Measurement of angular distributions by use of low-coherence interferometry for light-scattering spectroscopy

Adam Wax, Changhuei Yang, Ramachandra R. Dasari, and Michael S. Feld

G. R. Harrison Spectroscopy Laboratory, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139

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We present a novel interferometer for measuring angular distributions of backscattered light. The new system exploits a low-coherence source in a modified Michelson interferometer to provide depth resolution, as in optical coherence tomography, but includes an imaging system that permits the angle of the reference field to be varied in the detector plane by simple translation of an optical element. We employ this system to examine the angular distribution of light scattered by polystyrene microspheres. The measured data indicate that size information can be recovered from angular-scattering distributions and that the coherence length of the source influences the applicability of Mie theory. © 2001 Optical Society of America

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Light-scattering spectroscopy is an established technique that uses the spectrum of backscattered light to infer structural characteristics, such as size and refractive index, of spherical scattering objects.[1] It was demonstrated by Yang *et al.*[2] that structural information can be recovered from a subsurface layer of a scattering medium by use of interferometric light-scattering spectroscopy. In this approach, multiple wavelengths of low-coherence light are used simultaneously in a Michelson interferometer, where the coherence properties of the source are exploited to yield depth resolution, and the multiple wavelengths probe the spectral variation of the scattering properties. This method has great potential for biological application, as it is compatible with optical coherence tomography, an imaging technique based on using a low-coherence source in a Michelson interferometer to obtain depth-resolved images.[3]

The structure of a light-scattering object can also be investigated by examination of its angular-scattering characteristics at a given wavelength. Angle-resolved scattering distributions are conventionally obtained by use of a goniometer[4] or through exploitation of the antenna properties of a heterodyne receiver.[5] Recently an interferometric technique was developed that can measure the optical phase-space distribution of a light field,[6] i.e., its joint position and momentum distribution. This technique has been used to study multiple diffractive scattering by examination of the angular distribution of transmitted coherent light[7] and to study the phase-conjugation properties of enhanced backscattering by measurement of the phase-space distribution of backscattered low-coherence light.[8] However, since this method is based on a Mach–Zehnder interferometer, it cannot be readily adapted as an adjunct to optical coherence tomography, which limits its applicability for biomedical imaging.

We present a means of obtaining light-scattering spectroscopy information by use of a low-coherence source in a Michelson interferometer that avoids the need for multiple wavelengths by measurement of the angular distribution of scattered light. The angle-resolved scattering information is obtained by simple scanning of an optical element and thus can be easily applied as an adjunct to optical coherence tomography, suggesting that the new method will have great potential for biological imaging. We demonstrate that structural information can be inferred by comparison of the measured angular distributions with the predictions of Mie theory. Further, we show that when the optical path of the light within the scatterer exceeds the coherence length of the source, the angular-scattering distributions are no longer described by a monochromatic Mie theory treatment because of the broad bandwidth of the low-coherence light.

The scheme of the low-coherence interferometer used to measure angular-scattering distributions is shown in Fig. 1. The light source is a superluminescent diode (SLD) from EG&G with a center wavelength of 845 nm and a FWHM bandwidth of 22 nm, resulting in a coherence length at $l_c = 2 \ln 2/\pi \times \lambda^2/\Delta\lambda = 14.3\ \mu\text{m}$. As in conventional low-coherence interferometry, the light from the source is split by a beam splitter (BS) into a reference beam and an input beam to the sample. The reference beam is reflected by a mirror (M) and recombined at the beam splitter with light reflected by the sample. The mixed fields generate an interference pattern, provided that the two optical path lengths are matched to within the coherence length of the source. To separate the interference signal from the dc background and low-frequency noise, we generate a heterodyne signal by translating the sample at a constant velocity to generate a Doppler shift.

The interferometer relies on four identical achromatic imaging lenses (L1–L4) to permit the measurement of angular-scattering distributions. Lenses L1 and L2 are arranged to form a $4f$ imaging system. In such a system the distance from the input plane (P) to the first lens (L1) is equal to the focal length of the lens, $f = 10$ cm. The distance between lenses L1 and L2 is twice the focal length, $2f$, and the output plane is a distance f beyond lens L2. This arrangement reproduces the phase and amplitude of the field at the input plane (plane P) at the output plane, in this case, reference mirror M. Similarly, the phase and amplitude of the field at plane P are reproduced at the

