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Polarimetry of Light Using Analysis of the Nonlinear Voltage-Retardance Relationship for Liquid-Crystal Variable Retarders

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Abstract. We present a method for using liquid-crystal variable retarders (LCVR's) with continually varying voltage to measure, both, the Stokes vector of a light beam and the complete Mueller matrix of a general sample.

Keywords: nonlinear voltage-retardance relationship, polarimetry of light.

1 Introduction

The measurement of the polarization of light is well established [1-3]. Recently, more use has been made of variable retarders, for example, liquid crystal retarders or electro-optic cells which have changes of the retardance depending on the voltage applied to the system. The LCVR's are usually employed with fixed retardance values due to the nonlinear voltage-retardance behavior that they show. For the measurement method presented here, the nonlinear voltage-retardance relationship is first measured and then a linear fit of the known retardance terms to the detected signal is performed. We use known waveplates (half-wave and quarter-wave) as devices to provide controlled polarization states to the Stokes polarimeter, and we use the measured Stokes parameters as functions of the orientation of the axes of the waveplates as an indication of the quality of the polarimeter. In addition, we present results of simulations for comparison. Also, we have used this technique to measure the complete Mueller matrix of a general sample. For a gap of air, the measurement error in the Mueller-matrix polarimeter is estimated at 1–10%, depending on the Mueller-matrix element. For this case, we present experimental results for a Glan–Thompson prism polarizer as a test sample, and we use the measured Mueller parameters as functions of the orientation of the optical axes of the polarizer as an indication of the quality of the polarimeter.

2 Stokes Polarimeter

Figure 1 shows the set-up used for the Stokes polarimeter. The light to be analyzed passes through two liquid crystal variable retarders with their axes at 45 degrees to each other and finally through a linear polarizer with its transmission axis parallel to the axis of the first retarder. The idea of this method is to adjust the detected intensity, I, to a linear combination

$$I = A + B\cos(\delta_2) + C\sin(\delta_1)\sin(\delta_2) + D\cos(\delta_1)\sin(\delta_2). \qquad (1)$$

So, we have

$$A = \frac{1}{2}S_0^{in}, \qquad B = \frac{1}{2}S_1^{in}, \qquad C = \frac{1}{2}S_2^{in}, \qquad D = \frac{1}{2}S_3^{in}, \qquad (2)$$

where S_0^{in} $S_1^{in}S_2^{in}$and S_3^{in}; are the components of the Stokes vector of the incident light beam, S^{in}. The development of the above equations and, also, details on the experimental set-up for the Stokes polarimeter are shown in [4].

Fig. 1. The set-up for a Stokes polarimeter. The angles associated with each component refer to the relative angle of the optical axis of that component. ω1 and ω2 are the frequencies of the variations of the retardances.

In this case, we have applied a voltage signal which has the form of a linear ramp (saw tooth), this is

$$V = V_{\min} + (V_{\max} - V_{\min})\operatorname{mod}\left(\frac{t}{t_i}\right), \qquad (3)$$

and the retardance, δ, is given by the nonlinear relationship of figure 2.

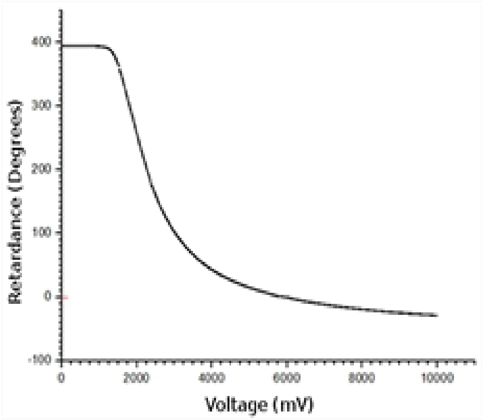

Fig. 2. Retardance vs. voltage for a typical liquid crystal retarder for a wavelength of 633nm [5, 6].

From a characterization previously performed on our LCVR's, figure 2 [5, 6], we know all the retardance (δ) values employed during the measurements. We have measured the Stokes vector of light passing through a linear polarizer and a half-wave retarder, as the retarder is rotated, and also for a linear polarizer and a quarter-wave retarder as the retarder is rotated. In the first case the polarization measured should shift between S1 (horizontal/vertical linear polarization) and S2 (+45 degrees/-45 degrees linear polarization), and in the second case the polarization should shift between linear and circular S3 polarization. Results of calculation for these cases give the curves shown in figure 3. The experimental results are shown in figure 4 for these two cases. It can be seen that the behavior of the results is, in general, as expected, although there are some small asymmetries in the curves, and noise. The measurement time for each Stokes vector was 1.8 seconds.

