Depolarization of light in a multiply scattering medium: Effect of the refractive index of a scatterer

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We report the results of a study carried out to investigate the influence of the refractive index and size parameter of a scatterer on the depolarization of linearly and circularly polarized light in a turbid medium. The results show that for a given refractive index of the surrounding medium, the influence of the refractive index of the scatterer on the depolarization of both linearly and circularly polarized light is rather weak for samples with smaller-sized scatterers (Rayleigh scatterers, radius $a \ll \lambda$, anisotropy parameter $g \leqslant 0.2$). For a given value of optical thickness ($\tau = \mu_s \times d$, μ_s being the scattering coefficient, d the physical thickness), the depolarization of circularly polarized light was observed to be higher than that of linearly polarized light for these samples. In contrast, for samples prepared using larger-sized scatterers (Mie scatterers, $a \geqslant \lambda$, $g \geqslant 0.7$), linearly polarized light was observed to depolarize much faster than circularly polarized light when the refractive index of scatterers was large ($n = 1.59$) but no appreciable difference in depolarization of linearly and circularly polarized light was observed when the refractive index of scatterers had a lower value ($n = 1.37$). Further, for scattering samples having Mie scatterers, for comparable values of τ and g, depolarization of polarized light was much higher for samples with scatterers of lower refractive index.

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I. INTRODUCTION

The promise of polarization gating for optical imaging through biological tissue [1–3] has motivated several studies on the depolarization of light in a turbid-medium-like tissue [4–8]. These studies have shown that with an increase in the value of size parameter of scatterer ($X = 2\pi a n_{\mathrm{medium}}/\lambda$, a being the radius of the scatterer, λ the wavelength, and n_{medium} the refractive index of the surrounding medium), the characteristic length of depolarization of incident polarized light increases significantly [5–7]. Further, for a medium containing smaller-sized scatterers ($a \ll \lambda$ and anisotropy parameter—i.e., average cosine of scattering angle $g \leqslant 0.2$), the characteristic length of depolarization for linearly polarized light is higher than that for circularly polarized light and the reverse is the case for a medium containing larger-sized scatterers ($a \geqslant \lambda$, $g \geqslant 0.7$) [5–7]. In the theoretical studies, the turbid medium has been modeled as being comprised of monodisperse spherical scatterers. For experimental studies, suspension of intralipid or aqueous suspension of polystyrene microspheres has been used to prepare tissue phantoms. The usual approach while designing tissue phantoms has been to use a chosen size of scatterers that would give a value of the anisotropy parameter (g) comparable to that of tissue. The concentration of scatterers is then adjusted to yield the value of optical thickness (τ) or reduced optical thickness [$\tau' = \mu_s' d$, μ_s' being the reduced scattering coefficient $= \mu_s(1-g)$] comparable to that of actual tissue. However, important differences have been observed in depolarization of linearly and circularly polarized light between these commonly used tissue phantoms and actual tissues [8–10]. The observed difference in depolarization between tissue and matched tissue phantoms (comparable τ and g) may arise due to a difference in a large number of parameters like the density of scatterers or a distribution in the size and shape of the scatterers. Since it is difficult to quantify these parameters in biological tissue, elucidation of the reasons responsible for the observed differences in polarized light propagation through biologic tissue and matched tissue phantoms requires careful experiments using well-characterized tissue phantoms. Earlier studies in this direction have shown that one important reason for this discrepancy is the presence of a much wider distribution in the size of tissue scatterers as compared to commonly used tissue phantoms [11]. Another important factor that could contribute to the observed difference in depolarization in actual tissues and matched tissue phantoms is the fact that the commonly used tissue phantoms are prepared with scatterers that have a value of refractive index much higher ($\sim$1.5–1.6) than that of natural tissue scatterers ($\sim$1.4). Indeed previous theoretical investigations of Kim and Moscoso [12] have shown that in a turbid medium, the depolarization of light is significantly affected by the refractive index of scatterers present in the medium. Kim and Moscoso used the theory of radiative transfer to show that in a multiply scattering medium, the characteristic length of depolarization of circularly polarized light increases significantly with increasing value of the refractive index of the scatterer for range of values of the size parameter of the scatterer, $X > 1.5$.

