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Plastic fiber optic sensor for continuous liquid level monitoring

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ABSTRACT

The study demonstrates the development of a novel low-cost plastic optical fiber (POF) based sensor for liquid level measurement. The sensor works on the principle of reduction in scattering-based optical losses (in contrast to the increase in optical losses for evanescent wave-based sensing) in a straight decladded fiber with an increase in the liquid level due to refractive index changes in the medium surrounding the fiber. A compact optical setup is developed in-house consisting of two U-bent fiber probes coupled to a single LED on one end and two photodetectors on the other ends to measure the optical intensity changes. One of the U-bent probes is decladded over the length of the fiber to act as a test probe to measure the liquid level, while the other probe acts as a reference to compensate for the light intensity fluctuations due to light source instability and ambient conditions. The difference in voltage responses of the two photodetectors gives a measure for liquid level. We have investigated the fiber optic level sensor response to rising and falling liquid levels over 55 cm in presence of aqueous liquids of different refractive index values (1.33 to 1.38) and 95% ethanol as well as DI water at various temperatures from 16 °C up to 70 °C. A level sensitivity of 1.4 and 3.3 mV/mm for water level changes was obtained for the liquid level below and above 45 cm respectively. In addition, the fiber optic level sensor shows a stable and reproducible response over several cycles of 30 min duration at different liquid levels. The results demonstrate that this fiber optic level sensor is not only easy-to-make, cost-effective and robust but also offers sensitive, stable and reproducible instantaneous level measurements.

1. Introduction

Instantaneous monitoring of liquid level is an indispensable requirement in many processes and chemical industries that involve long storage containers for water, oil, fuel/petroleum and chemicals [1]. A wide range of liquid level sensors have been reported in the literature for monitoring the liquid level. Conventional level sensors available in the market are mainly based on mechanical [2–4], ultrasonic [5], and electrical [6] techniques. These sensors are mostly meant for point measurement and often limited by bulk size, susceptibility to interferences or inadaptability for conductive liquids or in potentially explosive environments. Optical sensing schemes have been proposed to overcome these limitations by exploiting their improved safety, low maintenance cost, less mechanical moving parts and continuous level measurement [7].

Over the past three decades, several compact and reliable fiber optic sensing schemes have been realized that give rise to a change in frequency spectrum/characteristic wavelength or light intensity with the change in liquid level. Most of these sensors rely on a change in the refractive index (RI) around the sensing element due to a change in the liquid level. Various fiber optic sensor configurations based on wavelength or phase interrogation including fiber Bragg grating [8], long period grating [10,11], modal interference using few-mode fiber [9,10], multimode fiber [11], D-shaped fiber [12] and polarization-maintaining fiber [13] have been reported in literature for continuous level sensing with a limited liquid level range of ≲20 cm. Although these sensors have demonstrated high sensitivity, they demand precise optical connectors for better coupling and relatively expensive photodetection schemes which increase the overall cost and complexity of the sensor. Evanescent wave (EW) based fiber optic sensors provide an alternative means of low-cost intensity modulation based level sensing, where the optical losses are proportional to the liquid level [14]. However, many EW configurations typically employ silica optical fibers, which are fragile and hence not suitable for wider measurement range (several tens of cm).

POF based sensors are gaining attention as an alternative to silica fibers due to low cost, ease in machinability and optical coupling and robustness [15]. A variety of intensity modulation based POF

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sensing schemes has been reported for single point and multipoint (discrete) level sensing. Bent and side-polished POF either in the form of discrete sensing elements or helically mounted on a solid support have been proposed [16–18]. In other reports, the liquid medium dependent optical coupling between a pair of twisted POF has been demonstrated [19–21]. In addition, micro-holes [22] or V-grooves [23] in a buffered fiber have also been exploited for level sensing. The dynamic range of most of the above sensing schemes was found to be around 5̃0 cm. In a different study, Perez-Ocon et al., have demonstrated an EW based continuous level sensing using a cladded POF coupled to a pair of LED and PIN diode. A large dynamic range of 200 cm was obtained however with a low sensitivity of 1̃2 mV/m [24].

The objective of this study is to develop a highly sensitive reliable,compact and cost-effective sensor for continuous liquid level monitoring in a decladded POF probe coupled to a LED and a pair of photodetector. A proof-of-the-concept POF based level sensor with test and reference fiber probes is realized with water and different RI solutions as the test liquids over a dynamic range of more than 50 cm. In addition, the influence of liquid temperature over level measurement is evaluated. Finally, the stability and reproducibility of the fiber optic level sensor are investigated. A discussion on understanding the functioning of the POF based liquid level sensor, its advantages and limitations over similar sensor configurations is presented.

