Origin of low-coherence enhanced backscattering

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The origin of low-coherence enhanced backscattering (EBS) of light in random media when the spatial coherence length of illumination is much smaller than the transport mean free path has been poorly understood. We report that in weakly scattering discrete random media low-coherence EBS originates from time-reversed paths of double scattering. Low spatial coherence illumination dephases the time-reversed waves outside its finite coherence area, which isolates the minimal number of scattering events in EBS from higher-order scattering. Moreover, we show the first experimental evidence that the minimal number of scattering events in EBS is double scattering, which has been hypothesized since the first observation of EBS. © 2006 Optical Society of America

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Enhanced backscattering (EBS), otherwise known as coherent backscattering, is a spectacular manifestation of self-interference effects in elastic light scattering, which gives rise to an enhanced scattered intensity in the backward direction. For a plane wave illuminating a semi-infinite random medium, every photon scattered from the medium in the backward direction has a time-reversed photon traveling along the same path in the opposite direction. These photons have the same phase at the exit points and thus interfere constructively with each other, resulting in EBS. This fascinating phenomenon has been the object of intensive investigations in a variety of different systems, including biological tissues, since the first observations of EBS of light.[1–3]

In conventional EBS measurements using highly coherent light sources with an infinite spatial coherence area of illumination (i.e., the spatial coherence length of illumination $L_{sc} \gg$ the transport mean free path length of light in the medium, l_s^*), any time-reversed waves reflected by means of multiple scattering from the sample are capable of interfering with each other. On the other hand, the time-reversed invariance in EBS in elastic light scattering can be altered: time-resolved EBS measurements can probe short time-reversed paths, which in turn change the profile of EBS peaks.[4,5] Faraday rotation by an external magnetic field,[6] a phase screw dislocation in an incident field,[7] and the quantum internal structure of cold atoms[8] can destroy the time-reversal invariance, resulting in a small (or broad) EBS peak. Theoretical work about the effect of low coherence illumination on EBS was also performed[9] in the case of $L_{sc} > l_s^*$.

Recently we demonstrated[10–12] experimentally that low spatial coherence illumination dephases the conjugated time-reversed paths outside its spatial coherence area and rejects long scattering paths, resulting in a broad EBS peak when $L_{sc} \ll l_s^*$. EBS under low spatial coherence illumination is henceforth referred to as low-coherence EBS (LEBS) in the low-coherence regime (i.e., $L_{sc} \ll l_s^*$). LEBS possesses novel and intriguing properties—speckle reduction and several orders of magnitude broadening of the EBS peak—that facilitate depth-resolved measurements by probing different scattering angles within the EBS peak. The rationale for investigation of LEBS is further substantiated by our demonstration that LEBS can be used to detect early precancerous alterations in the colon far earlier than any other currently available molecular and genetic techniques.[10–12] However, the origin of LEBS in terms of the number of scattering events has not been completely understood yet.

In this Letter we report that LEBS originates from the time-reversed paths of double-scattering events in weakly scattering media such as biological tissue in the low-coherence regime ($L_{sc} \ll l_s^*$). Our main finding is that dephasing induced by low spatial coherence illumination in EBS isolates double scattering from higher-order scattering in a discrete random medium when L_{sc} is of the order of the scattering mean free path l_s of light in the medium ($l_s = 1/\mu_s = l_s^*(1-g)$, where g is the anisotropy factor and μ_s is the scattering coefficient). In addition, we show for the first time to our knowledge direct experimental evidence that the minimal number of scattering events to generate an EBS peak in a discrete random medium is double scattering. In previous theoretical studies[13,14] it was hypothesized that double scattering is the minimal number of scattering events that are necessary to generate an EBS peak, because single scattering contributes to the incoherent baseline backscattering signal but not to the EBS peak.

