Determination of light absorption, scattering and anisotropy factor of a highly scattering medium using backscattered circularly polarized light

M. Xu[a], M. Alrubaiee[b], S. K. Gayen[b] and R. R. Alfano[b]

[a]Department of Physics, Fairfield University, Connecticut, CT 06824
[b]Institute for Ultrafast Spectroscopy and Lasers and Department of Physics,
The City College and Graduate Center of City University of New York, New York, NY 10031
Email: mxu@mail.fairfield.edu

ABSTRACT

The absorption coefficient, the scattering coefficient and the anisotropy factor of a highly scattering medium are determined using the diffuse reflectance of an obliquely incident beam of circularly polarized light. This approach determines both the anisotropy factor and the cutoff size parameter for the fractal continuous scattering medium such as biological tissue and tissue phantoms from depolarization of the backscattered light.

Keywords: absorption, scattering, anisotropy factor, backscattering, depolarization, circular polarization, tissue, turbid medium

1. INTRODUCTION

The estimation of the optical properties (absorption coefficient μ_a and scattering coefficient μ_s) and the anisotropy factor (g) of a turbid medium is an important problem in atmospheric, biomedical and hydrologic optics. Light diffuses in a highly scattering medium, whose behavior essentially depends on the reduced scattering coefficient $\mu'_s = \mu_s(1-g)$. The diffusion of light remains almost the same when varying μ_s and g yet keeping μ'_s unchanged. This explains why μ_a and μ'_s, instead of μ_a, μ_s and g, are commonly used in optical imaging. Light absorption and scattering coefficients depend on the optical properties of constituent particles and their concentration. The g-factor measures how much forward peaked is the angular distribution of light when it is scattered once by a particle in the medium, and is independent of the concentration of the scatterers. The value of the g-factor correlates strongly with the size of the scatterer. Determination of the g-factor then provides a direct probe of the size of scatterer, which constitutes one useful fingerprint in discriminating normal and diseased tissues.[1,2]

One way to estimate the g-factor is to use an iterative method that consists of repeatedly solving the corresponding direct radiative transfer problem by, for example, Monte Carlo simulations, with updated optical properties until the irradiance matches the measured values.[3] Explicit analytical equations have also been developed (analytic inverse radiative transfer method) for determining the optical properties in the simplest problems. [4] In both approaches, the type of the phase function of light scattering by the medium is usually assumed known and the Henyey-Greenstein phase function [5] has been commonly used.

In this paper, we report on a scheme of detecting light absorption coefficient, scattering coefficient and the g-factor simultaneously from measurement of the circularly polarized backscattered light at different positions along a line. Light is obliquely incident on the surface of the medium with an incidence angle ~ 70 degree. Both co-polarized and cross-polarized backscattered light are measured. The difference of the backscattered co-polarized and cross-polarized light intensities is used to find the g-factor of the medium. Experimental demonstrations of this approach to obtain the three parameters (absorption coefficient, scattering coefficient and the g-factor) of tissue phantoms are presented.

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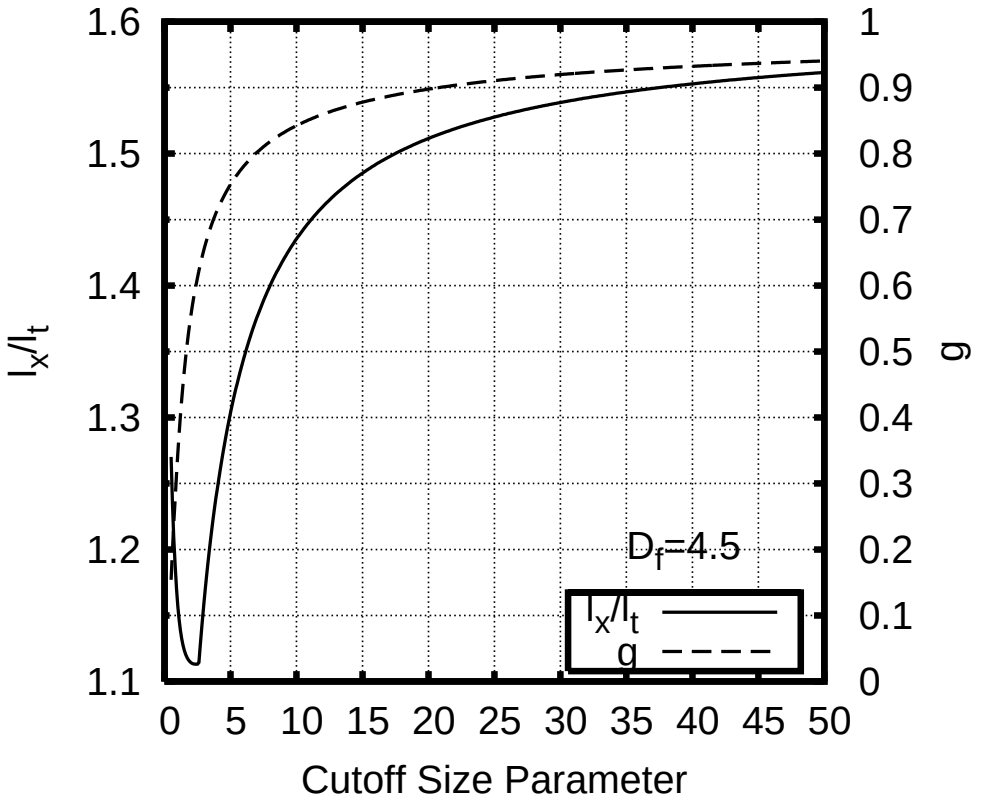