2. POF based level sensor design

We propose to design a fiber optic level sensor based on the optical losses in a straight decladded optical fiber that change with an increase or decrease in the liquid level due to a change in the RI of the medium surrounding the fiber. However, the measurement of optical losses through an optical fiber interacting with the medium could be an outcome of not only the level changes alone but also the unpredictable fluctuations in the measurement of light intensity caused by light source fluctuations as well as the influence of ambient conditions on the photodetector response. This results in an ambiguity to attribute the sensor response to level changes alone. Hence, a reliable fiber optic level sensor design based on the optical power losses involves the measurement of difference in the optical intensities and thus mandates the use of a reference probe in addition to the test probe for instantaneous level measurements.

In order to realize a simple, compact and highly sensitive fiber optic level sensor for continuous liquid level monitoring over a range of 55 cm, a POF of smaller diameter (0.5 mm) and length 2 L (L is the maximum value of the level) is bent into U-shape. (Note: This is mainly to (i) obtain small footprint of the sensor to be able to insert through a small hole as well as (ii) simplify the optical coupling by keeping the light source and the photodetector on the same side, adjacent to each other and (iii) avoid any need for additional optical components such as beam splitter and lenses required in the case of straight distal end probes.) One of the legs is decladded to function as a test probe to measure the changes in optical intensity changes due to the liquid level change. A reference probe, which is also a U-shaped but cladded POF, is introduced to eliminates the influence of external disturbances such as ambient noise and light source fluctuations. One end of the test and reference probes are coupled to a LED, while their other ends are coupled to two different photodetectors. The optoelectronic components are placed in a compact custom-made plastic block to reduce the footprint of the sensor and realize a portable module with only electrical input and output leads as shown in Fig. 1. An optoelectronic circuitry including a regulated power supply, constant current circuit as an LED driver and a transconductance (photocurrent to photovoltage) circuit is developed to measure the optical power at the end of the test and reference probes in terms of photovoltage in real-time. More details are given in the subsequent section.

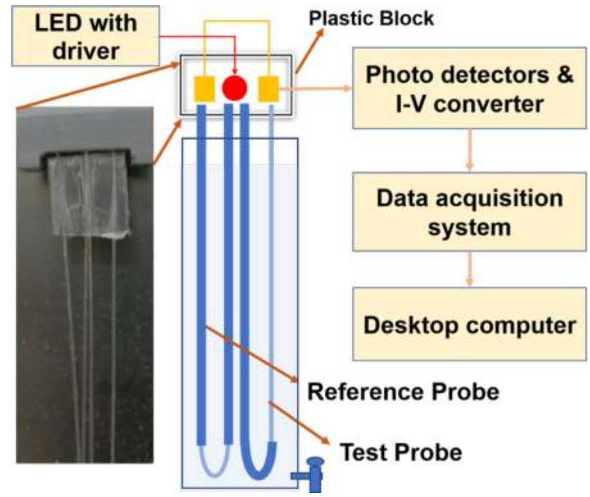

Fig. 1. Schematic showing block diagram of experimental setup consists of two U-bent POFs (decladded region of fiber represented as a thin line) dipped in a 55 cm long liquid column, home-made plastic block to house LED and PDs, optoelectronic circuitry, and DAQ.

3. Materials and methods

POF (0.5 mm, SK20), consisting of polymethylmethacrylate core and fluorinated polymer cladding with RI of 1.49 and 1.41 respectively, was purchased from Mitsubishi Rayon Co., Ltd. Ethyl acetate, Ethanol (98%) and NaCl were procured from Merck, India. Green LED and photodetectors (PD) were procured from Digikey Inc. Data acquisition system (DAQ) card with resolution of 16 bit (USB6002, National Instruments, USA) was used to acquire data from the photodetectors. Milli-Q deionized (DI) water was used in all experiments.

