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Optical fibre probes in the measurement of scattered light: Application for sensing turbidity

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Abstract. Optical fibre probes or optrodes often form the heart of multimode fibre-based measurements and sensors. An optrode usually comprises a bundle of multimode fibres, out of which one or more fibres are used for irradiating the sample, and the remaining fibres are used to collect the light reflected/scattered/fluoresced from the sample containing the measurand(s). The so-collected light carries the characteristic signature of the measurand. Here we present our work on the design and realization of optrodes for the measurement of scattered light from liquid samples. Optical properties of a solution are usually characterized by the parameters absorption coefficient μ_a, scattering coefficient μ_s, and anisotropy factor g. We have developed a simple method to determine μ_a, μ_s, and g, of a turbid medium, and a Monte–Carlo model was used to simulate the light scattering from the turbid medium. As an application, we describe the development of a turbidity sensor that has been designed and realized by employing an optrode in conjunction with a concave mirror. The estimation of turbidity is done on the basis of total interaction, by considering scattering and absorption of light from the sample solution. Details of the experiments and results are presented here.

Keywords. Fibre optic sensors; optical fibre probes; turbidity sensor; optical properties.

PACS Nos 42.81.−I; 42.81.Pa; 78.15.+e

1. Introduction

Apart from being the transmission medium in optical fibre communication systems, optical fibre is an important medium as a sensing element (as in intrinsic sensors), and as a means for relaying signals from a remote sensor to the signal processing unit (as in extrinsic sensors). By analysing the light scattered from a sample environment, for example, one can sense displacement, temperature, pH, etc. of the sample. Fibre-optic probes or optrodes often form the heart of several multimode fibre-based sensors. An optrode usually comprises a bundle of multimode fibres, out of which one or more fibres are used for irradiating the sample and the remaining fibres are used to collect the light reflected/scattered/fluoresced from the sample containing the measurand(s). The so-collected light carries the characteristic signature of the measurand. Such optrodes can be used to remotely identify, for example, samples in hazardous and corrosive environments. On the other hand, fluorescent light from a biological sample such as tissue, under excitation by light, can be studied using an optrode [1,2]. Fluorescence spectroscopy using optrodes has become a useful tool for identifying cancerous cells in oncology. Such techniques involving the use of fibre-optic probes, allow flexible delivery and collection of light even in hard-to-reach anatomical sites.

The design of a fibre-optic probe has to be optimized for any given application. These are typically custom-designed, and a standard design of fibre probes is nearly impossible. However, there exist some popular arrangements of the optical fibres in the form of fibre-bundles that can be used as a probe. These probes (may) include a single fibre, a fibre pair, or fibres arranged in a bundle. When the signal to be sensed is relatively weak, the optrode needs to be appropriately optimized. In general, the fibre probes used in medicine and biology have size restrictions in accordance with the small sizes of biological cells and tissues. However, in chemical engineering and nuclear industries, size of the probe is usually not a constraint.

In this paper, we discuss our work on the design and realization of optrodes, under the ‘extrinsic category’ of fibre-optic sensors, for measuring scattered light from a turbid liquid. In our work, optrodes in different geometries, employing multimode fibres of various dimensions, i.e. various core diameters and core-clad ratios were fabricated. To determine the performance of the fabricated fibre probes, samples in the form of distilled water, turbid suspensions such as milk, and fluorescent dyes were used for measurements. The light-collection efficiency of the optrodes, at the design stage, was modelled using Monte–Carlo simulations. Various possible probe configurations/geometries were simulated to determine the light collection efficiency, so as to choose the probe configuration that collects the maximum optical power for a given input.

2. Optical properties of the medium

Optical properties of a solution are often characterized by absorption coefficient, scattering coefficient and anisotropy factor. There exist some methods to determine these properties but most of these methods are insufficient for the explicit determination of the anisotropy factor, and the methods (e.g. integrating sphere method) that can measure the above-mentioned three parameters, require extensive set-ups that are expensive and cumbersome [3,4]. Recently, we have developed a simple method to determine the optical properties of a turbid medium [5]. In our experiment, diluted fresh dairy milk, a fountain-pen red ink and an alkaline (calcium/magnesium hydroxide) suspension were chosen as samples to represent turbid media. These samples simultaneously contain both scattering and absorbing particles, making them suitable samples for studying light propagation through turbid media. A Monte–Carlo model [6] was developed to simulate the forward scattered light in terms of total interaction coefficient, μ_t, anisotropy factor, g, and albedo, b. The optical parameters were uniquely estimated by parametric optimization using both experiments and simulations [5]. The parameters μ_a and μ_s can easily be deduced from μ_t and b.

