Studies on the propagation of light from a light-emitting diode through a glass tube and development of an optosensor for the continuous detection of liquid level

N. B. Manik
Jadavpur University
Condensed Matter Physics Research Centre
Department of Physics
Calcutta 700 032, India
E-mail: nabin@juphys.ernet.in

S. C. Mukherjee
Advanced Centre of Cryogenic Research —Calcutta
Calcutta 700 032, India

A. N. Basu
Jadavpur University
Condensed Matter Physics Research Centre
Department of Physics
Calcutta 700 032, India

Abstract. The authors develop a new technique for continuous measurement of liquid level by an optosensor. The objectives are (i) to study the propagation of light from a light-emitting diode (LED) through a glass tube and (ii) based on this principle, to develop a continuous liquid level sensor. The attenuation of light from an LED through a glass tube with distance has been investigated and an empirical relation for it has been established. The result is applied to the detection of water level. The sensor comprises a hollow glass tube with a combined LED-photodetector assembly (the optosensor) and a light reflector inside the tube. The reflector floats on the liquid surface, and light emitted from the LED is detected after reflection from it. The detected light intensity varies with the distance between the optosensor and the reflector. The position of the float changes with the variation of the liquid level. The present level sensor can detect a change of liquid level at distances up to 80 cm with an accuracy of the order of 0.5 mm. [DOI: 10.1117/1.1417496]

Subject terms: light, propagation, diodes.

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1 Introduction

Automatic detection as well as continuous monitoring of the liquid level inside a container is important for both scientific and technological studies. Along with mechanical level sensors, different types of resistive, capacitive, and inductive sensors are also found,[1–6] as well as optical and acoustic sensors.[7–10] Either the length of the liquid column or that of the empty portion of the container above the liquid can be measured. Basically, liquid level measurement is a special case of displacement measurement. For continuous liquid level measurement one should continuously monitor the distance from some reference point to the surface of the liquid.

Here we briefly discuss some relevant work on contactless optical and acoustic level sensors used for liquid level measurement. A commercially available level sensor using a 90-deg prism[7] works well. The amount of light transmitted from the source to the detector depends on whether the liquid covers the prism or not.

Another type of optical level indicator has been reported whose sensing element is a bihelical-conical light-guide structure (BHCS).[8] The BHCS is fabricated from a polymer multimode optical fiber with a polystyrene core. The sensing element was made by twisting, pulling, and fusing the optical fibers and then truncating the conical part. When the end of the sensing element contacts the liquid surface, the light transmission of the structure is suddenly reduced, indicating the presence of liquid at the contact point.

Yet another type of meter to detect the liquid surface level[9] uses two independent fibers, which are connected to the base of a 90-deg glass microprism. The paths of the light rays are such that when the prism is surrounded by air, the detector will pick up a relatively large signal due to total internal reflection at the sides of the prism. If the prism touches the liquid, the light suffers attenuation due to frustrated total internal reflection, resulting in a drop in the signal level at the output detector. A modification of this principle is also used[9] where a Y coupler made of a plastic fiber is used. The signal end of the fiber coupler is cut into a conical shape to detect the liquid level.

But all these optical level sensors are basically point detectors and can indicate only a predetermined liquid level. The continuous detection of liquid level is not possible with these sensors. It is also difficult to ensure proper coupling between the fiber and the prism. The matching of the refractive index of the liquid and that of the material of the prism is a prerequisite for getting a proper signal.

The reflection of ultrasonic and light-wave pulses[10] is another widely used technique for contactless distance measurement. In this method ultrasonic or light waves are generated by a transmitter and are detected by a receiver after reflection from the liquid surface. By measuring the time interval between the emission and detection of the wave, the distance can be estimated. But this principle is not suitable for short-distance measurement or liquid level measurement inside a container. Moreover, it is observed that if one uses the liquid surface itself as reflector, most of the light will penetrate into the liquid. Therefore, to collect a significant amount of light after reflection from the surface, a reflecting medium should be placed on the liquid surface. Considering all these effects, in this work we have modified the above-mentioned[7–10] techniques and suggest a low-cost continuous liquid level sensor.