3.1. Fabrication of fiber optic probes

The probes were bent into U-shape to bring the distal ends of the probe adjacent to each other for convenience of optical coupling with a pair of LED and PD. A POF of 110 cm length was U-bent at the center by using heat treatment. Briefly, the distal ends of the fiber were held together and pushed into a 60 cm long glass capillary with an inner diameter of 2 mm. Then the capillary was placed in a hot air oven at 100 °C for 10 min. Heat treatment causes a permanent deformation resulting in U-bent POF probes of 55 cm length [25]. Two such fibers were fabricated to serve as a reference and test probes. It may be noted that the bend diameter of the probes is not an important criterion since the level measurements depend only on the length of a straight portion of the decladded fiber submerged in the liquid of interest.

The test probe was fabricated by decladding the fluorinated polymer layer over one of the legs of a U-bent POF probe by chemical etching. Briefly, one of the legs was dipped in a 100 cm long burette with ethyl acetate, for a duration of 3.5 min. Then, immediately the fiber was wiped with ethyl acetate wet optical fiber tissues. The probes are required to be handled with care while whipping the cladding flakes to avoid breakage of the fiber at any region. The test probe was visualized under an optical microscope to confirm the complete removal of the cladding. The reference probe is fabricated using the same technique, except that only the U-bent region of the probe is precisely decladded by chemical etching followed by visual examination under an optical microscope as described above (Fig. S5). The U-bent region of the reference probe was decladded mainly to match the photovoltage response from the test probe.

3.2. Experimental setup

The experimental set-up as shown in Fig. 1 was used to carry out liquid level measurements with the POF probes. It mainly consists of a home-made plastic block, optoelectronic circuitry, DAQ and a liquid column. The plastic block (made of Delrin) was custom-made to house an LED and two PDs as well as to hold the test and reference probes. After inserting the LED and PDs, the block was sealed to avoid any cross coupling between the LED and the PDs as well as from the ambiance. Cladded ends of the test and reference probes were coupled together to the LED with an optical coupling efficiency of 0.78% (the optical power of LED was > 5 mW, as measured by S150C, Thorlabs Inc. USA). The other end of each of the probes was coupled to two PDs on either side of LED as shown in Fig. 1. The fiber probes are held tightly to a rigid support over their entire length such that the sensing leg is spatially isolated from the other legs in order to avoid cohesion of legs, which may lead to erroneous results.

3.3. Optoelectronic circuitry

The electronic circuitry used to drive the LED and PDs is shown in Fig. S1. A rechargeable 9 V battery was used to power the circuit. A voltage regulator was used to drive the circuit at 5 V. The LED was driven by BJT based constant current source. Voltage signals corresponding to the photocurrents through the two PDs were obtained with the help of resistors in series with the PDs. The voltage signals were fed to DAQ where the signals from the PDs were monitored using NI-DAQ. A LabVIEW program was developed for logging the voltage values from the PDs for differential measurements and real-time monitoring. The difference in the response of the test and reference probes is measured and calibrated in terms of the liquid level.

3.4. Level measurements

The test and reference probes were placed in a graduated glass column with a drain valve at the bottom. The dimensions of the glass column were 5 and 60 cm in width and length respectively. A water pump was used to fill a liquid of interest at room temperature in the glass column (burette) as well as to adjust the liquid level to the desired value. A hose from the water pump was placed at the bottom of the graduated glass column to avoid the formation of any air bubbles in the glass column during filling, which affects the level sensing. The liquid in the glass column is drained by opening the valve at the bottom of the burette. The response from the test and reference probes, as well as differential output, was monitored with changes in the liquid level.

4. Results

4.1. Optical intensity-based level measurements

In this study, we have used a reference probe consisting of a U-bent fiber with cladding while the test probe is decladded over one of its two legs. A sensitive PD (3.2 mA/mW/cm^2 @ 935 nm) was used to monitor the optical intensity changes. Due to this reason, the PD at the end of the reference probe was found to be saturated because of significant optical coupling. Hence, optical losses were introduced in the reference probe by decladding the U-bent region alone. Since the U-bent probes are known for their excellent refractive index sensing applications, this provision also helps in continuous assessment of the refractive index of the liquid under investigation. On the other hand, the test probe was coupled to PD such that the decladded leg of the probe is always towards the PD for the sake of consistency.

