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Stokes-Mueller matrix polarimetry system for glucose sensing

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ABSTRACT

A Stokes-Mueller matrix polarimetry system consisting of a polarization scanning generator (PSG) and a high-accuracy Stokes polarimeter is used to sense the glucose concentration in aqueous solutions with and without scattering effects, respectively. In the proposed system, an electro-optic (EO) modulator driven by a saw-tooth waveform voltage is used to perform full state of polarization (linear/circular) scanning, while a self-built Stokes polarimeter is used to obtain dynamic measurements of the output polarized light intensity. It is shown that the measured output Stokes vectors have an accuracy of 10^{-4}, i.e., one order higher than that of existing commercial Stokes polarimeters. The experimental results show that the optical rotation angle varies linearly with the glucose concentration over the range of 0-0.5 g/dl. Moreover, glucose sensing is successfully achieved at concentrations as low as 0.02 g/dl with a resolution of 10^{-6} deg/mm and an average deviation of 10^{-4} deg. In general, the polarimetry system proposed in this study provides a fast and reliable method for measuring the Stokes vectors, and thus has significant potential for biological sensing applications.

1. Introduction

Polarization is a fundamental property of light and has many practical applications in industry and engineering science. Many studies have shown that the polarization state of a light beam (including depolarization effects) can be fully described by four Stokes parameters (S_0, S_1, S_2 and S_3) [1–3]. Meanwhile, the Mueller matrix formalism provides a complete description of the optical properties of a sample when illuminated by light with different states of polarization [4–6]. Consequently, Stokes-Mueller matrix polarimetry provides a powerful technique for characterizing a wide range of materials and biomaterials, and for performing gas sensing [7–10]. Over the years, many Stokes-Mueller matrix polarimeters (generally referred to simply as polarimeters) have been proposed based on static [11] or dynamic [12] measurement methods. Azzam et al. [13] proposed a simple static measurement system in which the sample was placed between a rotation polarizer and an analyzer and the Mueller matrix was extracted using a Fourier transformation technique. Dev and Asundi [14] developed a static polarimeter for evaluating the polarimetric properties of twisted nematic liquid crystal spatial light modulators. Bakshi et al. [15] proposed a full Stokes dynamic system for measuring the refractive index of nickel and optical properties of steel under shock compression. Hall et al. [16] presented a dynamic polarimeter for the real time measurement of protein adsorption at a solid liquid interface. In general, all of the aforementioned methods overcome the fundamental limitations of traditional polarimeter systems, namely a long measurement time and a low measurement accuracy.

Glucose monitoring has attracted significant attention for the testing and diagnosis of diabetes. The literature contains many optical-based sensors for glucose concentration measurement based on such techniques as optical polarimetry [17], surface plasmon resonance (SPR) [18], and surface enhanced Raman spectroscopy (SERS) [19]. Among these techniques, optical polarimetry is commonly preferred due to its wider detection range than SPR and less complicated experimental setup than SERS. In the optical polarimetry technique, the optical rotation of the detected polarized light is proportional to the specific rotation (dependent on the temperature and wavelength), the glucose concentration, and the optical path length [20]. Honma et al. [21] demonstrated an optical system based on liquid crystal polarization gratings (LCPGs) for measuring glucose concentrations ranging from 30 to 500 mg/dl with a measurement error of 5%. Malik et al. [22] proposed an optical polarimetric method based on a birefringent eye model for detecting glucose concentrations in the range of 0–0.6 g/dl with a detection limit of 0.05 g/dl. Ansari et al. [23] presented an optical scheme for measuring the glucose concentration in the aqueous humor of the human eye over the range of 0–1 g/dl. Wang and Wang [24] developed a Monte Carlo based method for extracting the Mueller elements of birefringent turbid

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media containing glucose using either a single-scattering model or a double-scattering model. Ghosh and Wood [25] developed a Mueller matrix decomposition method for extracting the polarization parameters of complex turbid media and biological tissues with multiple scattering. The feasibility of the proposed approach was demonstrated using human blood samples with glucose concentrations ranging from 3 to 30 mM. However, the methods presented in [21–25] are unable to detect glucose concentrations lower than 0.05 g/dl. Furthermore, the effects of scattering on the glucose detection performance for samples with such low concentrations have yet to be reported.

In a previous study [26], the present group proposed a linear polarization scanning ellipsometry system for characterizing the properties of twisted nematic liquid crystal samples under a varying external voltage. In the present study, the polarimetric system is extended to facilitate full state of polarization scanning (i.e., both linear and circular) in order to improve the accuracy of the Stokes vector measurements and to accommodate depolarization effects. The validity of the proposed system is demonstrated by measuring the low glucose concentration of aqueous samples with and without scattering effects, respectively.