For this purpose we have developed a device comprising a light source, a light detector, and an optical waveguide. But a suitable waveguide for this purpose is not easily found. The most widely used optical waveguide is the optical fiber into which light is commonly launched from a coherent laser source and detected by a corresponding detector.[11–14] For communication it is helpful that the attenuation of the incident power is small and light can be transmitted over a long distance. For the same reason, however, the use of optical fiber will not serve our present purpose. So, we looked for a combination of optical source, detector, and waveguide that would be cost-effective.

Unlike laser light, the light coming from a LED diverges while propagating through free space. Recently, very high-performance LEDs have become available,[15–25] but they are rather costly and thus are not of interest. On the other hand it is known that for low-cost commercially available LEDs at a particular viewing angle the intensity falls with distance. Here, it is shown that the range of the propagation is enhanced significantly if the light from the LED is guided by a glass tube coated with a highly polished Mylar sheet. The propagation of the emission from the LED through the tube has a much stronger directivity and larger propagation range than free-space propagation, and this phenomenon may fruitfully be applied for liquid-level detection. In order to carry out this work we have performed some initial experiments, which are described in the following section.

2 Studies of the Propagation of Light from an LED through a Glass Tube

Although the law of propagation of light through free space, optical waveguides, and optical fibers is well established and has been studied both theoretically and experimentally under various conditions,[12–14,26,27] its propagation through a hollow glass tube seems not to have received much attention with commercially available LEDs as light sources and photodetectors as light detectors. In the following section we systematically investigate the phenomenon, as is necessary for the development of the liquid level sensor to be discussed later.

The experimental setup to study the law of propagation of light through a glass tube is shown in Fig. 1. A tube of Pyrex glass having refractive index (r.i.) 1.5, internal diameter 10 mm, thickness 0.2 mm, and length 100 cm is taken. The outside of the tube is coated with a highly polished Mylar sheet. One LED (viewing angle 25 deg, peak wavelength of emission 650 nm, maximum power 75 nW) is placed in one end of the tube. The photodetector is mounted on a long stick and placed inside the tube. By moving the stick the photodetector can be placed at different distances from the LED inside the tube.

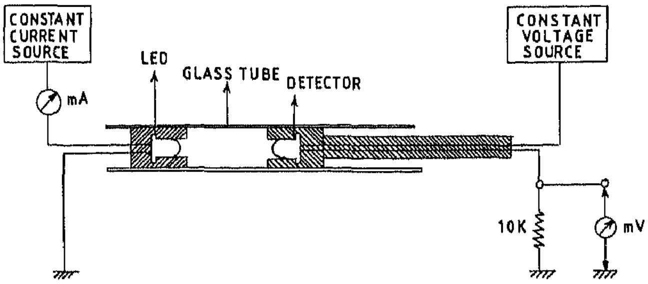

Fig. 1 Experimental setup to study the propagation of light from an LED through a glass tube. The LED is placed at one side of the tube. By holding the photodetector on the tip of a stick, it may be placed at different positions.

The LED is illuminated by a constant current source. The current is fixed at 10 mA. The photodetector is connected to a reverse bias of 2 V with a 10-kΩ resistance in series. The photovoltage across this sensing resistance gives a measure of the intensity of light incident on the photodetector. The intensity in terms of photovoltage is measured at different positions of the photodetector. The experiment was repeated for different driving currents of the LED, and resulting plots of the intensity versus distance between the LED and photodetector are shown in Fig. 2. In this experiment the background light (i.e., the illumination from outside the tube) does not interfere the measurements, because the tube is isolated by the Mylar.

To find the nature of this propagation and to ensure the reproducibility of the results, we have carried out the experiment with different LEDs and at different viewing angle (10 and 55 deg), wavelengths (650 nm, 635 nm, etc.), and operating currents. In all these measurements, curves similar to those in Fig. 2 are obtained. In all these experiments the photodetector used remained the same, it was an ordinary wide-angle photodetector (TIL-78).