3. Turbidity sensor

As an application, we describe the realization of a turbidity sensor that would be useful for estimating the turbidity of liquids, particularly for low levels of turbidity. Turbidity is an important indicator for checking the quality of liquids, e.g. water, olive oil [7]. Turbidity of water, for example, is determined by the amount of particulate matter such as soil, sand, organic particles, suspended in water [8]. We have devised a novel method for sensing the turbidity of a solution by using a fibre-optic probe in conjunction with a concave mirror [9]. The use of concave mirror effectively increases the volume of interaction between light and the sample, and hence enhances the sensitivity.

3.1 *Seven-fibre optrode*

We first used a seven-fibre in-house fabricated optrode. Figure 1a shows a schematic of the cross-section, while figure 1b shows a photograph of the fabricated probe. The central fibre (darkened in figure 1a) illuminates the sample solution, and the remaining fibres collect the light scattered inside the sample solution, including the light reflected from the mirror (figure 2). The experiments were performed with solutions of different turbidity that were prepared, for example, by mixing different quantities of an alkaline suspension in de-ionized water. The turbidity of each sample was estimated in terms of its total interaction coefficient, μ_t, a parameter that contains strong signature of the turbidity of a liquid. Figure 2 shows a schematic of the experimental set-up. The separation, d, between the fibre probe and the mirror (see figure 2) was varied, and the light collected by the fibre probe was measured for each sample solution. The collected light peaks at certain positions and drops at other, depending on d and the properties of the medium.

Figure 3 shows the variation of the collected power as a function of d, for different samples of milk (with different values of μ_t). The location of the observed peaks in the measurements can be explained as follows: When the fibre bundle is close to the mirror (nearly touching), the reflected light does not overlap with the location of the collecting fibres, which corresponds to very little detected optical power at this position. When the

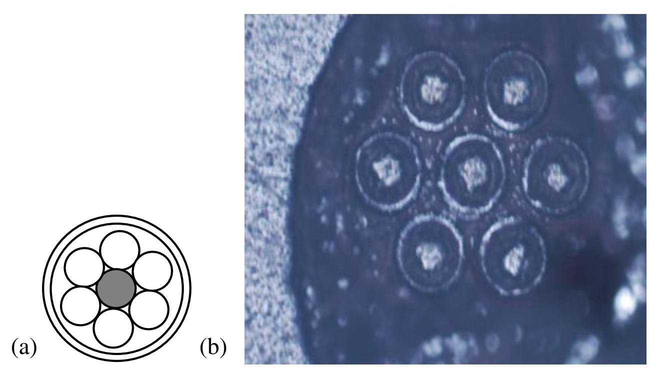

Figure 1. (**a**) Schematic cross-section of the 7-fibre probe and (**b**) photograph of the fabricated probe using multimode fibres with 200 μm core diameter.

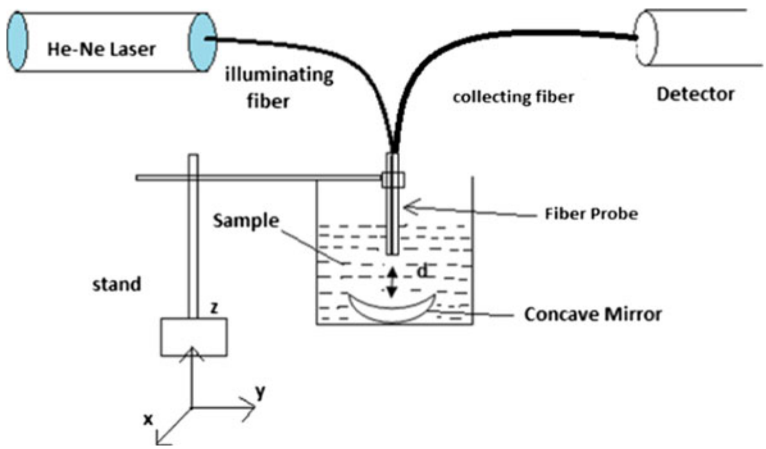

Figure 2. Schematic of the experimental set-up of the turbidity sensor based on measurement of the reflected/scattered light from liquid samples.

