Optics Communications 382 (2017) 501–508

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Rapid full Mueller matrix imaging polarimetry based on the hybrid phase modulation technique

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ARTICLE INFO

Article history:
Received 3 May 2016
Received in revised form
8 August 2016
Accepted 12 August 2016

Keywords:
Mueller matrix
Liquid crystal variable retarder
Photoelastic modulator
Imaging polarimetry

ABSTRACT

In this work, we present a novel method of Mueller matrix imaging polarimetry, which comprises dual liquid crystal variable retarders at the polarization generation portion and a photoelastic modulator at the polarization analysis portion. The light source can be operated either in the continuous mode, which provides an in-situ calibration process for the liquid crystal variable retarders, or in the pulse mode to deduce the full two-dimensional Mueller matrix with 16 images from the camera. We measured the Mueller matrix images of air as a standard test, as well as a quarter wave plate to determine its azimuthal angle and phase retardation by the polar decomposition technique. Finally, the decomposed Mueller matrix images of a biopolymer specimen with the conformational change produced by heat treatment are presented.

1. Introduction

Optical imaging is a widely applied technique used to examine biological specimens from the cell to organ level which facilitates the diagnosis and investigation of pathologic processes in medicine. In recent decades, the use of optical polarimetry approaches for biological tissue characterization and imaging has gained much attention, as polarization proved to be an effective tool to filter out the multiple scattered light, and thus can improve the resolution and contrast of images [1,2]. Mueller matrix imaging, as a powerful tool for polarimetric characterization of a linear media, contains extensive information on the morphological and functional properties of the biological samples as well as the birefringence, dichroism, and depolarization of the specimens [3–5]. With a variety of azimuth angles of the polarizer, analyzer and retarders, conventional imaging polarimetry methods were based on measurements involving sequential detection [6,7]. However, the rotation of optical elements to obtain the full elements of Mueller matrix was actually a time-consuming process that impeded the use of the system for in vivo imaging studies. In order to improve the speed of measurement, the configuration of the Mueller matrix polarimeter was mainly focused on the process of using liquid crystal to control and analyze the state of the input or output polarizations [8,9]. As the measurements with these approaches usually employed unmodulated light irradiance, the results were more sensitive to noise than methods using an intensity-modulated light. Particularly for low light intensity conditions, such as determining the polarization characteristics of highly scattering samples. Meanwhile, the tuning curve of the liquid crystal variable retarder (LCVR), which determines the relation between the driving voltage and phase retardation, has to be recognized as the calibration procedure before the measurement. However, the tuning curve of the LCVR was found to be sensitive to its alignment and temperature [10,11]. Such uncertainties often resulted in systematic errors and also impacted the overall performance of the instrument. Accordingly, it is highly necessary to take great care and calibrate the LCVR before the measurement of Mueller matrix polarimetry.

Here, a novel Mueller matrix imaging system is developed and a hybrid phase modulation technique is proposed to evaluate the optical polarization characteristics of the specimens. The polarization state generator of this system is composed of a linear polarizer and two LCVRs, allowing the sequential generation of four polarizations, analogous to that in used in previous reports [12,13]. However, the polarizations state analyzer is composed of a photoelastic modulator (PEM) and an analyzer, which work with a laser diode light source. While the laser diode operates in the continues mode and without insertion of a sample, the polarization state analyzer can examine the characteristics of the output polarized light from the LCVRs, as an in-situ calibration approach, before the measurement. Afterwards the laser diode is operated in the pulse mode and synchronized with the PEM reference signal that makes it possible for the CCD camera to receive light pulses carrying specific polarization information. With 16 unique combinations of generated and analyzed polarization states, the image of full Mueller matrix components of the sample can be

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http://dx.doi.org/10.1016/j.optcom.2016.08.026
0030-4018/© 2016 Published by Elsevier B.V.

determined with an acceptable precision. Except for the static condition of the Mueller matrix imaging measurement of the standard samples, the dynamic optical characteristics of a biopolymer specimen with heat-induced conformational change are also illustrated throughout the heat treatment.

2. Principle and experiment

Usually, the Mueller matrix polarimeter consists of two main components: a polarization state generator (PSG), where the incident polarization is systematically varied, and a polarization state analyzer (PSA), where the polarization of the outgoing light is determined. The schematic setup of the proposed optical system for imaging is shown in Fig. 1. The light source used, a 100 mW laser diode @658 nm then passed through a spatial filter with the beam expander feature, is able to modify the beam diameter about 10 mm. The PSG is composed of one polarizer and two LCVRs (LCC1113-A, Thorlabs, Newton, NJ, USA) whose retardations (δ_1 , δ_2) are dependent on their driving voltages. As for the azimuth angle of the polarizer, it was set at −45° and the slow axis of the two LCVRs were oriented to an angle of 90° and 45°, respectively. Thus, the Mueller matrix of the PSG in terms of the Mueller matrices of their components can be expressed as:

$$M_{PSG} = M_{LCVR_2}\left(\delta_2, 45^\circ\right)\cdot M_{LCVR_1}\left(\delta_1, 90^\circ\right)\cdot M_P\left(-45^\circ\right) \tag{1}$$

where

$$M_{LCVR_1}\left(\delta_1, 90^\circ\right) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\delta_1 & -\sin\delta_1 \\ 0 & 0 & \sin\delta_1 & \cos\delta_1 \end{bmatrix}, \text{ and}$$
$$M_{LCVR_2}\left(\delta_2, 45^\circ\right) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\delta_2 & 0 & -\sin\delta_2 \\ 0 & 0 & 1 & 0 \\ 0 & \sin\delta_2 & 0 & \cos\delta_2 \end{bmatrix} \tag{2}$$

