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Dedicated to

Prof Kehar Singh

Formerly Professor of Physics

at IIT Delhi

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Light Scattering by Turbid Media

M R Shenoy* and Kalpak Gupta
Department of Physics, Indian Institute of Technology Delhi, New Delhi – 110 016

This article is dedicated to Prof Kehar Singh for his significant contributions to Optics and Photonics

Study of scattered light has emerged as an important and practical method of analysing a turbid medium in a fast and non-invasive manner. From light scattering measurements, the scattering parameters of the turbid medium can be estimated, which in turn depend on the intrinsic properties of the scatterers. Measurements of multiple physical quantities such as transmitted light, reflected light and scattered light at different angles lead to a better estimation of the scattering parameters. Using the scattering theory and simulations such as Monte-Carlo technique, in conjunction with experiments, leads to substantial reduction in the number of measurements required, and help in optimizing efficient and compact devices for practical use. There is also scope for studies on mixtures of turbid media, and the effect of various changes in the ambience, in specific applications. In this paper, we first review the basics of light scattering from turbid media, and briefly discuss the methodologies to simulate and characterize a turbid medium. We then detail some of our recent work on estimation of the scattering parameters of a turbid medium, including the use of fiber-optic probes as turbidity sensors, with potential applications in remote sensing and telemetry.

Keywords: Light scattering, Turbid media, Optical properties, Monte-Carlo simulation

1 Introduction

Scattering of light is a phenomenon that is often observed in nature; scattering is responsible for the blue colour of sky and the white colour of clouds, and even our vision is primarily due to light scattered from various objects. Light is said to 'scatter' when it encounters an object in its path, like a particle in a homogeneous medium (Fig 1). The particles interact with the light, and re-radiate it in various directions; the amount of light scattered, and the direction of scattering, depend on the physical properties of the particles such as shape, size, and refractive index, and also on the refractive index of the surrounding medium [1,2]. For example, if the refractive index of the medium is complex, then some of the light is also absorbed. A medium with suspended particulate matter, wherein the particles are distributed uniformly, is referred to as a *turbid medium*, and it is broadly characterized by the parameter 'turbidity'. In light scattering studies, the scattered light is analysed to obtain information about the scatterer, which is often called the *inverse problem* [3,4]. If light is scattered by multiple particles, then the scattering mechanism becomes more complicated, but it is still possible to study such a system and extract useful information, such as the concentration and size distribution of the particles [5-7]. Hence, light scattering has emerged as an ubiquitous method for probing a system of particles in a non-invasive manner. Some of the important applications of light scattering are: monitoring turbidity of waste water and potable water [8,9], characterization of biological tissues [10], and determination of turbidity of liquids in chemical processes [11]. In the case of potable water, it is extremely important to monitor the turbidity. Although pathogens or dissolved impurities make it contaminated even if there is no particulate matter, level of turbidity above a certain standard is a definite indication that the water

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Corresponding author
e-mail: mrshenoy@physics.iitd.ac.in (M R Shenoy)

is unfit for drinking, which can be detected using the scattered light. Light scattering techniques can be used to determine the presence of particulate matter even when the liquid looks clear to the naked eye; therefore, it arises as a very sensitive and reliable method for detection of turbidity.

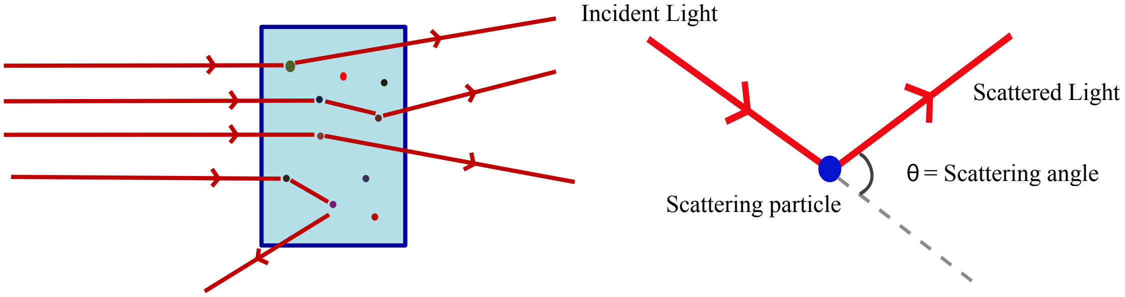

Fig 1. Schematic illustration of light scattering by particles in a turbid medium.

