Circular polarization memory effect in low-coherence enhanced backscattering of light

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We experimentally study the propagation of circularly polarized light in the subdiffusion regime by exploiting enhanced backscattering [(EBS), also known as coherent backscattering] of light under low spatial coherence illumination. We demonstrate for the first time, to the best of our knowledge, that a circular polarization memory effect exists in EBS over a large range of scatterers' sizes in this regime. We show that low-coherence EBS signals from the helicity preserving and orthogonal helicity channels cross over as the mean free path length of light in media varies, and that the cross point indicates the transition from multiple to double scattering in EBS. © 2006 Optical Society of America

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The circular polarization memory effect is an unexpected preservation of the initial helicity (or handedness) of circular polarization of multiply scattered light in scattering media consisting of large particles. Mackintosh *et al.*[1] first observed that the randomization of the helicity required unexpectedly far more scattering events than did the randomization of its propagation in media of large scatterers. Bicout *et al.*[2] demonstrated that the memory effect can be shown by measuring the degree of circular polarization of transmitted light in slabs. Using numerical simulations of vector radiative transport equations, Kim and Moscoso[3] explained the effect as the result of successive near-forward-scattering events in large scatterers. Recently, Xu and Alfano[4] derived a characteristic length of the helicity loss in the diffuse regime and showed that this characteristic length was greater than the transport mean free path length l_s^* for the scatterers of large sizes. Indeed, the propagation of circularly polarized light in random media has been investigated mainly by using either numerical simulations or experiments in the diffusion regime, in part, because its experimental investigation in the subdiffusion regime has been extremely challenging. Therefore the experimental investigation of circularly polarized light in the low-order scattering (or short traveling photons) regime using enhanced backscattering [(EBS), also known as coherent backscattering] of light under low spatial coherence illumination will provide a better understanding of its mechanisms and the polarization properties of EBS as well.

EBS is a self-interference effect in elastic light scattering, which gives rise to an enhanced scattered intensity in the backward direction. In our previous publications,[5–8] we demonstrated that low spatial coherence illumination (the spatial coherence length of illumination $L_{sc} \ll l_s^*$) dephases the time-reversed partial waves outside its finite coherence area, rejecting long traveling waves in weakly scattering media. EBS under low spatial coherence illumination ($L_{sc} \ll l_s^*$) is henceforth referred to as low-coherence EBS (LEBS). The angular profile of LEBS, $I_{\mathrm{LEBS}}(\theta)$, can be expressed as an integral transform of the radial probability distribution $P(r)$ of the conjugated time-reversed light paths.[6–8]

$$I_{\mathrm{LEBS}}(\theta) = \int_0^\infty C(r) r P(r) \exp(\mathrm{i}2\pi r\theta/\lambda) \mathrm{d}r, \qquad (1)$$

where r is the radial distance from the first to the last points on a time-reversed light path and $C(r) = |2J_1(r/L_{sc})/(r/L_{sc})|$ is the degree of spatial coherence of illumination with the first-order Bessel function J_1.[9] As $C(r)$ is a decay function of r, it acts as a spatial filter, allowing only photons emerging within its coherence areas ($\sim L_{sc}^2$) to contribute to $P(r)$. Therefore LEBS provides the information about $P(r)$ for a small $r(\lesssim 100\ \mu\mathrm{m})$ that is on the order of L_{sc} as a tool for the investigation of light propagation in the subdiffusion regime.

To investigate the helicity preservation of circularly polarized light in the subdiffusion regime by exploiting LEBS, we used the experimental setup described in detail elsewhere.[5,6] In brief, a beam of broadband cw light from a 100 W xenon lamp (Spectra-Physics, Oriel) was collimated using a 4-*f* lens system, polarized, and delivered onto a sample with the illumination diameter of 3 mm. By changing the size of the aperture in the 4-*f* lens system, we varied spatial coherence length L_{sc} of the incident light from 35 to 200 μm. The temporal coherence length of illumination was 0.7 μm with the central wavelength $\lambda_c = 520$ nm and its FWHM = 135 nm. The circular polarization of LEBS signals was analyzed by means of an achromatic quarter-wavelet plate (Karl Lambrecht) positioned between the beam splitter and the

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sample. The light backscattered by the sample was collected by a sequence of a lens, a linear analyzer (Lambda Research Optics), and a CCD camera (Princeton Instruments). We collected LEBS signals from two different circular polarization channels: the helicity preserving $(h \| h)$ channel and the orthogonal helicity $(h \perp h)$ channel. In the $(h \| h)$ channel, the helicity of the detected circular polarization was the same as that of the incident circular polarization. In the $(h \perp h)$ channel, the helicity of the detected circular polarization was orthogonal to that of the incident circular polarization.