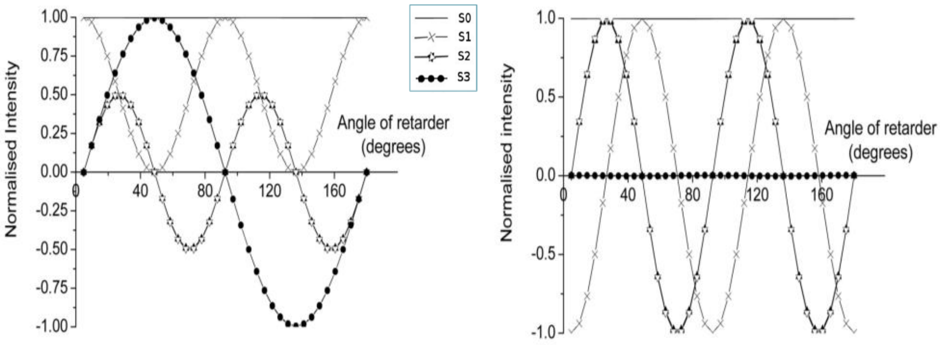

Fig. 3. Simulation of the Stokes vector of light passing through a linear polarizer and a quarter-wave plate (left) and also for a linear polarizer and a half-wave plate (right).

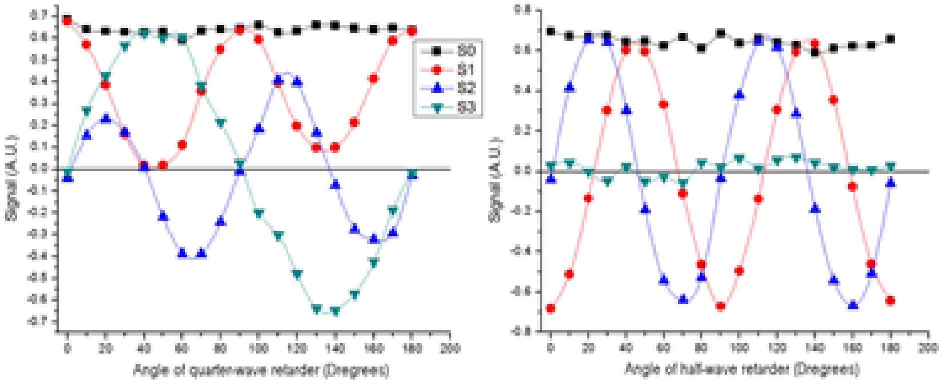

Fig. 4. Experimental measurements of the Stokes vector of light using a fitting procedure. The light is passing through a linear polarizer and a quarter-wave plate (left) and also for a linear polarizer and a half-wave plate (right).

3 Mueller Polarimeter

A Mueller matrix polarimeter is an instrument designed and built to measure the 16 elements of the Mueller matrix. Figure 5 shows the set-up for the Mueller matrix polarimeter using LCVR's. This device consists of two modules: a polarization state generator (PSG) and a polarization state analyzer (PSA). The sample under test is analyzed between those two modules.

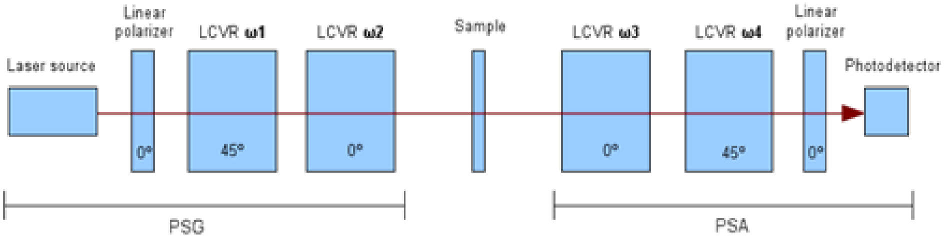

Fig. 5. The set-up for a Mueller matrix polarimeter. The angles associated with each component refer to the relative angle of the optical axis of that component. ω1, ω2, ω3 and ω4 are the frequencies of the variations of the retardances.