The mechanism of light scattering is governed by the laws of electromagnetism. Given the particle size, refractive index, etc., the properties of scattered light (intensity, polarization, and direction) can be determined from the Maxwell's equations, by applying appropriate boundary conditions. If the particle size is much smaller than the wavelength of light, then the Rayleigh scattering theory [12] can be used. The Rayleigh scattering theory is an approximation, and is valid when the size of the scattering particle is much smaller than the wavelength of light; the particle can be assumed to be a dipole oscillating due to the electromagnetic field, and the scattered light is an outcome of the oscillating dipole. The particles giving rise to turbidity usually have sizes comparable to or larger than the wavelength of light, and the Maxwell's equations have to be solved using analytical or numerical techniques. For particles with spherical shape, Mie theory [1] gives analytical solutions in terms of infinite series of spherical harmonics.

2. Scattering parameters of a turbid medium

A turbid medium consists of many suspended particles which scatter the light incident on them, giving the medium a hazy or cloudy appearance. As the profile of the scattered light depends on the properties of the scatterers, measurements on the scattered light can be used to extract information about the turbid medium.

The propagation of light in a turbid medium can be described using various scattering parameters, which in turn depend on the properties of the scattering particles in the ambience. Some of the commonly used scattering parameters are [1,12-14] —

- *Scattering Coefficient* (μ_s): The scattering coefficient μ_s is the probability of light being scattered by a particle per unit infinitesimal length of the medium.
- *Absorption Coefficient* (μ_a): If the medium is absorbing, there is also a probability of light being absorbed during the light-matter interaction. Similar to the scattering coefficient, the absorption coefficient is the probability of light being absorbed by a particle per unit infinitesimal length of the medium.
- *Phase Function* ($p(\theta)$): It describes the angular distribution of the light scattered from a single particle in the medium; $p(\theta)d\theta$ is the probability of light being scattered between angles θ and $\theta + d\theta$.
- *Total Interaction Coefficient* (μ_t): It is defined as the probability of light interacting with a particle per unit infinitesimal length of the medium. The reciprocal of μ_t gives the mean free path of the photons in the medium. It can also be defined as the total cross-section per unit volume of the medium. The

total interaction coefficient (or interaction coefficient) is equal to the sum of the scattering coefficient μ_s and the absorption coefficient μ_a, i.e.

$$\mu_t = \mu_s + \mu_a \tag{1}$$

- *Anisotropy parameter* (g): The actual form of the phase function $p(\theta)$ is often complicated and is not exactly known for a random particle shape. The anisotropy parameter g can be used as a measure of the angular distribution of scattered light in such cases. It is defined by the average of cosine of all the scattering angles due to the light-particle interactions in the medium.

  $$g = \langle \cos\theta \rangle \tag{2}$$

  The anisotropy parameter g always lies within the range −1 to 1. The two extreme values correspond to the cases of complete backward and forward scattering, respectively; if the scattering is isotropic, g is equal to 0.

- *Reduced Scattering Coefficient* (μ_s'): It is defined as $\mu_s' = \mu_s\,(1- g)$. It combines the effect of scattering coefficient and the average scattering angle. Determination of μ_s' is useful to get some information about the scattering system when μ_s and g cannot be independently determined.

Determination of the scattering parameters is essential to characterize a turbid medium. For example, turbidity less than 5 Nephelometric Turbidity Units (NTU, a standard defined unit) may not be distinguished with the naked eye. However, the interaction coefficient can be measured and used to estimate the turbidity even at lower particle concentrations [8].

3 Simulation of light propagation in a turbid medium

If the particles are not spherical, the analysis becomes complicated, and the solution has to be obtained using numerical methods, such as finite element method (FEM), the adding-doubling method [14], and the T-Matrix method [15]. If the particle size is very large compared to the wavelength of light, then geometric ray tracing methods can also give good results. This reduces the complexity of the problem, but this method is not accurate if the ratio of particle size to wavelength is less than one or two orders of magnitude. When the number of scattering particles is large, the total scattered output can be averaged over the scattered output of each particle, depending on the distribution of particle shapes, orientation and sizes.

