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**9TH INTERNATIONAL CONFERENCE
ON EDUCATION AND NEW LEARNING
TECHNOLOGIES**

**BARCELONA (SPAIN)
3RD - 5TH OF JULY, 2017**

CONFERENCE PROCEEDINGS

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VISUALIZATION OF STOKES PARAMETERS WITH THE HELP OF ROTATING-WAVEPLATE POLARIMETER AND A LIQUID CRYSTAL ON SILICON MICRODISPLAY

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Abstract

Mueller-Stokes formalism enable us to deal with polarized and unpolarized light. This formalism is hard to understand by the students because it is a new introduced concept and less intuitive than the Jones formalism. Because of that, we have designed some experiences that help students to understand and see how the Stokes parameters vary in real time. We use two commercially available optoelectronic devices. They are a Rotating Waveplate polarimeter and a Parallel Aligned Liquid Crystal on Silicon (PA-LCoS) microdisplay. The PA-LCoS acts as a variable linear retarder controlled by voltage, and the polarimeter allows us to measure the Stokes parameters in real time, and it shows the representation in the Poincaré Sphere, that it is the most intuitive representation for the Stokes parameters.

Apart from the Stokes parameters, we can also use these experiences to introduce the students in a research laboratory, adding some knowledge about using LabView to automate experiments. In addition, we can use these devices and the measurements related to the light polarization to remark some basics concepts about the optical processing of information and the Fourier Transform.

These experiences are suitable for different subjects, such as "Fundamentals of Engineering Optics", basic subject included in the second course of the Degree in Telecommunication, for "Photonic Devices and Optoelectronics" mandatory subject taught during the second year of the Master in Telecommunication, or the optative subject "Optical Image Acquisition and Processing" from the Master in Automation and Robotics in the University of Alicante too.

Keywords: Physics, Optics, Liquid Crystal, Parallel-Aligned, Spatial Light Modulators, Displays, Polarization, Stokes, Automation.

1 MUELLER-STOKES FORMALISM

At this level, students are familiarized with Jones formalism to study polarized light. Jones formalism is less general to manage polarized light since the unpolarized light case is not included [1]. The Jones formalism describes the electric field amplitude, so the intensity is not directly managed. We, as humans, perceive the intensity, so it is a more natural concept for us. We will see how Stokes formalism is based in intensity measures. For this reason we try to introduce Mueller-Stokes formalism in a practical way. That means, using specific equipment and a "hands-on" approach.

1.1 The Polarization Ellipse

It is known that light can be described as a vectorial quantity that propagates as a transversal wave. The oscillations are produced in the transverse components. This vectorial nature of light is called polarization, and it can be described by the so called Polarization Ellipse.

Figure 1: The Polarization Ellipse. The different angles and a explanation can be found in the text.

The Polarization Ellipse, that is presented in Fig. 1, represents the trajectory followed by the Electrical field in the transverse plane. For convenience, we have assumed that the light propagates along the z-axis, that in Fig. 1 is normal to the paper. This Ellipse is described by equation (1):

$$\frac{E_x^2}{E_{0x}^2} + \frac{E_y^2}{E_{0y}^2} - 2 \frac{E_x E_y}{E_{0x} E_{0y}} \cos \delta = \sin^2 \chi \quad (1)$$

Where $\delta = \delta_x - \delta_y$ is the phase difference between the electrical field components E_x and E_y . Note that the ellipse only depends on phase difference. The presence of the $E_x E_y$ term shows that it is a rotated ellipse, as it was represented in Fig. 1. So we can define some angles that helps us to describe the electrical field trajectory. This angles are: ψ that it is the azimuth, and define the rotation angle of the ellipse with respect the x-y axis, χ is the ellipticity angle and it evaluates the relation between the two ellipse axis, a and b. And α is an auxiliary angle that it is defined by the Electrical Field amplitudes.

We can find relations between these angles, that fully describe the polarization ellipse, and the electrical parameters:

$$= \frac{2E_{0x}E_{0y} \cos \delta}{E_{0x}^2 - E_{0y}^2} \quad (2)$$

$$= \frac{E_{0y}}{E_{0x}} \quad (3)$$

$$= (\sin \alpha) \sin \chi \quad (4)$$

A complete derivation of equations (1), (2), (3) and (4) can be found in [2]. All these relations will be useful to relate this geometric description to the Mueller-Stokes parameters that will be presented in the next section.

1.2 Stokes parameters

After presenting the polarization ellipse to the students it is time to introduce the Stokes parameters. As long as the student can understand the description of a ellipse by means of the geometrical parameters presented in equation (2), (3) and (4), it is difficult to add another representation by means of the Stokes parameters. We are defining the Stokes parameters in this subsection.