We report here the results of a detailed experimental study carried out to characterize the influence of the refractive index of the scatterer on depolarization of linearly and circularly polarized light in a turbid medium. Our results show that for a given refractive index of the surrounding medium, the influence of the refractive index of the scatterer on the depolarization of both linearly and circularly polarized light is rather weak for samples with smaller-sized scatterers ($a \ll \lambda$, $g \leq 0.2$). In contrast, for samples prepared using larger-sized scatterers ($a \geq \lambda$, $g \geq 0.7$), depolarization was found to be significantly influenced by the refractive index of scatterers. A single-scattering theoretical treatment was used to investigate the dependence of depolarization of light on the size and refractive index of the scatterer. The results of these studies are in qualitative agreement with earlier theoretical results of Kim and Moscoso and are also able to account for the experimental observations.

II. EXPERIMENTAL METHODS

The 632.8-nm output from a He-Ne laser was used as excitation source in our studies. It was passed through a polarizer to produce linearly polarized light. A quarter-wave plate was inserted between the linear polarizer and the sample for generating circularly polarized light when required. An aperture was placed to limit the spot size of the incident laser beam at the sample site to 0.5 mm. The diffused light emerging from the sample was collected with an $f/3$ lens after passing through subsequent polarizing optics and was imaged onto a charge-coupled-device (CCD) detector (Apogee AP475, Auburn, California, USA) with an active area of $13.3\ \text{mm} \times 13.3\ \text{mm}$. The samples were kept in a quartz cuvette with path length of 10 mm. The scattering samples used in this study were monodisperse aqueous suspensions of polystyrene microspheres and silica microspheres (Bangs Lab., Fishers, Indiana, USA). The mean diameters of polystyrene microspheres were 0.11, 0.30, and 1.08 μm. The corresponding mean diameters for silica microspheres were 0.16, 0.30, and 1.08 μm. The refractive index of the polystyrene and silica microspheres in the visible wavelength range were $\sim$1.59 and 1.37, respectively. The optical thickness (τ) of the samples was varied by changing the μ_s of the samples through dilution. The values of μ_s of the samples were calculated using Mie theory [13]. When linearly polarized light was incident on the sample, measurements were made to record the transmitted intensity with polarization parallel ($I_\parallel$) and perpendicular ($I_\perp$) to the incident state of polarization by orienting the axis of an analyzer either parallel or perpendicular to the incident direction of polarization. When circularly polarized light was incident on the sample, the quarter-wave plate was inserted between the sample and the analyzer to obtain left and right circularly polarized transmitted light. The amount of copolarized (I_{co}) and cross-polarized (I_{cross}) components of the transmitted light were detected. The value for degree of polarization (P) was determined as

$$P_L = (I_\parallel - I_\perp)/(I_\parallel + I_\perp),$$

$$P_C = (I_{co} - I_{cross})/(I_{co} + I_{cross}).$$

For measurements of the spatial distribution of the degree of polarization at the detector, the degree of polarization at individual CCD pixels along the horizontal direction containing the center of the beam was measured.

III. THEORETICAL TREATMENT FOR DEPOLARIZATION OF POLARIZED LIGHT BY SINGLE SCATTERING

A theoretical model for depolarization of linearly and circularly polarized light following single scattering by a spherical scatterer has been provided in Ref. [14]. Briefly, the electric field vector of linearly polarized light (assume that the propagation is along the Z direction and the polarization is along the X direction) incident on the scatterer was resolved into components parallel and perpendicular to the scattering plane (the plane described by the incident and scattered wave vector). The scattered field due to each component was calculated at the observation point using Mie theory in a far-field approximation [14,15]. By making Euler transformation the expressions for components of scattered intensity polarized parallel ($I_\parallel$) and perpendicular ($I_\perp$) to the incident direction of polarization were worked out to be