Experiments were carried out to investigate the ability of the fiber optic sensor to continuously measure the changes in the liquid level over 55 cm in real-time. Fig. 2a shows the voltage responses of test and reference probes and the corresponding differential output of the liquid (water at room temperature) level changes over time for an increase and decrease of the liquid level. As soon as the liquid level rises and comes in contact with the test and reference probes, an abrupt drop in the voltage response was obtained mainly due to the high RI sensitivity of the decladded U-bent region of the reference probe, bringing the PD into the active region and its response remained almost constant irrespective of the liquid level. Similarly, a small but abrupt drop in the test probe response was observed. This could be attributed to the optical losses due to refraction of the higher order modes soon after of the bend region (fiber bending is known to convert the lower order modes in to higher order modes) at the beginning of the decladded region as a result of a change in the surrounding medium. However, a proportional change in the voltage was observed with a further change in the liquid level during filling as well as draining phase (from 0 cm to 55 cm with a volume rate of 2.4 mL/sec for about 7.5 min and subsequently, draining at a flow rate of $\tilde{1}.8$ mL/sec for about 9.5 min). It is important to note that this response of the POF probes is contrary to the EW based sensing principle. A further discussion on understanding this behavior is presented in Section 5. The absolute voltage response of the test probe at the end of draining phase was typically higher than that of the initial condition (before filling phase). More importantly, while the sensor showed a linear response during the filling phase and a curvilinear response was observed during the drain phase with a significant variation amongst the three test probes investigated here (Fig. 2b). One important observation was the presence of a significant number of small water droplets remaining on the surface of the test fiber probes during the drain phase, probably due to certain surface defects on the fiber core (formed during the decladding process) and a relatively hydrophobic nature of the PMMA surface (Fig S2, Supplementary material). Despite the absence of liquid medium around the fiber sensor, these droplets can significantly alter the refractive index surrounding the fiber core, leading to an altered voltage response from the test probe, resulting in a severe hysteresis in the sensor behavior. Fig. 2c shows the sensor response plotted against liquid level based on the voltages recorded during the filling phase. The sensor response to level variation is neither linear over the range of interest as shown in simplified Eq. 5 (see supplementary material) nor exponential as anticipated in Eq. 1 (see supplementary material), which could be more suitable for a few-mode optical fiber. This behavior could be attributed to the existence of a large number of modes and their interaction with the medium. From Fig. 2c, a linear fit (sensitivity) was introduced between 0–45 cm (1.4 mV/mm) and 45–55 cm (3.3 mV/mm) with a resolution of 0.21 and 0.09 mm respectively.

4.2. Sensor response to liquid media of different refractive indices

The sensor response is expected to be highly sensitive to the refractive index of the liquid under investigation as described in Section 2.1 and shown in Eq. 5. The fiber optic level sensor response was evaluated for salt solutions of refractive index values 1.33, 1.36 and 1.38, in addition to ethanol (98%) having a RI value of 1.363 (measured with Atago PAL1 digital refractometer). Experiments were carried out with three different sets of test and reference probes placed in a glass column as described in the previous section. The level sensor response was monitored in real-time while a liquid of a given RI value was filled and drained. Fig. 3 shows

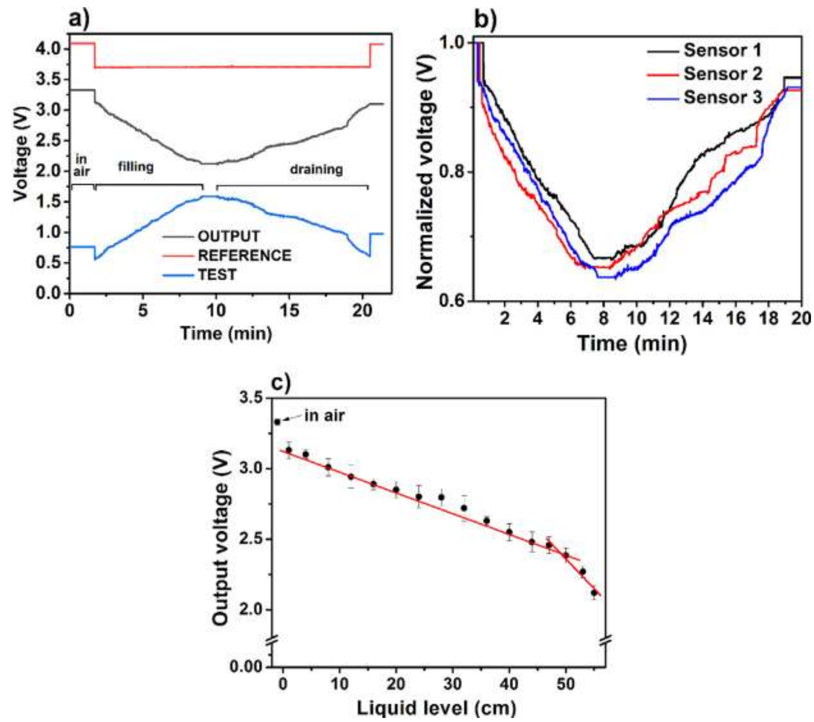

Fig. 2. (a) Sensor response recorded in terms of voltage while the 60 cm long glass column is continuously filled and drained with water over time of 20 min. (b) Normalized voltage response from three different test probes over time. c) The relationship between output voltage and the liquid level.

