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Full Length Article

Experimental study of thickness dependence of polarization and depolarization properties of anisotropic turbid media using Mueller matrix polarimetry and differential decomposition

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ABSTRACT

We investigate the influence of sample thickness on the polarization and depolarization properties of light when it propagates through anisotropic turbid media using transmission Mueller matrix polarimetry. Since depolarization originates from light that has been multiply-scattered inside the sample, measurements were done by a polarimetric scatterometer equipped with large aperture optics to efficiently capture direct and scattered light. We made measurements in both, real and Fourier planes to study the distribution of polarization across the surface as well as their angular distribution respectively. We show that when properly averaged, the information obtained from images in both planes is equivalent. Rough stretched plastic sheets are used as model samples representing anisotropic turbid media which show both retardance and depolarization. The plastic sheets were stacked in different orientations to create different distributions of form birefringence, which in turn gave rise to different polarimetric properties such as linear (0°–90°, 45°–135°) and circular birefringence. We show that the dependency on the values of both, polarization properties and depolarization follows the theory of the fluctuating medium model, formulated in the framework of the differential Mueller matrix formalism. These results are used as a validation of the polarimetric scatterometer, and also, to show the interest of transmission Mueller matrix polarimetry to characterize samples showing scattering, which can be typically found in biomedicine and materials sciences.

1. Introduction

In general, natural and manmade scattering media exhibit both polarizing and depolarizing properties. In such media, the polarization and depolarization properties manifest themselves simultaneously in an entwined fashion, and also they evolve differently with the thickness of the sample.

Our goal was to study the influence of sample thickness on the polarization and depolarization properties of light when it propagates through of uniform anisotropic turbid media using transmission Mueller matrix polarimetry. For the purposes of the present study, we consider that in such media, light is mainly scattered inside the bulk of the material and the effects of the surfaces are not taken into account. Since the instantaneous direction of propagation and the polarization of light change after each scattering event, each photon of the illuminating light beam emerges from the sample with a particular trajectory, and a polarization state that can be very different from those of the other photons in the same beam. The physical properties of the sample can strongly influence both, the rate of change of polarization of photons propagating inside it, and also the angular distribution of polarization states of the light emerging from it. The detailed description of those to phenomena can be very complex see for instance [1,2]; and fall well beyond the purposes of this work. Here we limit ourselves to present a method to characterize the evolution of the light properties inside of a sample and to interpret the measurements in terms of a phenomenological method which does not consider the details of the microscopic interaction of light with the turbid media.

To investigate these polarimetric properties, we use the Mueller matrix formalism which is a complete and unambiguous way to represent the interaction of polarized light inside of a given sample [3–7]. A Mueller matrix decomposition is a way to extract phenomenological polarimetric properties from the Mueller matrix such as dichroism, birefringence, depolarization and polarizance. Decomposition methods are not based on a microscopic model related to the internal structure of the material. Indeed, they are in

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general applied as a previous step before going to a detailed modelization of the material, or else, when the sample is so complex than a "classic" microscopic and realistic model is just impossible to be built. To date different types of decompositions have been shown, which can be divided into three groups: multiplicative decompositions, addition decompositions and differential decompositions. The choice of a given decomposition method is mainly determined by the structure of the sample, more details can be found in [3,8,9]. In our case we use the differential decomposition, because it is well-suited to describe uniform samples in which polarization and depolarization properties appear together and are well distributed across the sample. Moreover the differential decomposition approach can only be applied for measurements in transmission, such the ones performed in the present study. Therefore, transmission Mueller matrix polarimetry, combined with the Mueller matrix differential decomposition approach, appears to be well adapted experimental and analysis tool for the characterization of the polarimetric properties of turbid media [10,11].

This paper discusses the results obtained using this combined approach to study the thickness dependence of the polarization and depolarization properties of anisotropic turbid media. For this illustrative study, we used rough stretched plastic sheets, which can be considered as a simple "case" example of anisotropic turbid media. The molecules of the plastic sheets are well-aligned, thus creating a noticeable linear birefringence which is primarily oriented parallel to the sample surface. Moreover the density of the plastic sheets is not uniform in a microscopic scale. Therefore, light is multiply scattered when it propagates across them, losing part of its initial polarization, and becoming partially polarized [12–16]. In particular, we show that the polarization and depolarization properties of the studied media evolve linearly and quadratically, respectively, with the sample thickness, in agreement with the fluctuating homogeneous medium model [10,17]. The samples are measured with an innovative in-house Mueller matrix polarimetric scatterometer in transmission which is able to take images in the real and back focal (Fourier) planes of a microscope objective used to image the studied sample. Real plane images allow measuring the spatial distribution of the polarimetric response of the sample, whereas Fourier plane images allow measuring the angular distribution of the intensity and polarization of light scattered by the sample [18].

The paper is organized as follows: in the following section, there is a short review of the most important aspects of the differential decomposition and the fluctuating homogeneous model. Section 3 is devoted to the description of the polarimetric scatterometer, as well as the description of the samples considered here. In Section 4, we show the experimental measurements together with the results the data analysis. Finally, a summary is presented in the last section.