For comparison, experiments were also made where the glass tube was not coated with Mylar, and also on free-space propagation. For the first case the Mylar sheet was removed from the glass tube. In that case the background light interferes with observation, so the experiment was done in a dark room. To examine free-space propagation

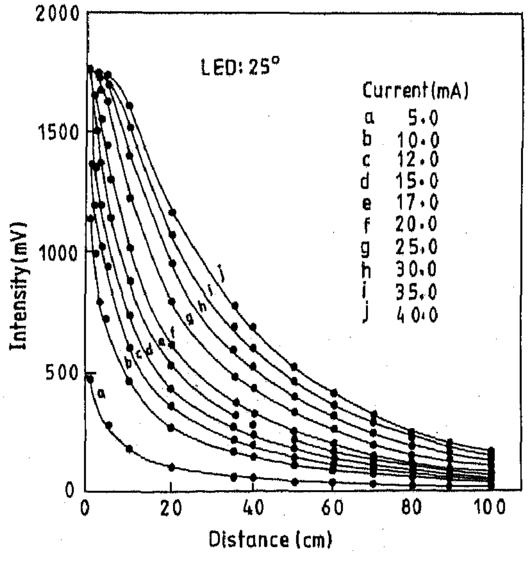

Fig. 2 Intensity at different distances when the glass tube is coated with Mylar sheet.

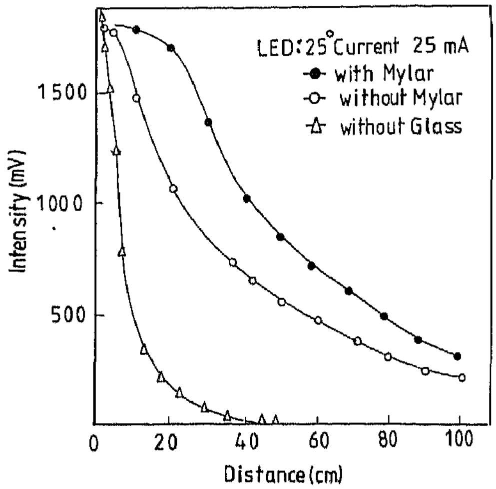

Fig. 3 Intensity versus distance in three different situations: (a) glass tube coated with Mylar; (b) glass tube not coated with Mylar; (c) free-space propagation (no tube).

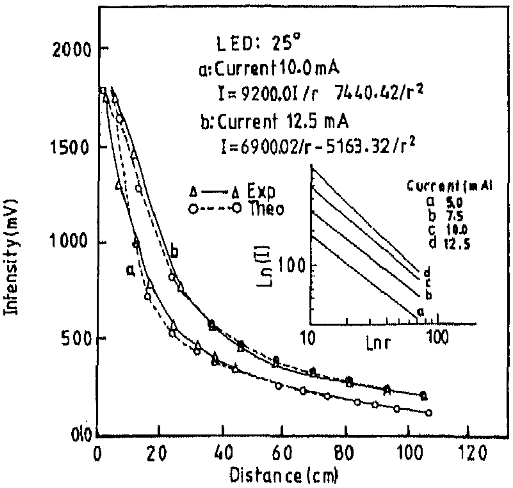

Fig. 4 Fitting of intensity-versus-distance curve of Fig. 2. *Inset*: Logarithmic plot of intensity-versus distance.

the experimental setup of Fig. 1 was modified a little. The glass tube was removed entirely. For a fixed driving current of the LED the photovoltage was measured by placing the photodetector at different distances from the LED. It is found that for free-space propagation the radiation falls sharply and follows an inverse square relation with distance.

Figure 3 shows a comparative study for the fall of intensity for a particular driving current of the LED for the above three cases. It is found, as expected, that light is guided much more when the tube is coated with Mylar than in an uncoated tube or free-space propagation.

3 Law of Propagation of Light in a Glass Tube

From Fig. 3 it is seen that the light is guided much more when the tube is coated with Mylar. It is presumed that the propagation profile inside a glass tube has a definite pattern distinctly different from that of free-space propagation. By fitting the experimental points empirically we could obtain the following formula, which would reproduce all the data with a very small dispersion (≈2%):

$$I(r)=a/r-b/r^2, \tag{1}$$

where $I(r)$ is the intensity inside the glass tube coated with Mylar at a distance r from the source, (i.e., the LED at one end of the tube) and a and b are constants for a particular setup and driving current of the LED.

