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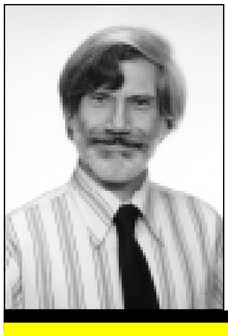
WINTER 1997/98

Seeing Through Foggy Media with Phase-Modulated Light



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Trinity College

Anyone who has ever held a glass of milk up to the light realises how difficult it is to see through a turbid or cloudy medium. The problem is not that the milk appreciably absorbs light (like India ink, for example). Rather, the fat globules in the milk scatter light numerous times so that there is virtually no correlation in direction between entering and emerging light rays. To see an object clearly through a surrounding medium, the viewer must receive light that has passed directly from the object to his eyes or instruments without diffusive scattering.

Although few people need to peer through a glass of milk, there are many naturally occuring turbid media (fog, clouds, aerosols, seawater, skin, internal tissue, blood...) which are critical to a wide range of scientific, technological, and medical applications. For example, one outstanding problem of clinical medicine is the noninvasive detection of subcutaneous malignancies without the use of tissue-damaging ionizing radiation. At an altogether different scale of operation, remote monitoring of soil conditions and the health of arboreal canopies often require remote sensing through a turbid atmosphere. Indeed, the problem of visual penetration of light-scattering media is of such pressing importance that several international symposia have been devoted to it over the past year alone.

One approach which I have developed entails the use of phase-modulated light to delineate targets embedded in optically dense turbid media and entirely hidden from direct viewing by ambient illumination.[1,2] The guiding principle of these experiments, for which the Hinds PEM-90 is a seminal component, is to detect nearly instantaneously the difference in scattering of two orthogonal states of linear or circular polarization. If

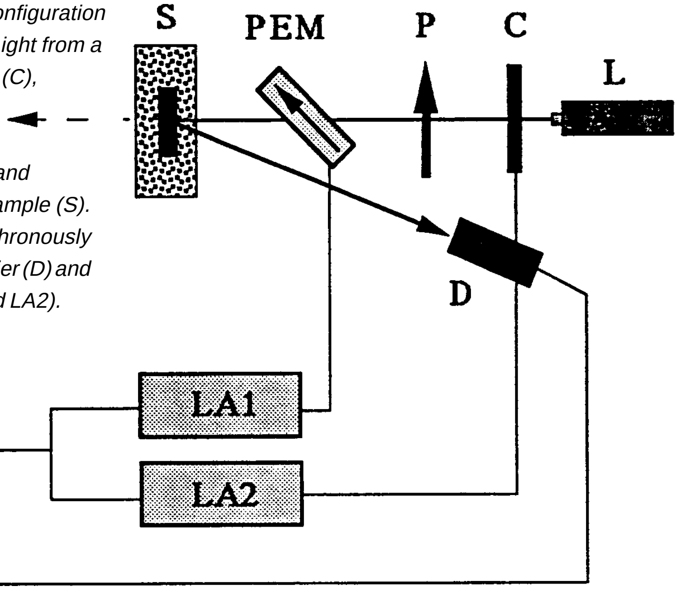

Figure 1: Experimental configuration for polarimetric imaging. Light from a laser (L) passes a chopper (C), polariser (P), and the PEM; it is scattered by both the turbid medium and embedded target of the sample (S). The scattered light is synchronously detected by a photomultiplier (D) and lock-in amplifiers (LA1 and LA2).

ABOUT THE SCIENTIST

Currently Professor of Physics at Trinity College (Hartford CT), Dr. Silverman has held a number of distinguished appointments at universities throughout the world, including the Joliot Chair of Physics at the Ecole Superieure de Physique et Chemie in Paris, the institution at which the earliest version photoelastic modulator was invented.

Physics has been a lifelong passion, although Silverman became a professional physicist in a somewhat circuitous way, having first undertaken research in medicine and microbiology, and then later in organic and physical chemistry. He earned his Ph.D. in physics from Harvard University. "I do not in the least regret the time that I spent engaged in other fields," he says, "for these experiences have enriched my knowledge of the behavior and properties of matter and helped me become overall a more capable scientist."