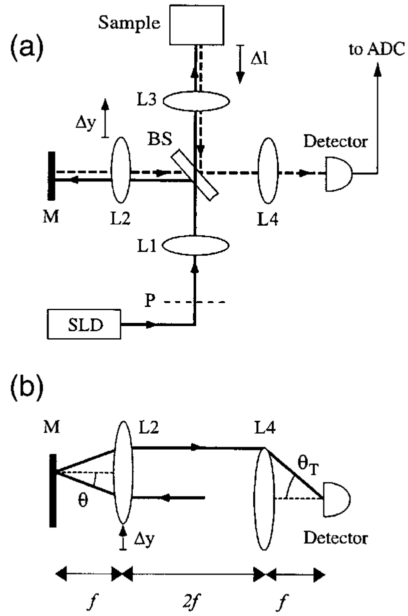

Fig. 1. (a) Schematic of the interferometer system. The photocurrent is digitized by an analog-to-digital converter (ADC) and recorded with a PC. See text for other definitions. (b) Ray-trace diagram showing the effect of translating lens L2 by a distance Δy, resulting in the reference field's crossing the detector at an angle θ_T.

focal plane of lens L3. This arrangement permits selection of both the reference field and the field used to probe the sample simply by insertion of a lens at the output of the superluminescent diode to shape the beam to the desired size and angular divergence at plane P.

Identical $4f$ imaging systems, constituted by lenses L2 and L4 (reference) and L3 and L4 (signal), are also used to reproduce the phase and amplitude of the scattered and the reference fields in the plane of the detector. Analysis of the imaging system by use of Fourier optics shows that scanning lens L2 a distance Δy perpendicular to the beam path reproduces the reference field in the plane of the detector with its angle of propagation changed as $\theta_T = 2\Delta y/f$ but its position unchanged.[9] The path length of the light through the system remains unchanged as the lens is translated. Figure 1(b) illustrates the effects of transversely scanning one lens in the imaging system by use of ray traces. In our experiments the maximum clear aperture limits the angular scans to a range of ± 120 mrad. The angular resolution is given by the diffraction angle of the 1-mm-diameter collimated beam at plane P, $\theta_{\mathrm{res}} = 0.7$ mrad.

The experimental scheme permits the center angle of propagation of the reference field to be varied, yet leaves its position fixed in the detector plane for probing the angular distribution of a signal field. To illustrate the capabilities of this system we examine the angular distribution of low-coherence light backscattered by turbid media consisting of polystyrene beads suspended in water (0.5% by volume). Figure 2 shows typical data for the angular variation of backscattered light as a function of the displacement of the sample. The data for any given angle show an initial rapid attenuation followed by a transition to a regime of slower attenuation. We fit the rapid attenuation by an exponential decay, $A \exp(-aL)$, where L is the optical path length ($L = 2\,\Delta l/1.33$) in the medium ($n = 1.33$) and A and a are fitting parameters that vary with the detection angle.

At very short photon path delays, $L \rightarrow 0$, we expect to measure the angular distribution of singly scattered light, as predicted by Mie theory. This information is contained in the amplitude of the backscattered signal from the superficial layer, which we obtain from fitting parameter A. Figures 3(a)–3(c) show the fitted value of A as a function of angle for 1.9-, 4.6-, and 6.1-μm-diameter microspheres, compared with the Mie theory prediction for heterodyne detection of scattered light. One can see that for the smaller sizes (1.9 and 4.6 μm) the theory agrees well with the data, but for the 6.1-μm microspheres, only the central lobe is correctly predicted by Mie theory.

This discrepancy can be easily understood. Mie theory models the interference between coherent monochromatic light that is reflected from the front

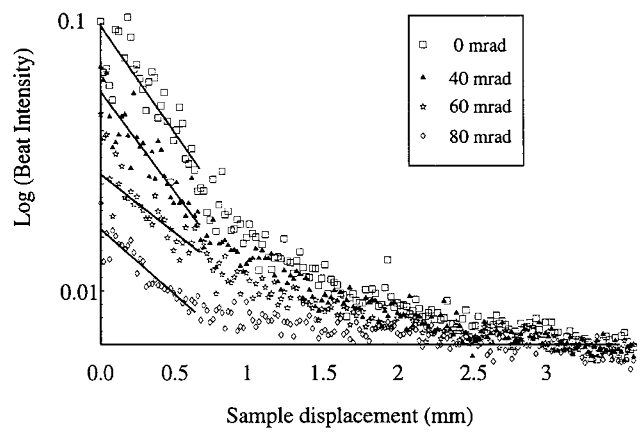

Fig. 2. Heterodyne beat intensity as a function of sample displacement for selected scattering angles (points, data; lines, exponential fits). The sample used to obtain these data was 6.1-μm polystyrene microspheres suspended in water.