The most common way of simulating a random scattering system is to use a model based on Monte-Carlo method [16-19], which is considered to be a 'gold standard' [20] when simulating light transport in a turbid medium; in practice it is often computationally fast as well as accurate when compared to other numerical methods. In a typical Monte-Carlo simulation [16,21], the propagation of light is modelled as propagation of photon packets, with the step size s_i between each interaction site, determined as

$$s_i = -\frac{\ln(\xi)}{\mu_t} \tag{3}$$

A large number of photon packets are launched into the turbid medium, the packets propagate according to the medium parameters and a random variable ξ, which takes into account the stochastic nature of the process (Fig 2). After each interaction, the coordinates of the photon packet are updated depending on the step size and the scattering angle. The scattering angle after each interaction is determined using a suitable phase function, such as the Henyey-Greenstein phase function [16], the Reynolds-McCormick function [22], or the Mie phase function [21]. Propagation of the photon packet is terminated when it is detected (i.e. collected at the detector), or when it goes out of the system boundary such that it cannot reach the detector, and then a new photon packet is launched. After all the packets have been propagated, the total number of packets which reach the detector area is considered to be equivalent to the fractional power scattered, which represents the measured power at the detector.

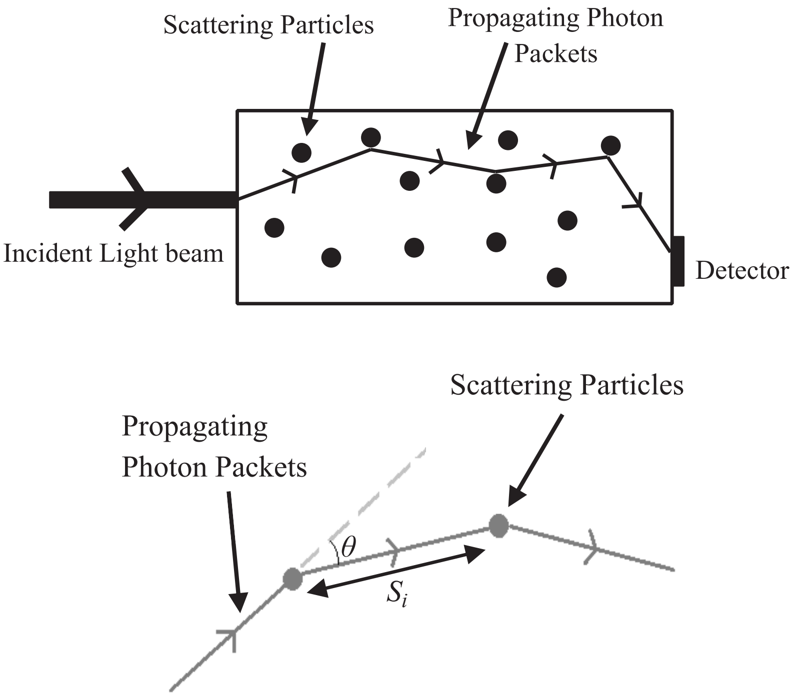

Fig 2. Propagation of photon packets in turbid medium.

4 Characterization of turbid medium by measurements on the scattered light

The scattering parameters or particle properties of a turbid medium are obtained from experimentally measured quantities like reflected light, collimated transmission, etc., depending on the experimental setup and methodology used [17,23-25]. The experimental techniques are accompanied by theoretical studies of the system, using scattering theories and various simulation models [1,2,16,26,27], which help in extracting the required parameters from the measured data. The simulations or theoretical models are also used to optimize the measurement system and verify the experimental results for test solutions. In some cases, numerical simulation or theoretical analysis is used in conjunction with experimental methods to find the results, either in the form of (empirical) formulae [10] or relevant graphs [13,28]. For example, the experimental data can be fitted by linear regression to obtain a phase function and the anisotropy parameter [17,29,30], or the data can be collected over a period of time to find the results [31]. Multiple experimental readings can also be used to obtain various scattering parameters via neural networking [32]. It is also possible to use a smaller set of data to obtain the simulation results over a wide range of parameters [18,33]. Another method of determining the scattering parameters is to plot calibration curves with known solutions and then use the results to estimate the scattering parameters of unknown samples [8,24,34]; however, the drawbacks of this method are that the range or resolution of the results is narrow, and the results are not valid if some new particle (not experimented with before) is present in the unknown sample.