$$I_X = I_\parallel = [|S_2(\theta)|^2\cos^2\theta \cos^4\phi + |S_1(\theta)|^2\sin^4\phi + 2\{|S_2(\theta)|^2|S_1(\theta)|^2\}^{1/2} \cos\theta \sin^2\phi \cos^2\phi](1/k^2r^2)I_0, \tag{1}$$

$$I_Y = I_\perp = [|S_2(\theta)|^2\cos^2\theta \sin^2\phi \cos^2\phi + |S_1(\theta)|^2\sin^2\phi \cos^2\phi - 2\{|S_2(\theta)|^2|S_1(\theta)|^2\}^{1/2}\cos\theta \sin^2\phi \cos^2\phi](1/k^2r^2)I_0. \tag{2}$$

Here, θ is the scattering angle and ϕ is the azimuthal angle. $|S_2(\theta)|^2$ and $|S_1(\theta)|^2$ are the scattering phase functions of scattered light polarized parallel and perpendicular to the scattering plane for a spherical scatterer of radius a, and I_0 is the incident intensity.

Summing up contributions for all azimuthal angles [ϕ varying from 0 to 2π in Eqs. (1) and (2)], one can obtain the average variation in the value of degree of linear polarization (P_{0L}) after a single-scattering event as a function of the scattering angle (θ)

$$P_{0L}(\theta) = [I_\parallel^{tot}(\theta) - I_\perp^{tot}(\theta)]/[I_\parallel^{tot}(\theta) + I_\perp^{tot}(\theta)]. \tag{3}$$

Depolarization of circularly polarized light can be worked out by expressing it as composed of two orthogonal linear polarizations with a phase difference of $\pi/2$ between them. The field for right circularly polarized light propagating along the Z direction can be written as

$$E_{\mathrm{in}} = E_{0\parallel} - jE_{0\perp},$$

where

$$E_{0\parallel}=E_{0\perp}=E_0.$$

The incident electric field vector (E_{in}) at the position of the scatterer can be resolved into components parallel and perpendicular to the scattering plane and expressions for the components of scattered fields ($E_\parallel$ and $E_\perp$) at the observation point can be obtained in a manner similar to that for linearly polarized light.

The degree of circular polarization viewed through laboratory polarizers placed in the X-Y plane can be determined by calculating the two components I_s and V_s of the Stokes matrix [13] as

$$\begin{aligned} I_s = I_R + I_L &= [E_\parallel E_\parallel^* + E_\perp E_\perp^*] \\ &= \{\cos^2\theta|S_2(\theta)|^2 + |S_1(\theta)|^2\}(1/k^2r^2)I_0 \end{aligned} \tag{4}$$

and

$$\begin{aligned} V_s = I_R - I_L &= j[E_\parallel E_\perp^* - E_\perp E_\parallel^*] \\ &= \cos\,\theta[S_2(\theta)S_1^*(\theta) + S_2^*(\theta)S_1(\theta)](1/k^2r^2)I_0 \\ &= 2\,\cos\,\theta\, S_{33}(\theta)(1/k^2r^2)I_0. \end{aligned} \tag{5}$$

Here I_R and I_L are the intensities of right and left circularly polarized scattered light, respectively.

Summing up contributions for all azimuthal angles [ϕ varying from 0 to 2π in Eqs. (4) and (5)], one can obtain the average variation in the value of degree of circular polarization (P_{0C}) after a single-scattering event as a function of scattering angle (θ) as

$$P_{0C}(\theta) = [V_s^{\mathrm{tot}}(\theta)/I_s^{\mathrm{tot}}(\theta)]. \tag{6}$$

The values for the scattering matrix elements $|S_2(\theta)|$, $|S_1(\theta)|$, and $S_{33}(\theta)$ for a scatterer of known radius and refractive index at a particular wavelength can be computed using Mie theory [13]. The variation of degree of linear polarization $[P_{0L}(\theta)]$ and degree of circular polarization $[P_{0C}(\theta)]$ as a function of scattering angle after a single-scattering event can thus be worked out for any scattering medium with known size and refractive index of scatterer and refractive index of surrounding medium.

