

# A

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## Appendix

### Single-Scattering Mueller Matrix from Mie Theory

Mie theory describes the scattering of a vector plane wave by a homogeneous sphere. For a spherical particle, its single-scattering Jones matrix is

$$\mathbf{J} = \begin{pmatrix} S_2 & 0 \\ 0 & S_1 \end{pmatrix}, \quad (\text{A.1})$$

where  $S_1$  and  $S_2$  are functions of the polar scattering angle and can be obtained from the Mie theory:

$$\begin{aligned} S_1(\theta) &= \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \{a_n \pi_n(\cos \theta) + b_n \tau_n(\cos \theta)\}, \\ S_2(\theta) &= \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \{b_n \pi_n(\cos \theta) + a_n \tau_n(\cos \theta)\}. \end{aligned} \quad (\text{A.2})$$

The parameters  $\pi_n$  and  $\tau_n$  represent

$$\begin{aligned} \pi_n(\cos \theta) &= \frac{1}{\sin \theta} P_n^1(\cos \theta), \\ \tau_n(\cos \theta) &= \frac{d}{d\theta} P_n^1(\cos \theta), \end{aligned} \quad (\text{A.3})$$

where  $P_n^1(\cos \theta)$  is the associated Legendre polynomial. The following recursive relationships are used to calculate  $\pi_n$  and  $\tau_n$ :

$$\begin{aligned} \pi_n &= \frac{2n-1}{n-1} \pi_{n-1} \cos \theta - \frac{n}{n-1} \pi_{n-2}, \\ \tau_n &= n \pi_n \cos \theta - (n+1) \pi_{n-1}, \end{aligned} \quad (\text{A.4})$$

and the initial values are:

$$\begin{cases} \pi_1 = 1, \pi_2 = \cos \theta, \\ \tau_1 = \cos \theta, \tau_2 = 3 \cos 2\theta. \end{cases} \quad (\text{A.5})$$

The coefficients  $a_n$  and  $b_n$  are

$$\begin{cases} a_n = \frac{S'_n(y)S_n(x) - n_{\text{rel}}S_n(y)S'_n(x)}{S'_n(y)\zeta_n(x) - n_{\text{rel}}S_n(y)\zeta'_n(x)}, \\ b_n = \frac{n_{\text{rel}}S'_n(y)S_n(x) - S_n(y)S'_n(x)}{n_{\text{rel}}S'_n(y)\zeta_n(x) - S_n(y)\zeta'_n(x)}, \end{cases} \quad (\text{A.6})$$

where

$$\begin{aligned} x &= 2\pi a n_b / \lambda, \\ y &= 2\pi a n_s / \lambda, \\ n_{\text{rel}} &= n_s / n_b, \end{aligned} \quad (\text{A.7})$$

where  $a$  is the radius of the scattering sphere,  $\lambda$  is the wavelength in vacuo,  $n_s$  is the refractive index of the scattering spheres, and  $n_b$  is the refractive index of the background medium.  $\zeta_n$  and  $S_n$  can be written in terms of Bessel functions:

$$\begin{cases} S_n(z) = \left(\frac{\pi z}{2}\right)^{0.5} J_{n+0.5}(z), \\ \zeta_n(z) = S_n(z) + iC_n(z), \\ C_n(z) = -\left(\frac{\pi z}{2}\right)^{0.5} N_{n+0.5}(z), \end{cases} \quad (\text{A.8})$$

where  $J_{n+0.5}(z)$  is the Bessel function of the 1st kind and  $N_{n+0.5}(z)$  is the Bessel function of the 2nd kind. The derivatives of  $S_n$  and  $C_n$  can be obtained through

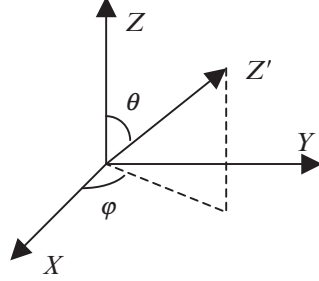
$$\begin{cases} S'_n(z) = \left(\frac{\pi}{8z}\right)^{0.5} J_{n+0.5}(z) + \left(\frac{\pi z}{2}\right)^{0.5} J'_{n+0.5}(z), \\ C'_n(z) = -\left(\frac{\pi}{8z}\right)^{0.5} N_{n+0.5}(z) - \left(\frac{\pi z}{2}\right)^{0.5} N'_{n+0.5}(z). \end{cases} \quad (\text{A.9})$$

The single-scattering Mueller matrix can be derived from the Jones matrix (A.1):

$$\mathbf{M}(\theta) = \frac{1}{2} \begin{bmatrix} |S_2|^2 + |S_1|^2 & |S_2|^2 - |S_1|^2 & 0 & 0 \\ |S_2|^2 - |S_1|^2 & |S_2|^2 + |S_1|^2 & 0 & 0 \\ 0 & 0 & S_2 S_1^* + S_1 S_2^* & -i(S_2 S_1^* - S_1 S_2^*) \\ 0 & 0 & i(S_2 S_1^* - S_1 S_2^*) & S_2 S_1^* + S_1 S_2^* \end{bmatrix}. \quad (\text{A.10})$$

## Coordinate Transformation in a Multiple Scattering Medium

In polarimetry, every Stokes vector and Mueller matrix are associated with a specific reference plane and coordinates. In the Mie theory, the Mueller



**Fig. A.1.** The coordinates transform of a single scattering event

matrix of a single scattering event is defined in the scattering plane that is formed by the incident light vector and the scattered light vector. For a general coordinate system associated with this scattering plane, the  $Z$ -axis is along the direction of photon propagation. The  $X$ -axis is within the reference plane and is perpendicular to the  $Z$ -axis. The  $Y$ -axis is perpendicular to both the  $Z$ -axis and the reference plane.