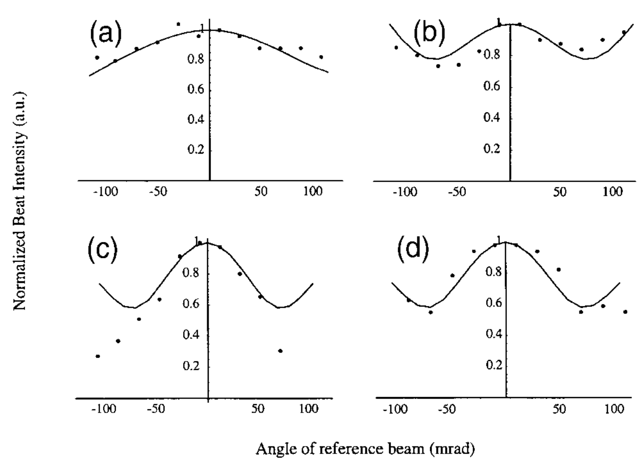

Fig. 3. Angular distributions for the fitted A parameter for media consisting of (a) 1.9-, (b) 4.6-, and (c) 6.1-μm-diameter microspheres. Increasing the coherence length of the source alters the angular scattering distribution (d) of the 6.1-μm microspheres.

and back surfaces of the sphere. In this experiment the two components do not interfere, as the difference in optical paths is greater than the coherence length of the light source. The optical path length of light reflected from the back surface of a 6.1-μm polystyrene bead exceeds that of light reflected from the front by $\Delta = 2 \times n \times D = 2 \times 1.59 \times 6.1\ \mu\text{m} = 19.4\ \mu\text{m}$, where n is the refractive index of the microspheres and D is their diameter. This path length is greater than the coherence length of the light (14.3 μm).

We can demonstrate the effects of coherence length on angular-scattering distributions by filtering the low-coherence light to produce a longer coherence length. By use of a filter with a 9.39-nm bandwidth, centered at 852.7 nm, the coherence length of the light is increased to 31.8 μm. The angular-scattering distribution obtained with filtered light, shown in Fig. 3(d), agrees well with the predictions of Mie theory, as the scattering from the front and back surfaces is coherent.

The variation in the rate of the initial decay (a parameter) can be viewed as an extension of the angular variation of the A parameter. The amplitudes at each angle can decay either faster or slower relative to their neighbors, as the features of the angular distribution are washed out owing to multiple scattering. Detailed study of these decay rates should open interesting possibilities for further investigations of light propagation in multiple-scattering media.

There are two key consequences of the data presented here for interferometric light-scattering spectroscopy. First, the use of low-coherence interferometry to obtain depth resolution also necessarily limits the applicability of Mie theory. The sensitivity of low-coherence interferometry to a limited range of spatial frequencies is already known,[10,11] but the implications for interferometric light-scattering spectroscopy are made apparent by the data presented here. To extract structural information from scattering distributions requires that the light be sufficiently coherent for comparison with Mie theory.

An additional consequence of the data presented here is that, since the Mie solution is recovered for only the superficial layer, the effects of multiple scattering must also be accounted for if we are to infer structure in subsurface layers. Multiple small-angle scattering is known to attenuate more slowly than ballistic light[7] and can result in stronger effective probe fields than expected.[12] Since multiple scattering also broadens the angular distribution of the probe field, the detected angular distribution of scattering originating from subsurface layers is smoothed through convolution with the angular width of the broadened probe field. A more sophisticated analysis is needed to describe the effects of multiple scattering on the measured angular-scattering distributions.

From the data of Fig. 3, taken with $f/4$ optics, using 845-nm center wavelength light and 10% uncertainty in the fitting parameters, one can clearly distinguish particle sizes of a few micrometers. With larger-aperture lenses, shorter-wavelength light, and less uncertainty in the fitting through a better signal-to-noise ratio, submicrometer-size determination should be achievable. Another means of improving accuracy and extending the range of sizes is to employ multiple wavelengths simultaneously. Properly accounting for the effects of coherence length and multiple scattering will allow recovery of structural information from subsurface layers by use of this technique.

In conclusion, we have demonstrated a system for obtaining depth-resolved angular-scattering distributions based on a modified Michelson interferometer with a low-coherence light source. The measured angular distributions provide information that can be used to determine the size of scattering objects, as in light-scattering spectroscopy. Structural information is important for assessing the health of biological tissue; in particular, the size of cell nuclei can indicate dysplasia, a precancerous state.[1] The experimental method presented here can be easily adopted as an adjunct for biomedical imaging systems such as optical coherence tomography that employ similar interferometers. We applied this system to obtain angular distributions of light scattered by ideal media. Using these data, we were able to identify limitations on the applicability of Mie theory for inferring the structure of scattering objects as a result of short coherence lengths.

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