tip of the fibre bundle is located at the centre of curvature of the mirror (i.e. $d = R$), the light emanating from the central fibre retraces its path back to the same (central) fibre in the absence of any suspended (scattering) particles. When the solution is turbid, fibres

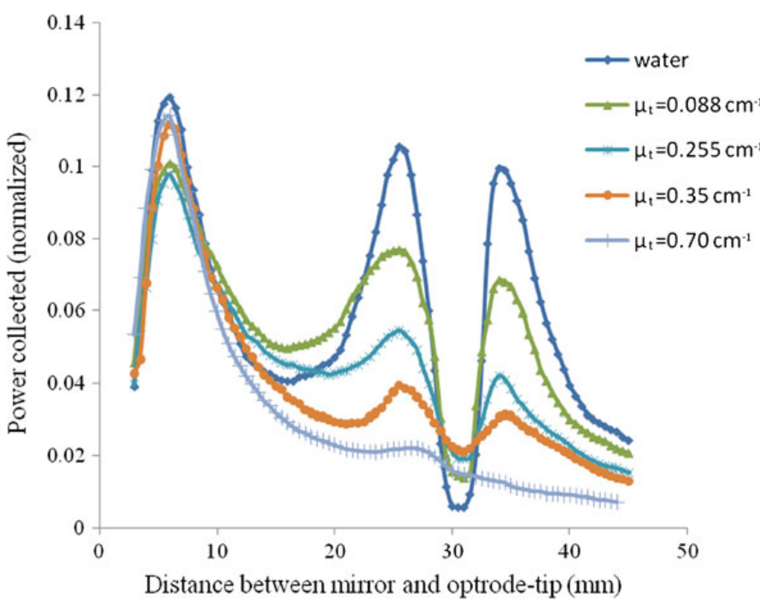

Figure 3. Experimental results for power collected by the optrode with increasing d, the separation between the concave mirror and the tip of the fibre, for different samples of milk, with different values of μ_t [11].

may collect some light, scattered from the suspended particles. On the contrary, a large (area) overlap of the reflected light with the collection fibres takes place when the probe is located at a short distance before (or beyond) the centre of curvature of the mirror, leading to higher detected powers at these positions. Thus, if one plots the light received by the collecting fibres vs. the separation d, two peaks appear – one just before and the other just beyond the position $d = R$ (figure 3).

3.2 *Simulation model*

A preliminary model based on geometrical optics was developed to simulate the behaviour of the designed fibre probe [9]. This yields a qualitatively correct variation of the power collected by the probe. However, to account for the interaction of light (i.e. scattering and absorption, in this case) with the particles suspended in the sample, the Monte–Carlo simulation tools were used [10]. Light exiting from the central fibre in the form of photon packets propagate in the turbid medium, thereby getting either absorbed, reflected or scattered in a random manner, for which a photon step size s could be ascribed to indicate the events at various stages (figure 4). These packets take random steps whose step size is decided by the total interaction coefficient of the medium. By following recipe for the Monte–Carlo simulation, as described by Wang *et al* [10], a group of photon packets (e.g., 10^7 packets), each having an initial weight of unity, is assumed to be emitted from the end of the central fibre. The photon packets are emitted within the numerical aperture of the fibre in the turbid medium. For simulation purposes, the intensity distribution of the light coming out of the fibre-end is assumed to have a uniform (transverse) distribution. A photon step size s, given by an exponential probability distribution (of mean length $1/\mu_t$), is assigned to the packet through [10]

$$s = \frac{-\ln(\xi)}{\mu_t}, \tag{1}$$

where ξ is a uniformly generated random number between 0 and 1. The packet is then assumed to propagate through a distance s. At the next step, the weight (ω_i) of the packet is reduced by a factor of $(1 - \mu_a/\mu_t)$ to account for the absorption, i.e.,

$$\omega_i = \omega_{i-1}\left(1 - \frac{\mu_a}{\mu_t}\right), \tag{2}$$

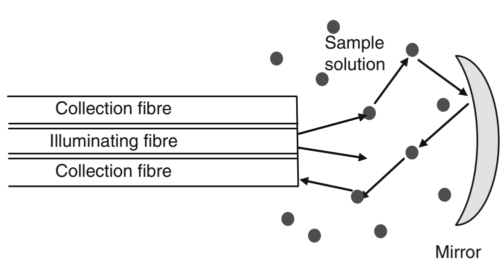

Figure 4. Schematic of the longitudinal cross-section of the optrode-mirror assembly, as employed in the simulation.