There is a local coordinate system associated with each incident photon packet, and its Stokes vector  $\mathbf{S}_{\text{in}}$  is associated with this local coordinate system. As shown in Fig. A.1, the local coordinate system of the photon before scattering is  $(X, Y, Z)$ . After the scattering event, the photon propagates along the  $Z'$ -axis;  $\theta$  is the polar scattering angle and  $\varphi$  is the azimuth angle. The scattering plane is formed by the  $Z$ -axis and the  $Z'$ -axis, which is the new reference plane.

We use (9.1) to calculate the Stokes vector of the scattered light. As the Mueller matrix of the scattering event is defined in the reference plane, we first need to transform the Stokes vector of the incident light to the coordinate system associated with the reference plane. This transformation can be done by rotating the local coordinate system  $(X, Y, Z)$  by  $\varphi$  along the  $Z$ -axis, where the rotation matrix is

$$\mathbf{R}(\varphi) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(2\varphi) & \sin(2\varphi) & 0 \\ 0 & -\sin(2\varphi) & \cos(2\varphi) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (\text{A.11})$$

and the new Stokes vector is obtained by

$$\mathbf{S}'_{\text{in}} = \mathbf{R}(\varphi)\mathbf{S}_{\text{in}}. \quad (\text{A.12})$$

The local coordinate system of the photon packet is tracked in the process. The transformation can be divided into two steps. From Fig. A.1, the first step is to rotate the  $(X, Y, Z)$  system by  $\varphi$  about the  $Z$ -axis, and the second step is to rotate the coordinate by  $\theta$  about the rotated  $Y$ -axis to get  $(X', Y', Z')$ . After the transformation, the  $Z'$ -axis is aligned with the new light vector.

The transformation matrix is

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} \cos \theta & 0 & -\sin \theta \\ 0 & 1 & 0 \\ \sin \theta & 0 & \cos \theta \end{bmatrix} \begin{bmatrix} \cos \phi & \sin \phi & 0 \\ -\sin \phi & \cos \phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}. \quad (\text{A.13})$$

After a photon packet passes through the turbid medium, its Stokes vector is recorded and accumulated. The local coordinate system was tracked in the simulation. In order to record the Stokes vector, the local coordinate system of each photon packet must be transformed into the laboratory coordinate system. In the laboratory coordinate system  $(e_1, e_2, e_3)$ , the local photon coordinate can be written as

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} e_{1x} & e_{2x} & e_{3x} \\ e_{1y} & e_{2y} & e_{3y} \\ e_{1z} & e_{2z} & e_{3z} \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix}. \quad (\text{A.14})$$

To transform the photon Stokes vector from the local coordinate system into the laboratory coordinate system, the local coordinate system is rotated by its  $Z$ -axis so that the new  $X$ -axis lies within the  $(e_2, e_3)$  plane in the laboratory coordinate. The rotation angle is

$$\varphi = \tan^{-1}(e_{1x}/e_{1y}). \quad (\text{A.15})$$

The rotation matrix and the new Stokes vector can be obtained from (A.11) and (A.12).

## Glossary

This glossary was compiled using mostly [1-7] (Chap. 1).

<b>absorption</b>	the transformation of light (radiant) energy to some other form of energy, usually heat, as the light transverses matter
<b>absorption spectrum</b>	the spectrum formed by light that has passed through a medium in which light of certain wavelengths was absorbed
<b>acquisition time</b>	the period of time of acquiring experimental data
<b>anisotropic scattering</b>	a scattering process characterized by a clearly-apparent direction of photons that may be due to the presence of large scatterers
<b>attenuation</b>	a decrease in energy per unit area of a wave or beam of light; it occurs as the distance from the source increases and is caused by absorption or scattering
<b>attenuation (extinction) coefficient</b>	the reciprocal of the distance over which light of intensity $I$ is attenuated to $I/e \approx 0.37I$ ; the units are typically $\text{cm}^{-1}$
<b>autocorrelation</b>	the correlation of an ordered series of observations with the same series in an altered order
<b>autocorrelation function</b>	the characteristic of the second-order statistics of a random process that shows how fast the random value changes from point to point, e.g., the autocorrelation function of intensity fluctuations caused by scattering of a laser beam by a rough surface characterizes the size and distribution of speckle sizes in the induced speckle pattern; the Fourier transform of the autocorrelation function represents the power spectrum of a random process
<b>autofluorescence</b>	natural tissue fluorescence
<b>ballistic (coherent) photons</b>	a group of unscattered and strictly straight-forward scattered photons
<b>backscattering</b>	the dispersion of a fraction of the incident radiation in a backward direction
<b>bimodal distribution</b>	a distribution having two modes