Figure 1. The ratio of the uncoiling length over the transport mean free path l_x/l_t and the anisotropy factor g of soft tissue of a fractal dimension 4.5 and of varying cutoff size parameter $X = 2\pi n l_{\max}/\lambda$.

2. THEORETICAL FORMALISM AND EXPERIMENTAL METHOD

Light propagation in a turbid medium can be described by radiative transfer theory. Diffusion approximation to radiative transfer theory is a valid model for light propagation if the medium is highly scattering and optically thick. For a polarized incident beam, light propagation in the medium accompanies its depolarization. The characteristic lengths governing light depolarization in turbid media have been obtained earlier.[6,7] The depolarization of circularly polarized light is found to be determined by the uncoiling length l_x, the distance over which the degree of circular polarization of the beam drops by $1/e$. The uncoiling length for a turbid medium is given by[7]

$$l_x \equiv \mu_s^{-1} / \ln \frac{1}{\lambda_x} \tag{1}$$

where $\lambda_x = \max(\Lambda_0, \Lambda_1)$, $\Lambda_0 = \frac{1}{2\gamma}\int_{-1}^{1} \Re\left[S_1^* S_2\right] d\mu$, $\Lambda_1 = \frac{1}{2\gamma}\int_{-1}^{1} \Re\left[S_1^* S_2\right] \mu d\mu$, $\gamma = \frac{1}{4}\int_{-1}^{1}(|S_1|^2 + |S_2|^2)d\mu$, $\mu \equiv \cos\theta$, and $S_{1,2}(\theta)$ is the amplitude scattering function with θ the scattering angle.[8]

Light scattering by biological tissue and cells can be described by the fractal continuous random medium model.[1,2] In this model, tissue light scattering is determined by two morphological parameters: the fractal dimension D_f and the cutoff correlation length $l_{\max}$. The parameter D_f reveals the weight of small vs large scattering centers in the sample and $l_{\max}$ measures the maximum size of scattering centers. Light depolarization characteristic lengths, including the uncoiling length l_x, in biological tissue and tissue phantoms have been investigated.[9] Fig. (1) displays the ratio l_x/l_t and the g-factor versus the cutoff size parameter $X = 2\pi n l_{\max}/\lambda$ for a fractal continuous random medium with $D_f = 4.5$ where n is the refractive index of the medium and λ is the wavelength of the incident beam in vacuum. This figure suggests that the anisotropy factor g (and $l_{\max}$) can be determined if the fractal dimension D_f and the uncoiling length l_x can be found in addition to the transport mean free path l_t.

