

## Introduction

### 1.1 Light Interaction with Tissues

Utilizing the interaction of light with biological tissues and fluids for practical purposes depends on understanding the properties of two large classes of biological media. One of them comprises weakly scattering (transparent) tissues and fluids like cornea, crystalline lens, vitreous humor, and aqueous humor of the front chamber of eye. The other class includes strongly scattering (opaque or turbid) tissues and fluids like skin, brain, vessel wall, eye sclera, blood, and lymph [1–7]. The interaction of light with biological media of the first class can be described by a model of single (or low-step) scattering in an ordered medium with closely packed scatterers that have a complex refractive index. Light propagation in tissues of the second class can be described by a model of multiple scattering of scalar or vector waves in a random or ordered low-absorbing medium.

The optical transparency of tissues is maximal in the near infrared (NIR) region, which is due to the absence, in this spectral range, of strong intrinsic chromophores that would absorb radiation in living tissues [1–7]. However, these tissues are characterized by rather strong scattering of NIR radiation, which prevents the attainment of clear images of localized inhomogeneities arising due to various pathologies, e.g., tumor formation or the growth of microvessels. Thus, this volume devotes special attention in the sections on tissue optical tomography and spectroscopy to the development of methods for the selection of image-carrying photons and the detection of photons providing spectroscopic information. Often the vector nature of light transport in scattering media, such as tissues, is ignored because of its rapid depolarization during propagation in a randomly inhomogeneous medium. However, in certain tissues (transparent eye tissues, cellular monolayers, mucous membrane, superficial skin layers, etc.), the degree of polarization of the transmitted or reflected light is measurable even when the tissue has considerable thickness.

Many tissues – such as eye cornea, sclera, tendon, cartilage, which are classified as fibrous tissues, and other structured tissues such as retina, tooth

enamel and dentin – show a wide variety of polarization properties: linear birefringence, optical activity, and diattenuation. These properties are primarily defined by the tissue structure – anisotropy of form – or by the intrinsic anisotropic character of the tissue components or metabolic molecules – anisotropy of material. Collagen, muscle fibers, keratin, and glucose belong to this latter group.

The propagation of polarized light in a birefringent turbid medium is complicated because both the birefringent and the scattering effects can change the polarization state of light. Information about the structure of a tissue and the birefringence of its components can be extracted from the registered depolarization degree of initially polarized light, the polarization state transformation, or the appearance of a polarized component in the scattered light.

Since incident polarized light is rapidly depolarized in turbid tissues by light scattering, polarization-sensitive detection of reflected or transmitted light selects only the early escaping photons and rejects the multiply scattered light [1–7]. Thus, for a light beam reflected from a tissue, the polarization properties of light can be employed as a selector of the photons coming from different depths in the tissue. For transmitted light, they can act as a selector of ballistic or quasi-ballistic photons. Such polarization gating can, therefore, provide novel contrast mechanisms for tissue imaging and spectroscopy. As for practical implications, polarization techniques are expected to lead to simpler schemes of optical medical tomography than those used in existing diagnostic methods and also to provide additional information about the structure of tissues.

Since a variety of optical medical techniques employ lasers, light coherence is very important for the analysis of light interaction with tissues and cells. The problem can be viewed in terms of a loss of coherence due to the scattering of light in a random medium with multiple scattering and/or a change in the statistics and polarization states of speckles in a scattered field. Similarly, the coherence of light is of fundamental importance for the selection of photons that have experienced no, or a small number, of scattering events, as well as for the generation of speckle-modulated fields from scattering phase objects with single and multiple scattering. Such approaches are important for coherence tomography, diffractometry, holography, photon-correlation spectroscopy, and the speckle-interferometry of tissues and biological flows. The use of optical sources with a short coherence length opens up new opportunities in coherent interferometry and the tomography of tissues and blood flows.

To understand the general formalism for the scattering and absorption of light by arbitrarily shaped and arbitrarily oriented particles in tissue components, to learn exact and approximate theoretical methods and computer codes for calculating the scattering and polarization properties of these arbitrary shaped small particles, the following literature is recommended [8–20].

## 1.2 Definitions of Polarized Light

Definitions of polarized light, its properties, as well as production and detection techniques are described in a voluminous literature on this topic [21–28].

Polarization refers to the pattern described by the electric field vector as a function of time at a fixed point in space. When the electrical field vector oscillates in a single, fixed plane all along the beam, the light is said to be linearly polarized. A linearly polarized wave can be resolved into two mutually orthogonal components. If the plane of the electrical field rotates, the light is said to be elliptically polarized, because the electrical field vector traces out an ellipse at a fixed point in space as a function of time. If the ellipse happens to be a circle, the light is said to be circularly polarized. The connection between phase and polarization can be understood as follows: circularly polarized light consists of equal quantities of linear mutually orthogonal polarized components that oscillate exactly  $90^\circ$  out of phase. In general, light of arbitrary elliptical polarization consists of unequal amplitudes of linearly polarized components where the electrical fields of the two polarizations oscillate at the same frequency but have some constant phase difference. Light of arbitrary polarization can be represented by four numbers known as Stokes parameters [21–28].

