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Circular birefringence/dichroism measurement of optical scattering samples using amplitude-modulation polarimetry

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ABSTRACT

A method is proposed for extracting the circular birefringence (CB), circular dichroism (CD) and depolarization (Dep) properties of optical scattering samples using an amplitude-modulation polarimetry technique. The validity of the proposed method is demonstrated by extracting the CB property of pure glucose aqueous samples, the CB/Dep properties of glucose solutions containing 0.02% lipofundin particles, and the CD/Dep properties of chlorophyllin solutions containing suspended polystyrene microspheres. The results show that the proposed technique has the ability to detect pure glucose with a resolution of 66 mg/dL over a concentration range of 0–500 mg/dL. Moreover, the glucose concentration of the CB/Dep samples can be detected over the same range with a resolution of 168 mg/dL. Finally, the chlorophyllin concentration of the CD/Dep sample can be detected over the range of 0–200 μg/dL with a resolution of 6.5×10^{-5}. In general, the results show that the proposed technique provides a reliable and accurate means of measuring the CB/CD properties of optical samples with scattering effects, and thus has significant potential for biological sensing applications.

1. Introduction

Glucose monitoring plays a key role in the testing and diagnosis of diabetes. As with all chiral samples, the optical activity of glucose samples can be characterized by their circular birefringence (CB) and circular dichroism (CD) properties. Consequently, many measurement systems based on polarimetry techniques have been proposed for obtaining high-accuracy glucose concentration measurements in recent years [1–3]. Cote and Vitkin [4] proposed a polarimetric measurement method for evaluating the optical activity of clear and turbid media containing glucose using a balanced detection technique. The proposed technique reduced the common-mode noise in the polarized intensity measurements by means of a phase-locked detection method, and hence significantly improved the precision of the extracted results. Cameron and Li [5] used a custom-designed imaging polarimeter and a partial least squares (PLS) regression method to obtain noninvasive measurements of the glucose concentration in the aqueous humor of the human eye.

Circular dichroism (CD) is one of the most important optical properties for characterizing the structure of proteins [6,7]. Neyer et al. [8] proposed a pulsed four-wave mixing technique for the real-time measurement of the CD properties of liquid samples using transient thermal gratings formed by the interference of two laser beams with polarization states controlled by a photoelastic modulator. Bahar [9] detected and identified biological and chemical materials by measuring the CD property of the polarized light scattered from the sample surface. However, the techniques proposed in [8–9] are rather complicated and have a low sensitivity. Accordingly, Sianglam et al. [10] recently proposed a new CD sensor for the selective detection of Cd^{+2} and S^{2-} based on chiral Cds quantum dots synthesized via a facile in-situ reaction process. The experimental results showed that the proposed sensor achieved a resolution of approximately 1000 mg/dL and 100 mg/dL for Cd^{+2} and S^{2-}, respectively. Ngamdee et al. [11] presented a new CD sensor based on cysteamine-capped cadmium sulfide quantum dots for D-penicillamine (DPA) detection with a resolution of 60 mg/dL. However, the quantum dot-based techniques presented in [10–11] are experimentally complex and expensive.

The present study proposes a polarimetric measurement system for extracting the CB, CD and depolarization (Dep) properties of optical scattering samples. In the proposed approach, the intensity of the noise in the polarized intensity measurements is reduced using an optical chopper and a phase-locked detection method, and hence the accuracy of the extraction results is improved. The validity of the proposed method is demonstrated by extracting the CB property of pure glucose aqueous samples, the CB/Dep properties of glucose solutions containing

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0.02% lipofundin, and the CD/Dep properties of chlorophyllin solutions containing polystyrene microspheres.

2. Amplitude-modulation polarimetry method for extracting CB, CD and Dep properties of optical samples

2.1. Mueller matrix decomposition method

Polarized light can be described by the following four-element Stokes vector [12]:

$$S = I\begin{pmatrix} I & Q & V & U \end{pmatrix}^T, \tag{1}$$

where I is the overall intensity, Q and U describe the linear polarization, and V describes the circular polarization. Stokes vectors are generally normalized by dividing each element by I. Thus Eq. (1) can be rewritten as

$$S = I\begin{pmatrix} i & q & v & u \end{pmatrix}^T = I' \tag{2}$$

where $q = Q/I$, $u = U/I$ and $v = V/I$. When an input polarized light beam with Stokes vector S_{in} interacts with a sample, its polarization state is altered. For the amplitude-modulation polarimetry system developed in the present study, the detected light is described by $S = I' = M'MS'$, where S is the Stokes vector of the output light, M' is the Mueller matrix of the additional elements placed in the optical system, M is the Mueller matrix of the sample, and S' is the Stokes vector of the input light. The general form of this relation is given as