Figure 4 shows the nature of the fit for some selected experimental data as an example. Solid curves represent fitted data of Eq. (1), and dashed curves represent experimental data. The mean deviation is of the order of ±1%. A major part of the deviation arises from the data points close to the source.

As the distance r increases, the contribution of the second term becomes negligible. Table 1 shows how the contributions of the two terms vary with distance. For a large distance ($r>15$ cm) the second term has no significant effect. So Eq. (1) is approximated as

$$I=a/r. \tag{2}$$

On taking logarithms of both sides we get

$$\ln I=\ln a-\ln r, \tag{3}$$

which is a linear relation between $\ln I$ and $\ln r$. The inset of Fig. 8 in Sec. 5 compares the above relation with observation.

The values of the constants a and b as obtained from the experiment are shown in Table 1. The constants a and b have a complicated dependence on many factors, including the nature of the LED source, the viewing angle of the LED, the intensity profile, the wavelength of emission, the thickness, diameter, refractive index, and reflection and the absorption coefficient, of the glass tube, and the reflection coefficient of the Mylar coating. However, for a particular setup a and b depend only on the driving current of the LED.

To give a qualitative idea of how a and b depend on the tube diameter, we have measured the intensity with distance using the experimental setup of Fig. 1 for different

Table 1 Contributions of the first and second terms in Eq. (1); versus distance r. Intensity is measured in terms of photovoltage (in volts). $a=3880.00$ V cm, $b=2008.00$ V cm^2 for 25-deg red LED; current=15 mA.

r (cm)	A/r	b/r^2	$\frac{b/r^2}{a/r}$
1	3880.00	2008.00	0.518
3	1293.33	223.11	0.172
5	776.00	80.32	0.013
10	388.00	20.08	0.051
15	258.66	8.92	0.034
20	194.00	5.02	0.025
25	155.20	3.21	0.020
30	129.33	2.23	0.017
40	97.00	1.25	0.012

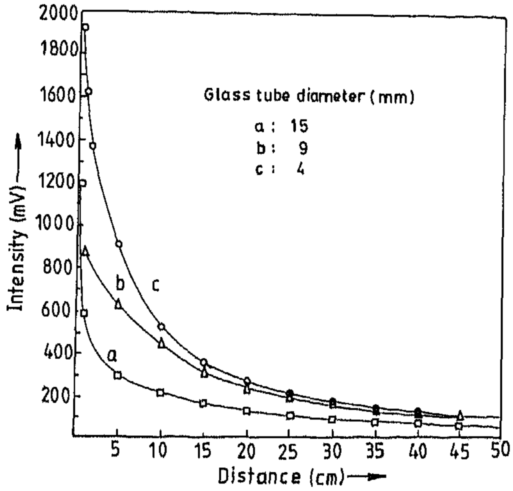

Fig. 5 Intensity versus distance with different tube diameters. The glass tubes are coated with Mylar sheet.

tube diameters. Figure 5 shows that in general, for the same distance, with an increase in tube diameter the intensity decreases, indicating a lowering of the values of the constants. It will of course be instructive to study the precise nature of the dependence of the constants on the variables mentioned above.

4 Experimental Setup to Study the Propagation of Radiation from an LED through a Glass Tube When the LED and the Photodetector Are Placed on the Same Side and Light is Reflected Back by a Reflecting Surface

The previous experiment clearly shows that light is guided much more while it propagates through a Mylar-coated glass tube. To utilize the above findings and apply them to develop a liquid level sensor, the above experiment was slightly modified. Now the LED and the photodetector are mounted on the same side of the glass tube as shown in Fig. 6. A highly polished strip with a reflecting surface (Mylar on an aluminum sheet) is placed inside the tube with its reflecting face towards the optosensor mounting. With a long stick the position of the reflector can be altered as before. Light emitted from the LED is detected by the photodetector after back reflection from the reflector. The detected light intensity varies with the distance between the LED-photodetector assembly and the reflector. The LED and the photodetector are operated as before. The LED is powered by a current source (10 mA), and the photodetector is biased with reverse bias (2 V) with a series resistance of 10 kΩ. On switching on the LED, a photovoltage is observed. By adjusting the stick, the reflecting surface is placed at different positions. Figure 7 shows the variation of the photodetector output with distance between the optosensor and the reflector for different driving currents of the LED. The measurements were repeated several times with different LEDs at different viewing angles, wavelengths, and driving currents in order to check the reproducibility of the results.