IV. RESULTS AND DISCUSSION

Measurements were carried out for the spatial distribution of the degrees of linear and circular polarization at the detector for a set of scattering samples having the same scatterer size but varying τ. In Fig. 1(a), we show the value for the degree of polarization at the pixel corresponding to the center of the ballistic beam as a function of τ for the two samples, prepared using aqueous suspension of 0.11-μm-diam polystyrene microspheres ($g=0.09$, $X=0.72$ at 632.8 nm) and 0.16-μm-diam silica microspheres ($g=0.18$, $X=1.05$ at 632.8 nm). The rate of depolarization for the two samples is seen to be similar. Further, consistent with previous reports [7,11], for both scattering samples, the degree of circular polarization falls sharper than the degree of linear polarization with increasing value of τ. The observed larger depolarization of circularly polarized light in these isotropic scattering samples arises because, while backscattering does not affect linear polarization significantly, it reverses the helicity of the circularly polarized light, leading to rapid depolarization of circularly polarized light [4–6,12]. In Fig. 1(b), we show the measured spatial distribution of the degree of circular polarization for three different values of τ. For samples prepared with either polystyrene or silica microspheres, a distinct peak around the beam center is observed. For comparable values of the degree of polarization at the beam center, no appreciable differences are observed in the full width at half maximum (FWHM) of the spatial distribution of the degree of polarization. Similar results were obtained for the spatial distribution of the degree of linear polarization for these samples (data not shown here). The

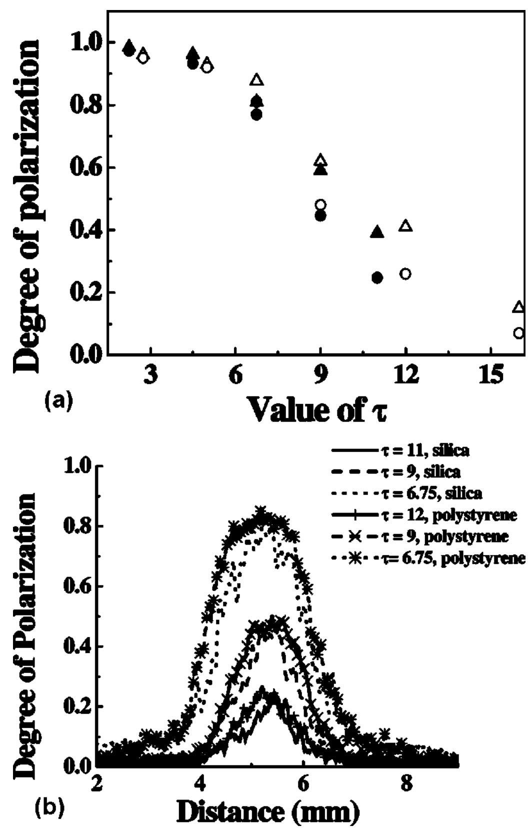

FIG. 1. (a) Measured degree of linear polarization (triangle) and degree of circular polarization (circles) from samples prepared using aqueous suspension of 0.11-μm-diam polystyrene microspheres (open symbols) and 0.16 μm diameter silica microspheres (solid symbols). (b) The measured spatial distribution of the degree of circular polarization for samples prepared using aqueous suspension of 0.11-μm-diam polystyrene microspheres (line + symbol) and 0.16-μm-diam silica microspheres (line).

