applications in various fields, such as manufacturing, biotechnology, nanotechnology, optical communication, remote sensing, and astronomy [4-7]. Polarimeters are optical instruments that determine the polarization properties of light beams and samples. They are used for various applications such as calibration of polarization elements, ellipsometry, spectroscopic studies of materials, and remote sensing. There are two principal groups of polarimeters [8]: light-measuring and sample-measuring

(Fig 4, in which PSG refers to a polarization state generator and PSA to a polarization state analyzer, respectively). The former determines the polarization state of an incident beam of light and some of its polarization characteristics, while the PSA defines the relationship between the polarization states of an incident and exiting beams of a sample [9].

In a polarimeter, a PSG consist of all the optical and mechanical elements needed to produce a beam with a known polarization state. The analyzer (PSA) typically consists of a linear polarizer which rotates around the propagation axis of the beam, measuring its output intensity with a detector [10].

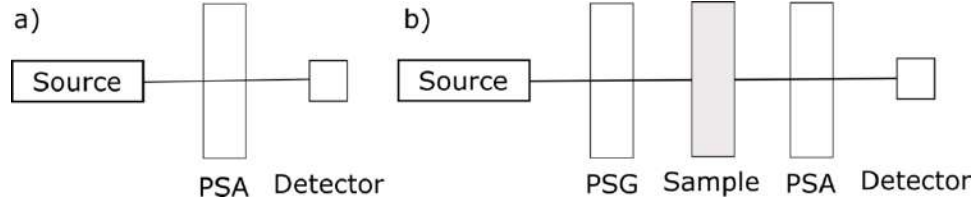


Fig 4. General schematic diagram of (a) light-measuring and (b) sample-measuring polarimeter.

Polarimeters are generally classified into light measuring instruments, such as Stokes polarimeters, and sample measuring instruments, such as Mueller matrix polarimeters [11]. They can operate in DC mode or use modulation based detection, the latter offering advantages in sensitivity, noise rejection, and large area imaging [12]. Some other optical setups use photoelastic modulators for polarimetry based on Muller matrix [13] or Stokes parameters calculation [14]. If a polarimeter measures a Stokes vector or a full Mueller matrix, it is categorized as a "complete" polarimeter [15,17].

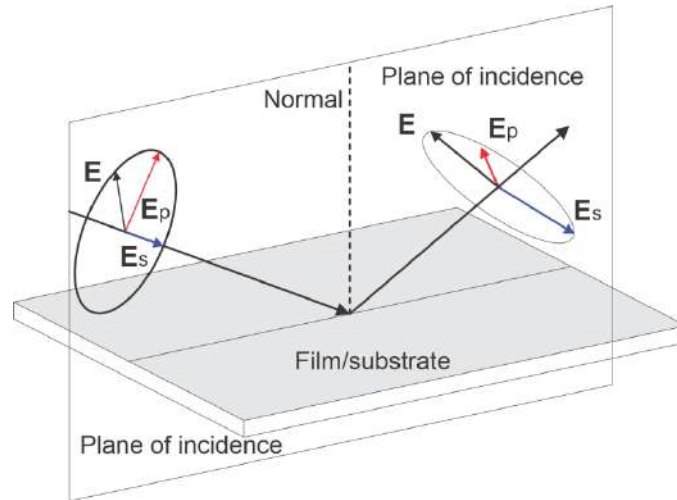


Fig 5. Change in the input polarization state due to reflection.

Ellipsometers can be mentioned among the instruments for measuring optical parameters related to polarization. They measure the change of polarization when light reflects or transmits from a material (commonly used to characterize thin films) [18]. Figure 5 shows a change in polarization state when a beam is reflected from a thin film, modifying the amplitude of the perpendicular (E_s) and parallel component (E_p) of the electric field E with respect to the plane of incidence. Rotating waveplate and rotating polarizer schemes are well established in the literature. In this context, the present work does not aim to replicate a full Stokes or Mueller polarimeter, but rather demonstrates a simplified light measuring approach with automated visualization, designed for accessibility in teaching laboratories.

Therefore, polarimeters are instruments that measure and interpret polarization information, while ellipsometers refer to the polarimetry that characterizes thin films and surfaces using polarization changes. It is worth mentioning that there are polarimeters based on interferometric configurations [19] that allow us to know, for example, the concentration in solutions based on the intensity of the interference fringes [20]. Finally, another method of obtaining the polarization state of a beam is based on the Stokes parameters measurement from the intensity of a ring formed by the phenomenon of conical refraction [21,22].

In addition to the applications mentioned above, where it is important to know the polarization state of a light beam, there is also an application of optical metrology to obtain the phase of a test object using the phase shifting technique (PSI) in an interference pattern, which are generated by changing the polarization state in the input beam [23] or in a single-shot setup [24,25].