"Nominally an atomic physicist, I have had little inclination during my career to become a specialist, but rather have followed wherever my curiosity led.[1] Thus, I have been engaged in both 'serious' research (of a kind likely to attract funding from research agencies) as well as purely 'entertaining' research like the study of counter-intuitive physics toys and gadgets." Such gadgets include the "vortex tube" (a kind of Maxwell Demon with no moving parts that blows hot air out of one

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the linear or circular intensity difference (LID or CID) of light returned by the embedded object differs from that scattered by the surrounding turbid medium, then scanning a light source across the sample will yield an intensity profile that varies in correspondence with structural features of the target. Figure 1 shows a schematic diagram of the configuration for one set of experiments.

Light from a helium-neon laser (λ = 544 nm) is mechanically chopped, polarized vertically (with respect to the optical bench), and phase-modulated with a Hinds PEM. After scattering from a turbid sample consisting of an optically dense suspension of micron-sized latex particles, the light is synchronously detected by means of two lock-in amplifiers that yield the dc photocurrent I(0) (effectively the signal at the low chopping frequency), the component I(f) at the modulation frequency f ~ 50 kHz, and the component I(2f) at the first harmonic. Analysis of the scattering configuration shows that the signal I(f) is proportional to the CID

$$I(f) = KJ_1(\varphi^o_m)(\mathcal{I}_{LCP}-\mathcal{I}_{RCP}) \qquad (1a)$$

(where $\mathcal{I}_{LCP}$ and $\mathcal{I}_{RCP}$ are the light fluxes corresponding to left and right circular polarizations), and the signal I(2f) is proportional to the LID

$$I(2f) = KJ_2(\varphi^o_m)(\mathcal{I}_{\sigma}-\mathcal{I}_{\pi}) \qquad (1b)$$

(in which linear polarizations σ, π are respectively perpendicular to, and parallel to, the scattering plane defined by the incident and scattering wave vectors). In the above equations, K is a common instrumental factor and $J_1(\varphi^o_m)$, $J_2(\varphi^o_m)$ are Bessel functions of the modulation amplitude φ^o_m= 2.405 radians. This choice of modulation amplitude, equal to the first zero of the Bessel function J_0, strikes an excellent compromise between optimization of the signal and simplification of the theoretical analysis.

Why should polarimetric imaging work? After all, multiple scattering not only randomizes the direction of light propagation, but also depolarizes light to an extent dependent on the number of scattering interactions. Depending on wavelength and particle size, nearly complete depolarization can result after roughly 10 collisions – and yet polarimetric imaging has rendered objects visible in media with optical densities well in excess of 100. The optical density δ, defined as the product of the number of particles per volume (N), the collision cross section (σ), and sample thickness (ℓ), is effectively the mean number of collisions undergone by a photon in the medium. Nevertheless, in the passage of light through a turbid medium, there are always photons that have suffered only a few collisions rather than the (much larger) average number. The light that is scattered least is depolarized least and, as pointed out above, constitute the rays that give sharp images. Moreover, since multiple light scattering from suspended particles is often much less sensitive to polarization than is scattering from macroscopic objects, the diffusive contribution from the particles tends to cancel in the LID and CID, thereby leading to enhanced visibility.

An example of polarimetric imaging with backscattered light in shown in Figure 2 for the case of a target consisting of an opaque mask with periodic slots of width ~2 mm and separation ~3 mm superposed on a reflective metallic base. In the companion frame one sees the results of a horizontal pointwise scan of photocurrents I(0) and I(2f) when the target was immersed in the center of a 1 cm thick suspension of 1 µm diameter particles with an optical density δ ~ 125. The peaks of I(0) correspond to the centers of the slots where the reflectance is greatest. By contrast, the I(2f) scan attains maximum values (both positive and negative) near the maximum slopes of the I(0) scan – that is, at the edges of the slots. Thus the LID (and the CID as well) of a target with sharp edges is particularly sensitive to the location of these boundaries.

It is worth noting that the dc signal I(0), which shows target structure with a visibility of ~13%, does *not* correspond to what one sees by direct viewing in ambient lighting. To the unaided eye the sample appears milky white and reveals no presence at all of the embedded object. The I(2f) scan, however, renders the topography of the object with 63% contrast.