In our experiments, we used media consisting of aqueous suspensions of polystyrene microspheres ($n_{\text{sphere}}=1.599$ and $n_{\text{water}}=1.335$ at 520 nm) (Duke Scientific) of various radii $a=0.05$, 0.10, 0.15, 0.25, and 0.45 μm (the size parameter $ka=0.8$ to 7.2 and the anisotropic factor $g=0.11$ to 0.92). The dimension of the samples was $\pi \times 25^2\ \text{mm}^2 \times 50$ mm. Using Mie theory,[10] we calculated the optical properties of the samples such as the scattering mean-free path length of light in the medium l_s $(=1/\mu_s$, where μ_s is the scattering coefficient), the anisotropy factor g (=the average cosine of the phase function), and the transport mean free path length l_s^* $[=1/\mu_s^*=l_s/(1-g)$, where μ_s^* is the reduced scattering coefficient]. We also varied L_{sc} from 40 to 110 μm. We used g as a metric of the tendency of light to be scattered in the forward direction.

The total experimental backscattered intensity I_T can be expressed as $I_T = I_{\text{SS}} + I_{\text{MS}} + I_{\text{EBS}}$, where I_{SS}, I_{MS}, and I_{EBS} are the contributions from single scattering, multiple scattering, and interference from the time-reserved waves (i.e., EBS), respectively. In media of relatively small particles (radius $\leq \lambda$), the angular dependence of $I_T(\theta)$ around the backward direction is primarily due to the interference term, while the multiple- and single scattering terms have weaker angular dependence.[11] Thus $I_{\text{SS}}+I_{\text{MS}}$ ($\equiv$the baseline intensity) can be measured at large backscattering angles ($\theta > 3°$). Conventionally, the enhancement factor $E=1+I_{\text{EBS}}(\theta=0°)/(I_{\text{SS}}+I_{\text{MS}})$ is commonly used. However, in the studies of circularly polarized light, the enhancement factor should be modified, because the intensity of multiple scattering can be different in the two different channels and because in the $(h \| h)$ channel, single scattering is suppressed due to the helicity flip. Thus in our studies we calculated I_{EBS} by subtracting $I_{\text{SS}}+I_{\text{MS}}$ from I_T.

Figure 1 shows representative LEBS intensity profiles $I_{\text{LEBS}}(\theta)$ from the suspension of the microspheres with $a=0.15\ \mu$m ($ka=2.4$ and $g=0.73$ at $\lambda=520$ nm). $I^{\|}_{\text{LEBS}}(\theta)$ and $I^{\perp}_{\text{LEBS}}(\theta)$ denote $I_{\text{LEBS}}(\theta)$ from the $(h \| h)$ and $(h \perp h)$ channels, respectively. We varied l_s^* from 67 to 1056 μm (l_s from 18 to 285 μm) with $L_{\text{sc}}=110\ \mu$m. In Fig. 2(a), we plot $I_{\text{LEBS}}(\theta=0°)$ as a function of l_s^* (the curves are third-degree polynomial fitting), showing two characteristic regimes: (i) the multiply scattering regime ($L_{\text{sc}} \gg l_s^*$) and (ii) the minimally scattering regime ($L_{\text{sc}} \ll l_s^*$). As expected, in the multiply scattering regime (i), $I^{\|}_{\text{LEBS}}(\theta=0°)$ is