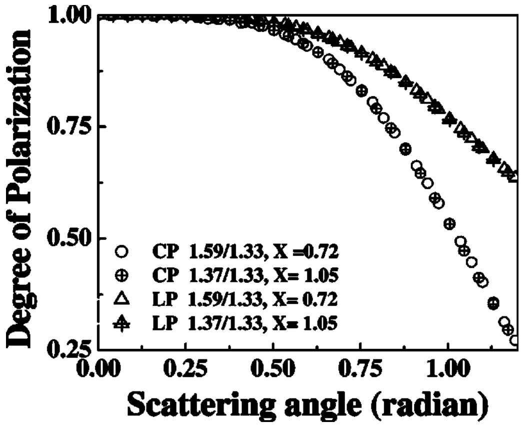

FIG. 2. Theoretically computed values for the degree of linear polarization (triangles) and degree of circular polarization (circles) after single scattering as a function of scattering angle for both 0.11-μm polystyrene microspheres (open symbols) ($n=1.59$) and 0.16-μm silica microspheres ($n=1.37$) (symbols with cross inside) suspension in water ($n_{\text{medium}}=1.33$).

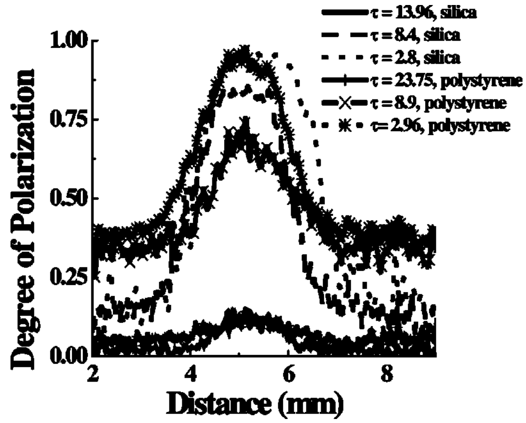

FIG. 3. The measured spatial distribution of the degree of circular polarization for samples prepared using aqueous suspension of 0.30-μm-diam polystyrene microspheres (line + symbol) and 0.30-μm-diam silica microspheres (line).

observed distinct peaks in the spatial spread of the degree of polarization arises because for these isotropic scattering samples, the transmitted light located at the beam center is primarily contributed by unscattered or weakly scattered (scattered at narrow angle) photons that maintain its initial state of polarization. In contrast, the transmitted light located far away from the propagation axis is dominated by multiply scattered photons that suffer series of large-angle scattering events and are therefore depolarized to a larger extent. With increasing value of τ, however, the fraction of the polarization preserving weakly scattered photons reduces gradually, leading to flatter profiles for a spatial spread of the degree of polarization. For a given value of τ, the sharpness of the profile for the spatial spread of the degree of polarization would depend upon the rate at which the value of the degree of polarization decreases with increasing scattering angle after individual scattering events. In Fig. 2, we show the theoretically computed values for degrees of linear and circular polarization after single scattering [computed using Eqs. (3) and (6) of Sec. III] as a function of scattering angle for both 0.11-μm polystyrene microspheres ($n=1.59$) and 0.16-μm silica microspheres ($n=1.37$) suspensions in water ($n_{\text{medium}}=1.33$). For both these scatterers having different refractive indices, the values of the degree of polarization at all the scattering angles are observed to be similar with the degree of circular polarization being lower as compared to the degree of linear polarization. This is consistent with the observed similar FWHM of spatial spread of the degree of polarization for these isotropic scattering samples with either polystyrene or silica microspheres as scatterer. The experimental and theoretical results presented above show that for samples prepared using smaller-sized scatterers ($a \ll \lambda$, $g \leqslant 0.2$), for a given refractive index of the surrounding medium, the depolarization behavior of scattered light is not significantly influenced by the refractive index of scatterer, with the depolarization of circularly polarized light being higher than linearly polarized light.