It is possible to find in the literature some proposed low-cost polarimeters based on the measurement of the received radiation using light sensors or naked-eye observation [26-32]. However, none of them fully automates the process or shows the real-time reconstruction of the polarization ellipse and its inclination angle θ . By considering this, the proposal presents a simple and automated polarimeter based on intensity measurements of an input beam. It utilizes a photo-resistor as the detector and generates intensity variations as from the input beam passes through a rotating linear polarizer. These variations are plotted in real-time on a Time vs. Voltage graph to visualize the corresponding polarization ellipse. The orientation angle of the polarization state is also displayed at the end of the process. In addition, this tool allows remote measurement by emailing a screenshot of the user interface showing the calculated parameter. To ensure the proposal's applicability, some polarization states described by the method will be compared with those obtained with a Thorlabs polarimeter PAX1000VIS.

This work also relates to the research areas in which Prof Wolfgang Osten has made important contributions, particularly in the development of measurement-based optical techniques. Throughout his career, Prof Osten emphasized experimental approaches that make the characterization of optical fields both reliable and accessible. In this sense, the polarimeter presented here follows the same spirit: a simple setup that allows the visualization and analysis of polarization states using basic elements such as an LDR and a rotating polarizer [33] (while rotating polarizer schemes are well established, the novelty of the present work lies in its simplified and automated implementation). The proposed system is intentionally focused on well-defined, predominantly pure polarization states, and does not aim at the characterization of mixed or weakly polarized light in the presence of strong depolarizing noise. Instead, it is designed to facilitate experimental access to polarization concepts in teaching laboratories and controlled experimental settings, where such measurements are often addressed mainly at a theoretical level. In addition, beyond the optical simplification, the system integrates automated control and remote activation features, including data transfer via e mail and triggering through a phone call, which enhance its accessibility and pedagogical value.

2 Setup and methodology

The proposed scheme is illustrated in Fig 6. In particular, Fig 6(a) shows the polarizing optics used to generate input polarization states (PSG) using a half-wave plate (HWP) and a quarter-wave plate (QWP). The induced polarization states will be analyzed by the proposed polarimeter, which consists of a linear polarizer (P) attached to a Thorlabs motorized rotational stage (with KDC101 driver) and a photoresistor (LDR), as depicted in Fig 6(b). The code and the user interface of the polarimeter were created using LabVIEW. The input and output signals from the LDR and the rotational stage are acquired through a Data Acquisition Device, DAQ (NI-USB6008).

The experimental setup, including how the PAX-1000 polarimeter is placed for calibration and comparison, is depicted in Fig 7.

The polarization state figures are generated by plotting each calculated coordinate pair (x, y) :

$$x = x_0 + V_{out} \cos \alpha \quad (1)$$

$$y = y_0 + V_{out} \sin \alpha \quad (2)$$

where x_0, y_0 are the coordinate origin $(0,0)$, V_{out} is the output voltage given by the divider configuration [34] and detected by the LDR, depicted in Fig 8(a). V_{out} decreases if the input light intensity I increases (Fig 8(b-c)). The variable α is the angle at which the polarizer rotates at a constant speed.

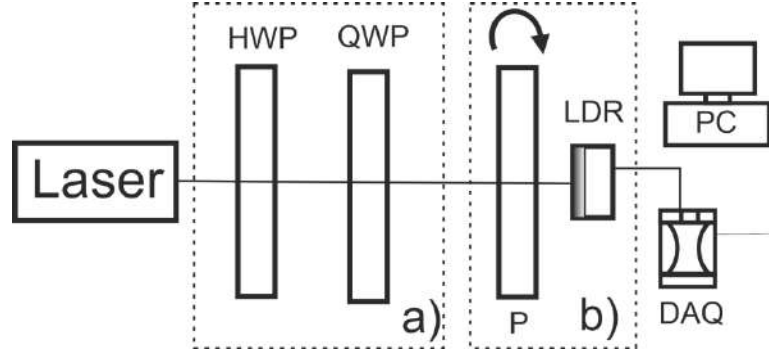


Fig 6. Schematic setup of the polarimeter.

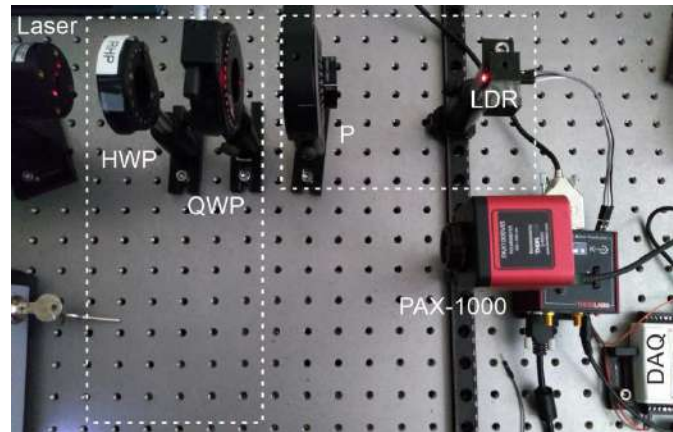


Fig 7. Experimental setup.