Our experimental setup was described in detail elsewhere.[10,11] In brief, a beam of broadband cw light from a 100 W xenon lamp (Spectra-Physics Oriel) was collimated by using a 4-f lens system (divergence angle ranging from ~0.04° for $L_{sc} = 200\ \mu$m to ~0.30° for $L_{sc} = 35\ \mu$m), polarized, and delivered onto a sample. By changing the aperture size in the 4-f lens system, we varied the spatial coherence length L_{sc} of the incident light from 200 to 35 μm. The value of L_{sc} was confirmed by double-slit interference experiments.[15] The light backscattered by the sample was collected by a sequence of a lens, a linear analyzer (Lambda Research Optics), and an imaging spectrograph (Acton Research). The imaging spectrograph dispersed this light according to its wavelength in the direction perpendicular to the slit and projected it onto the CCD camera (Princeton Instruments). Thus the CCD camera recorded a matrix of scattered intensity as a function of wavelength λ and backscattering angle θ. The linear analyzer was also oriented along the polarization of the incident light, which provided a linear parallel channel. The spectrally resolved EBS signals were normalized $I_{\mathrm{EBS}}(\theta,\lambda)=[I(\theta,\lambda)-I_{\mathrm{Base}}(\lambda)]/I_{\mathrm{Ref}}(\lambda)$, where $I(\theta,\lambda)$ is the total scattered intensity, $I_{\mathrm{Base}}(\lambda)$ is the baseline (incoherent) intensity measured at large backscattering angles ($\theta>3°$), and $I_{\mathrm{Ref}}(\lambda)$ is a reference intensity collected from a reflectance standard (Ocean Optics).

LEBS possesses unique advantageous features compared with conventional EBS. (i) The independent coherence area can be as small as a few tens of micrometers. Thus L_{sc} can be made to be the shortest length scale (except particle sizes) in weakly scattering media (in biological tissue, l_s^* is of the order of a few millimeters). (ii) The finite spatial coherence area ($\sim L_{\mathrm{sc}}^2$) on the sample defines virtually a narrow elongated coherence volume in a large volume of a weakly scattering medium. (iii) LEBS provides statistical information about the optical properties of random media. A single reading averages over multiple independent coherence areas, which reduces the complications of realization averaging. For example, for $L_{\mathrm{sc}}=35\ \mu\mathrm{m}$, the number of independent coherence areas $(D/L_{\mathrm{sc}})^2\approx 7000$, where $D=3$ mm is the diameter of illumination area on the sample. (iv) LEBS allows L_{sc} to be varied to control the dephasing rate externally.

We used discrete random media consisting of aqueous suspensions of polystyrene microspheres (Duke Scientific) of various diameters from 0.89 to 1.5 μm. The dimension of the samples was $\pi\times 25^2\ \mathrm{mm}^2 \times 50$ mm. We varied the scattering mean free path l_s from 3 μm to 800 μm for two selected different values of L_{sc} ($L_{\mathrm{sc}}=110\ \mu\mathrm{m}$ and $L_{\mathrm{sc}}=35\ \mu\mathrm{m}$). The optical scattering properties of the samples were calculated by using Mie theory.[16]

Figure 1 shows representative EBS intensity

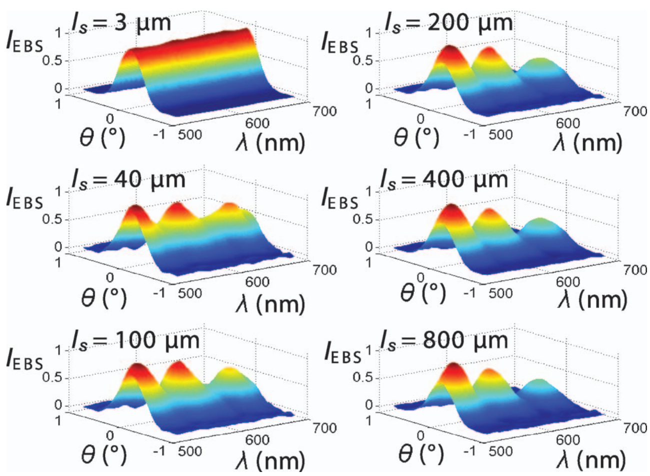

Fig. 1. $I_{\mathrm{EBS}}(\theta,\lambda)$ obtained from the aqueous suspension of microspheres ($d=1.5\ \mu\mathrm{m}$) under low spatial coherence illumination ($L_{\mathrm{sc}}=35\ \mu\mathrm{m}$) for various mean free paths l_s. For $l_s \gg L_{\mathrm{sc}}$, the spectral shape remains unchanged, indicating that it reaches the minimal number of scattering events in EBS (i.e., double scattering).