<b>birefringence</b>	the phenomenon exhibited by certain crystals in which an incident ray of light is split into two rays, called an ordinary ray and an extraordinary ray, which are plane- (linear) polarized in mutually orthogonal planes
<b>chirality</b>	in an object, describes the mirror-equal “right” or “left” modification; <i>optical activity</i> is one of the exhibitions of chirality, when the asymmetric structure of a molecule or crystal existing of two forms (“right” and “left”) causes the substance (ensemble of these molecules or crystal) to rotate the plane of the incident linear polarized light; the pure “right” or “left” optically active substances have identical physical and chemical properties, but their biochemical and physiological properties can be quite different
<b>chromophore</b>	a chemical that absorbs light with a characteristic spectral pattern
<b>coherence length</b>	characterizes the degree of temporal coherence of a light source: $l_C = c\tau_C$ , where $c$ is the light speed and $\tau_C$ is the coherence time, which is approximately equal to the pulse duration of the pulse light source or inversely proportional to the frequency bandwidth of a continuous wave light source
<b>coherent light</b>	light in which the electromagnetic waves maintain a fixed phase relationship over a period of time and in which the phase relationship remains constant for various points that are perpendicular to the direction of propagation
<b>constructive interference</b>	the interference of two or more waves of equal frequency and phase, resulting in their mutual reinforcement and producing a single amplitude equal to the sum of the amplitudes of the individual waves
<b>contrast of the intensity fluctuations</b>	the relative difference between light and dark areas of a speckle pattern
<b>correlation</b>	the degree of correlation between two or more attributes or measurements on the same group of elements

<b>correlation length</b>	the length within which the degree of correlation between two measurements of a spatially dependent quantity is high (close to unity); for example, $L_c$ is the correlation length of the scattering surface of the spatial inhomogeneities (random relief)
<b>decorrelation of speckles</b>	relates to statistics of the second order that characterize the size and distribution of speckle sizes and show how fast the intensity changes from point to point in the speckle pattern; decorrelation means that such changes of intensity tend to be faster
<b>depolarization</b>	depriving (destruction) of light polarization
<b>destructive interference</b>	the interference of two waves of equal frequency and opposite phase, resulting in their cancellation where the negative displacement of one always coincides with the positive displacement of the other
<b>developed speckles</b>	the speckles that are characterized by Gaussian statistics of the complex amplitude, the unity contrast of intensity fluctuations, and a negative exponential function of the intensity probability distribution (the most probable intensity value in the corresponding speckle pattern is equal to zero; i.e., destructive interference occurs with the highest probability)
<b>diagnostic (or therapeutic) window</b>	the spectral range from 600 to 1,600 nm within which the penetration depth of the light beams for most living tissues and blood is the highest; certain phototherapeutic and diagnostic modalities take advantage of this range for visible and NIR light
<b>dichroism</b>	a phenomenon related to pleochroism of a uniaxial crystal so that it exhibits two different colors when viewed from two different directions under transmitted light; <i>pleochroism</i> is the property possessed by certain crystals that exhibit different colors when viewed from different directions under transmitted light; this is one exhibition of the optical anisotropy caused by the anisotropy of absorption; the varieties of pleochroism are <i>circular dichroism</i> , different absorption for light with “right” and “left” circular polarization, and <i>linear dichroism</i> , different absorption for ordinary and extraordinary rays

<b>diffuse photons</b>	the photons that undertake multiple scatter with a broad variety of angles
<b>diffusion wave spectroscopy (DWS)</b>	the spectroscopy based on the study of dynamic light scattering in dense media with multiple scattering and related to the investigation of the dynamics of particles within very short time intervals
<b>digital electronic autocorrelator</b>	a device that reconstructs the time-domain autocorrelation function of intensity fluctuations
<b>dispersion</b>	the state of being dispersed, such as a photon trajectory (general); the variation of the index of refraction of a transparent substance, such as a glass, with the wavelength of light, the index of refraction increasing as the wavelength decreases (optics); the separation of white or compound light into its respective colors, as in the formation of a spectrum by a prism (optics); the scattering of values of a variable around the mean or median of a distribution (statistics); a system of dispersed particles suspended in a solid, liquid, or gas (chemistry)
<b>Doppler effect</b>	the apparent change in the frequency of a wave, such as a light wave or sound wave, resulting from a change in the distance between the source of the wave and the receiver
<b>Doppler interferometry</b>	the dynamic dual-beam interferometry when the reference beam pathlength is scanned with a constant speed; the Doppler signal induced is the measuring signal for depth profiling of an object placed in the measuring beam; the method is used in partially coherent interferometry or tomography of tissues
<b>Doppler spectroscopy</b>	the spectroscopy based on the study of the dynamic light scattering ( <i>Doppler effect</i> ) in media with single scattering and related to the investigation of the dynamics (velocity) of particles from the measurements of the Doppler shifts in the frequency of the waves scattered by the moving particles