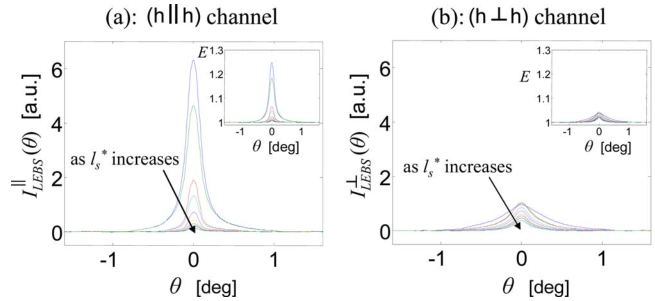

Fig. 1. (Color online) Representative $I_{\text{LEBS}}(\theta)$ with $L_{\text{sc}}=110\ \mu$m obtained from the suspensions of microspheres ($a=0.15\ \mu$m, $ka=2.4$, and $g=0.73$). We obtained $I_{\text{LEBS}}(\theta)$ for various $l_s^*=67$ to 1056 μm ($l_s=18$ to 285 μm) from the (a) $(h \| h)$ and (b) $(h \perp h)$ channels. The insets show the enhancement factors E.

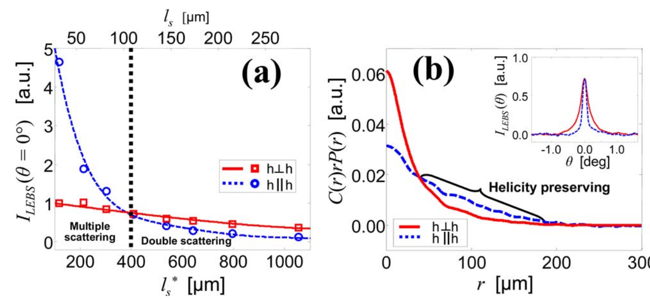

Fig. 2. (Color online) I_{LEBS} in the backward direction from Fig. 1. (a) $I^{\|}_{\text{LEBS}}(\theta=0°)$ and $I^{\perp}_{\text{LEBS}}(\theta=0°)$ cross over at $l_s^*=408\ \mu$m ($l_s=110\ \mu$m). The curves are third-degree polynomial fitting. (b) Inset, $I^{\|}_{\text{LEBS}}(\theta)$ and $I^{\perp}_{\text{LEBS}}(\theta)$ at the cross point. $C(r)rP(r)$ obtained by calculating the inverse Fourier transform of $I_{\text{LEBS}}(\theta)$ reveals helicity preserving in the $(h \| h)$ channel when $r \gtrsim 50\ \mu$m.

higher than $I^{\perp}_{\text{LEBS}}(\theta=0°)$ because of the reciprocity principle in the $(h \| h)$ channel. On the other hand, in the minimal scattering regime (ii), *a priori* surprisingly, $I^{\|}_{\text{LEBS}}(\theta=0°)$ is lower than $I^{\perp}_{\text{LEBS}}(\theta=0°)$. This is because in this regime, LEBS originates mainly from the time-reversed paths of the minimal number of scattering events in EBS (i.e., mainly double scattering) in a narrow elongated coherence volume.[8] In this case, the direction of light scattered by one of the scatterers should be close to the forward direction, while the direction of the light scattered by the other scatterer should be close to the backscattering that flips the helicity of circular polarization. After the cross point, the difference between $I^{\|}_{\text{LEBS}}(\theta=0°)$ and $I^{\perp}_{\text{LEBS}}(\theta=0°)$ remains nearly constant, indicating that LEBS reaches to the asymptotic regime of double scattering.

More important, Fig. 2(a) shows that $I^{\|}_{\text{LEBS}}(\theta=0°)$ and $I^{\perp}_{\text{LEBS}}(\theta=0°)$ cross over at $l_s^*=408\ \mu$m ($l_s=110\ \mu$m). The cross point can be understood in the context of the circular polarization memory effect as follows. As shown in the inset of Fig. 2(b), at the cross point, $\int_0^\infty C(r)P^{\|}(r)r\mathrm{d}r=\int_0^\infty C(r)P^{\perp}(r)r\mathrm{d}r$, where $P^{\|}(r)$ and $P^{\perp}(r)$ are the radial intensity distributions of the $(h \| h)$ and $(h \perp h)$ channels, respectively. Thus the cross point R_i determines the optical properties (l_s^* or l_s) such that $\int_0^{\sim L_{\text{sc}}} P^{\|}(r)\mathrm{d}r=\int_0^{\sim L_{\text{sc}}} P^{\perp}(r)\mathrm{d}r$. In other words, R_i defines l_s^* or l_s such that $P^{\parallel}(r)$ and $P^{\perp}(r)$ are equal within L_{sc} and thus the degree of circular polarization within L_{sc} becomes zero as well. As shown in Fig. 2(b), the $C(r)rP(r)$, which can be obtained by the inverse Fourier transform of $I_{\text{LEBS}}(\theta)$ using Eq. (1), reveals more detailed information about the helicity preservation. For small r, $P^{\perp}(r) > P^{\parallel}(r)$. For $r \gtrsim 50\ \mu\text{m}$, $(\sim l_s/2)$, $P^{\parallel}(r) > P^{\perp}(r)$, showing that the initial helicity is preserved. This is because the successive scattering events of the highly forward scatterers direct photons away from the incident point of illumination, while maintaining the initial helicity.