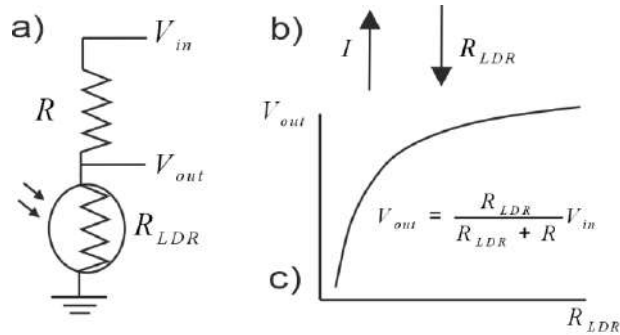


Fig 8. Voltage divider configuration and V_{out} vs R_{LDR} graph.

Figure 9 shows a section of the LabVIEW code responsible for graphing the ellipse corresponding to the detected polarization state based on Eqs (1-2). The variable “amplitude” is given by the voltage from the voltage divider and read by the DAQ (Fig 9(a)). The argument of the sine and cosine functions represented by the variable “angle,” is given by each rotation step of the polarizer attached to the rotational stage (Fig 9(b)). The “x” and “y” components used to graph the ellipse are calculated in a “formula node” block (Fig 9(c)). To plot the resulting polarization ellipse, the “x” components will be plotted along the x axis, while the “y” components will be plotted along the y axis using an XY plot (Fig 9(d)).

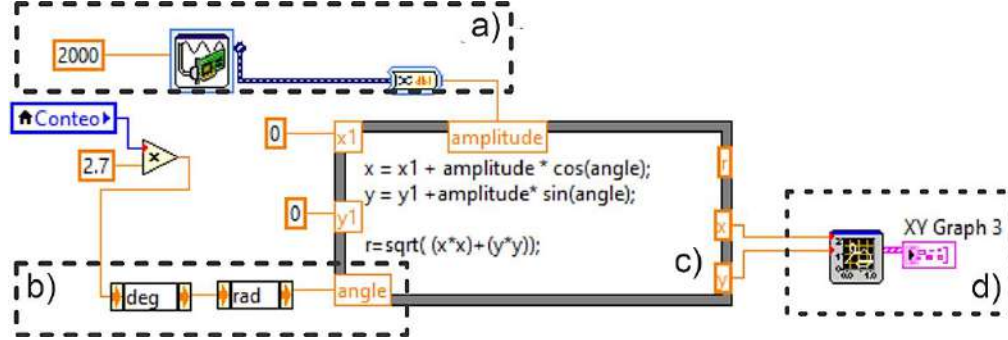


Fig 9. The polarization ellipse is calculated and displayed with LabVIEW.

Identifying various polarization states, such as linear, elliptical, and circular, relies on determining the respective ranges of angles associated with each state. This is done by measuring the output intensity of the light as a polarizer is rotated by a certain angle. The values obtained are then estimated using Malus' law [35], which provides a formula for calculating the output intensity of light based on the angle of rotation :

$$I(\alpha) = I_0 \cos^2(\alpha), \quad (3)$$

where I_0 is the total input intensity. For simplicity, an elliptical polarization can be created by two orthogonal linear polarizations at a relative phase of 90° :

$$\mathbf{E}(t) = \frac{E_0}{\sqrt{(1 + \varepsilon^2)}} \begin{pmatrix} \cos \omega t \\ \varepsilon \sin \omega t \end{pmatrix}, \quad (4)$$

where ε is its ellipticity, so that the Malus' law can be calculated by its scalar product with the unit vector $\hat{\mathbf{u}} = (\cos(\alpha), \sin(\alpha))$

$$I(\alpha) = \langle (\mathbf{E}(t) \cdot \hat{\mathbf{u}})^2 \rangle. \quad (5)$$

$$I(\alpha) = \frac{1}{2} \frac{E_0^2}{1 + \varepsilon^2} (\cos^2(\alpha) + \varepsilon^2 \sin^2(\alpha)) \quad (6)$$

This configuration's minimum and maximum light intensities are equivalent to 5V and 0V, respectively. Based on this, we can estimate the voltage ranges for each polarization state, as shown in Fig 10. The polarimeter also displays these voltage ranges, considering that there is a constant voltage range for circular polarization.

The bars depicted in Fig 10 indicate the voltage range in which each of the polarization states is found. These ranges are specific to the configuration of the voltage divider used, which may change if the input voltage and resistances are modified.