2. Stokes-Mueller matrix polarimeter for extracting optical rotation angle of circular birefringence (CB) property

As with all optical samples, glucose samples can be modeled as $S' = M_{Glucose}\, S$, where S and S' are the input and output Stokes vectors, respectively, and M is the 4×4 Mueller matrix of the sample. Given the use of four input lights with different polarization states, namely three linear polarization states (0°, 45° and 90°) and one right-hand circular polarization state (R-), the Muller matrix of the glucose sample can be obtained as

$$\begin{bmatrix} S'_0 \\ S'_1 \\ S'_2 \\ S'_3 \end{bmatrix}_{(0^\circ,45^\circ,90^\circ,R)} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{bmatrix}_{\text{Glucose}} \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix}_{(0^\circ,45^\circ,90^\circ,R)} \quad (1)$$

In a recent study [27], the present group proposed the following differential Mueller matrix formulism for extracting the optical properties of anisotropic turbid media:

$$m = \frac{1}{d}\begin{bmatrix} X & Y\cos(2\theta_d) + \kappa'_q & Y\sin(2\theta_d) + \kappa'_u & U + \kappa'_v \\ Y\cos(2\theta_d) - \kappa'_q & X - \kappa'_{iq} & 2\gamma + \eta'_v & -\beta\sin(2\alpha) + \eta'_u \\ Y\sin(2\theta_d) - \kappa'_u & -2\gamma + \eta'_v & X - \kappa'_{iu} & \beta\cos(2\alpha) + \eta'_q \\ U - \kappa'_v & -\beta\sin(2\alpha) + \eta'_u & -\beta\cos(2\alpha) + \eta'_q & X - \kappa'_{iv} \end{bmatrix} \quad (2)$$

where

$$X = \ln\left[\left[\left(1 - R^2\right)\sqrt{\frac{1-D}{1+D}}\right]\right] \quad (3)$$

$$Y = -\ \ln\sqrt{\frac{1-D}{1+D}} \quad (4)$$

$$U = \ln\left(\frac{1+R}{1-R}\right) \quad (5)$$

and d is the sample thickness; α and β are the orientation angle and phase retardation of the linear birefringence property, respectively; γ is the optical rotation angle of the circular birefringence property; θ_d and D are the orientation angle and linear dichroism of the linear dichroism property, respectively; R is the circular amplitude anisotropy of the circular dichroism property; $\kappa'_{iq,\ iu,\ iv}$ are diagonal depolarization parameters; and $\kappa'_{q,u,v}$ and $\eta'_{iq,\ iu,\ iv}$ are anomalous dichroism and depolarization parameters, respectively. Having solved the differential Mueller matrix m obtained from an eigenvalue analysis of M in Eq. (1), the optical rotation angle and differential depolarization Mueller matrix of the sample can be obtained respectively as [27]

$$\gamma = \frac{m_{23} - m_{32}}{4},\ 0 \le \gamma \le 180^\circ \quad (6)$$

$$m_\Delta = \begin{bmatrix} 0 & \frac{m_{12}-m_{21}}{2} & \frac{m_{13}-m_{31}}{2} & \frac{m_{14}-m_{41}}{2} \\ \frac{m_{21}-m_{12}}{2} & e_1 & \frac{m_{23}+m_{32}}{2} & \frac{m_{24}+m_{42}}{2} \\ \frac{m_{31}-m_{13}}{2} & \frac{m_{23}+m_{32}}{2} & e_2 & \frac{m_{34}+m_{43}}{2} \\ \frac{m_{41}-m_{14}}{2} & \frac{m_{24}+m_{42}}{2} & \frac{m_{34}+m_{43}}{2} & e_3 \end{bmatrix} \quad (7)$$

where m_{ij} (i, j1–4) are the elements of the differential Mueller matrix m, e_1 and e_2 are the degrees of linear depolarization (defined as $e_1 = m_{22} - m_{11}$ and $e_2 = m_{33} - m_{11}$), and e_3 is the degree of circular depolarization (defined as $e_3 = m_{44} - m_{11}$). The degree of depolarization (DOP) is thus obtained as [27]

$$\Delta = 1 - \sqrt{e_1^{\,2} + e_2^{\,2} + e_3^{\,2}},\ 0 \le \Delta \le 1 \quad (8)$$

3. Stokes-Mueller matrix polarimetry system

In [26], the present authors proposed a dynamic polarization scanning ellipsometry system for characterizing samples without depolarization effects. The PSG in the proposed system comprized a polarizer placed in front of an EO modulator with a principal axis of 45° followed by a quarter-wave plate with a principal axis angle of 0° (horizontal) (see Fig. 1(a)). The Stokes vectors of the light emerging from the PSG were thus given as

$$S' = Q(0^\circ)EO(45^\circ)P(0^\circ)S_{in} \quad (9)$$

The system proposed in [26] is capable of performing linear polarization scanning only. Thus, in the present study, the PSG in [26] is extended to facilitate both linear and circular polarization

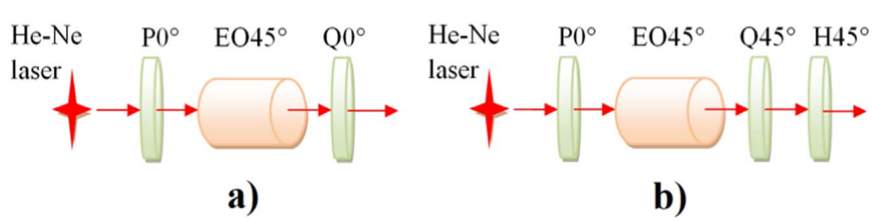

Fig. 1. (a) Linear polarization scanning and (b) circular polarization scanning.