The measured spatial distribution of the degree of circular polarization for samples with aqueous suspension of 0.30-μm polystyrene microspheres ($X=1.98$ and $g=0.65$ at 632.8 nm) and 0.30-μm silica microspheres ($X=1.98$ and $g=0.61$ at 632.8 nm) for three different values of τ are shown in Fig. 3. In agreement with previous reports [5,7], the variations of the measured degree of polarization (measured at the pixel corresponding to the center of the ballistic beam) as a function of τ for these samples did not show any appreciable difference in the depolarization of linearly and circularly polarized light (data not shown here). However, the degree of polarization was seen to be destroyed faster for the samples with silica microspheres as compared to those with polystyrene microspheres. The degree of polarization reduced to less than 0.1 for $\tau=14$ for silica microspheres as compared to $\tau=24$ for polystyrene microspheres. Further, from Fig. 3, it can also be seen that for comparable values of the degree of polarization at the beam center, the spatial distribution of the degree of polarization for samples with silica microspheres is sharper as compared to that for the samples prepared using polystyrene microspheres. Similar results were also obtained for the spatial distribution of degree of linear polarization with the difference being less pronounced (data not shown here). In Fig. 4, we show the theoretically computed values for the degree of circular polarization after single scattering as a function of scattering angle for aqueous suspension ($n_{\text{medium}}=1.33$) of the two 0.30-μm-diam scatterers, one having a refractive index of 1.59 and the other with 1.37. The inset of the figure shows the scattering matrix element S_{33} (a measure of helicity) as a function of the scattering angle for these scatterers. The values of S_{33} have been normalized with respect to the total scattered intensity. The figure shows that for larger scattering angles, the degree of circular polarization is lower for the scatterer having a lower value of the refractive index (silica microspheres). Further, the inset of the figure shows that S_{33} goes to negative values (indicating a flip of helicity) at a smaller scattering angle for a lower refractive index scatterer as compared to the scatterer having a higher refractive index. For linear polarization also, for all scattering angles, the theoretically computed values of degree of polarization were observed to be lower for the scatterer having a lower value of the refractive index (data not

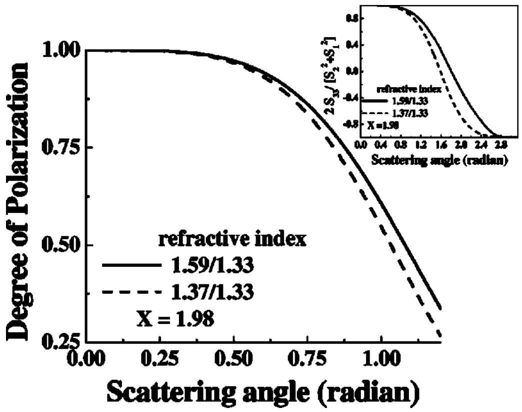

FIG. 4. Theoretically computed values for the degree of circular polarization after single scattering as a function of scattering angle for both 0.30-μm polystyrene microspheres ($n=1.59$) (solid line) and 0.30-μm silica microspheres ($n=1.37$) (dashed line) suspension in water ($n_{\text{medium}}=1.33$). The inset of the figure shows scattering matrix element S_{33} (normalized with respect to total scattered intensity) as a function of scattering angle for these scatterers.

shown here). The lower value of the degree of polarization and the sharper fall of the degree of polarization with scattering angle for the low-refractive-index scatterer is consistent with the experimentally observed faster depolarization of polarized light and the sharper spatial distribution of the degree of polarization for the samples with low-refractive-index silica microspheres as compared to those with higher-refractive-index-polystyrene microspheres. These results would indicate that for these anisotropic scattering samples, the polarization state can be used to filter out the multiply scattered photons from the weakly scattered photons more efficiently for samples with a lower refractive index of the scatterer.

In Fig. 5, we show the value for the degree of polarization at the pixel corresponding to the center of the ballistic beam as a function of τ for the samples having 1.08-μm-diam polystyrene ($X=7.13$ and $g=0.92$ at 632.8 nm) and silica microspheres ($X=7.13$ and $g=0.95$ at 632.8 nm). It can be seen

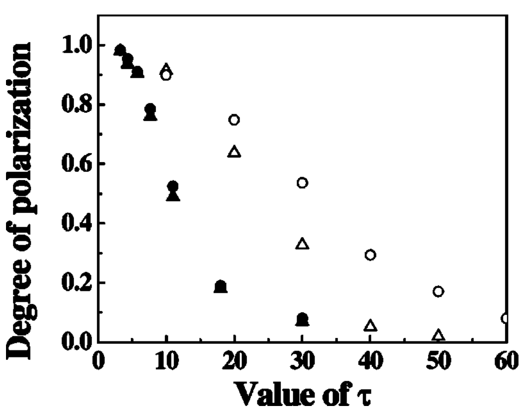

FIG. 5. Measured degree of liner polarization (triangle) and degree of circular polarization (circle) from samples prepared using aqueous suspension of 1.08-μm-diam polystyrene microspheres (open symbols) and 1.08-μm-diam silica microspheres (solid symbols).