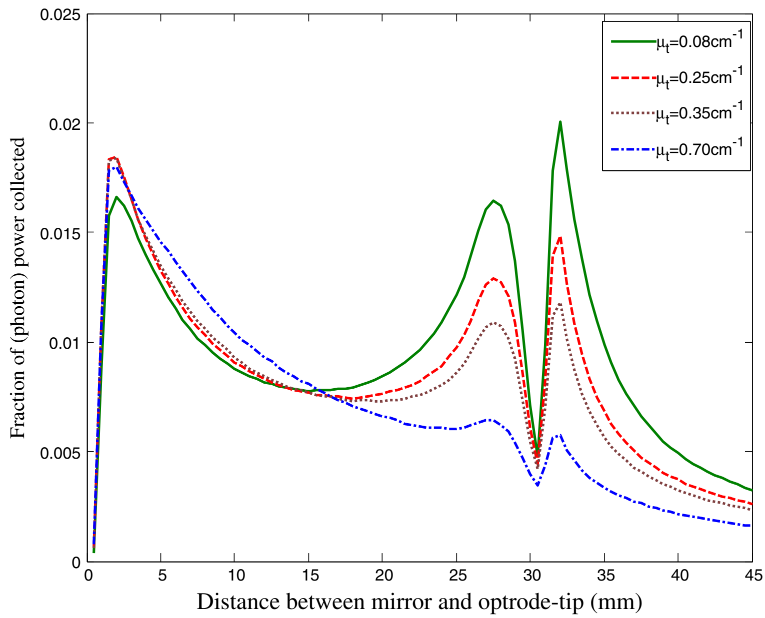

Figure 5. Numerical results of Monte–Carlo simulation for the power collected, corresponding to the parameters in figure 3.

where ω_i denotes the weight of the packet after the ith scattering event. The scattering angle θ is determined using the Henyey–Greenstein function [10]. The scattering angle and the position of the photon packets are updated after each scattering event. In this way, the photon packet from the irradiating fibre is propagated in the medium until it either reaches the core of the collecting fibres or it leaves the field of view that is defined by the computational domain. The sum of weights of the collected photon packets gives the fractional power collected after scattering/reflection and absorption. A qualitatively good match between the experimental and simulated results was obtained (figure 5).

Figure 6 shows the variation of the power collected as a function of μ_t for the (fixed) value of d, corresponding to the second peak in figure 3. This graph forms a calibration curve to determine μ_t of a given type of turbid liquid (milk, in this case). Similar calibration curves can be generated for any type of turbid solution for a particular application. One can also determine the turbidity in nephelometric turbidity units (NTU) through a calibration graph relating μ_t and NTU, which shows a near-linear relation [12].

3.3 *Two-fibre optrode*

In this subsection, we present a novel configuration of the turbidity sensor using a two-fibre optrode which shows a complementary (to that of the seven-fibre optrode) response with improved sensitivity and design flexibility [13]. The probe consists of two fibres (see figure 7a): one fibre to illuminate the sample and the other fibre to collect light scattered from the sample after reflection from the concave mirror. The cone of light emanating