Another example of polarimetric imaging is shown in Figure 3 for the case of a target consisting of two orthogonally oriented segments of grooves of width ≤1 µm scratched into a metallic surface. In contrast to the preceding example, line width and spacing are now much smaller than the diameter of the probe beam and comparable in scale to the wavelength of the light. In the companion frame are shown the dc and I(2f) scans when the object is immersed

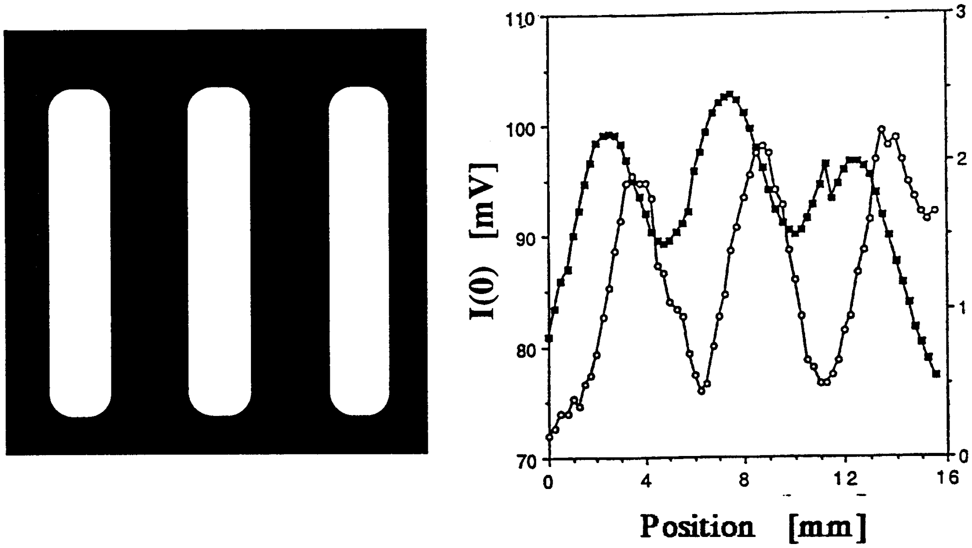

Figure 2: [Left] Slotted target and [Right] horizontal scans of I(0) and I(2f) for an optically dense (2.8 x 10^{-3} g/cm^3) suspension of 1 µm diameter latex particles.

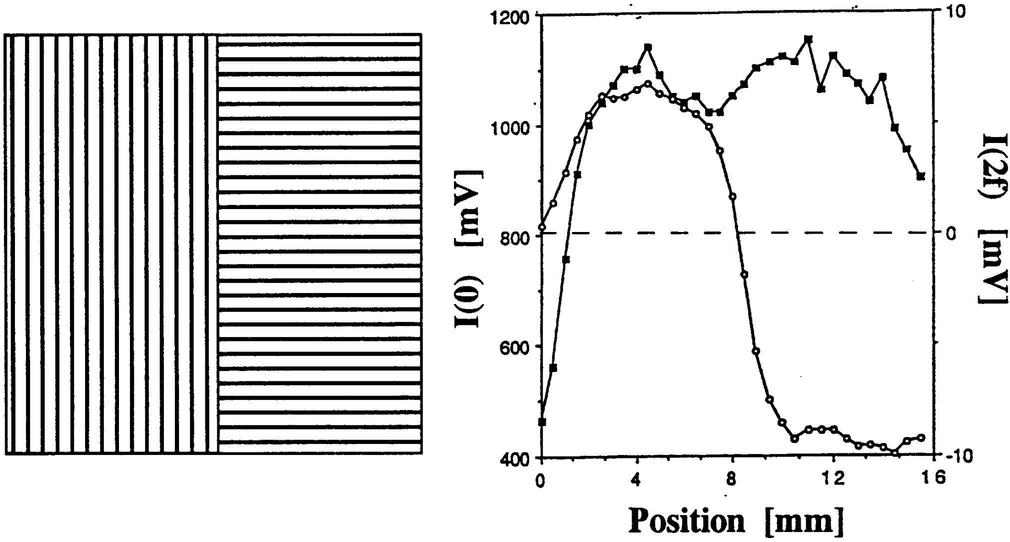

Figure 3: [Left] Grooved target and [Right] horizontal scans of I(0) and I(2f) for an optically dense (1.4×10^{-3} g/cm^3) suspension of 1 µm diameter latex particles.

in the same kind of suspension as before (but with one half the optical density). The eye again sees nothing but a white opacity. In this case the dc scan, which is essentially flat across the object and drops off at the edges, also shows no structural features beyond a small dip where the two segments are joined. The I(2f) scan, however, resembles a square pulse waveform with a positive LID on the left half of the figure (0-8 mm) and a negative LID on the right half (8-16 mm). This is precisely what one would expect [see Eq. (1b)] for a conducting grating with grooves oriented vertically on the left half (thereby backscattering a preponderance of σ-polarized light) and horizontally on the right half (leading to a preponderance of π-polarized light).