Many times, the measurement of angular spectra is not possible, and hence there are several methods which rely on the transmitted or reflected light for determination of scattering parameters. The transmitted and reflected light mostly depend on the concentration of particles in the media and can be a good measure of the turbidity [8,35]. However, the dependence on the particle size and shape cannot be completely ignored, and the accuracy or range of results is limited if only the transmitted or the backscattered light is measured; this is because the various scattering parameters exhibit cross-dependence in the measured light.

To determine the scattering matrix of a particle, which characterizes it completely, measurements on the scattered light is carried out using a polarizer whose pass-axis is oriented at various angles [36]; however, it is not always feasible because practical implementation of the methodology requires a certain minimum number of components to be used, for example, as in remote sensing application. Therefore, several methods have been proposed which use limited number of measurements while extracting maximum information about the scattering system, especially in the context of fiber optic sensors. Fiber optic sensors have a range of advantages like flexibility, durability, immunity from electromagnetic interference, and most importantly, scope for telemetry. The rapid advent of optical fibers in communication and sensing has also led to the development of fiber optic sensors based on light scattering, including turbidity sensors [9, 34]. In a common configuration of a fiber optic turbidity sensor, one or more fibers are used to irradiate the medium and collect the scattered light, which is then used to determine the parameters of the system [8]. In the development of practical sensors for applications, several problems such as low output intensity, background noise, and complications due to limited numerical aperture of fibers and detectors, have to be solved. For example, decrease in output may be either due to increase in turbidity or due to damage to a detecting fiber. To deal with such kind of challenges, there should be a provision of local reference to identify spurious results, and increase reliability of the system. Another possible issue is fluctuation of source intensity, which has to be taken into account in order to increase the accuracy [37].

5 Recent advents in light scattering techniques

5.1 Determination of concentration

The concentration of particles is easier to measure than the size, as it can be directly correlated to the *extinction* of the incident light. The interaction coefficient μ_t depends on the cross-section and the concentration of particles; it can be determined by using a simple setup to measure the unscattered light, remaining after passing through the turbid sample (Fig 3). From Beer-Lambert's law [13], the intensity of the unscattered light is given by

$$I = I_0\, e^{-\mu_t L} \tag{4}$$

where L is the interaction length and I_0 is the intensity of the incident light.

From the point of view of light scattering, only the extinction matters, and not the particle concentration alone; therefore, measurement of μ_t is enough to characterize the turbid medium in most cases. However, if the concentration of particles is also required, then the interaction coefficient must be calibrated with respect to different concentrations of particles using different turbid samples. The results would be valid only for the specific type of particle used in the calibration, because the cross-section depends on the particle size and shape.

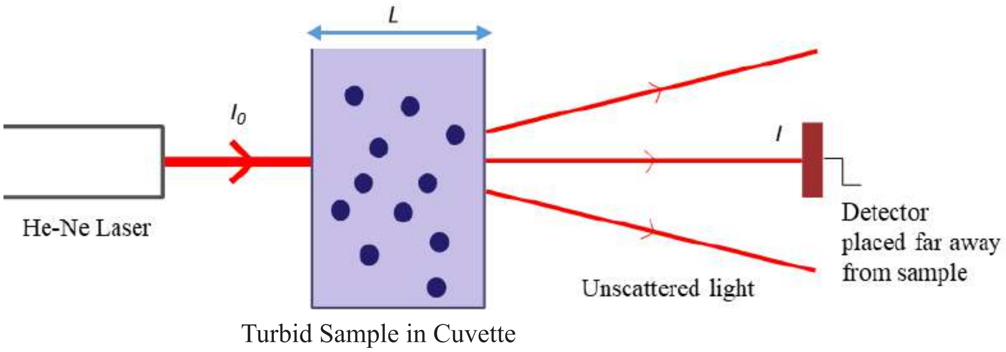

Fig 3. Experimental setup to measure interaction coefficient μ_t by using Beer-Lambert's law.