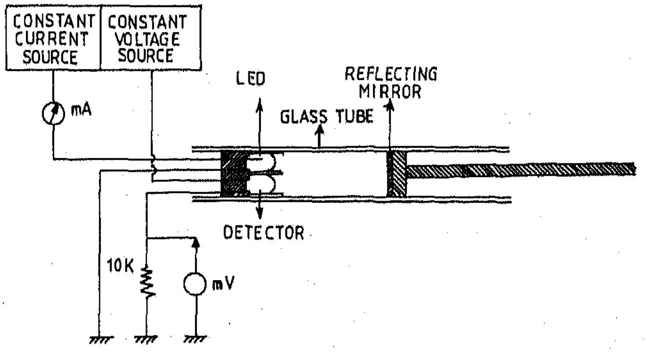

Fig. 6 Experimental setup with the LED and the photodetector placed on one side of the tube and a reflecting surface used for back reflection. The glass tube is coated with Mylar sheet.

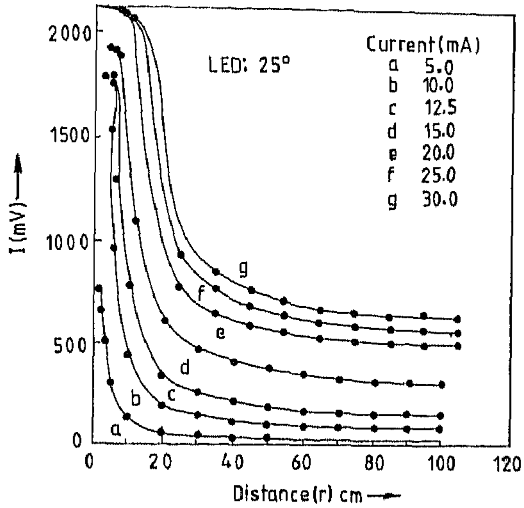

Fig. 7 Intensity versus distance when the LED and the photodetector are placed in one side of the tube and a reflecting surface is used for back reflection.

5 Results and Analysis

The experimental results of Fig. 7 were fitted by a relation of the form (1). The theoretical fit with the experimental points is shown in Fig. 8.

For a large distance ($r > 10\,\mathrm{cm}$), we may again use the approximation (3). The inset of Fig. 8 compares it with observation.

The values of the constants a and b depend on several factors as mentioned in Sec. 3. Although we shall use the approximate relation (3) for our subsequent work, the full relation (1) is sometimes needed, in particular for the region close to the source, where a small change in distance causes a large change in intensity. This fact may be useful for some applications.

6 Continuous Liquid Level Meter for Water

The experiment mentioned above (Fig. 8) is not commonly found in the literature. This type of propagation of light may, however, have many possibilities of application in different areas. The principle may be used to develop different types of displacement sensors, continuous liquid level sensors, pressure sensors, vacuum sensors, etc. Based on this principle, a continuous liquid level sensor has been developed by using a LED, a photodetector, and a glass tube

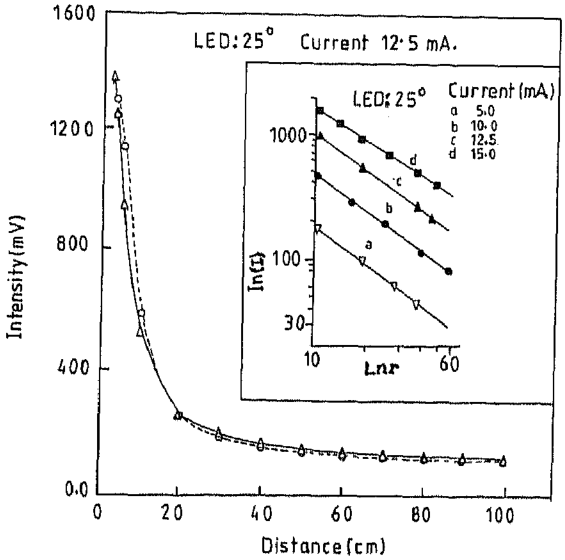

Fig. 8 Fitting of intensity-versus-distance data for a Mylar-coated glass tube when the LED and the photodetector are placed in one side of the tube and a reflecting surface is used for back reflection. *Inset*: Logarithmic plot of intensity versus distance.