The PSA, composed of a PEM and an analyzer, uses a pulse laser diode with stroboscopic illumination technique [14]. In order to obtain a complete set of PSA, we set the azimuth angle of the PEM at 0°, and the Mueller matrix representing the PSA module is obtained from:

$$M_{PSA} = M_a(A)\cdot M_{PEM}\left(\Delta_p, 0^\circ\right) \tag{3}$$

$$M_{PEM}\left(\Delta_p, 0^\circ\right) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\Delta_p & -\sin\Delta_p \\ 0 & 0 & \sin\Delta_p & \cos\Delta_p \end{bmatrix} \tag{4}$$

where M_a and M_{PEM} represent the Mueller matrix of the analyzer and PEM, respectively; A is the azimuth angle of the analyzer; Δ_p is the phase retardation of the PEM, which was modulated as $\delta_0 \sin\theta_p$. Here, the amplitude of modulation δ_0 is set at π, and the temporal phase angle is represented as θ_p. Consequently, the total Mueller matrix of the system is given by:

$$M_T = M_{PSA}M_SM_{PSG} = M_a(A)\cdot M_{PEM}\left(\Delta_p, 0^\circ\right)\cdot M_S\cdot M_{LCVR_2}\left(\delta_2, 45^\circ\right)\cdot M_{LCVR_1}\left(\delta_2, 90^\circ\right)\cdot M_P\left(-45^\circ\right) \tag{5}$$

$$M_s = \begin{bmatrix} m_{00} & m_{01} & m_{02} & m_{03} \\ m_{10} & m_{11} & m_{12} & m_{13} \\ m_{20} & m_{21} & m_{22} & m_{23} \\ m_{30} & m_{31} & m_{32} & m_{33} \end{bmatrix} \tag{6}$$

where M_s refers to the Mueller matrix of the sample being tested. As the system is based on irradiance modulation, only the first Stokes parameter in Eq. (5) has to be considered. One can formulate the temporal intensity behavior as follows:

$$\begin{aligned} I(A, \theta_p, \delta_1, \delta_2) = \frac{I_0}{4}\Big\langle & m_{00} - m_{02}\cos\delta_1 - \frac{1}{2}m_{01}\sin\delta_1\sin\delta_2 \\ & + \cos 2A\left(m_{01} - \frac{1}{2}m_{11}\sin\delta_1\sin\delta_2 - m_{12}\cos\delta_1 + m_{13}\sin\delta_1\cos\delta_2\right) \\ & + \frac{1}{2}\sin 2A\Big[\cos(\pi\sin\theta_p)(2m_{20} - m_{21}\sin\delta_1\sin\delta_2 \\ & - 2m_{22}\cos\delta_1) + \sin(\pi\sin\theta_p)(2m_{30}\sin 2A - m_{31}\sin\delta_1\sin\delta_2 \\ & - 2m_{32}\sin 2A)\Big] + \sin\delta_1\cos\delta_2\Big\{m_{03} + \sin 2A\Big[m_{23}\cos(\pi\sin\theta_p) \\ & + m_{33}\sin(\pi\sin\theta_p)\Big]\Big\}\Big\rangle \end{aligned} \tag{7}$$

As it is widely known, at least 16 individual polarization-state measurements are required to determine the full Mueller matrix. The measurements are usually performed by generating four specific polarization states from the PSG, and the Stokes vectors of the light after passing through the sample can thus be analyzed through the PSA. When it comes to determining the single Stokes vector, at least four intensity measurements are required. Accordingly, both the PSG and the PSA must be "complete", with at least 4 basis states to obtain the full Mueller matrix M_s.

In detail, the four phase retardations (δ_1 ,δ_2)=(90°, 0°), (0°, 0°), (75.5°, 206.5°), and (75.5°, 153.5°) were set by driving the voltages for both LCVRs in a time sequence, so that four specific

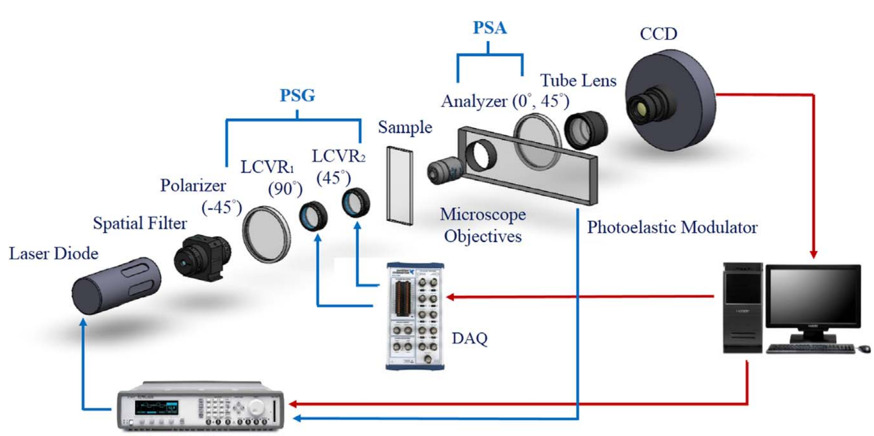

Fig. 1. Optical setup for Mueller matrix imaging polarimetry with hybrid phase modulation technique.