The angle at which the polarization state is oriented that is, the azimuth angle of the central axis about the x-axis, will be referred to as θ (previously depicted in Fig 3). In the case of elliptical polarization, this angle is linked to the row number (d) where the first peak of voltage measurements is found, as shown in Fig 11. After verifying with the Thorlabs polarimeter, it was found that for $d = 32 \rightarrow 90^\circ$. This means

that:

$$\theta = \frac{d \cdot 90^\circ}{32} \quad (7)$$

This orientation angle corresponds to the azimuth of the polarization ellipse. The ellipticity is inferred from the relative amplitudes of the orthogonal components, which are estimated from the voltage variations as the analyzer rotates. This procedure enables the reconstruction of the polarization ellipse for pure states using only intensity measurements obtained with the voltage divider circuit.

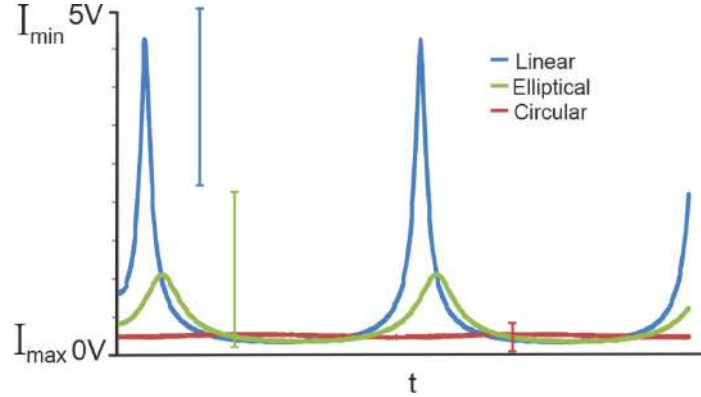


Fig 10. Estimated voltage ranges related to each polarization state.

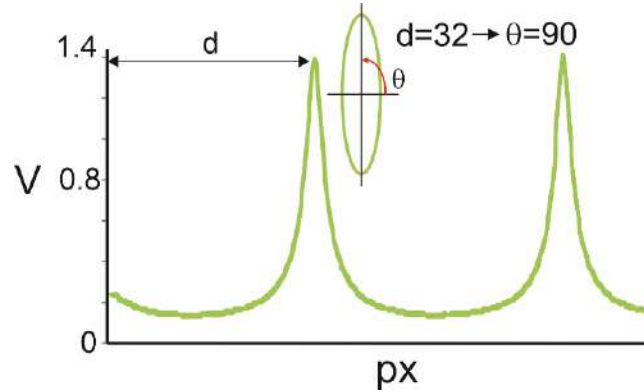


Fig 11. The orientation angle θ of the polarization state which is related to the position d .

3 Experimental results

The measurements begin when the polarizer is automatically positioned with its transmission axis parallel to the horizontal x-axis, and will end up showing the data obtained in the process in the user interface (sending it via email if it has been activated remotely or locally). The entire process can be followed in the block diagram shown in Fig 12.

In Fig 13(a₁-a₂), you can see linear polarization states that have been rotated from 0° to 180° with increments of 15°. The figure also shows the polarization states' inclination per the current proposal. Figure 13(b₁-b₂) depicts the polarization states obtained with the Thorlabs polarimeter [36]. The polarization states shown in Figs 13 and 14 are compared with measurements obtained using a commercial Thorlabs polarimeter, providing a qualitative validation of the proposed method.

Figure 14 displays the circular, linear, and elliptical polarization states and their inclination angles. These values were obtained by fixing the HWP at an arbitrary position and rotating the QWP at 15° intervals. The experimental measurements of the proposed method are shown in Fig 13(a₁-a₂), while Fig 13(b₁-b₂) depicts the results obtained with the Thorlabs PAX-1000 polarimeter.