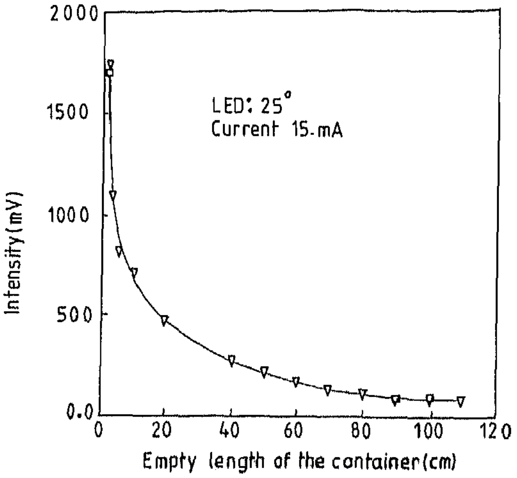

Fig. 10 Empty length of the liquid container versus photovoltage. By subtracting the empty length from the total length of the container, the height of the liquid level can be estimated.

with a float inside it. In the previous experiment the light coming from the LED was reflected back by the reflector and finally detected by the photodetector. Instead of using a reflector inside the glass tube, if we use a float having a reflecting surface towards the optosensor, the same phenomenon will occur. The float resides on the liquid surface and indicates its position. Variation of the surface level causes a change of distance between the optosensor and the float and thereby a change of photovoltage for a fixed driving current of the LED.

The experimental setup for the water level meter is shown in Fig. 9. The optosensor (the LED-photodetector assembly) is placed on the top of the glass tube coated with polished Mylar sheet. Inside the tube a hollow metallic cylindrical (length ≈1 cm, diameter ≈1 cm) float, made of aluminum with a Mylar reflecting coating on one side, is inserted. The diameter may be adjusted without much difficulty so that the float can move smoothly through the tube without tilting. The reflecting surface of the float faces the optosensor. The optosensor probe is shown in the inset of Fig. 9. The viewing angle of the LED is 25 deg, and the detector is an ordinary wide-angle photodetector (TIL 78). The glass tube (the sensor probe) is held vertically inside a glass tank, which is filled with water as shown in Fig. 9. To vary the water level inside the water tank we adopt the siphon mechanism shown in this figure. The LED is connected to a constant current source and the photodetector to a constant voltage source with a 10-kΩ resistance in series, as before.

Now the LED is driven by a 10-mA current and the photodetector is reverse biased at 2 V. For a particular value of the water level inside the container a reading is obtained at the output of the photodetector. Now by using the siphon tube the liquid level and hence the position of the float is varied. Due to the variation of the liquid level, a change in the photodetector output is observed. The length of the empty portion of the tank is noted by a scale attached to it. The length of the liquid level can be estimated by subtracting the empty length of the container from its total length. With variation of the liquid level, different readings are recorded. The output reading versus the scale reading (i.e., the empty length of the container) is plotted in Fig. 10. The reproducibility is checked by performing the experiment a number of times. A logarithmic plot of these data gives a straight line.