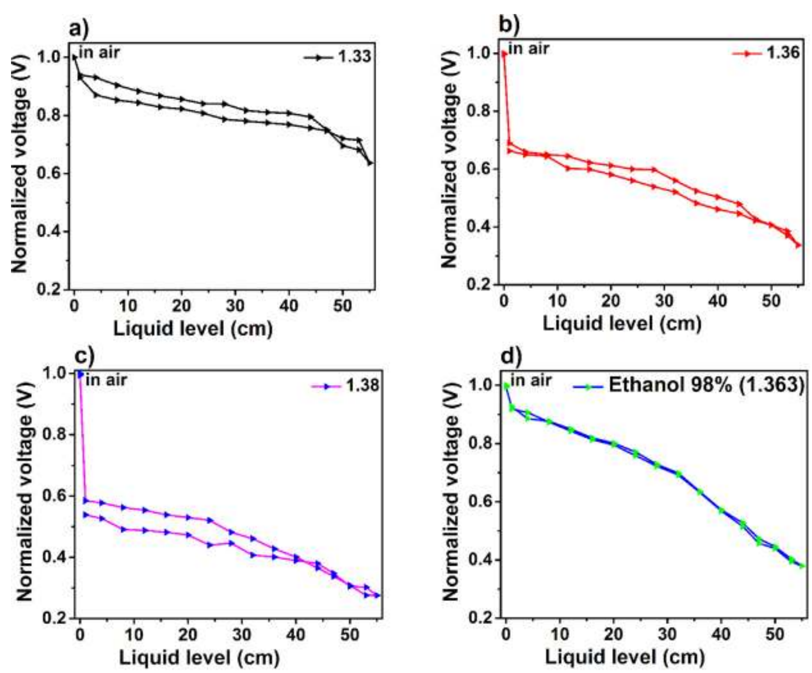

Fig. 3. Normalized differential voltage response from the fiberoptic level sensor subjected to filling and draining of liquids of different refractive index values including salt solutions of RI (a) 1.33 (no salt), (b) 1.36 and (c) 1.38 as well as (d) ethanol 98% with RI value of 1.363.

normalized response of differential voltage from the sensor. Two key observations from the salt solutions include (i) a considerable increase in negative slope of the response curve in the filling phase, (ii) more pronounced hysteresis during the draining phase and (iii) an increasing deviation in the voltage response upon completion of one filling-draining cycle with an increase in the RI value of the liquid. However, the sensor response to ethanol 98% showed a negligible hysteresis in comparison to aqueous solutions. The hysteresis in the sensor response was quantified by calculating the maximum and mean of the deviation between the responses for the liquid level rise and drop. The mean of the deviation between the curves was 0.0275, 0.256, 0.034 and 0.005 for the RI solution of 1.33, 1.360, and 1.38 units and 98% ethanol (1.363) respectively. A noticeable observation was the absence of liquid droplets over fiber core after the liquid has drained (due to faster evaporation) in contrast to that of the aqueous solutions (Fig. S2). These experiments with ethanol (1.363) 98% liquid demonstrate the capability of the sensor for the absolute level monitoring with minimal error

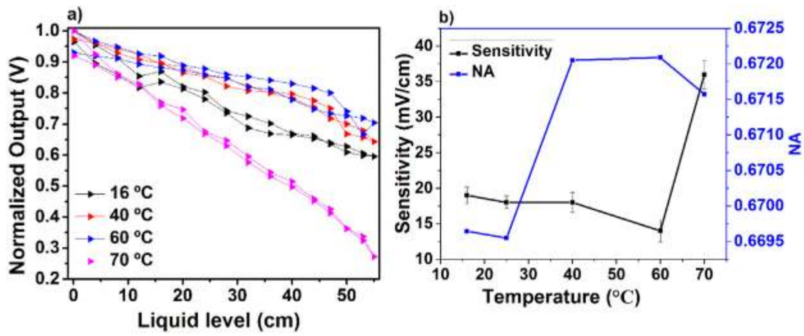

Fig. 4. (a) The relationship between normalized voltage and the liquid level with temperature various of 16 °C, 40 °C, 60 °C and 70 °C (b) The relationship between sensitivity vs temperature of 16 °C, 25 °C, 40 °C, 60 °C and 70 °C having sensitivity of 1.9, 1.8, 1.8, 1.4 and 3.6 mV/mm respectively.