A fiber optic probe can be used to make the setup compact and apply it for remote sensing [8,9] e.g., for monitoring turbidity of drinking water—as shown in Fig 4, where a mirror is used to enhance the collected backscattered power. A calibration plot relating the backscattered power to μ_t can be obtained (Fig 5), where the interaction coefficient is determined using the setup in Fig 3. Using standard formazine samples, μ_t can also be related to the Nephelometric Turbidity Unit (NTU), which is a standard unit of turbidity (Fig 6).Therefore, such a fiber optic probe can be used to measure the backscattered power from an unknown sample, and estimate the turbidity in terms of NTU. The backscattered power collected by the fiber probe in Fig 4 can be further enhanced by using a concave mirror of appropriate radius of curvature, in place of the plane mirror [8,38]; this is particularly useful for measurements on liquids with very low turbidity.

Another challenge in devising a real-time telemetric fiber probe is related to the case of flowing liquids: In this case, the calibrations performed with a static medium in the laboratory do not remain valid, and hence errors in the measurement appear. The calibration thus has to be performed using flowing medium, which has been demonstrated in the laboratory [17,39].

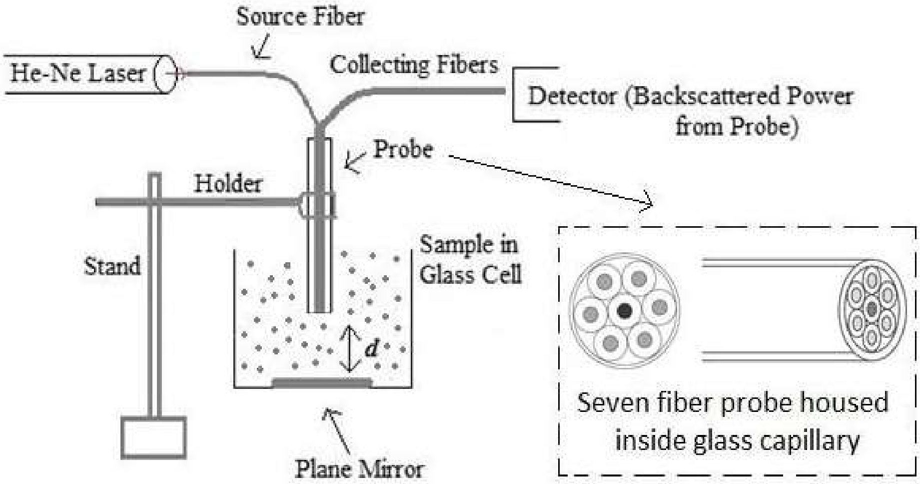

Fig 4. Experimental setup to measure backscattered power with 7 fiber probe.

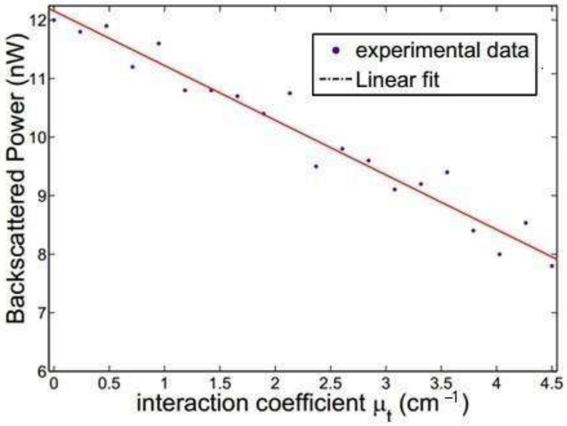

Fig 5. Backscattered power vs interaction coefficient for Gelusil.

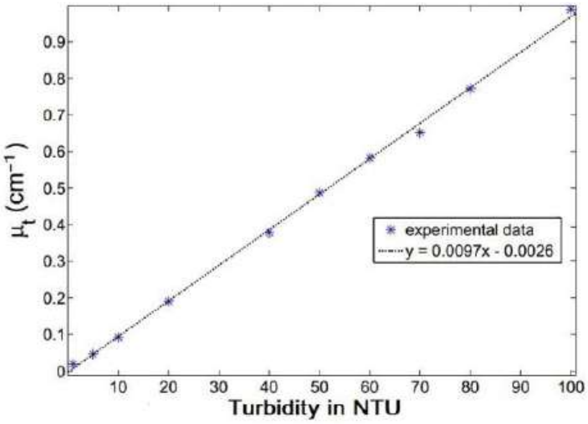

Fig 6. Interaction coefficient μ_t vs turbidity in NTU for formazine samples.