from the figure that while for samples with 1.08-μm polystyrene microspheres the degree of linear polarization fall sharper than the degree of circular polarization with increasing values of τ, there is no appreciable difference in the depolarization of linearly and circularly polarized light for samples prepared using silica microspheres. Further both degrees of linear and circular polarization are observed to be preserved up to a much larger value of τ for the samples with polystyrene microspheres. Consistent with previous reports [4,11], the spatial distribution of the degree of polarization for these samples with larger-sized scatterer (1.08 μm diameter) was much flatter than the smaller-sized scatterers with no distinct peak at the beam center. However, the spatial distribution of the degree of polarization for samples prepared using silica microspheres was slightly sharper than for samples with polystyrene microspheres for lower values of τ. The results presented in Fig. 5 show that the difference in depolarization behavior between scattering samples having different refractive indices of scatterers is much more pronounced for samples with large-sized scatterers. Further, the influence of the refractive index of the scatterer is seen to be more pronounced for circularly polarized light. It is pertinent to note here that the value for g is larger for samples with silica microspheres. Therefore, the faster depolarization observed in the samples with 1.08-μm silica microspheres as compared to those with 1.08-μm polystyrene microspheres cannot be explained by the anisotropy parameter g. These results are in qualitative agreement with the results of the theoretical study of Kim and Moscoso [12]. The reason for this difference in depolarization behavior originates from the difference in the nature of the scattering matrix elements (S_1, S_2 and S_{33}) of the two scattering samples having the same refractive index of the surrounding medium but different refractive indices of scatterers. In Fig. 6(a), we show the theoretically computed values for the degree of circular polarization and degree of linear polarization after single scattering as a function of scattering angle for the aqueous suspension ($n_{\text{medium}}=1.33$) of these 1.08-μm scatterers with refractive indices of 1.59 and 1.37. For larger scattering angles the degree of polarization is seen to be lower for the scatterer with a lower refractive index as compared to that with a higher refractive index, with the effect being more pronounced for circularly polarized light. The scattering matrix element S_{33} as a function of scattering angle for these two scatterers and for a Rayleigh scatterer (diameter of 0.11 μm and refractive index of 1.59) is shown in Fig. 6(b). The figure shows that while for the 1.08-μm scatterer having a refractive index of 1.37, S_{33} changes sign (indicating a flip of helicity) at an angle $\sim 90°$, which is closer to that of a Rayleigh scatterer, the helicity flips at a much larger scattering angle for the 1.08-μm scatterer having a refractive index of 1.59. Thus, for the same size parameter, the depolarization properties of the lower-refractive-index scatterer appear comparable to those of a scatterer with a smaller physical dimension. This would explain the observed faster depolarization in the samples with 1.08-μm silica microspheres as compared to those prepared using 1.08-μm polystyrene microspheres. The results of computations performed for several other scatterers (size $a \geqslant \lambda$) confirmed that, for the range of scatterer refractive index $\sim 1.35-1.8$, even though the value