<b>dynamic light scattering</b>	light scattering by a moving object that causes a Doppler shift in the frequency of the scattered wave relative to the frequency of the incident light
<b>elastic (static) light scattering</b>	light scattering by static (motionless) objects that occurs elastically, without changes of a photon energy or light frequency
<b>emission spectrum</b>	the emission obtained from a luminescent material at different wavelengths when it is excited by a narrow range of shorter wavelengths
<b>excitation spectrum</b>	the emission spectrum at one wavelength is monitored and the intensity at this wavelength is measured as a function of the exciting wavelength
<b>far-field diffraction zone</b>	the zone where Fraunhofer diffraction takes place; this is a type of diffraction in which the light source and the receiving screen are effectively at an infinite distance from the diffraction object, i.e., parallel beams of wave trains are used
<b>form birefringence</b>	birefringence that is caused by the structure of a medium; for example, a system of long dielectric cylinders made from an isotropic substance and arranged in a parallel fashion shows birefringence of form
<b>forward scattering problem</b>	the modeling of light propagation in a scattering medium by taking into account the experimental geometry, source, and detector characteristics and the known optical properties of a sample, and predicting the measurements and associated accuracies that result
<b>fractal object</b>	an object with a self-similar geometry, i.e., each arbitrary selected part of it is similar to the whole object
<b>Fresnel diffraction</b>	a type of diffraction in which the light source and the receiving screen are both at a finite distance from the diffraction object, i.e., divergent and convergent beams of wavetrains are used
<b>Fresnel reflection</b>	the reflection of a beam of radiation, such as light, which takes place at the interface between two media of different refractive indexes; not all the radiation is reflected, some may be refracted

<b>Gaussian correlation function</b>	the correlation function described by a bell-shaped (Gaussian) curve
<b>Gaussian light beam</b>	a light beam with a Gaussian shape for the transverse intensity profile; if the intensity at the center of the beam is $I_0$ , then the formula for a Gaussian beam is $I = I_0 \exp(-2r^2/w^2)$ , where $r$ is the radial distance from the axis and $w$ is the beam "waist;" the intensity profile of such a beam is said to be bell shaped; a laser beam is a Gaussian one; a single mode fiber also creates a Gaussian beam at its output
<b>Gaussian statistics (normal statistics)</b>	statistics when a bell-shaped (Gaussian) curve showing a distribution of probability associated with different values of a variate are valid
<b>group refractive index</b>	the refractive index associated with the group velocity of a train of waves traveling in a dispersive medium; the group velocity, and correspondingly the group refractive index, depends on the mean wavelength of a train of waves and on the rate of change of velocity with wavelength
<b>hemoglobin spectrum</b>	the main bands are the following: Soret band: 400–440 nm segment; Q bands: 540–580-nm segment
<b>Henyeey-Greenstein phase function (HG)</b>	one of the practical semiempirical approximations of the scattering phase function
<b>homogeneous medium</b>	a medium that has common physical properties, including optical properties, throughout
<b>image-carrying photons</b>	a group of photons selected for producing an image of a certain macroinhomogeneity within a scattering medium
<b>immersion medium (liquid)</b>	a liquid that provides optical matching between an objective and a biological object; it enhances the numerical aperture of the objective and the microscope resolution; in addition, optical matching reduces surface reflection and scattering and consequently allows for receiving higher contrast images
<b>immersion technique</b>	the technique used for reduction of light scattering in a bulk inhomogeneous medium by matching of the refractive index of the scatterers and ground substance; immersion liquids with an appropriate refractive index and rate of diffusion are usually used

<b>index of refraction</b>	a number indicating the speed of light in a given medium as either the ratio of the speed of light in a vacuum to that in the given medium (absolute index of refraction) or the ratio of the speed of light in a specified medium to that in the given medium (relative index of refraction)
<b>inhomogeneous medium</b>	a medium with regular or irregular spatial distribution of physical properties, including optical properties
<b>intensity probability density distribution function</b>	a function that describes the distribution of probability over the values of the light intensity
<b>interference of speckle fields (speckle-modulated fields)</b>	the interference of the fields in which amplitudes and phases are randomly modulated due to their interaction (scattering) with inhomogeneous (scattering) media
<b>inverse MC (IMC) method</b>	the iterative method that is based on the statistical simulation of photon transport in the scattering media and that provides a tool for the most accurate solutions of inverse scattering problem; it takes into account the real geometry of the object, the measuring system, and light beams; the main disadvantage is the long computation time
<b>inverse scattering problem</b>	the attempt to take a set of measurements and error estimates, and only a limited set of parameters describing the sample and experiment, and to derive the remaining parameters; usually the geometry is known, intensities or their parameters are measured, and the optical properties or sizes of scatterers need to be derived; if these properties are considered to be spatially varying, then the resultant solutions can be presented as a 2 or 3D function of space, i.e., as an image
<b>isotropic scattering</b>	an equality of scattering properties along all axes
<b>LASCA</b>	acronym for laser speckle contrast analysis; the method uses the spatial statistics of time-integrated speckles; the full-field technique for visualizing capillary blood flow
<b>latex</b>	a suspension of micron-sized polystyrene spheres