As discussed above, the cross point R_i is determined by both the spatial coherence length of illumination L_{sc} and the optical properties of the media. Thus we investigated the relationship between L_{sc} and R_i using the fixed scatterer size with $a = 0.25\ \mu\text{m}$ ($ka = 4.0$, and $g = 0.86$). Figure 3(a) shows that R_i (in the units of l_s^*) is linearly proportional to L_{sc} and that small reduced scattering coefficients μ_s^* ($=1/l_s^*$) are necessary to reach a cross point as L_{sc} increases. Because the linear fitting line passes through the origin [the 95% confidence interval of the intercept of the L_{sc} axis is (−32, 44 μm)], R_i can be normalized by L_{sc}. Next, to elucidate how the tendency of the propagation direction (i.e., g) plays a role in the memory effect, we further studied the effect of g on R_i using the various size parameters ka ranging from 0.8 to 7.2 ($g = 0.11$ to 0.92) with the fixed $L_{\text{sc}} = 110\ \mu\text{m}$. In Fig. 3(b), we plot R_i (in the units of l_s^*) versus g. This shows R_i increases dramatically as g increases, which is in good agreement with the conventional notion that a small μ_s^* is required for the memory effect to occur in media of larger particles because of the stronger memory effect in media of larger scatterers. When we plot R_i in the units of l_s versus g, as shown in Fig. 3(c), on the other hand, R_i does not depend strongly on g. This result shows that when l_s is of the order of L_{sc}, the helicity of circular polarization is maintained over a large range of the size parameters. Moreover, Fig. 3(c) demonstrates

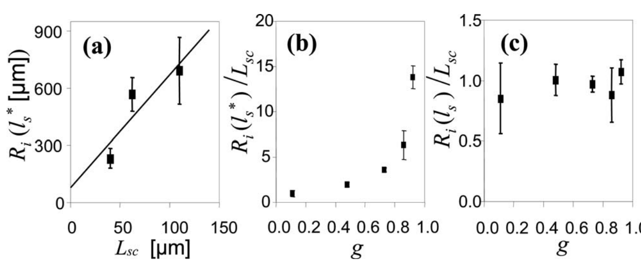

Fig. 3. Dependence of R_i on L_{sc} and g in LEBS measurements. (a) Plot of R_i (in the units of l_s^*) versus L_{sc} for a fixed $g = 0.86$ ($ka = 4.0$). (b) R_i (in the units of l_s^*)/L_{sc} as a function of g. (c) R_i is recalculated in the units of l_s.

that the average distance of single-scattering events (i.e., l_s) is a main characteristic length scale that plays major roles in the memory effect in the subdiffusion regime.

In summary, we experimentally investigated for the first time, to the best of our knowledge, the circular polarization memory effect in the subdiffusion regime by taking advantage of LEBS, which suppresses time-reserved waves beyond the spatial coherence area; and thus isolates low-order scattering in weakly scattering media. We reported that LEBS introduces the new length scale (i.e., cross point) at which the degree of circular polarization becomes zero; and the scale is determined by both the spatial coherence length of illumination and the optical properties of the media. Using the cross point of the LEBS measurements from the $(h \parallel h)$ and $(h \perp h)$ channels, we further elucidated the memory effect in the subdiffusion regime. Our results demonstrate that the memory effect exists in the EBS phenomenon. Furthermore, we show that the cross point is the transition point from multiple-scattering to double-scattering events this regime. Finally, our results will further facilitate the understanding of the propagation of circularly polarized light in weakly scattering media such as biological tissue.

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