5.2 Determination of the anisotropy parameter g

For determination of the anisotropy parameter *g*, it is not enough to measure just the forward or backward scattered light. This is because the anisotropy parameter (or equivalently the size and shape of particle) affects the distribution of scattered light. If the shape of the particle is not known, the angular spectra of the turbid sample is required, from which the average of the cosine of the scattering angle, and hence the *g*, can be determined. If the particle is known to be spherical, then only a few angular measurements may be sufficient to determine the anisotropy parameter or the size. With the help of simulation results, the number of angular positions where the scattered light is to be measured may be reduced to even one [21]; this is achieved by measuring the scattered power at an off-axis detector (Fig 7), and comparing it with the scattered power simulated for different values of *g* (Fig 8). The interaction coefficient in the Monte-Carlo simulation is kept to be the same as that of the unknown sample (whose μ_t can be determined using the Beer-Lambert's law). The advantage of this methodology is that a single experimental measurement of the scattered light is sufficient to estimate *g*.

Using two detectors (Fig 9), the need to measure μ_t can also be removed [28], and the particle size can be determined by comparing the ratio of phase functions at the two angles, obtained from Mie Theory and experimental measurements (Fig 10). However, if the particles are not spherical, Monte-Carlo simulation may have to be performed as the Mie theory is not applicable.

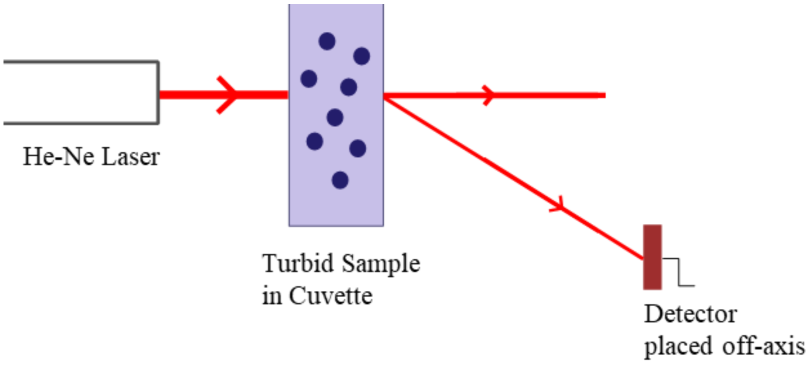

Fig 7. Experimental setup to measure scattered power.

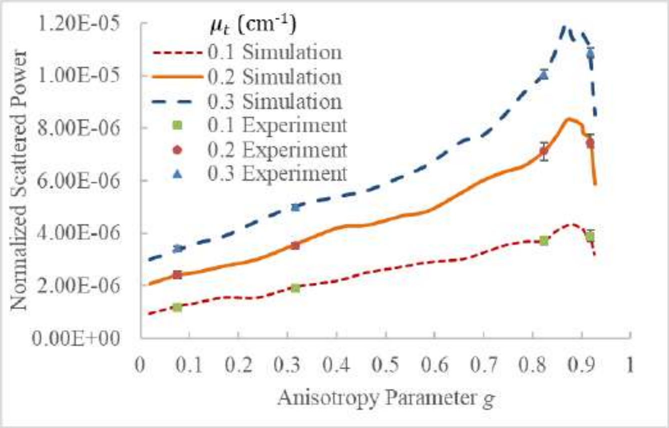

Fig 8. Variation of scattered power with *g* for different values of μ_t . Experimental measurements are shown with markers, and solid lines show the simulation results.

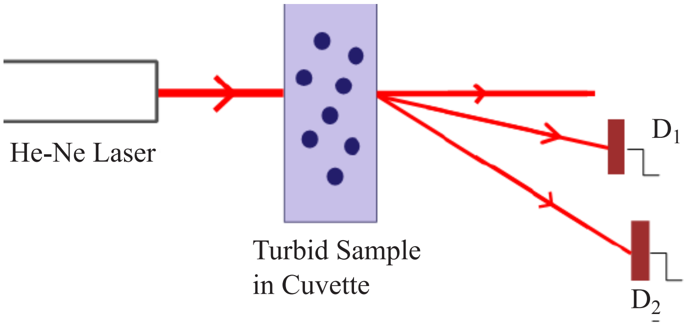

Fig 9. Experimental setup showing measurement of scattered power at two different angles.