The preceding experiments, along with others carried out in my laboratory, help define the conditions under which polarimetric imaging within turbid media can be implemented successfully.[3] They illustrate, for example, the significance of particle size (as well as concentration) as gauged by the size parameter $\zeta = 2\pi na/\lambda$, where n is the relative refractive index of the medium and a is a characteristic size parameter (e.g. the radius of a spherical particle). Very small particles ($\zeta \ll 1$) give rise to a radiation distribution (for single scattering) symmetric about the scattering angle $\theta = \pi/2$ radians. Large particles ($\zeta > 1$), however, give rise to a forward-peaked angular distribution. The asymmetry parameter $g \equiv \langle\cos\theta\rangle$, where the brackets signify an angular average of the scattered light intensity, varies between zero for small particles and unity for large ones. For example, $g \sim 0.93$ for 1 µm diameter particles scattering 0.544 µm light (green line of the HeNe laser). Our experiments show that the transport optical density $\delta^* = \delta(1-g)$, which takes account of the anisotropy of scattering, is a more significant indicator than δ of the upper limit of tubidity beyond which light, for all practical purposes, is completely depolarized. In the turbid media leading to Figures 2 and 3, the high value of g leads to a δ^* that is just 7% of δ.

In addition to the detection and imaging of objects immersed in turbid media, my research also focuses on the optics and electrodynamics of chiral systems, i.e. materials containing molecules that cannot be superposed on their mirror images. Chiral (or left-right) asymmetry has profound consequences in both the physical and biological sciences. It is, for example, the hallmark of the living state; all sugars and amino acids of biological origin display a particular handedness, rather than a 50-50 mix of both isomeric forms.

Early in the 19th century the French physicist Augustin Fresnel was the first to realize that LCP and RCP light have different phase velocities in a chiral medium and thence to separate an unpolarized light beam into two circularly polarized components by differential refraction through a series of chiral prisms. Nearly 175 years later my colleagues and I were the first to observe the companion phenomenon of differential reflection of LCP and RCP light from a naturally optically active material.[4] In this research, which opened up new possibilities for investigating chiral materials, the PEM was again an indispensable component, for it provided the means to measure the differential circular reflection in effectively a single step. So small is the difference in LCP and RCP refractive indices (a few parts in ten million in our experiments), that one could never hope to observe the difference in specular reflection of separate circularly polarized beams.

It was, in fact, the extension of these chiral studies on homogeneous materials into the domain of turbid media that led me to pursue methods of polarimetric imaging. Motivated in part by the challenge of finding a noninvasive way to monitor blood glucose levels (a procedure critical to patients with diabetes), my laboratory undertook to measure optical rotatory power in optically dense chiral media. Using a Hinds PEM in a configuration similar to that of Figure 1, but with a rotatable linear polarizer and precision angular micrometer before the photomultiplier detector, we determined the optical rotation for different concentrations of aqueous glucose solution and achiral scatterers by nulling the photocurrent I(2f).[5] The results were highly surprising.

We expected, in accordance with prevailing views, that multiple scattering would randomize the polarization of the incident probe beam and lead to vanishingly small optical rotations for highly turbid media. Instead we found relatively large optical rotations – in some cases considerably *larger* than that of the corresponding particle-free, transparent, homogeneous glucose solution. The explanation of this unusual outcome is attributable in part to two effects: (a) multiple scattering lengthens the total optical pathlength through the medium, and (b) for a given number of collisional interactions, circularly polarized light is depolarized to a lesser extent than is linearly polarized light.

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Seeing Through Foggy Media

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The observation of optical rotation of backscattered light was especially interesting, for it indicated that photons had in effect freely (i.e. without scattering) traversed the distance from the interior of the turbid medium to the photodetector. This is, in fact, what one would have expected for large particles scattering predominantly in the forward direction. Had the light been scattered backward and forward multiple times before reaching the detector, the optical rotation would have been largely randomized. The light-scattering conditions revealed by our studies of optical activity in turbid chiral media are precisely those that are conducive to polarimetric imaging by backscattering. This is a felicitous outcome, for the backscattering configuration is often the most convenient for materials analysis and medical diagnostics.