The polarization behaviour can be represented in terms of observables. Any state of polarized light can be completely described by four measurable quantities known as the Stokes polarization parameters. [2]. One of the problem, with the formulation presented in previous subsection, it is that the optical field amplitude cannot be directly measured. The quantity that can be observed is the intensity. So, the Stokes parameters will be expressed in terms of intensities.

$$I = E_{0x}^2 + E_{0y}^2 \quad (5)$$

$$Q = E_{0x}^2 - E_{0y}^2 \quad (6)$$

$$U = 2E_{0x}E_{0y} \cos \delta \quad (7)$$

$$= \frac{1}{2} E_{0x} E_{0y} \quad (8)$$

$$= S_1^2 + S_2^2 + S_3^2 \quad (9)$$

Equations (5-8) are the Stokes polarization parameters for a plane wave. It is important to notice that all of them are real quantities, and they are the observables of the polarization ellipse and, hence, the optical field. The first parameter S_0 , equation (5), is the total intensity of the light. S_1 , equation (6), describes the amount of linear horizontal or vertical polarization. S_2 , equation (7), describes the amount of linear $+45^\circ$ or -45° polarization. S_3 , equation (8), describes the amount of right or left circular polarization contained within the beam, and equation (9) describes the relation between all the four parameters for a fully polarized light beam. In the case that the light is not fully polarized we can use the Schwarz's inequality, that says that, for any state of polarized light, the Stokes parameters always satisfy the relation:

$$S_0^2 \geq S_1^2 + S_2^2 + S_3^2 \quad (10)$$

Equation (10) allows us to define the Degree of Polarization (DoP) as follows:

$$DoP = \frac{I_{pol}}{I_{tot}} = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0} \leq 1 \quad (11)$$

Where I_{pol} is the intensity of the sum of the polarization components and I_{tot} is the total intensity of the beam. Taking into account equation (2) and (4) we can express them as a function of the Stokes parameters:

$$I_{pol} = \frac{S_1}{2} \quad (12)$$

$$I_{pol} = \frac{S_3}{2} \quad (13)$$

Now we have access to the geometric properties of the polarization ellipse by means of the Stokes parameters.

We can define the Stokes vector by arranging the four parameters in a column matrix:

$$\vec{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} \quad (14)$$

This Stokes vector presented in equation (14) allows us to represent some special polarization states in a easier way. For example, a Right Circularly Polarized Light (RCP) is represented as:

$$\vec{S} = I_0 \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix} \quad (15)$$

Where $I_0 = \frac{1}{2} E_0^2$, and we have to take into account that a RCP light beam meets the following conditions: $E_{0x}=E_{0y}=E_0$ and $\delta=90^\circ$.

From equation (13) we can extrapolate that if $S_3=0$ then Ellipticity is 0 ($\chi=0$) so we can easily observed that we are managing a linearly polarized light beam. And this is the kind of knowledge that we want to show to students.

As a vector we can represent the Stokes vector in a three dimensional way using the Poincaré Sphere.

Figure 2: The Poincaré Sphere. Representation of the Stokes vector in a Sphere.

Fig. 2 shows how the Stokes vector can be represented in a sphere, and we show how the azimuth (ψ) and the ellipticity (χ) angle can be interpreted. In this sense, we can inherit that linearly polarized light will be represented by a vector contained in the equator plane. The right-handed states will be represented in the states belonging to the up-hemisphere, while RCP will be the up-pole. The left-handed states will be contained in the down-hemisphere, the down-pole will be a Left Circular Polarized light beam (LCP).

2 INSTRUMENTS

As we have mentioned before, the Stokes parameters are useful because they are directly accessible to measurement. They are formulated in terms of intensities of the polarization state of the optical beam. The measurements of the Stokes parameters are done by allowing an optical beam to pass through two optical elements, normally a retarder and a linear polarizer. [2]

A retarder is an element that introduces certain phase difference between the two components of the electrical field. A linear polarizer is an element that allows to pass only the light that is polarized in the same direction (or angle) defined by the transmission line.

2.1 Polarimeter

In the lab we use a commercial polarimeter, model PAX5710VIS-T, distributed by the company THORLABS [3]. This is a rotating wave-plate-based polarimeter, which belong to time-division mode polarimeters [4]. This polarimeter is based on the situation described above. It is based on a wave-plate, the retarder, that turns in front of a linear-polarizer, after this two elements a photodetector is measuring the intensity in every moment.

The Discrete Fourier Transform (DFT) of this intensity signal provide us a directly measurement of the Stokes parameters [5].

The polarimeter has several operating modes. One of them show us the Stokes Parameters values in real time (Oscilloscope mode), and we can visualize the stokes vector in a Poincaré Sphere in real time too. The instrument also show us the Ellipticity, Azimuth and DoP values. In this form the use and data representation of the instrument is very intuitive.

Figure 3: Software Interface showing the Poincaré Sphere and Polarization Ellipse.

In Fig. 3 we can see the Poincaré Sphere that can be plotted with the software, the arrow shows how, as explained in section 2, elliptical polarization light beam correspond with a point out of the equator.

Figure 4: Software Interface showing the Poincaré Sphere when a linear polarized light impinges the sensor.

In Fig. 4 is showed the case for a linear polarized light beam, as expected the point is plotted in the equator line (remarked with the arrow). In addition, we can see how the polarization ellipse is degenerated in a straight line.