With this setup one can measure the empty portion above the liquid. So to measure the depth of liquid one should know the total depth of the container. Unlike other types of level detector, this sensor has no interaction with the liquids: no chemical or electrical change occurs in the liquid, as may happen in capacitive and potentiometric methods. The sensor is independent of the optical properties of the liquid. But at the same time, in using this sensor some care should be taken. In designing the sensor probe it should be checked that the distance between the optosensor and the maximum extent of the liquid column is at least 10 to 15 cm. The density of the liquid needs to be considered in choosing the material of the float. By this sensor a liquid

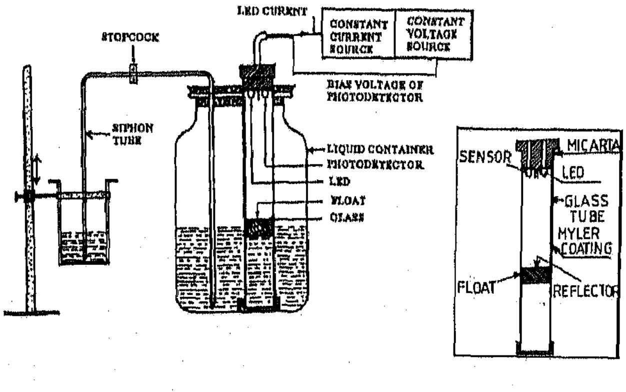

Fig. 9 Experimental setup for water level meter. *Inset*: Schematic diagram of the float.

length of about 80 cm can be measured with an accuracy of the order of 0.5 mm.[28]

7 Conclusion

In our laboratory, in looking for a continuous liquid level meter, we found that existing sensors have demerits, including cost. In this work we have described a new low-cost type of continuous liquid level meter using an optosensor comprising a glass tube, a LED, photodetector, and a reflector float. For this purpose the light propagation through the glass tube has been investigated and an empirical law of propagation with distance inside the glass tube has been established. The present sensor can detect a liquid level up to 80 cm with an accuracy of the order of 0.5 mm. With better design the accuracy may be further improved.

The principle may be applied to develop other sensors to measure pressure, vacuum, and weight. One weighing machine is being designed based on the present principle. Experiments are being conducted to explore the possibility of utilizing this principle to develop other sensors as well.

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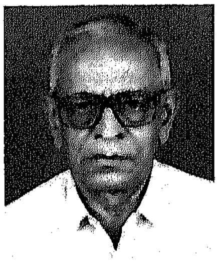
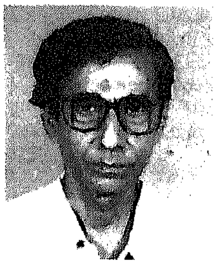
N. B. Manik graduated with physics honors from Jadavpur University, Calcutta in 1991 and subsequently did his MSc and PhD in 1993 and 1998 respectively from the same university. During his research period, he has worked in the areas of cryogenic instrumentation, particularly in the development of cryogenic level meter using opto-sensors. After his PhD, he joined as a lecturer in the Department of Physics of the same university. Along with development of different instrumental techniques for computer based low temperature measurement and control systems, and optical cryostat, he is recently working on the study and development of optical detector and solar cells using semiconducting conjugated polymer and organic dyes. From 1998, he has been working as the Advisor (Honorary) of Cryoinstrumentation Division of the Advanced Centre of Cryogenic Research Centre-Calcutta. He has around 15 publications in different national and international journals.



S. C. Mukherjee obtained his MSc and PhD degree (electronics timing circuits) in applied physics from Calcutta University in 1948 and 1968 respectively. Subsequently, he served in different capacities in India Electric Works Ltd., Marshall Sons and Co. Ltd. as a research assistant, and then as a lecturer in electronics and communication engineering in Bengal Engineering College, before finally joining as an engineer for research and development of instruments in the Saha Institute of Nuclear Physics, Calcutta in 1966 where he continued to work till 1988. Thereafter, he worked as Head and Advisor of Cryogenics Instrumentation Division at the Advanced Centre of Cryogenic Research Centre, Calcutta until 1999. He has guided three PhD theses and has published about fifty research papers. He is a fellow of the Institution of Electronics and Telecommunication Engineers, India.



A. N. Basu received the PhD degree in physics from the Calcutta University, Calcutta, India in 1972. During the mid-sixties, he joined Jadavpur University, Calcutta as a lecturer in physics, became a professor of physics in the eighties and still continues teaching and research in the same university. He has worked in different areas of condensed matter physics and material science. His recent contributions and interest are in the areas of superconductivity, low temperature instrumentation (liquid nitrogen) including optical measurements, and foundational problems of quantum mechanics. He has almost 125 publications in his credit and more than 15 students have done their PhD degrees under his guidance.