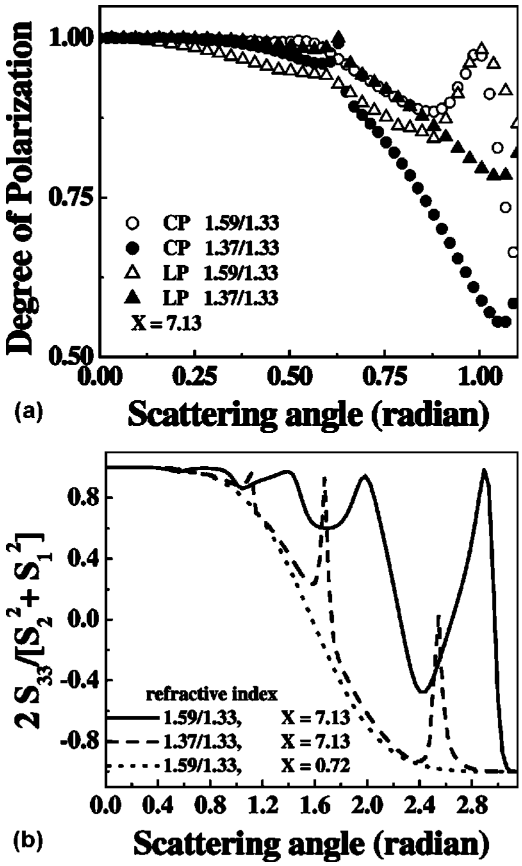

FIG. 6. (a) Theoretically computed values for the degree of circular polarization (circle) and degree of linear polarization (triangle) after single scattering as a function of scattering angle for both 1.08-μm polystyrene microspheres ($n=1.59$) (open symbols) and 1.08-μm silica microspheres ($n=1.37$) (solid symbols) suspension in water ($n_{\mathrm{medium}}=1.33$). (b) The scattering matrix element S_{33} (normalized with respect to total scattered intensity) as a function of scattering angle for aqueous suspension of 1.08-μm polystyrene microspheres (solid line), 1.08-μm silica microspheres (dashed line), and 0.11-μm polystyrene microspheres (dotted line).

for anisotropy parameter g of a lower-refractive-index scatterer is comparable or slightly higher than that of a higher-refractive-index scatterer having the same value of the size parameter (X), the difference in the nature of the scattering matrix elements (S_1, S_2, and S_{33}) of these scatterers would result in a larger depolarization of polarized light with the effect being more pronounced for circularly polarized light. It should be mentioned here that the observed dependence of depolarization of linearly and circularly polarized light on the refractive index and size parameter of scatterer would be valid for the narrow range of these parameters (ratio of refractive index of scatterer to the surrounding medium $n_{\mathrm{rel}} \sim 1.02-1.4$, $X \sim 0-10$) investigated in this study. However, for an even larger refractive index of the scatterer, a different behavior of the depolarization of polarized light may arise due to the pronounced effects of resonance and the interference structures [13]. It is also pertinent to note that although the single-scattering theoretical treatment presented above does provide qualitative agreement with the experimental results, a quantitative evaluation would require incorporation of the effect of multiple scattering.

V. CONCLUSIONS

To conclude, the results of our study show that for samples prepared using larger-sized scatterers ($a \geqslant \lambda$, $g \geqslant 0.7$), the depolarization of both linearly and circularly polarized light is significantly affected by the refractive index of scatterers. While for larger scatterers with higher value of refractive index linearly polarized light depolarized much faster than circularly polarized light, no appreciable difference in the depolarization of linearly and circularly polarized light was observed for scatterers having a lower value of the refractive index. Further, for comparable values of τ and g, depolarization of both linearly and circularly polarized light was observed to be higher for samples with scatterers of a lower refractive index, with the effect being more pronounced for circularly polarized light. It might be useful to relate these results to the differences observed in the depolarization of polarized light between the commonly used tissue phantoms and actual tissues. It appears that the difference in the relative refractive index ratio of tissue (refractive indices of scatterer and surrounding medium are ~ 1.4 and $1.33-1.35$, respectively [16,17], $n_{\mathrm{rel}} \sim 1.04$) and commonly used tissue phantoms (refractive indices of scatterer and surrounding medium are $\sim 1.5-1.6$ and 1.33, respectively, $n_{\mathrm{rel}} \sim 1.2$) would be an important factor contributing to the differences observed in the relative behavior of depolarization of linearly and circularly polarized light in tissue and matched tissue phantoms [8–10]. This also would contribute to the observed faster depolarization of polarized light in tissue as compared to matched tissue phantoms [9].

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