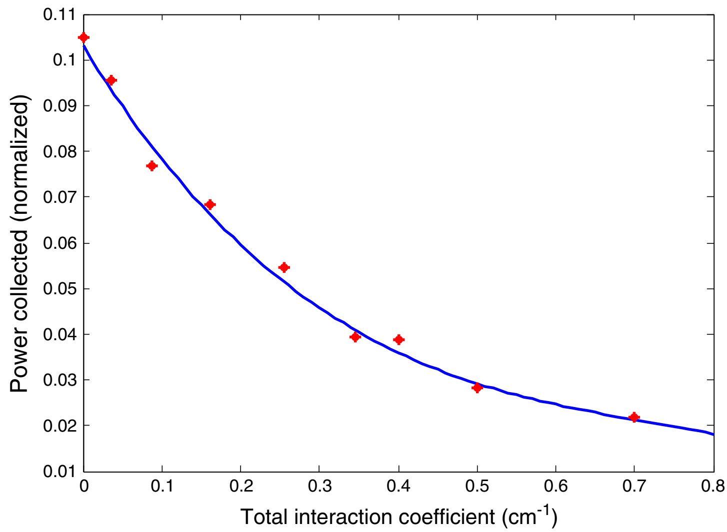

Figure 6. Fractional power collected as a function of μ_t for a fixed d, corresponding to the second peak in figure 3 [11].

from the source fibre propagates through the turbid solution and gets reflected/scattered towards the probe and is collected by the second fibre. The reflected/backscattered power is a function of the distance between the concave mirror and the tip of the probe, as before. However, this time it is maximum when the probe is at the centre of curvature of the mirror (figure 7b). The two fibres of the probe can have different core diameters, and experiments have been performed by changing the core diameter of the collecting fibre for comparative study of sensitivity.

For our experiments we fabricated two-fibre optrodes by fixing them in a suitable capillary tube. The end face of the capillary tube containing these two fibres is lapped and optically polished. Different types of samples have been studied; here, we present results for ink solutions of different concentrations, obtained by mixing different quantities of 'red ink' in de-ionized water. In the experimental set-up (see figure 2), the optrode is supported on an XYZ positioner in such a way that its tip is immersed in the turbid liquid. A concave mirror of 3 cm radius of curvature is fixed inside the sample container facing

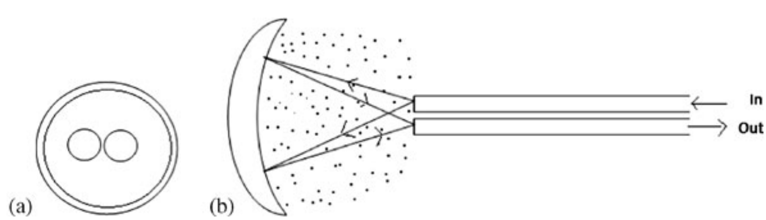

Figure 7. Schematic of (**a**) the cross-section of the two-fibre probe employed in the turbidity sensor, (**b**) ray diagram showing the cone of light incident on the mirror, and reflected light coupling into the collecting fibre.

the optrode tip as shown in figure 2. The alignment of the optrode with respect to the axis of the mirror is ensured by using the XYZ positioner.

Light from a He–Ne laser (632.8 nm) is coupled into the source fibre to irradiate the sample. Light after reflection/scattering inside the sample is collected by the second fibre of the optrode. Separation between the probe and the mirror is varied by moving the optrode in the z-direction, and power of the collected light is measured. This experiment is carried out for various samples of different turbidity. For comparative study of sensitivity, three probes were fabricated by using the same source fibre of 50 μm core diameter and three different collecting fibres of core diameters 50, 200 and 600 μm.

3.4 *Results and discussion*

Figure 8 shows the experimental results for samples of different turbidities. The turbidity of the samples has been quantified through the interaction coefficient μ_{t} (in cm^{-1}). For a given sample solution, the separation between the mirror and the tip of the fibre probe d, decides the power collected by the signal collecting fibre. When the fibre probe is placed at the centre of curvature of the mirror, the light emanating from the central fibre is collected almost completely by the collection fibre. Maximum power collection will take place at the centre of curvature (3 cm) of the mirror and power collected decreases as the probe moves away (in both directions) from the centre of curvature. As can be seen from figure 8 the maximum power collected depends on the turbidity of the solution. Figure 9