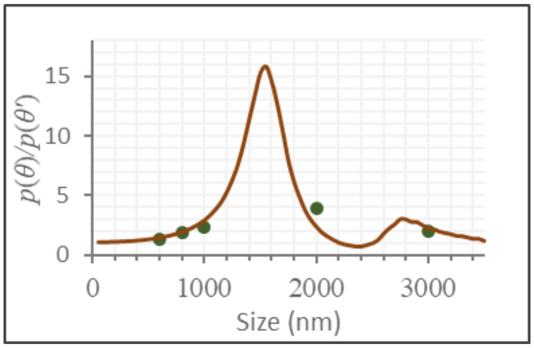

Fig 10. Ratio of phase functions at two scattering angles vs particle size, obtained using Mie theory. Some of the experimental measurements are shown as dark dots.

6 Conclusion

Study of scattered light is essential in the development of fast and non-invasive methods to analyse particles of a turbid medium. From light scattering experiments, the scattering parameters of turbid medium can be estimated, which in turn depend on the intrinsic properties of the scatterers and the surrounding medium. The interaction coefficient μ_t can be determined by using the Beer-Lambert's law in a simple experimental setup to measure the unscattered light through a turbid sample. For estimation of the particle size, or the anisotropy parameter *g*, usually the scattered light has to be measured at a few scattering angles. Since the properties of the scattered light depend on the specific size, shape and concentration of particles, the various methods require calibration in the laboratory with samples of known characteristics. Using either simulations or scattering theory, in conjunction with experiments, it is possible to reduce the number of measurements required; this could lead to the realization of compact devices for practical use. The various methodologies can also be implemented using fiber optic probes to determine the turbidity and concentration in remote sensing applications.

There are several challenges which are yet to be overcome in reliably using light scattering measurements to characterize a turbid medium. One of the problems is the lack of uniqueness, i.e. different combinations of scattering parameters could give same value for the scattered power. In other words, the measured power at any angle could correspond to different sets of scattering parameters, and therefore there are restrictions placed on the applicability of the various methods. Another issue is the difference between the relatively stable environment in the laboratory and that in a real-world application. There is also a need to study the light scattering in mixtures [40], which has been overlooked so far. Thus, although light scattering techniques have been developed significantly over the past few decades, improvements on the methodologies are taking place, along with the development of new methods for potential applications.

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M R Shenoy received the M. Sc. in Physics in 1979 from Mysore University and the PhD in the field of *Fiber and Integrated Optics* from IIT Delhi in 1987. He joined the faculty of IIT Delhi in 1988, where he is currently Professor in the Department of Physics.

Dr. Shenoy was a Visiting Scientist with the Department of Electrical and Electronic Engineering, University of Glasgow, Glasgow, U.K., in 1990 for 10 months, and on short-duration visits at the University of Nice – Sophia Antipolis, Nice, France, in 1992, 1997, 2006 and 2008 for collaborative research on Integrated Optical Devices. He has authored/co-authored a number of research papers and book chapters, and has supervised a number of student projects at the B.Tech, M.Sc., M.Tech, and Ph.D. levels. He is a co-editor of the book *Fiber Optics Through Experiments* (Viva Publications, New Delhi, 1994, 2008). He has delivered a full video course of 46 lectures on *Semiconductor Optoelectronics*, facilitated by NPTEL (MHRD, Govt. of India) and freely available for download on YouTube. He has been involved in several Sponsored R&D projects on the design and development of guided-wave optical components and devices, and nonlinear optical frequency generation in the near IR. His current research interests are in the area of *Guided Wave Optics and Optoelectronics*.

Kalpak Gupta completed his B Sc in Physics from Hindu College, University of Delhi in 2013. He received the M.Sc. degree in Physics from Indian Institute of Technology (IIT) Delhi in 2015, and is currently working towards the Ph.D. degree at the Department of Physics, IIT Delhi. His research areas are light scattering studies in turbid media and development of fiber-optic sensors. He is a student member of OSA-The Optical Society, Delhi Chapter.