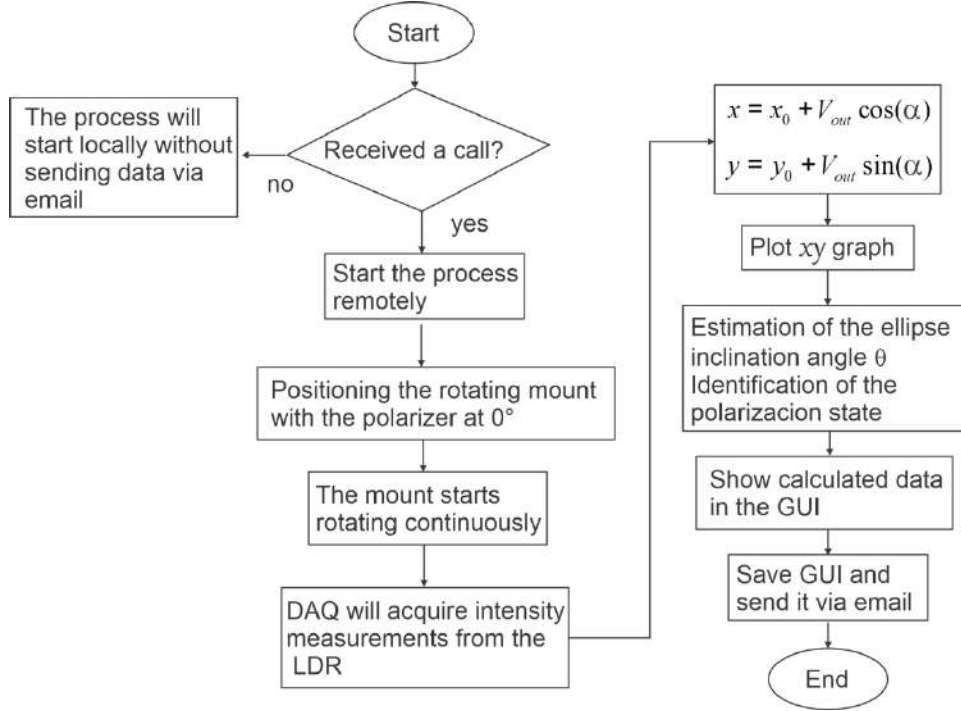


Fig 12. Block diagram of the stages and data acquisition regarding the polarimeter implementation.

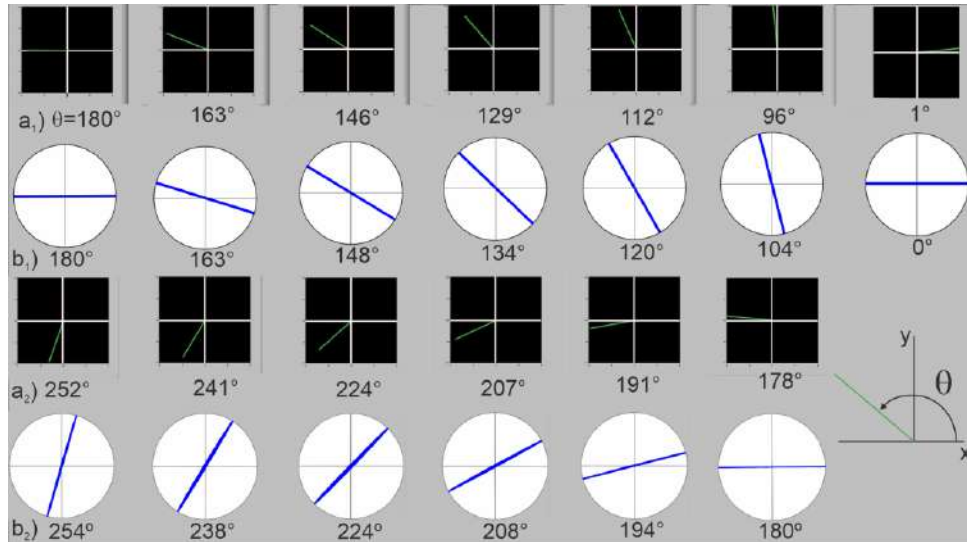


Fig 13. Experimental linear polarization states rotated from 0 to 180° , with corresponding measurements obtained using a commercial Thorlabs polarimeter for comparison.

The user interface is illustrated in the figure below, (Fig 15). Figure 15(a,d) displays the real-time voltage measurements sensed by the LDR and the overall measurements from which the orientation angle is computed, as described in Fig 11. Figure 15(b-c) showcases the polarization state and its inclination. Finally, Fig 15(e-f) shows the current position angle of the rotational stage and the starting switch. To better understand the entire process, you can watch the video in Visualization1 (<https://doi.org/10.5281/zenodo.17905314>).

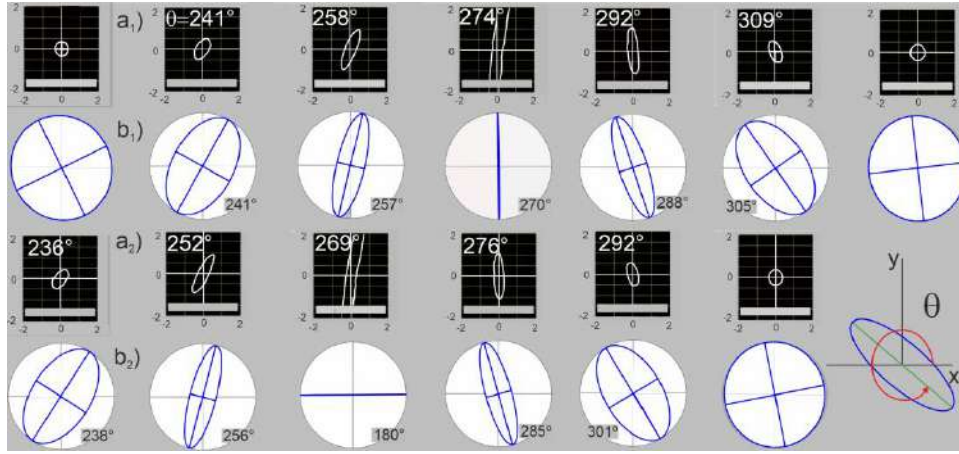


Fig 14. Experimental polarization states by rotating a QWP at steps of 15° , with corresponding measurements obtained using a commercial Thorlabs polarimeter for comparison.