Moreover, with the help of the software, we can study the variation of the different polarization stokes by using the oscilloscope mode.

Figure 4: Oscilloscope mode of the Software Interface showing the Poincaré Sphere when a linear polarized light impinges the sensor.

In Fig. 4 we captured the evolution of the polarized light beam. We only have changed the angle of a linear polarizer placed in front of the polarimeter. As can be seen the parameter S_3 is always zero as the ellipticity value.

2.2 Parallel Aligned LCoS

The other equipment used is a Parallel Aligned Liquid Crystal on Silicon (PA-LCoS) microdisplay. We use the commercially available PLUTO from HOLOEYE [6]. The PA-LCoS microdisplay are especially interesting because they allow phase only modulation, without any modulation of amplitude. They act as a wave-plate controlled by voltage [7]. We only have to set an specific gray level, with the help of the software provided. The display is controlled by an standard DVI interface.

We developed a fully characterization method [7]. That means that we know the retardance introduced for every gray level.

Figure 5: PA-LCoS microdisplay used in the experiences.

This microdisplay acting as a retarder can be programmed to modify its gray level and see how the Stokes parameters change in the polarimeter.

3 EXPERIENCES

The experiences proposed are designed to introduced all the concepts presented in section 1. For this reason we will use the simplest setup possible.

Figure 6: Experimental setup available in the lab.

Fig. 6 shows the setup that would be used during the experiments. The linear polarizer would define the angle of the linear polarized light when it impinges to the PA-LCoS. Then just by changing the gray level in the microdisplay we can see how the polarization ellipse evolves in the polarimeter. The quarter waveplate showed in Fig. 6 is used to ensure that we always have enough intensity in the polarimeter.

The access to the lab is organized in groups of about 10 students. First, we present the equipment to use and we explain the setup. After that, the students use some known polarization states to test the setup: We observe how the polarimeter shows a linear polarized light beam (Shown in Fig. 4) and how changing the polarization angle the Stokes vector is moving in the equatorial line. This first step is done by confronting the light beam after the linear polarizer directly to the polarimeter, without using the PA-LCoS.

Once the students have tested the polarimeter with a linear polarization state, then the PA-LCoS is introduced in the setup. In a first place, they observed how the changes in gray level affects to the polarization ellipse.

As long as we have characterized the PA-LCoS, we inquire the students to look for a gray level that transforms the linear polarization light, that impinges to the display, into a RCP. They have to try to predict the gray level to be used.

Apart from the basic measurement exposed, we introduced them to the programming language of National Instruments LabVIEW [8]. This language is very useful to automatize the data collection. This gives the student a complete vision about how to work in a research lab. We proposed them an experiment to show a complete variation of the gray level in the display and collect all the stokes parameters to see the complete evolution of the polarization state at the exit. The data will have to be plotted and explained in class.

As an addendum, we can observe how the display introduces a certain degree of unpolarized light. This fact is explained by the digital nature of the electronic signal driven the display. In the data obtained we have to analyze which gray levels reduce the most the DoP.

4 CONCLUSIONS

The experience proposed is very visual. The students, especially those who are studying the Master degree, are very interested in knowing the research that are being done in their university. So, visiting a research lab is a very motivating experience.

The Stokes parameters are difficult to understand and to translate it into a polarization state, with these experiences the concepts involved are much clearer, because they have to analyze the data,

and the equipment used gives a very complete vision of the evolution produced in the polarization ellipse.

We have checked that students show great satisfaction and interest with the experience, mainly because of the contact with the research equipment and the visualization of such theoretical concepts.

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REFERENCES

- [1] Justiniano Casas, "Óptica". Zaragoza (Spain): Librería General, 7ª Edición, 1994.
- [2] Dennis Goldstein, "Polarized Light", New York (U.S.A.) Marcel Dekker Inc. 2º Edition. 2003
- [3] Access to the User Manual of PAX4710VIS-T polarimeter (<https://www.thorlabs.com/thorproduct.cfm?partnumber=PAX5710VIS-T>) Accessed 16/05/2017
- [4] Costel Fluerau et al, "Error Analysis of a Rotating Quarter-Wave Plate Stokes' Polarimeter", IEEE Transactions on Instrumentation and Measurements, vol. 57, no. 4, pp. 731-735, 2008
- [5] H. G. Berry et al, "Measurement of the Stokes parameters of light" Applied Optics, vol. 16, no. 12, pp. 3200-3205, 1977.
- [6] Access to the HOLOEYE PLUTO characteristics (<http://holoeys.com/spatial-light-modulators/slm-pluto-phase-only/>) Accessed 16/05/2017
- [7] F. J. Martínez et al, "Retardance and flicker modeling and characterization of electro-optic linear retarders by averaged Stokes polarimetry", Optics Letters, vol. 39, no. 4, pp. 1011-1014, 2014.
- [8] National Instruments LabVIEW webpage (<http://www.ni.com/labview/>) Accessed 16/07/2017