<b>light</b>	ultraviolet (UV): UVC: 100 – 280 nm, UVB: 280 – 315 nm, UVA: 315 – 400 nm; visible: 400 – 780 nm (violet: 400 – 450 nm, blue: 450 – 480 nm, green: 510 – 560 nm, yellow: 560 – 590 nm, orange: 590 – 620 nm, red: 620 – 780 nm); infrared (IR) light: IRA (or NIR): 780 – 1400 nm, IRB (or middle IR (MIR)): 1400 – 3000 nm, IRC (or far IR (FIR)): 3 – 1000 $\mu\text{m}$
<b>light scattering</b>	change in direction of the propagation of light in a turbid medium caused by reflection and refraction by microscopic internal structures
<b>low-step scattering</b>	the scattering process in which on average each photon undertakes no more than a few scattering events (approximately less than five to ten)
<b>LSM [light-scattering matrix (intensity or Mueller's matrix)]</b>	the $4 \times 4$ matrix which connects the <i>Stokes vector</i> of the incident light with the <i>Stokes vector</i> of the scattered light; it describes the polarization state of the scattered light in the far zone that is dependent on the polarization state of the incident light and structural and optical properties of the object
<b>LSM element</b>	one of 16 elements of the light-scattering matrix; each element depends on the scattering angle and the wavelength, and geometrical and optical parameters of the scatterers and their arrangement
<b>Mie or Lorenz–Mie scattering theory monodisperse model</b>	exact solution of Maxwell's electromagnetic field equations for a homogeneous sphere a model presenting a disperse medium as a monodisperse one, such as an ensemble of scatterers with an equal size and refractive index for each scatterer
<b>monodisperse system</b>	a disperse system (medium) with a single value of characteristic parameter, such as an ensemble of scatterers with the equal size and refractive index for each scatterer; a healthy eye cornea is a good example of the monodisperse system, because it consists of dielectric rods with the same refractive index and radius dispersed in a homogeneous ground substance

<b>Monte Carlo method</b>	a numerical method of statistical modeling; in tissue studies it provides the most accurate simulation of photon transport in the samples with a complex geometry, accounting for the specificity of the measuring system and light beams configuration
<b>multilayered tissue</b>	a tissue that consists of many layers with different structural and optical properties, such as skin, blood vessel wall, and wall of bladder
<b>multiple scattering</b>	a scattering process in which on average each photon undertakes many scattering events (approximately more than five to ten)
<b>non-Gaussian statistics</b>	a statistically nonuniform process in which the statistical characteristics of the scattered light essentially depend on the observation angle and the degree of nonuniformity of an object
<b>nonuniform medium</b>	see <b>inhomogeneous medium</b>
<b>objective speckles</b>	the speckles formed in a free space and usually observed on a screen placed at a certain distance from an object
<b>optical activity</b>	the ability of a substance to rotate the plane of polarization of plane- (linear) polarized light (see <b>chirality</b> )
<b>optical slicing</b>	the process of extracting the optical image of a thin layer of tissue; the image is used for tomographic reconstruction of a whole body organ
<b>optical path</b>	the path of light through a medium, having a magnitude equal to the geometric distance through the system times the index of refraction of the medium
<b>optical phantom</b>	a medium that models the transport of visible and infrared light in tissue and is needed to evaluate techniques, to calibrate equipment, to optimize procedures, and for quality assurance
<b>optical retarder</b>	a device that provides an optical retardation: phase shift or optical path difference; such retarders as the half- or the quarter-wavelength plates provide, respectively, the half-wave or the quarter-wave phase difference

- osmotic phenomenon** the tendency of a fluid to pass through a semipermeable membrane into a solution where its concentration is lower, thus equalizing the conditions on either side of the membrane
- osmotic stress** the force that a dissolved substance exerts on a semipermeable membrane through which it cannot penetrate, when it is separated from a pure solvent by the membrane
- paraxial region** the region where paraxial rays, lying close to the axis of an optical system, propagate
- phase-contrast microscopy (phase microscopy)** a microscopy that translates the difference in the phase of light transmitted through or reflected by an object into difference of intensity in the image
- phase fluctuations of the scattered field** the fluctuations that are induced by different optical paths for different parts or time periods of a wave front interacting with an inhomogeneous generally dynamic medium
- phase object** an object that introduces the difference in phase of the light transmitted through or reflected by an object
- $\lambda/4$ -phase plate** see **optical retarder**; a device that provides an optical phase shift of  $90^\circ$  ( $\pi/2$  radians) or an optical path difference equal to a quarter of the wavelength; a thin plate of birefringent substance, such as calcite or quartz, is cut parallel to the optical axis of the crystal and of a specific thickness that is calculated to give a phase difference of  $90^\circ$  ( $\pi/2$  radians) between the emergent ordinary ray and the emergent extraordinary ray for light of a specified wavelength; quarter-wave plates are usually constructed for the wavelength of sodium light (589 nm); if the angle between the plane of polarization of light incident upon the plate and the optic axis of the plate is  $45^\circ$ , then circularly polarized light is produced and emerges from the plate; if the angle is other than  $45^\circ$ , elliptically polarized light is produced