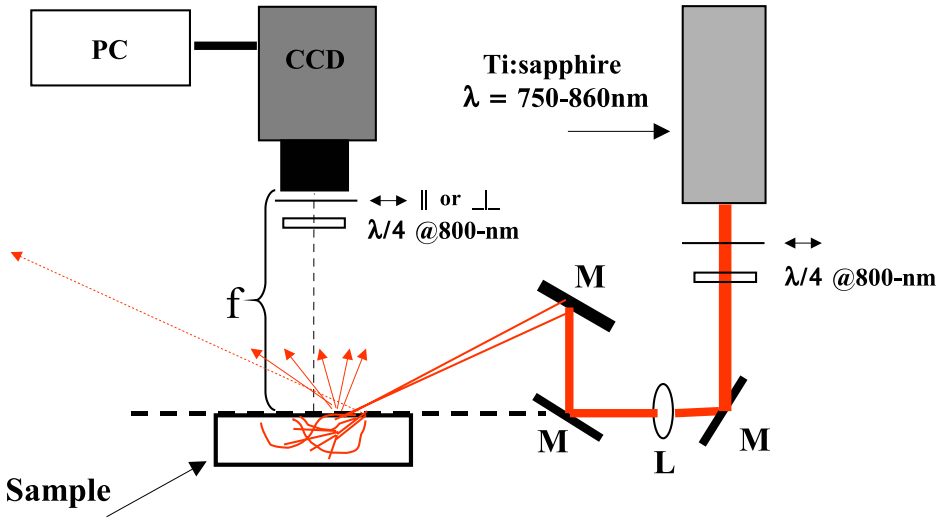

Figure 2. Schematic diagram of the experimental setup. M stands for mirror, L lens, and f is the focal length of the CCD camera. The $\lambda/4$ wave plates and polarizers are used to generate a circularly polarized beam and to detect co- or cross-polarized light at the wavelength of 800nm.

Our procedure for the determination of μ_a, μ_s and g is as follows. First μ_a and μ_s' are determined from the diffuse reflectance of the sample for an obliquely incident beam at various wavelengths centering at λ. Second, the fractal dimension D_f is determined from $\mu_s'(\lambda) \propto \lambda^{3-D_f}$. Third, the uncoiling length l_x is found from the depolarized diffuse reflectance of a circularly polarized incident beam. And finally, the anisotropy factor g is obtained by the ratio of l_x/l_t (see Fig. 1). The first two steps can be combined to retrieve μ_a, μ_s' and D_f simultaneously from fitting to the diffuse reflectance data at all wavelengths together assuming the power law for $\mu_s'(\lambda)$ is strictly satisfied.

For an obliquely incident pencil beam at the origin on the surface $z = 0$ of the sample and propagating in the direction $(\sin\alpha, 0, -\cos\alpha)$ where α is the angle of incidence, the initial ballistic motion of the beam within the medium is in the direction $(\sin\beta, 0, -\cos\beta)$ where $n\sin\beta = \sin\alpha$. The diffuse reflectance at the position $(x, y, 0)$ on the surface is given by[10]

$$R(x,y) = \frac{l_t\cos\beta}{4\pi\rho_1^3}(1+\mu_{\text{eff}}\rho_1)\exp(-\mu_{\text{eff}}\rho_1) + \frac{l_t\cos\beta + 2z_e}{4\pi\rho_2^3}(1+\mu_{\text{eff}}\rho_2)\exp(-\mu_{\text{eff}}\rho_2), \tag{2}$$

where $\mu_{\text{eff}} = \sqrt{3\mu_a/l_t}$, $\rho_1 = \sqrt{(x - l_t\sin\beta)^2 + y^2 + l_t^2\cos^2\beta}$, and $\rho_2 = \sqrt{(x - l_t\sin\beta)^2 + y^2 + (2z_e + l_t\cos\beta)^2}$. The parameter z_e is the extrapolation length, dependent on the refractive index mismatch at the interface. [11] Eq. (2) is used to fit the measured diffuse reflectance along a line in the x direction on the surface to obtain μ_a and l_t.

For an incident circularly polarized beam, light depolarization presents one extra channel that light leaves the co-polarized state to the cross-polarized state. Denote the co-polarized and cross-polarized backscattered light intensity for an incident circularly polarized light as $I_\pm$, respectively. The depolarized diffuse reflectance is proportional to $\Delta I = I_+ - I_-$ and can be modelled by the same expression (2) with the only modification of $\mu_a \to \mu_a' = \mu_a + l_x^{-1}$. The same technique hence can be used to fit for l_x in the region far away from the incidence point where the diffusion model is valid.