In polarimetry, the Stokes vector  $\mathbf{S}$  of a light beam is constructed based on six flux measurements obtained with different polarization analyzers in front of the detector

$$\mathbf{S} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} I_H + I_V \\ I_H - I_V \\ I_{+45^\circ} - I_{-45^\circ} \\ I_R - I_L \end{pmatrix}, \quad (1.1)$$

where  $I_H$ ,  $I_V$ ,  $I_{+45^\circ}$ ,  $I_{-45^\circ}$ ,  $I_R$ , and  $I_L$  are the light intensities measured with a horizontal linear polarizer, a vertical linear polarizer, a  $+45^\circ$  linear polarizer, a  $45^\circ$  linear polarizer, a right circular analyzer, and a left circular analyzer in front of the detector, respectively. Because of the relationship  $I_H + I_V = I_{+45^\circ} + I_{-45^\circ} = I_R + I_L = I$ , where  $I$  is the intensity of the light beam measured without any analyzer in front of the detector, a Stokes vector can be determined by four independent measurements, for example,  $I_H, I_V, I_{+45^\circ}$ , and  $I_R$ ,

$$\mathbf{S} = \begin{pmatrix} I_H + I_V \\ I_H - I_V \\ 2I_{+45^\circ} - (I_H + I_V) \\ 2I_R - (I_H + I_V) \end{pmatrix}. \quad (1.2)$$

From the Stokes vector, the degree of polarization (DOP), the degree of linear polarization (DOLP), and the degree of circular polarization (DOCP) are derived as

$$\begin{aligned}
\text{DOP} &= \sqrt{Q^2 + U^2 + V^2} / I, \\
\text{DOLP} &= \sqrt{Q^2 + U^2} / I, \\
\text{DOCP} &= \sqrt{V^2} / I.
\end{aligned} \tag{1.3}$$

If the DOP of a light field remains unity after transformation by an optical system, this system is nondepolarizing; otherwise, the system is depolarizing.

The Mueller matrix ( $\mathbf{M}$ ) of a sample transforms an incident Stokes vector  $\mathbf{S}_{\text{in}}$  into the corresponding output Stokes vector  $\mathbf{S}_{\text{out}}$ :

$$\mathbf{S}_{\text{out}} = \mathbf{M}\mathbf{S}_{\text{in}}. \tag{1.4}$$

Obviously, the output Stokes vector varies with the state of the incident beam, but the Mueller matrix is determined only by the sample and the optical path. Conversely, the Mueller matrix can fully characterize the optical polarization properties of the sample. The Mueller matrix can be experimentally obtained from measurements with different combinations of source polarizers and detection analyzers. In most general cases, a  $4 \times 4$  Mueller matrix has 16 independent elements; therefore, at least 16 independent measurements must be acquired to determine a full Mueller matrix.

The normalized Stokes vectors for the four incident polarization states, H, V,  $+45^\circ$ , and R, are, respectively,

$$\mathbf{S}_{\text{Hi}} = \begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix}, \mathbf{S}_{\text{Vi}} = \begin{pmatrix} 1 \\ -1 \\ 0 \\ 0 \end{pmatrix}, \mathbf{S}_{+45^\circ\text{i}} = \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix}, \mathbf{S}_{\text{Ri}} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix}, \tag{1.5}$$

where H, V,  $+45^\circ$ , and R, represent horizontal linear polarization, vertical linear polarization,  $+45^\circ$  linear polarization, and right circular polarization, respectively. We may express the  $4 \times 4$  Mueller matrix as  $\mathbf{M} = [\mathbf{M}_1 \ \mathbf{M}_2 \ \mathbf{M}_3 \ \mathbf{M}_4]$ , where  $\mathbf{M}_1$ ,  $\mathbf{M}_2$ ,  $\mathbf{M}_3$ , and  $\mathbf{M}_4$  are four column vectors of four elements each. The four output Stokes vectors corresponding to the four incident polarization states, H, V,  $+45^\circ$  and R, are denoted, respectively, by  $\mathbf{S}_{\text{Ho}}$ ,  $\mathbf{S}_{\text{Vo}}$ ,  $\mathbf{S}_{+45^\circ\text{o}}$ , and  $\mathbf{S}_{\text{Ro}}$ . These four output Stokes vectors are experimentally measured based on (1.2) and can be expressed as

$$\begin{cases} \mathbf{S}_{\text{Ho}} = \mathbf{M}\mathbf{S}_{\text{Hi}} = \mathbf{M}_1 + \mathbf{M}_2 \\ \mathbf{S}_{\text{Vo}} = \mathbf{M}\mathbf{S}_{\text{Vi}} = \mathbf{M}_1 - \mathbf{M}_2 \\ \mathbf{S}_{+45^\circ\text{o}} = \mathbf{M}\mathbf{S}_{+45^\circ\text{i}} = \mathbf{M}_1 + \mathbf{M}_3 \\ \mathbf{S}_{\text{Ro}} = \mathbf{M}\mathbf{S}_{\text{Ri}} = \mathbf{M}_1 + \mathbf{M}_4. \end{cases} \tag{1.6}$$

The Mueller matrix can be calculated from the four output Stokes vectors [29]:

$$\mathbf{M} = \frac{1}{2} \times \begin{bmatrix} S_{\text{Ho}} + S_{\text{Vo}}, S_{\text{Ho}} - S_{\text{Vo}}, 2S_{+45^\circ\text{o}} - (S_{\text{Ho}} + S_{\text{Vo}}), 2S_{\text{Ro}} - (S_{\text{Ho}} + S_{\text{Vo}}) \end{bmatrix}. \quad (1.7)$$

In other words, at least four independent Stokes vectors must be measured to determine a full Mueller matrix, and each Stokes vector requires four independent intensity measurements with different analyzers.

For an overview of light polarization properties, its fundamentals and applications, the reader is referred to [21–28].



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