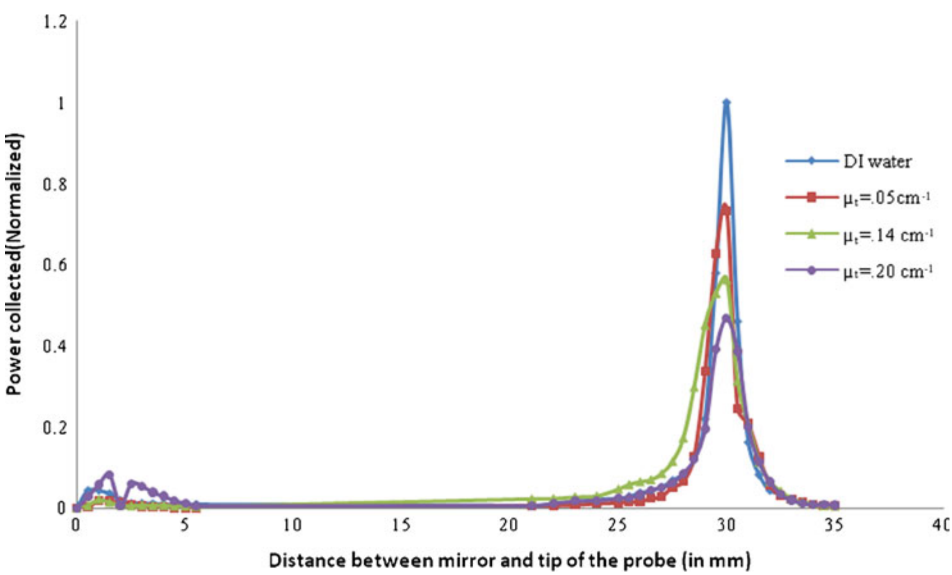

Figure 8. Experimental results for the power collected by the optrode after reflection from the mirror with increasing d, the separation between the optrode tip and the mirror, for different samples of 'ink' [13].

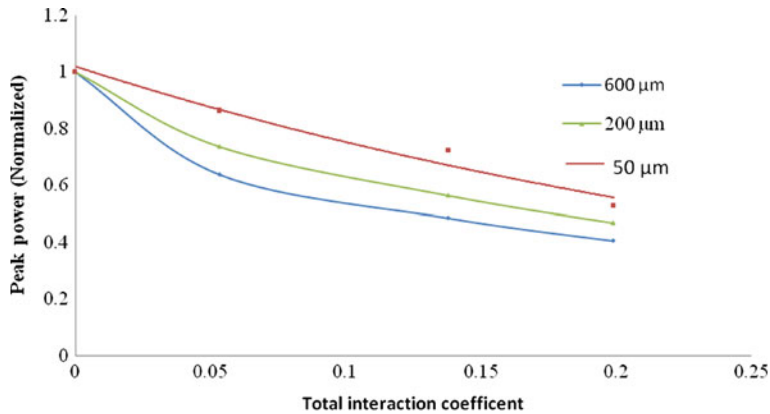

Figure 9. Variation of the peak power, corresponding to $d = 3$ cm, with the total interaction coefficient for three different collection fibres [13].

shows the comparative study of sensitivity by varying the core diameter of the collecting fibre of the two-fibre optrode. It shows that the sensitivity increases as we increase the core diameter of the collecting fibre.

4. Conclusion

We have presented our work on the design and realization of optrodes for measuring scattered light from liquid samples. In our experiment, diluted fresh dairy milk, fountain-pen red ink and an alkaline (calcium/magnesium hydroxide) suspension were chosen as samples to represent turbid media. These samples simultaneously contain both scattering and absorbing particles, making them suitable for studying light propagation through turbid media. A Monte–Carlo model was also used to simulate scattering from the turbid liquid, to estimate the collected power and hence μ_t.

As an application employing optrodes, we have described the development of a turbidity sensor that should be useful for estimating the turbidity of liquids, even for very low levels of turbidity. The turbidity sensor has been designed and realized by employing an optrode in conjunction with a concave mirror. The estimation of turbidity was done on the basis of reflection and scattering of light from the sample solution. First, we have used a standard seven-fibre in-house fabricated optrode, with the central fibre illuminating the sample solution, and the remaining fibres collecting the light scattered inside the sample solution, including the light reflected from the mirror. The collected light showed distinct peaks at certain positions of the optrode, depending on the distance from the mirror and the properties of the medium. Recently, we have investigated the use of two-fibre probes to study the scattering properties of turbid media. Using appropriate fibres, in this case, we obtained unambiguous single peak in the back-scattered light, with higher sensitivity. Knowledge of μ_t can be used to obtain turbidity in NTU from a calibration graph.

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