The experimental setup is shown in Fig. 2. The light source is a Ti:sapphire laser (Spectra-Physics Tsunami) tunable over the 750–860nm spectral range. The laser was operated in CW mode by turning off the acousto-optic modulator and had a spectral FWHM (full width at half maximum) bandwidth less than 1nm. The beam passes through a converging lens (focal length 40cm) and focused on the surface of the sample after elevated using a periscope mirror configuration. The incidence angle is set to be $\alpha = 72.4^\circ$. The refractive index of the diluted Intralipid-10% suspension is $n = 1.334$ and the extrapolation length is computed to be $z_e = 1.69 l_t$.[11] Backscattered light in the direction normal to the surface of the sample is recorded by a CCD camera for the wavelengths from 760nm to 860nm with a step of 10nm.

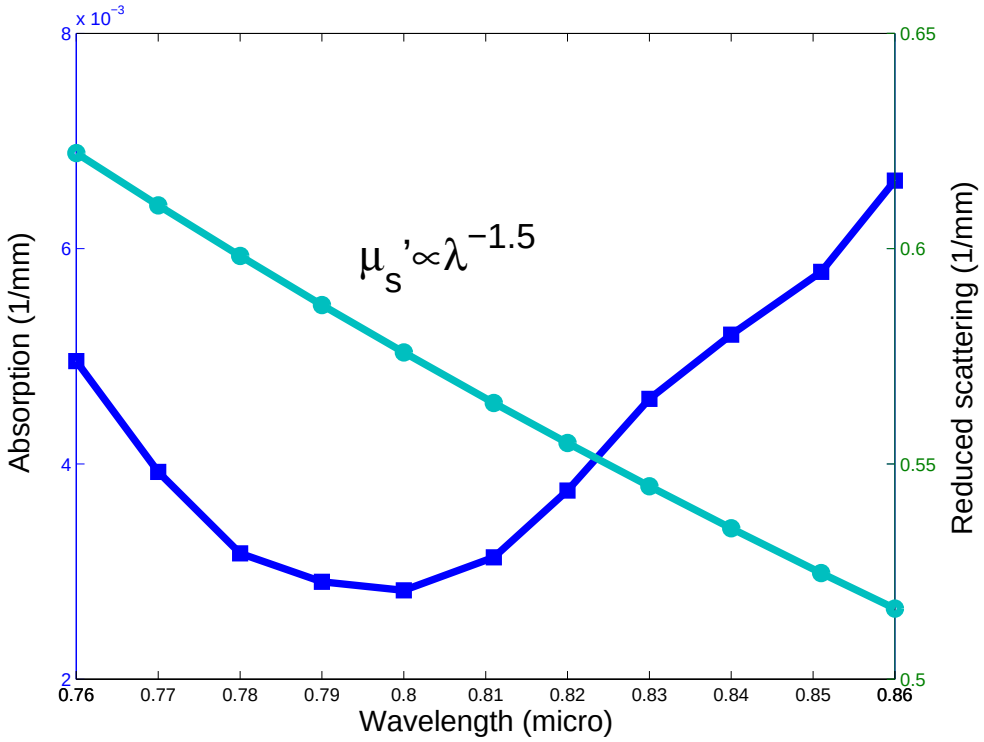

Figure 3. The wavelength dependence of the absorption and the reduced scattering coefficients of the Intralipid-10% suspension.

3. RESULT

Fig. 3 displays the wavelength dependence of μ_a and μ_s' from fitting the total diffuse reflectance where light is collected regardless of its polarization. The absorption spectrum follows essentially that of water. The wavelength dependence of the reduced scattering coefficient follows $\mu_s' \propto \lambda^{-1.5}$. The fractal dimension of the Intralipid-10% suspension is then 4.5. It should be noted this experimental value of D_f is a bit larger than the value ($D_f = 4.2$) obtained[2] from the Mie scattering computation based on the particle size distribution of the Intralipid-10% suspension measured by Staveren *et. al.* [12]

The depolarized diffuse reflectance is then measured at the wavelength of 800nm at which the absorption coefficient and the transport mean free path have been found to be $\mu_a = 0.003\text{mm}^{-1}$and $l_t = 1.77\text{mm}$, respectively, from Fig. (3). Fig. 4 displays the total backscattered light $I = I_+ + I_-$ and the depolarized backscattered light $\Delta I = I_+ - I_-$. Nearby the origin, the intensity of the cross-polarized light is stronger than that of the co-polarized light and $\Delta I < 0$. In the far zone (the region far away from the origin), the intensity of the co-polarized light is stronger than that of the cross-polarized light and $\Delta I > 0$. Fitting of the depolarized diffuse reflectance $\propto \Delta I$ along a horizontal line $3l_t$ away from the incidence point inside the far zone yields the effective absorption $\mu_a' = 0.47\text{mm}^{-1}$. The uncoiling length is then 2.13mm and the ratio $l_x/l_t = 1.20$.