<b>phase shift (phase difference)</b>	the difference in phase between two wave forms; phase difference is measured by the phase angle between the waves; when two waves have a phase shift (difference) of $90^\circ$ (or $\pi/2$ radians), one wave is at maximum amplitude when the other wave is at zero amplitude; with a phase difference of $180^\circ$ ( $\pi$ radians), both waves have zero amplitude at the same time, but one wave is at a crest when the other wave is at a trough
<b>photon</b>	a quantum of electromagnetic radiation, usually considered as an elementary particle that has its own antiparticle and that has zero rest mass and charge and a spin of 1
<b>photon-correlation spectroscopy</b>	a noninvasive method for studying the dynamics of particles on a comparatively large time scale; the implementation of the single-scattering regime and the use of coherent light sources are of fundamental importance in this case; the spatial scale of testing a colloid structure (an ensemble of biological particles) is determined by the inverse of the wave vector; <i>quasielastic light scattering</i> spectroscopy, <i>spectroscopy of intensity fluctuations</i> , and <i>Doppler spectroscopy</i> are synonymous terms related to <i>dynamic light scattering</i>
<b>photon-counting system</b>	a system that makes use of a specific method of photoelectron signal processing and provides sequential detection of single photons; photomultipliers (PMT) or avalanche photodetectors (APD) are usually used for photoncounting; the technique is applicable for detecting very weak signals
<b>photon-density wave</b>	a wave of progressively decaying intensity; microscopically, individual photons migrate randomly in a scattering medium, but collectively they form a photon-density wave at a modulation frequency that moves away from a radiation source
<b>photosensitizer</b>	a substance that increases the absorption of another substance at a particular wavelength band

<b>photon transport</b>	the process of photon travel in a homogeneous or inhomogeneous medium with possible macroinhomogeneities; a photon changes its direction due to reflection, refraction, diffraction or scattering and can be absorbed by an appropriate molecule on its way
<b>pixel</b>	the smallest element of an image that can be individually displayed
<b>polarimetry</b>	measurement of the polarization properties of light
<b>polarization of light</b>	a state, or the production of a state, in which rays of light exhibit different properties in different directions; <i>linear (plane)</i> : when the electric field vector oscillates in a single, fixed plane all along the beam, the light is said to be linearly (plane) polarized; <i>elliptical</i> : when the plane of the electric field rotates, the light is said to be elliptically polarized because the electric field vector traces out an ellipse at a fixed point in space as a function of time; <i>circular</i> : when the ellipse happens to be a circle, the light is said to be circularly polarized
<b>polarization anisotropy</b>	an inequality of polarization properties along different axes
<b>polarizer</b>	a device, often a crystal or prism, that produces polarized light from unpolarized light
<b>probability density function (probability density distribution)</b>	a function that describes the distribution of probability over the values of a variable
<b>quasielastic light scattering</b>	see <b>dynamic light scattering</b>
<b>quasimonochromatic wave</b>	a wave that has a very narrow but nonzero frequency (or wavelength) bandwidth; it can be presented as a group of monochromatic waves with a slightly different wavelength
<b>quasiordered medium</b>	a medium that has a structure very close to the ordered one, but nevertheless is not completely ordered which is caused by specific interactions between molecules and molecular structures; many of the natural media, including water and some living tissues, are examples of quasiordered media



<b>radiation transfer theory (RTT)</b>	the theory based on the integro-differential equation (the Boltzmann or linear transport equation), which is a balance equation describing the flow of particles (e.g., photons) in a given volume element that takes into account their velocity $c$ , location $\bar{r}$ , and changes due to collisions (i.e., scattering and absorption)
<b>random medium</b>	a specific state of a <i>nonuniform (inhomogeneous) medium</i> characterized by the irregular spatial distribution of its physical properties, including the optical properties
<b>random phase screen (RPS)</b>	a specific state of a <i>random medium</i> characterized by random spatial variations of the refractive index, which induce the corresponding variations in the phase shift of the optical wave transmitted through or reflected by the RPS
<b>Rayleigh theory</b>	the theory that addresses the problem of calculating scattering by small particles (with respect to the wavelength of the incident light) when individual particle scattering can be described as if it is a single dipole, the scattered irradiance is inversely proportional to $\lambda^4$ and increases as $a^6$ , and the angular distribution of the scattered light is isotropic
<b>Rayleigh–Debye–Gans theory (approximation)</b>	the theory that addresses the problem of calculating the scattering by a special class of arbitrary shaped particles; it requires that the electric field inside the particle be close to that of the incident field and that the particle can be viewed as a collection of independent dipoles that are all exposed to the same incident field
<b>reflectance (reflection coefficient)</b>	the ratio of the intensity reflected from a surface to the incident intensity; it is a dimensional quantity
<b>reflecting spectroscopy</b>	the spectroscopy that is used for the spectral analysis of the light back-reflected (scattered) by an object