due to extremely low hysteresis compared to the aqueous liquids. We attribute this behavior in our experiments to the rapid draining rates and the defects or dust particles on the fiber core surface that result in sites for accumulation of liquids such as water. One of the possible solutions to this problem could be the formation of a thin hydrophilic polymer coating over the fiber core. However, such investigations deserve a separate study.

4.3. Sensor response to liquid media at different temperatures

Temperature variation is known to significantly alter the refractive index properties of the liquid medium of interest, which in turn is going to influence the level measurements by the fiber optic sensor. In addition, the temperature of the medium is expected to alter the RI of fiber core (at least at its interface with the medium), thereby causing a significant change in the NA of the fiber with the medium. POF is functionally active over a limited temperature range, given their much lower melting point in comparison to fused silica fibers [30]. For example, PMMA is known to undergo deformation above 80 °C [30]. Hence, the performance of the proposed fiber optic sensor is investigated in presence of DI water heated to various temperatures including 16, 25, 40, 60 and 70 °C. The normalized sensor response during filling and draining phases of each of the media is shown in Fig. 4a. A comparison of the sensitivity of the sensor for DI water at different temperatures is shown in Fig. 4b. A gradual drop in the sensitivity was observed with increasing temperature of the liquid medium up to 60 °C followed by a sudden two-fold increase at 70 °C. It is interesting to note that the considerable decrease in the refractive index values of water (from 1.33 to 1.32438) and PMMA (1.49 to 1.487) with an increase in temperature (from 16 °C to 70 °C) as shown in Table S1 [31,32]. However, as a consequence, a 2.5% rise in NA of the fiber optic level sensor can be obtained. However, the drop in the level sensitivity is more pronounced (as much as 26%) than the rise in the NA. Similarly, the drop in NA at 70 °C (<0.5%) is much smaller in comparison to the sharp increase in the level sensitivity (100%). Thus, no considerable change in NA was obtained that matches well with the significant changes in the level sensitivity, indicating the least dependence of the sensor response on the NA of the decladded fiber. However, these results demonstrate that the sensor response is predictable for temperatures below 70 °C and hence the suitable working temperature range for the sensor is up to 60 °C. One important observation is the reduction of hysteresis in the sensor response at 70 °C. Since the fiber optic level sensing is a highly interfacial phenomenon and the temperature changes are known to alter the waveguide material properties, the sensor response is anticipated to be highly influenced by the minute morphological changes at the core-medium interface. We attribute the reason to the softening of PMMA at the core-medium interface and reduced surface tension of water at an elevated temperature resulting in reduced surface energy and hence lower probability of water droplet retention.

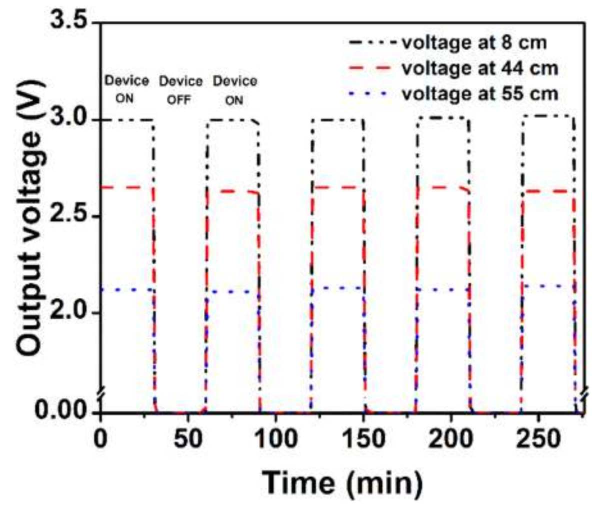

Fig. 5. Temporal response of the sensor over four hours indicating a stable response. The sensor was switched 'ON' for 30 min and then switched 'OFF' for the next 30 min at different liquid levels.