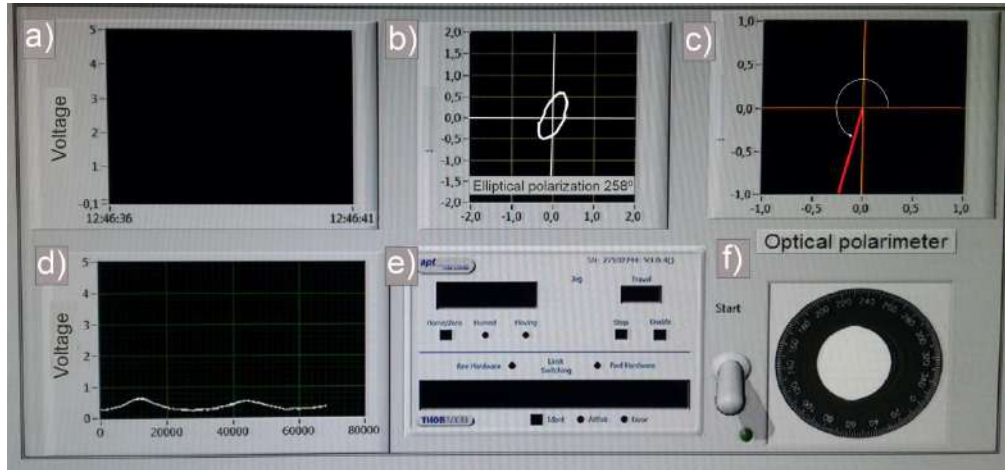


Fig 15. The user interface of the polarimeter was designed in LabVIEW (Visualization 1).

To demonstrate the proposal's feasibility, 62 repetitions were carried out for the measurement of the same polarization state. The x-axis corresponds to the number of measurements, while the y-axis represents the rotation angle. Figure 16(a-b) displays the measurements of two linear polarization states at 90° and 70° , respectively. The average value obtained from these measurements is $\bar{\theta} = 94.29^\circ$, with a standard deviation of $\sigma = \pm 2.21$ and $\varepsilon = 4.76\%$. Additionally, the value obtained from another set of measurements is $\bar{\theta} = 64^\circ$ with an error 8.57% . Figure 16(c-d) shows the measurements corresponding to two elliptical polarization states (at 180° and 135°), resulting in an average of $\bar{\theta} = 180.06$ with a standard deviation of $\sigma = \pm 1.55$.

with an error of $\varepsilon = 0.33\%$. Additionally, the value obtained from another set of measurements is $\bar{\theta} = 135^\circ$ with an error $\varepsilon = 0\%$.

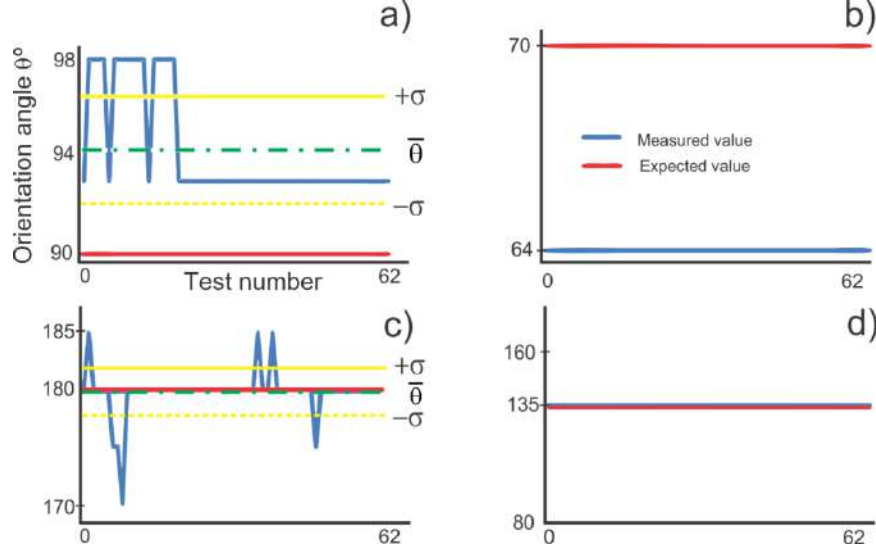


Fig 16. Sixty-two measurements of different polarization states, indicating their corresponding values of $\bar{\theta}$ and σ .