<b>refractive index mismatch</b>	a difference in the index of refraction of two media being in contact; a scattering medium can be considered as a medium containing scattering particles whose index of refraction is mismatched relative to index of refraction of the ground substance
<b>scatterer</b>	an inhomogeneity or a particle of a medium that refracts light or other electromagnetic radiation; light is diffused or deflected as a result of collisions between the wave and particles of the medium; sometimes it is a rough surface or a random-phase screen, also called scatterer
<b>scattering medium</b>	a medium in which a wave or beam of particles is diffused or deflected by collisions with particles of this medium
<b>scattering phase function</b>	the function that describes the scattering properties of the medium and is in fact the probability density function for scattering in the direction $\vec{s}'$ of a photon travelling in the direction $\vec{s}$ ; it characterizes an elementary scattering act; if scattering is symmetric relative to the direction of the incident wave, then the phase function depends only on the scattering angle $\theta$ (angle between directions $\vec{s}$ and $\vec{s}'$ )
<b>scattering spectrum</b>	the spectrum of scattered light; it can be differential, measured or calculated for a certain scattering angle, or integrated within an angle (field) of view of the measuring spectrometer
<b>single-mode fiber</b>	a fiber in which only a single mode can be excited; for a fiber with a numerical aperture $NA=0.1$ and wavelength 633 nm the single mode can be excited if the core diameter is less than $4.8\ \mu\text{m}$
<b>single-mode laser</b>	a laser that produces a light beam with a Gaussian shape of the transverse intensity profile without any spatial oscillations (see <b>Gaussian light beam</b> ); in general, such lasers generate many optical frequencies (so-called longitudinal modes), which have the same transverse Gaussian shape

<b>single scattering</b>	the scattering process that occurs when a wave undertakes no more than one collision with particles of the medium in which it propagates
<b>soft scattering particles</b>	the refractive index of these particles, $n_s$ , is close to the refractive index of the ground (interstitial) substance, $n_0$ ( $n_s \geq n_0$ )
<b>spatial frequency</b>	a spatial harmonic in the Fourier transform of a periodic or aperiodic (random) spatial distribution
<b>spatial resolution</b>	a measure of the ability of an optical imaging system to reveal the details of an image, i.e., to resolve adjacent elements
<b>speckle</b>	a single element of a speckle structure (pattern) that is produced as a result of the interference of a large number of elementary waves with random phases that arise when coherent light is reflected from a rough surface or when coherent light passes through a scattering medium
<b>speckle correlogometry</b>	a technique that is based on the measurement of the intensity <i>autocorrelation function</i> , characterizing the size and the distribution of speckle sizes in a speckle pattern, caused, for example, by a scattering of coherent light beam from a rough surface; the statistical properties of the scattering object's structure can be deduced from such measurement
<b>speckle photography</b>	the measuring technique that uses a set of sequential photos of the speckle pattern taken at different moments or with different exposures; this is a full-field technique and can be used to study the dynamic properties of a scattering object (see <b>LASCA</b> ); the updated instruments make use of computer controlled CCD cameras for averaging and storing the speckle patterns
<b>speckle statistics of the first order</b>	the statistics that define the properties of speckle fields at each point
<b>speckle statistics of the second order</b>	the statistics that show how fast the intensity changes from point to point in a speckle pattern, i.e., they characterize the size and distribution of speckle sizes in the pattern

<b>specular</b>	pertaining to or having the properties of a mirror
<b>Stokes parameters</b>	the four numbers $I$ , $Q$ , $U$ , and $V$ presenting an arbitrary polarization of light: $I$ refers to the irradiance or intensity of the light; the parameters $Q$ , $U$ , and $V$ represent the extent of horizontal linear, 45° linear, and circular polarization, respectively
<b>Stokes vector</b>	the vector that is formed by the four <i>Stokes parameters</i>
<b>structure function</b>	the function that describes the second-order statistics of a random process and is proportional to the difference between values of the autocorrelation function for zero and arbitrary values of the argument; the structure function is more sensitive to small-scale oscillations
<b>subjective speckles</b>	the speckles produced in the image space of an optical system (including an eye)
<b>time-of-flight</b>	the mean time of photon travel between two points which account for refractive index and scattering properties of the medium
<b>tissue optical parameters (properties) control</b>	any kind of physical or chemical action, such as mechanical stress or changes in osmolarity, which induces reversible or irreversible changes in the optical properties of a tissue [see <b>immersion medium (liquid)</b> and <b>immersion technique</b> ]
<b>tomographic reconstruction</b>	obtaining 3D images by which the size, shape, and position of a hidden object can be determined
<b>transmittance</b>	ratio of the intensity transmitted through a sample to the incident intensity; it is a dimensionless quantity
<b>two-photon fluorescence microscopy</b>	the microscopy that employs both the ballistic and scattered photons at the wavelength of the second harmonic of incident radiation coming to a wide-aperture photodetector exactly from the focal area of the excitation beam

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## Index

- A-scan, 162, 168, 169, 172
- absorption coefficient, 35
- aggregation particles, 26
- Airy disc, 141
- albedo, 51
- amplitude-based detection, 165
- attenuation coefficient, 48
- azimuth angle, 151, 152, 154, 156
  
- backscattering enhancement factors, 89
- Bethe–Salpeter equation, 112
- birefringence, 15, 161, 166, 173, 174, 207
- blood cells, 9, 73
- blood hematocrit, 63
- Born approximation, 96
- Brownian medium, 93
  
- cartilage, 14
- characteristic correlation time, 117
- chirality, 17
- circular birefringence, 149
- circular dichroism, 18
- coherence area, 100
- coherence areas, 139–142, 144–147
- coherent backscattering, 86
- collagen fibers, 12, 20, 173
- contrast of polarization image, 185
- correlation matrix, 103
  