4.4. Stability of sensor response

One of the limitations of the optical sensors is relatively higher power consumption in comparison to electrical sensors, which is a major concern, especially with battery operated devices. Hence, one of the important requirements of the level sensor is the ability of the sensor to accurately and instantaneously measure level as and when the sensor is switched ON irrespective of changes in the liquid level in comparison to the previous measurement. Fig. 5 shows the sensor response recorded for several ON/OFF cycles with 30 min duration when the liquid level was maintained at 8, 44 and 55 cm. When the sensing device was switched ON, it took 6̃0 s for the sensor response to stabilize back to normal value whenever the device is switched on. In addition, the stability of the sensor was investigated by repeating the experiments thrice (n = 3) and recorded its response for a constant level continuously over 12 h (data not shown). The error was found to be up to ±9 mV (0.3% of full-scale value, 3 V), which could be attributed to evaporation of water in the glass column.

5. Discussion and conclusions

In this study of POF based liquid level sensor, an increase in optical power coupling at the PD was observed with a rise in the

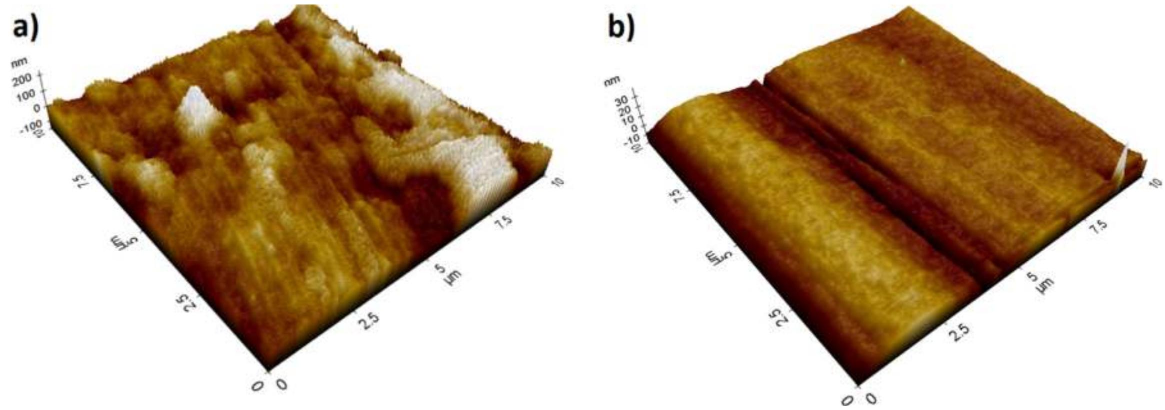

Fig. 6. AFM of a) decladded POF b) bare POF. Decladded POF shows a rough surface through the decladded surface with a roughness of 80 nm whereas the bare POF shows a smooth surface over the entire length.

liquid level, when the air is replaced with a liquid as the surrounding medium around the decladded fiber (Fig. 2a). This is in contrast to the EW based fiber optic level sensors with a long decladded fiber acting as a sensing element, which typically gives rise to optical power attenuation [14] (Please refer to Section S2 in the supplementary material). In order to understand the underlying phenomenon of POF based level sensor, further investigations were carried out on a short POF decladded over 5 cm placed in a glass capillary, while passing a green light through the fiber. Visual observations and optical images (Fig. S3, Supplementary material) of the decladded straight POF probes in the air show a significant amount of light leaking/scattering throughout the decladded region as shown in Fig. S3. However, a substantial drop in the scattered light was evident as soon as the glass capillary is filled with DI water. We anticipate the presence of defects on the fiber core surface, formed probably during the decladding process, that substantially refracts light out of the waveguide. Scanning electron microscopic images of the decladded POF surface were obtained to investigate the surface morphology and compared with conventional decladded silica fibers (Fig. S4, Supplementary material). Further, the decladded POF surface was characterized with atomic force microscopy (AFM) and compared with cladded POF (bare), showing arms roughness of about 80 nm, while the bare surface remains smooth as shown in Fig. 6. This evidently shows the presence of defects that possibly have led to the scattering of the light at the decladded fiber surface [26,27]. Hence, we propose the reduction in scattering-based optical losses as the phenomenon responsible for the working of POF based level sensor. It is important to note that our group has explored the U-bent POF based RI sensors utilizing the EWA phenomena, where the scattering is negligible [28,29]. A significant increase in scattering losses from the decladded POF under this study could be attributed to the difference in decladding conditions followed: while the U-bent region of fiber probes are chemical etched using ethyl acetate over a duration of 2 min. typically, POF were etched for 3.5 min. to declad the straight portion for level sensing.