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{bmatrix} = I' = M'MS' = \begin{bmatrix} M'_{11} & M'_{12} & M'_{13} & M'_{14} \\ M'_{21} & M'_{22} & M'_{23} & M'_{24} \\ M'_{31} & M'_{32} & M'_{33} & M'_{34} \\ M'_{41} & M'_{42} & M'_{43} & M'_{44} \end{bmatrix} \times \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{bmatrix} \begin{bmatrix} S'_0 \\ S'_1 \\ S'_2 \\ S'_3 \end{bmatrix} \tag{3}$$

while M' is formulated as $M' = \{M_{P0°}, M_{P45°}, M_{p45°Q0°}\}$ where $M_{P0°}$ is the Mueller matrix of a polarizer with the principal axis set to 0°, $M_{P45°}$ is the Mueller matrix of a polarizer with the principal axis set to 45°, and $M_{p45°Q0°}$ is the Mueller matrix of a hybrid optical element consisting of a polarizer with the principal axis set to 45° and a quarter-wave plate with the principal axis set to 0°. (Note that the details of the three Mueller matrices are presented in [12].)

2.2. Analytical model for extracting CB property

This section derives the analytical model used to extract the optical rotation angle γ of a pure CB sample. The Mueller matrix for such a sample is expressed as [13]

$$M_{CB} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(2\gamma) & \sin(2\gamma) & 0 \\ 0 & -\sin(2\gamma) & \cos(2\gamma) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \tag{4}$$

Using four linear input lights (i.e., 0°, 45°, 90° and 135°) with an additional polarizer $M_{P0°}$ behind the sample provides a sufficient number of equations to extract γ from Eq. (4). In particular, the Stokes vectors in Eq. (3) can be rewritten as

$$I' = M_{P0°}M_{CB}\begin{bmatrix} S'_0 \\ S'_1 \\ S'_2 \\ S'_3 \end{bmatrix}_{0°,45°,90°,135°} = \begin{bmatrix} 0.5 & 0.5 & 0 & 0 \\ 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(2\gamma) & \sin(2\gamma) & 0 \\ 0 & -\sin(2\gamma) & \cos(2\gamma) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} S'_0 \\ S'_1 \\ S'_2 \\ S'_3 \end{bmatrix}_{0°,45°,90°,135°} \tag{5}$$

As a result,

$$I'_{0°} = 0.5 + 0.5\cos(2\gamma) \tag{6}$$

$$I'_{45°} = 0.5 + 0.5\sin(2\gamma) \tag{7}$$

$$I'_{90°} = 0.5 - 0.5\cos(2\gamma) \tag{8}$$

$$I'_{135°} = 0.5 - 0.5\sin(2\gamma). \tag{9}$$

Thus, the optical rotation angle γ can be obtained as

$$\gamma = \frac{1}{2}\tan^{-1}\left(\frac{I'_{45°} - I'_{135°}}{I'_{0°} - I'_{90°}}\right). \tag{10}$$

2.3. Analytical model for extracting CB/Dep properties

This section introduces the analytical model used to extract the CB/Dep properties of a composite sample. The Mueller matrix model of a CB/Dep composite sample has the form [13–14]

$$M_D M_{CB} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ a_1 & e_1 & 0 & 0 \\ a_2 & 0 & e_2 & 0 \\ a_3 & 0 & 0 & e_3 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(2\gamma) & \sin(2\gamma) & 0 \\ 0 & -\sin(2\gamma) & \cos(2\gamma) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ a_1 & e_1\cos(2\gamma) & e_1\sin(2\gamma) & 0 \\ a_2 & -e_2\sin(2\gamma) & e_2\cos(2\gamma) & 0 \\ a_3 & 0 & 0 & e_3 \end{bmatrix}, \tag{11}$$

where a_1, a_2 and a_3 in the depolarization Mueller matrix M_D are the elements of the polarization vector, e_1 and e_2 are the degrees of linear depolarization, and e_3 is the degree of circular depolarization. The equations required to extract γ and Δ from Eq. (11) can be obtained using four linear polarization input lights (0°, 45°, 90° and 135°) with an additional polarizer $M_{P0°}$ behind the sample, and two circular polarization input lights (right-hand (R-) and left-hand (L-)) with a hybrid optical component $M_{p45°Q0°}$ behind the sample. Given such an arrangement, the Stokes vectors in Eq. (3) can be rewritten as

$$I' = M_{P0°}M_D M_{CB}\begin{bmatrix} S'_0 \\ S'_1 \\ S'_2 \\ S'_3 \end{bmatrix}_{0°,45°,90°,135°} = \begin{bmatrix} 0.5 & 0.5 & 0 & 0 \\ 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ a_1 & e_1\cos(2\gamma) & e_1\sin(2\gamma) & 0 \\ a_2 & -e_2\sin(2\gamma) & e_2\cos(2\gamma) & 0 \\ a_3 & 0 & 0 & e_3 \end{bmatrix} \begin{bmatrix} S'_0 \\ S'_1 \\ S'_2 \\ S'_3 \end{bmatrix}_{0°,45°,90°,135°} \tag{12}$$

and