Experiments like those described above show the feasibility of using phase-modulated light for physico-chemical analysis and object delineation in well-defined optically dense media. There remains still the task of ascertaining how well such methods work as practical tools to investigate naturally occuring turbid media of environmental and biomedical significance. If past experience is any guide, nature has not exhausted her store of intriguing problems surrounding the behavior of light and matter.

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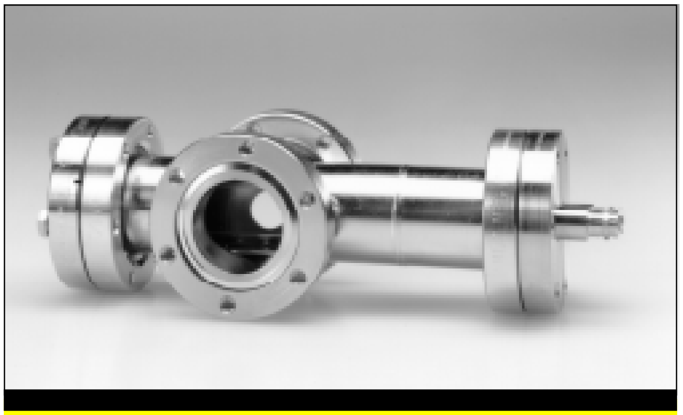

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Vacuum Chamber for the I/CF50 PEM

The PEM-90 photoelastic modulator is well suited for experiments that measure circular dichroism (CD), the measurement of the differential absorption between left and right circularly polarized light components. However, because of the absorption of ultraviolet radiation in air, a vacuum system is needed to make CD measurements in the ultraviolet spectral range below about 180 nm. In the past we have worked closely with our UV CD customers to design custom vacuum chambers to house the PEM’s optical head. However, following a new phase of product development, we now offer a standard vacuum chamber enclosure.

Our standard vacuum chamber is constructed from remelt 304 stainless steel. It is a four way cross configuration which uses 2 3/4” O. D. flanges with 1 3/8” I. D. tubes. This is the minimum size that will accommodate models I/CF50 and I/LF50 modulators. Inside the cross chamber, a specially designed tray (patent pending) supports the optical assembly so that its position is secure and normal to the light beam.

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About the Scientist *(from page 1)*

end and cold air out the other) and the Voice of the Dragon (a rotating tube that generates an eerie and puzzling spectrum of sounds). "Ironically – or perhaps not – it is the latter category of research that often presents some of the most difficult and challenging problems," Silverman adds.

One subject that has long held his attention is that of quantum interference – those curious, nonintuitive processes for which no imaginable classical mechanisms can be given.[2] During the 1980s he served as Visiting Chief Researcher at the Hitachi Advanced Research Laboratory (then near Tokyo) to develop new types of electron interferometry experiments partly for practical applications, but principally to probe hitherto untested predictions of quantum mechanics. He has also been fascinated by light, studying problems spanning the full range of physical optics including reflection, refraction, diffraction, interference, polarization, and light scatterings.[3] Recent work, apart from the studies of chiral media discussed briefly in the PEM article, include the investigation of methods of lensless imaging and optical information processing.

"Most of the physics I know I did not learn in school," Silverman says, "but acquired through the process of seeking answers to questions that interested me. That is also the way young children acquire knowledge about their world. As a teacher, as well as a research scientist, I believe that any educational system that does not allow for self-directed inquiry within its methodology cannot enlist effectively the innate drive of human beings to learn, and may well serve to suppress that drive."

Accordingly, in his college and university level classes, Silverman tries to stimulate students by engaging them in independent project work. "I have written and lectured extensively about the motivations and implementation of 'Self-Directed Learning' at all levels of education.[4] At home, my wife and I are the principal teachers of our own children – a serious responsibility we have undertaken from their elementary school years through high school." He concludes, "Teaching our own children has been a challenging but rewarding experience-and I have learned at least as much from them as they have from me."

NOTES

1 Silverman provides a nontechnical account of some of the diverse problems he has studied over the past 30 years in a recent book, *And Yet It Moves: Strange Systems and Subtle Questions in Physics* (Cambridge Univ. Press, 1993).

2 M.P. Silverman, *More Than One Mystery: Explorations in Quantum Interference* (Springer, 1995).

3 Silverman's forthcoming book, *Waves and Grains: Reflections on Light and Learning* (Princeton Univ. Press, 1998), describes his work in optics.

4 M.P. Silverman, "Self-Directed Learning: A Heretical Experiment in Teaching Physics," *American Journal of Physics* **63** (1995) 495-508.

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