From the analysis of the depolarization property of the fractal continuous medium of $D_f = 4.5$ (see Fig. 1), both the g-factor and the cut-off size parameter are now obtained. We find $g = 0.68$ at the cutoff size parameter 3.4 with $l_{\max} = 0.32\mu m$. The values of the g-factor and the cutoff size of scatterers were reported to be 0.64 at 800nm and $0.34\mu\text{m}$ in Staveren *et. al.*[12] Their agreement demonstrates the effectiveness of our proposed method.

4. DISCUSSION AND CONCLUSION

For a range of values of l_x/l_t in Fig. 1, there may be two sets of the g-factor and the cutoff size parameter giving the same ratio l_x/l_t. It does not pose any difficulty. The left branch of the l_x/l_t curve when the cutoff size parameter curve is less than 2.6 corresponds to $I_+ < I_-$ and its right branch corresponds to $I_+ > I_-$ far away from the incidence point.[7] The

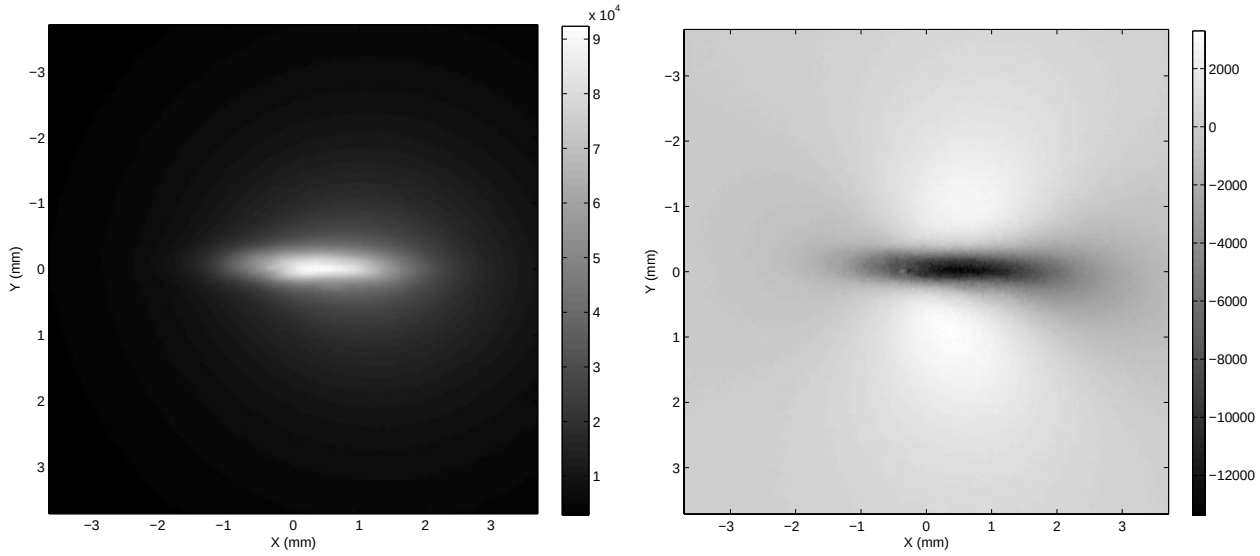

Figure 4. The intensities of backscattered light (a) the total intensity $I_+ + I_-$ and (b) the depolarized intensity $I_+ - I_-$. The circularly polarized light is incident on the origin and with an incident angle of 72.4°. The CCD camera measures $I_\pm$ directly.

experiment shows that $I_+ > I_-$ in the far zone (see Fig. 4b) and the right branch of the l_x/l_t curve should be used in our data analysis.

The absorption coefficient, the scattering coefficient and the anisotropy factor of a highly scattering medium are determined using the diffuse reflectance of an obliquely incident circularly polarized light. This approach obtains simply both the anisotropy factor and the cutoff size parameter for the fractal continuous scattering medium from circular depolarization of the backscattered light.

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