$I_{\mathrm{Ebs}}(\theta,\lambda)$ from the aqueous suspensions of the microspheres with the diameter $d=1.5\ \mu\mathrm{m}$ (standard deviation = 0.04 μm). We varied l_s from 3 to 800 μm ($g=0.93$ at $\lambda=550$ nm) with the fixed $L_{\mathrm{sc}}=35\ \mu\mathrm{m}$. As l_s increases, the Mie scattering features such as the oscillatory pattern and the slope of the overall decline of intensity with wavelength become obvious and prominent. These spectral features indicate that only a few scattering events give rise to EBS. Increasing l_s reduces the number of particles in the coherence volume that is determined by L_{sc}; hence only lower orders of scattering events contribute to the EBS peak. For example, the spectrum of the sample with $l_s=3\ \mu\mathrm{m}$ resembles that of the diffuse multiple scattering of highly packed media, As l_s increases, the Mie scattering patterns are revealed. Finally, for $l_s \gg L_{\mathrm{sc}}$, the spectral shape remains unchanged, indicating that the parametric condition reaches to the minimal number of scattering events required for EBS.

To explore the observations above quantitatively, we developed a Mie-theory-based double-scattering model, which provides the backscattering spectrum and the angular profile of EBS from double scattering. In EBS, every wave traveling a scattering path has its conjugated time-reversed wave traveling along the identical path in the opposite order, and the EBS peak is generated by the interference of these conjugate waves after emerging from the sample. The radial intensity probability $P(r,\lambda)$ of double scattering can be expressed as

$$P(r,\lambda)=\int_0^\infty\int_0^\infty \frac{\exp[-\mu_a(\sqrt{r^2+(z-z')^2}+z+z')]}{[r^2+(z-z')^2](z'+d)^2} \times\mu_s(\lambda)F(\Theta,\lambda)\mu_s(\lambda)F(\pi-\Theta,\lambda)\mathrm{d}z\mathrm{d}z', \quad (1)$$

where r is the transverse radial distance between two scatterers, z and z' are the vertical distances from the surface to the scatterers, respectively, $\Theta=\tan^{-1}[r/(z-z')]$ is the phase function of single scattering, d is the diameter of the microscophere, μ_a is an attenuation coefficient, and the denominator results from the solid angle of each scattering. μ_a was obtained separately by measuring reflectance intensity for various sample thicknesses and calculating the exponential attenuation length. $F(\Theta)$ and μ_s were calculated by using Mie theory.[16] Then, $I_{\mathrm{EBS}}(\theta,\lambda)$ can be expressed as an integral transform of the radial probability distribution of these paths:[13,14] $I_{\mathrm{EBS}}(q_\perp)=\iint C(r)P(r)\exp(i\boldsymbol{q}_\perp\cdot\boldsymbol{r})\mathrm{d}^2r$, where $\boldsymbol{q}_\perp$ is the projection of the wave vector onto the plane orthogonal to the backward direction, $P(\boldsymbol{r})$ is the probability of the radial intensity distribution of EBS photons with the radial vector $\boldsymbol{r}$ pointing from the first to the last points on a conjugated time-reversed light path ($\boldsymbol{r}$ is perpendicular to the incident light), and $C(r)=|2J_1(r/L_{\mathrm{sc}})/(r/L_{\mathrm{sc}})|$ is the degree of spatial coherence, with J_1 the first-order Bessel function.[15] If a medium is isotropic, the two-dimensional Fourier integral becomes the Fourier transform of $C(r)rP(r)$:

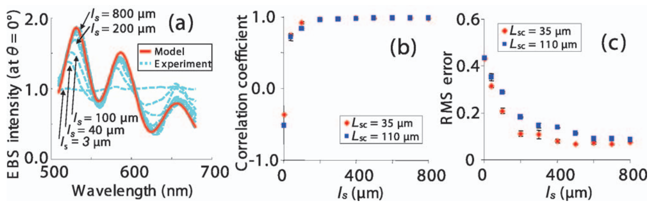

Fig. 2. Accuracy analyses of the double-scattering model of LEBS. (a) Spectra of LEBS in the backward direction. (b) Correlation coefficient. (c) RMS error.