2. Theory

In 1978, R.M.A. Azzam proposed a differential matrix formalism for linear optically anisotropic media based on the Mueller matrix calculus [19]. Accordingly, the multiplication of a differential Mueller matrix, **m**, by the Mueller matrix of the anisotropic sample, **M**, is equal to the gradient of **M** along the direction of light propagation z, as shown in the equation,

$$\frac{d\mathbf{M}(z)}{dz} = \mathbf{m}(z)\mathbf{M}(z), \tag{1}$$

the matrix **m** contains the elementary polarimetric properties of the sample per unit of distance (i.e. specific properties): linear dichroism along the xy coordinate axes 0°–90° (LD), linear dichroism along the xy coordinate axes 45°–135° (LD′), circular dichroism (CD), linear birefringence along the xy coordinate axes 0°–90° (LB), linear birefringence along the bisectors of the xy coordinate axes 45°–135° (LB'), circular birefringence (CB) and isotropic absorption (α). The advantage of, **m,** over, **M,** is that the polarimetric properties are decoupled from each other and also, each property appears in a specific matrix element according to:

$$\boldsymbol{m} = \begin{pmatrix} \alpha & \mathrm{LD} & \mathrm{LD}' & \mathrm{CD} \\ \mathrm{LD} & \alpha & \mathrm{CB} & \text{-}\mathrm{LB}' \\ \mathrm{LD}' & \text{-}\mathrm{CB} & \alpha & \mathrm{LB} \\ \mathrm{CD} & \mathrm{LB}' & \text{-}\mathrm{LB} & \alpha \end{pmatrix}. \tag{2}$$

Azzam discussed this model applied to a homogeneous nondepolarizing medium with arbitrary absorptive and refractive anisotropy. Years later the formalism was extended to depolarizing samples by R. Ossikovski, V. Devlaminck and O. Arteaga [18,20–22]. In this latter case, the matrix values of the matrix **m** can be assumed to randomly fluctuate around an average value . Fluctuations can be interpreted as the statistic variances of the elementary polarimetric properties $\Delta\mathbf{m}$ of the sample [10,18,21,22]. Assuming the fluctuations to be sufficiently small, a first-order approximation relating the Mueller matrix to the exponential of the matrix **m** times the thickness, z, leads to the following expression relating the polarization and the depolarization properties with the matrices and <$\boldsymbol{\Delta}\mathbf{m}$> respectively.

$$\boldsymbol{L}(z) = \boldsymbol{L}_{\mathrm{m}} + \boldsymbol{L}_{\mathrm{u}} = \langle \mathrm{m} \rangle z + \langle \Delta \mathbf{m}^2 \rangle z^2, \tag{3}$$

in which $\mathbf{L}(z) = \ln \mathbf{M}(z)$. The brackets stand for a statistical averaging of the matrices, necessary to take into account the multiple realizations, or paths that a photon can follow across the sample. The matrices $\mathbf{L}_{\mathrm{m}}$ and $\mathbf{L}_{\mathrm{u}}$, in Eq. (3), are the **G**-antisymmetric and **G**-symmetric parts of **L** according to:

$$\boldsymbol{L}_{\mathrm{m}} = \frac{1}{2}(\boldsymbol{L} - \boldsymbol{G}\boldsymbol{L}^T\boldsymbol{G})\mathrm{and}\mathrm{L}_{\mathrm{u}} = \frac{1}{2}(\boldsymbol{L} + \boldsymbol{G}\boldsymbol{L}^T\boldsymbol{G}), \quad ,(4)$$

in which $\mathbf{G} = \mathrm{diag}(1, -1, -1, -1)$ is the Minkowski metric matrix.

If the sample is nondepolarizing, $\langle \Delta \mathbf{m}^2 \rangle = 0$ so that the $\mathbf{L}_{\mathrm{u}} = 0$ in Eq. (3) leaving $\mathbf{L}(z) = \mathbf{L}_{\mathrm{m}}$. The matrix $\mathbf{L}_{\mathrm{m}}$ contains the elementary polarization properties of the sample, evolving linearly along z axis, as shown in Eq. (1). However, if the sample is depolarizing, $\langle \Delta\mathbf{m} \rangle \neq 0$ and the diagonal elements of $\mathbf{L}_{\mathrm{u}}$ contain the depolarization components,$\mathrm{diag}(\mathbf{L}_{\mathrm{u}}) = (0, \alpha_1, \alpha_2, \alpha_3)$, which depend quadratically on the propagation distance along z.

3. Methods

3.1. Polarimetric microscope description

The schematic description of the transmission Mueller polarimeter is shown in Fig. 1. The system contains two blocks, illumination and imaging. The illumination arm consists of a white LED source, which is followed by a spectral filter, a polarization states generator (PSG) and a first microscope objective. In our case, we selected a filter with a central wavelength of 550 nm and a spectral bandwidth of 20 nm to match the maximum spectral response of the CCD camera (AV Stingray F-080B) used as a detector in the system. The spectral width of the filter is chosen to minimize the depolarization arising from the use of a polychromatic light beam, while keeping an acceptable intensity of light reaching the detector. The light beam emitted by the LED source is focused on a pinhole, and then a couple of lenses are used to re-image the pinhole on the Fourier plane of the first microscope objective. The pinhole, with a diameter of 500 μm, ensures a homogeneous and optimal illumination of the first microscope objective. The imaging arm consists of a second microscope objective, a polarization states analyzer (PSA) and a set of lenses to create an image on the sensitive area of the CCD camera. One of the lenses, the one just after the PSA, is retractable and allows to create either a real image of the sample, or an image