The PSG determines the polarization state of the incident light whereas the PSA measures the change in this state after interaction with the sample. In a similar way as the previous case, we can found all the components of the Mueller matrix, M, by fitting the detected signal to a linear combination. Details of this measurement method are described in a previous paper [6]. The 4 × 4 identity matrix is the Mueller matrix of the air. An example of experimental values obtained for this Mueller matrix is:

$$M_{Air} = \begin{pmatrix} 1 & -0.054 & 0.052 & 0.021 \\ -0.029 & 0.986 & -0.031 & 0.083 \\ -0.014 & -0.037 & 0.955 & -0.046 \\ -0.039 & -0.001 & -0.051 & 0.897 \end{pmatrix}. \tag{4}$$

The Mueller elements are all normalized by the first entry, M11. In the example shown in Eq. (4), the Mueller matrix was obtained with an accuracy error estimated at 1–10%, depending on the Mueller-matrix element. The measurement error of each matrix element is ±0.005. This instrument was tested on samples with known Mueller matrices such as polarizers, quarter-wave retarders, and half-wave retarders; in transmission mode, always obtaining good results.

Experimental results for a rotating linear polarizer are shown in Figure 5; measurements were made in steps of 10 degrees, from 0 to 180 degrees. It can be seen that the behavior of the results is, in general, as expected. Measurements and calculations were performed in LabVIEW®. The measurement time for each complete Mueller matrix was 1.8 seconds.

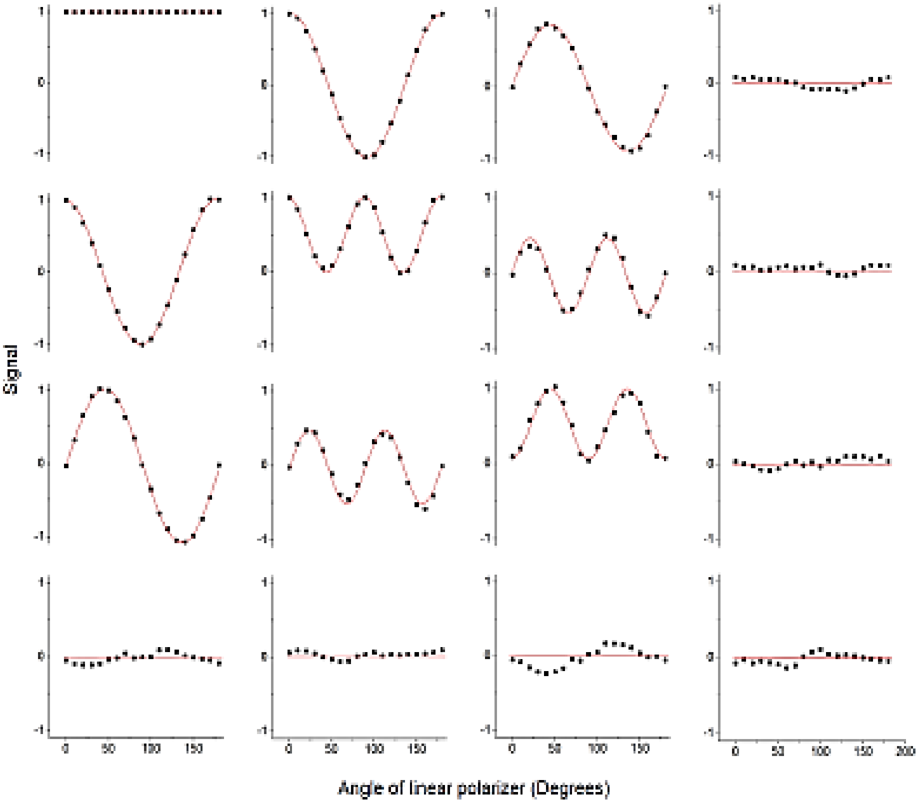

Fig. 6. Sixteen Mueller-matrix elements (classified as they appear in the matrix) of a Glan–Thompson prism polarizer drawn as a function of its optical angle (in degrees), obtained using a continually varying voltage method of measurement. The dots are the experimental results including device and sample imperfections; the solid curves are the fitted theoretical curves of an ideal polarizer. The Mueller elements are all normalized by the first entry, M11.

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