A plastic fiber optic (0.5 mm diameter) liquid level sensor with a measurement range of 55 cm and high sensitivity of 1.4 mV/mm is successfully realized using a straight decladded POF. The performance of the proposed fiber optic level sensor is compared with other designs based on intensity modulation technique reported elsewhere in Table 1. Fiber optic sensor configurations with modified geometry such as jacketed POF with grooves [33], microholes [22] and U-bent POF with lateral polishing for improved sensitivity [16] has been demonstrated for discrete level measurements up to 2 m and a poor resolution as low as 50 mm. A relatively efficient and simpler configuration was realized by winding the POF to a solid support in form of a race-trace helical geometrical structure to exploit higher modes leak out in the bend structure [18]. This sensor configuration resulted in a semi-continuous level measurement over a limited range of 50 mm and sensitivity and resolution of 0.12 dB/mm and 1.67 mm respectively. H–X Zhang et al [20] have exploited cladding mode frustrated total internal reflection based optical coupling within a pair of POF in the form of twisted helical macro-bending coupling structure (THMBCS) to realize a fiber optic level sensor with better range and resolution of 400 mm and 0.3 mm respectively [20]. A further modification of THMBCS with UV optical cement for efficient optical coupling has been demonstrated with 10-fold and 1.5-fold improvement in the sensitivity and the range respectively. Although this sensor configuration shows a better resolution, the fiber optic level sensor based on simple straight decladded POFs could be easier and faster to manufacture. The efficient optical interactions at the decladded fiber surface with the medium and sufficient optical power at the PDs in the proposed sensor allow better signal-to-noise ratio. Measurement of optical intensity losses is carried out with the help of an LED and two photodetectors, which together cost only less than USD 5. The inherent feature of this sensor design is that this sensor can be exploited as a sensitive point sensor as well by monitoring the response of the reference probe (Fig. 2). One of the important advantages of these sensors is their ability to improve the dynamic range for level measurement by simply choosing a larger diameter. POF of diameter up to 2.5 mm are commercially available, using which the dynamic range can be improved by at least 5 times, i.e. up to 250 cm. POF level sensors for beyond 300 cm can be realized by employing multiple test probes decladded at different regions along their length. Thus, the POF level sensor designed in this study offer several advantages over the previously reported sensing schemes. These sensors are highly suitable for several applications such as water and petroleum storage tanks.

On the other hand, we have noticed certain limitations with respect to the proposed sensor design. Exposure of the probes to turbid media has been found to be detrimental to the sensor performance mainly due to the silt formation on the decladded fiber core surface. This necessitates the requirement for regular maintenance of the probes or an intelligent mechanism to avoid exposure to turbid media with the help of dust filters. In addition, POF sensors are not suitable for harsh chemical environments such as organics, acids, and bases. The POF can be coated with a chemically inert material such as reduced graphene oxide to protect the POF surface and extend the utility of the sensor to certain organic solvents such as alcohols [29].

In conclusion, this study demonstrates the proof-of-concept for use of decladded plastic optical fiber probe as a liquid-level sensor

Table 1
Comparison of liquid level sensors based on optical losses.

Sensor platform	Sample	Measurement range, mm	Sensitivity	Resolution, mm	Ref.
Grooved POF	Ground water level	2000	0.0247 u.a. over 140 cm	200	[30]
Micro-drilled POF (8 holes)	Water	400	Non-linear	50	[22]
Lateral polished multi (8 point) U-bent POF	Water	2000	1.05 dB/m	250	[16]
Helical race-track POF (30 point)	1.35 and 1.38 (RI)	50	0.12 dB/mm	1.67	[18]
Twisted helical macro-bent coupling structures with 2 POFs	Water, sugar and salt solution	400	2.6 nW/mm	0.3	[20]
THMBCS with UV optical cement	Water	600	11.98 nW/mm	0.008	[21]
Straight decladded POF	Water, 1.36,1.38, Ethanol	550	1.4 mV/mm	0.21	Current study

for instantaneous and continuous measurement. POF based level sensor shown here could be a better alternative to some of the other fiber-based level sensors due to its simple LED-PD based instrumentation, ease of probe preparation and compact design. This concept can be extended to measure a smaller level magnitude with better accuracy as well as realize level sensor with a larger dynamic range. Further studies are necessary to extend their use to chemically harsh environments for wider applications.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.sna.2019.07.021.

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