- decay rate, 92
- degree of circular polarization, 3, 32, 79
- degree of linear polarization, 3, 32, 79
  
- degree of polarization, 3, 32, 112, 139, 149, 150
- degree of residual polarization, 92, 125, 127, 189
- depolarization length, 114, 125
- depolarization parameter, 104
- diagnostic window, 13
- diattenuator, 173
- diffusion-type equation, 50
- DOP, 139–145, 147, 161, 165, 166
  
- effective optical density, 129
- eigenstates, 164, 174
- eigenvectors, 165
- elastic mean free path, 87
- elastin fibers, 12
- elliptical retarder, 164, 173
- erythema index, 132
- extinction coefficient, 35
- extrapolation length, 96
- eye cornea, 10, 21
- eye lens, 25, 75
- eye sclera, 10, 22, 213
- eye tissues, 20
  
- Faraday rotation, 91
- fibrous tissue, 9
- flow cytometry, 203
- fluorescence anisotropy, 219, 222
- fluorescence polarization measurements, 218
- fluorescence spectrum, 221
- Fourier transform, 172, 175
- fractal clusters, 27

- fractal dimension, 28
- fractal-like structure, 26
- FWHM, 162, 167
- Gaussian statistics, 100
- generalized Malus law, 105
- glucose, 193
- hemoglobin, 130
- Henye–Greenstein function, 50
- Hilbert transformation, 171
- homogeneous polarizing element, 165
- humor analytes, 195
- hydroxyapatite crystals, 14
- interference heterodyne, 165
- Jones matrix, 161, 162, 164–172, 176
- Jones matrix (S-matrix), 31, 200
- Jones vector, 144, 164, 166–169, 171–173
- Jones vectors, 170
- Kronecker tensor product, 167
- lamellar bundles, 21
- light scattering matrix meters, 70
- linear birefringence, 149
- linear dichroism (diattenuation), 16, 34
- LSM elements, 32, 42, 57, 73, 78, 199
- mean transport free path, MTFP, 85, 87
- melanin, 130
- Mie theory, 150, 151
- Monte Carlo, 149–151, 159
- Monte Carlo method, 52, 78
- Mueller matrix, 150–155, 161–164, 166, 173, 174, 176
- Mueller matrix (light scattering matrix (LSM)), 4, 32, 56
- multiple scattering, 46
- multispectral imaging micropolarimeter, 205
- muscle, 15
- myocardium, 15
- OCT, 161–169, 172, 175, 176
- optical activity, 17, 91, 149
- optical coherence tomography, 147, 161
- optical coherence tomography (OCT), 31
- optical depth, 162, 174
- optical immersion technique, 212
- optical rotatory dispersion, 77
- packing dimension, 20
- partial polarizer, 164
- path length density distribution, 114
- phase differential scattering, 199
- photoelasticity, 216
- photon diffusion coefficient, 50
- polar angle, 151, 152
- polarimetric measurements, 196
- polarization cytometry, 199
- polarization ellipse, 101
- polarization imaging with backscattered light, 183
- polarization light microscopy, 204
- polarization memory, 93
- polarization microstatistics, 99, 105
- polarization purity, 163
- polarization-correlation universality, 103
- polarization-sensitive OCT, 161–163, 175
- polarization-sensitive OCT (PS OCT), 16
- polarized reflectance spectroscopy, 191
- porcine tendon, 172–174
- quasi-crystalline approximation, 62
- radial distribution function, 24, 37
- radiation diffusion coefficient, 127
- reduced (transport) scattering coefficient, 50, 66
- refractive index matching, 212
- residual correlation, 98
- scalar radiative transfer equation, 48
- scatter size parameter, 92
- scattering anisotropy factor, 34
- scattering coefficient, 35, 64
- scattering cross-section, 35
- scattering of light, 30
- scattering phase function, 34, 65
- scattering phase matrix, 46
- second harmonic generation (SHG), 211



- selective polarization imaging, 179
- self-diffusion coefficient, 93
- short-range order, 24, 36
- Siegert relationship, 98
- similarity in multiple scattering, 111
- single scattering approximation, 38
- single-path polarization degree, 113, 121
- single-scattering Mueller matrix,
  - 150–152, 154, 155
- size distributions of the scatterers, 10
- SLD, 162, 163, 167
- spatial correlation, 61
- spatial ordering, 19
- specific rotation, 193
- speckle, 139–147
- speckle modulation, 215
- spin flip, 97
- Stokes parameters, 31, 101
- Stokes vector, 3, 161, 163, 164, 166, 206
- Stokes vectors, 141, 144, 145, 147
- sum rule, 104
- superluminescent diode, 162, 163, 167
- surface-scattering sample, 140
- temporal coherence function, 162
- temporal correlation function, 92, 112
- tendon, 14, 211
- tissue anisotropy, 14
- tissue models, 8, 20
- tissue refractive index, 11, 23
- tooth dentin, 14
- tooth enamel, 14
- transfer matrix formalism, 89
- transillumination polarization diaphanography, 181
- transport mean free path, 50
  
- vector radiative transfer equation (VRTE), 46
- vector speckle field, 100
- volume fraction, 18
- volume-scattering sample, 140
  
- water absorption, 13
- weak scattering limit, 112
- white-noise model, 95