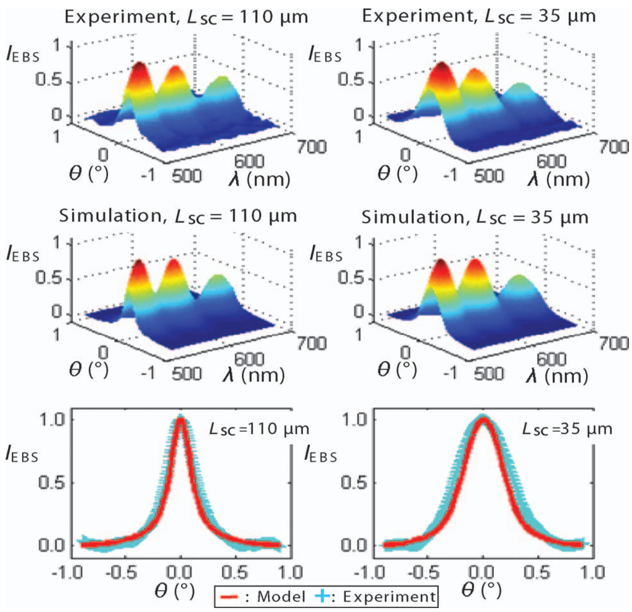

Fig. 3. $I_{\mathrm{EBS}}(\theta,\lambda)$ obtained from the experiment of the aqueous suspension of microspheres ($d=1.5\ \mu$m) and its simulation from the double-scattering model for $L_{\mathrm{sc}}=35$ and 110 μm with $l_s=700\ \mu$m. Bottom, angular profiles of the EBS peaks at $\lambda=532$ nm.

$$I_{\mathrm{EBS}}(\theta) \propto \int_0^{\infty} C(r)rP(r)\exp(i2\pi r\theta/\lambda)\mathrm{d}r, \qquad (2)$$

with $q_\perp = 2\pi\theta/\lambda$. As a result, the width of the LEBS peak is inversely proportional to $C(r)rP(r)$.

Figure 2(a) shows that for l_s greater than a few L_{sc} the spectral shape of $I_{\mathrm{EBS}}(\theta=0°,\lambda)$ approaches the spectrum of the double-scattering model and then remains unchanged for $l_s \gg L_{\mathrm{sc}}$. To quantify the agreement between the model and the experimental results, we used two complimentary measures: the root mean square (RMS) error and the correlation coefficient. The RMS error measures the overall estimation accuracy, while the correlation coefficient measures the capability of the double-scattering model to replicate the oscillation characteristics of the experimental spectra. Figures 2(b) and 2(c) plot the correlation coefficient and the RMS error, respectively, as a function of l_s for $L_{\mathrm{sc}}=35\ \mu$m and $L_{\mathrm{sc}}=110\ \mu$m. In both cases the two measures level off for $l_s > 4L_{\mathrm{sc}}$, thus indicating that the double-scattering model is in excellent agreement with the experimental data.

Figure 3 compares $I_{\mathrm{EBS}}(\theta,\lambda)$ obtained experimentally with the predictions of the double-scattering model. We convoluted the profiles of the LEBS peaks with the angular response of the instrument to take into account the finite point-spread function of the detection system and the incident beam divergence. The double-scattering model is in excellent agreement with experimental data and predicts both the angular and spectral profiles of LEBS. As expected from Eq. (2), the shorter L_{sc} generates the broader LEBS peak as shown in Fig. 3. These results confirm the hypothesis that in the low-coherence regime ($L_{\mathrm{sc}} \ll l_s$) the number of scattering events giving rise to EBS reaches its minimum (i.e., double scattering).

In conclusion, using low-coherence illumination, we were able to isolate double scattering in EBS. This led for the first time to proof of an existing theoretical hypothesis that the minimum number of scattering events needed to generate EBS is double scattering. Our finding that LEBS originates from the time-reversed paths of double scattering in weakly scattering media will facilitate understanding of LEBS signals for tissue diagnosis and characterization, providing a potential method to analyze LEBS signals from biological tissue.

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