4 Remote measurements

The user interface shown in Fig 15 includes the resulting polarization state corresponding to the input beam, which will be sent via email at the end of each measurement as a screenshot. To continue with the low-cost approach, the speaker output pins of a Nyx mobile model XYN305 was used to activate an analog input of the DAQ when receiving a call, as shown in Fig 17 (the pins are circled with a dashed line). This signal will begin the process of measuring and sending results, thus providing remote use of this device.

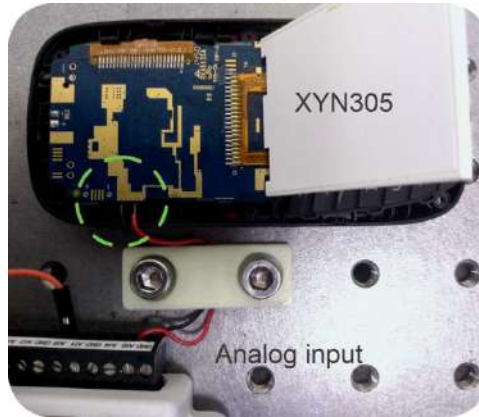


Fig 17. Using the cell phone speaker output to activate an analog input.

The complete implementation, including the implementation for remote measurements, is shown in Fig 18.

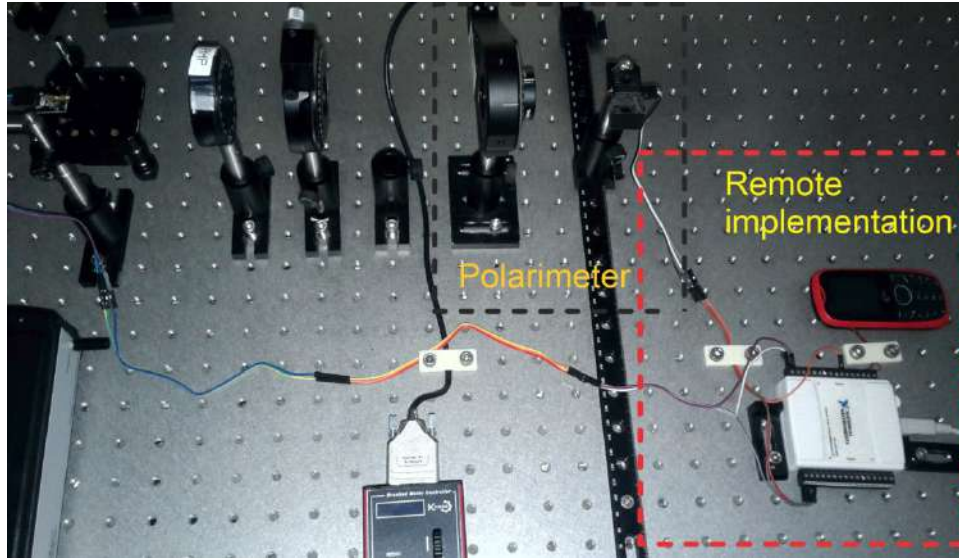


Fig 18. Main sections of the experimental arrangement, including the polarimeter (analyzer and photoresistor), the cell phone used for remote activation, and the DAQ interface.

Figure 19 contains the block code section responsible for saving the screenshot of the user interface in an MS-Word document, giving it a name with a different numerical ending for each measurement (Fig 19-1). Once the file is saved, it will be sent via email (Fig 19-2).

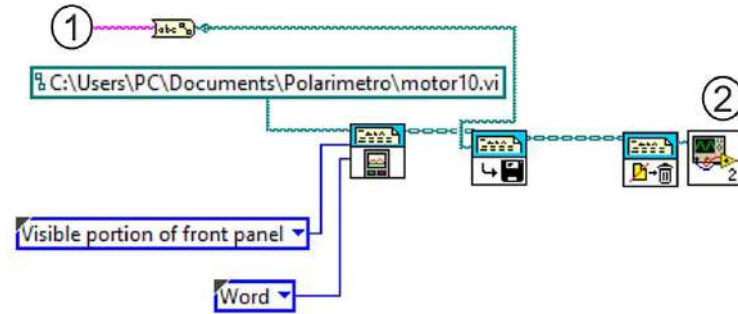


Fig 19. Section of the LabVIEW program where the measurements are saved in a Word file and sent to an e-mail address.

Figure 20 is included to exemplify how an email is received (Fig 20(a)) containing the screenshot in Word format of the user interface made in LabVIEW (Figs 20(b-d) show the captures of independent measurements in separate files).

5 Conclusion

The polarization state as well as the polarization ellipse and its inclination angle obtained with the proposal were compared with those obtained with a Thorlabs PAX1000VIS polarimeter, showing some examples in the user interface depicted in Figs 13-15 (the input polarization states were generated by setting a HWP and a QWP with different orientation angle among each other). In order to test the repeatability of the process, 62 individual tests were carried out for linear and elliptical polarization with different inclination angle. These results as well as the average) and standard deviation are depicted in Fig 16. The percent errors

were calculated with respect to the average of each set of measurements and the value measured by the polarimeter (red line in the graph labeled as expected value). According to these values, it can be deduced that there are two principal sources of error: the first one is the dynamic range and hysteresis effect of the sensor used (a photoresistor which exhibit a delay of approx. 10ms between exposure to light and the subsequent decrease in resistance), which could saturate the voltage and delay the measurements. The second and most important source of error is the methodology used to calculate the orientation angle θ , which is also related to the error introduced by the photoresistor. According to Fig 10, if the voltage reading presents a delay, the peak detection will also give a delay affecting the distance d and, consequently (as described by Eq (7)), the calculation of θ . However, these errors can be reduced by using sensors that do not present the drawbacks of an LDR; however this would increase the cost and ease of acquisition. An alternative configuration for the LDR sensor is to use a Wheatstone Bridge circuit. This configuration is mainly used to measure very small values of resistance, also operating as a voltage divider. Because of this, one of its best-known applications is to measure the variations of a resistive sensor [37,38].

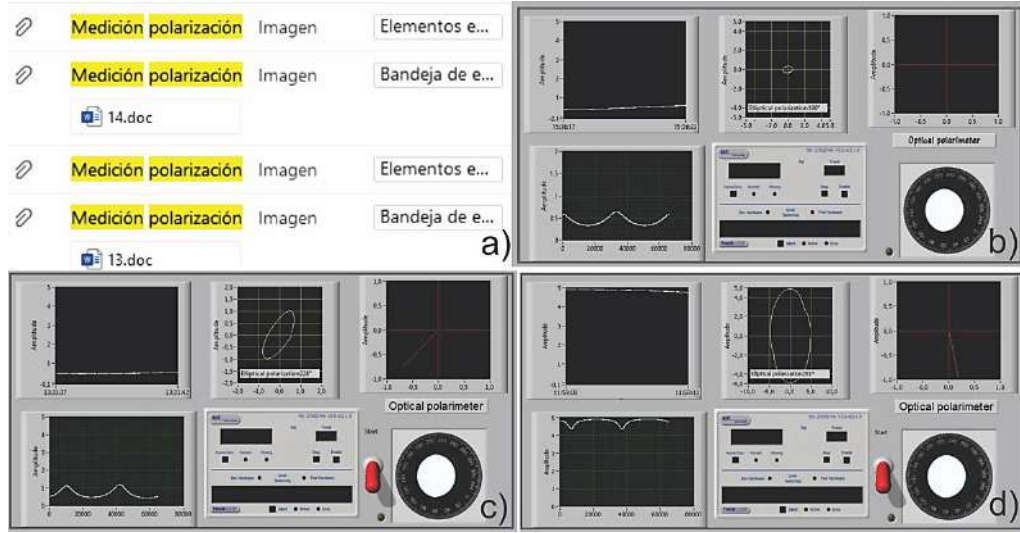


Fig 20. (a) Email received with the user interface (b) containing information of the polarization state, saved as a Word file.

As mentioned above, the materials/method used affects the accuracy of the instrument. However, in addition to functioning as a demonstrative/didactic element, it is possible to apply it, for example, in phase shift interferometry PSI based on phase-shifts due to polarization change (to name a few [23,25]). The proposed instrument can measure the polarization state and θ of the input beams used to generate phase-shift in the interference pattern; in which the accuracy of this measurement is not an important factor since, within the phase-shift algorithms, the Carré technique [39,40] allows knowing the wrapped phase of a test object with constant but unknown phase-shifts.

In this manuscript, we presented a low-cost, simple, and automated polarimeter which consists of a linear polarizer mounted on a rotational stage and a photoresistor (although a Thorlabs rotating mount was used, this component can be replaced with a low-cost mount or motor that performs the same function. Also, the software can be implemented in any free programming language such as Java and Python with an electronic interface such as Arduino or micro:bit, to name a few), aligning with one of Prof Osten's research themes and approaches, mainly related to metrology, inspection, and optical instrumentation [41,42]. Some input polarization states were generated using an HWP and a QWP to test the apparatus. The detected

polarization state is described by plotting the general polarization ellipse in a time-voltage graph (including linear and circular states) and the corresponding inclination angle θ .

The simple principle of the polarimeter (avoiding the measurement of Stokes parameters or Mueller matrix elements) allows it to be easily implemented and with a very low cost compared to some commercial light polarimeters. In addition, this tool can be activated remotely by making a call to a modified mobile phone, sending a screenshot of the user interface saved in Word format. Although other devices could be used for this purpose, using a cell phone was chosen to make the implementation accessible, low cost and without the use of knowledge involving protocols and programming for remote access. In this way, the polarimeter presented here can have measurement, demonstration, and teaching applications due to its construction and development characteristics, both locally and remotely.

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