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Liquid-level sensing based on periodic evanescent field absorption from a multimode optical fibre

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The working of a robust, long dynamic range, quasi-continuous fibre-optic liquid-level sensor is demonstrated in this communication. The sensor principle is based on periodic evanescent light wave absorption when rising level of liquid gradually replaces the surrounding air medium from a periodically uncladded step-index multimode optical fibre which would cause local variation in normalized frequency parameter (*V*) of the fibre. With our proposed sensor design, liquid-level variation as small as 2.5 cm can be measured with high accuracy and repeatability, which can be further enhanced by reducing the spacing between two adjacent regions of the fibre. Owing to its simplicity and robustness in operation, we envision that the proposed sensing technique could emerge as an alternative to the existing optical-based liquid-level sensors.

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WITH the availability of inexpensive optoelectronic components in the market, a large number of fibre-optic sensors have been available in the recent past[1–5]. Sensors based on optical fibres offer several advantages over their electronic counterparts such as low power consumption, immunity to electromagnetic interference, geometrical flexibility, multiplex sensing capability and remote monitoring capability. Liquid-level monitoring is important for various industrial and laboratory applications and fibre-optic sensors are ideal for such purposes. Over the last decade a large number of studies related to fibre-optic liquid level sensors (FOLLS) has been reported in the literature[6–11]. FOLLS can be either point contact sensor where rise of liquid level touches the fibre-sensing tip and modulates the reflected signal[6–8], or continuous mode where variation of rise and fall of liquid level changes the second outer cladding of the fibre and thus modulates the signal[9–11]. Although liquid-level variation using optical fibre sensor (OFS) can be monitored by measuring the change in intensity[10], spectral shift[9] and phase change (interferomertic approach)[9] in the output signal, intensity based sensors are the most popular due their robustness, ease of installation and being relatively inexpensive compared to other techniques. Recently, we have reported the working of a FOLLS[12] based on the principle of light signal modulation between two optically coupled fibres due to variation of liquid level in a container. Although continuous mode of liquid-level sensing could be monitored, the proposed technique was restricted to use in vibration-prone medium as it would introduce noise into the system.

In the present communication we report a simple, inexpensive quasi-continuous FOLLS. The sensor principle is based on periodic evanescent light signal absorption from a periodically uncladded step-index multimode optical fibre when rising level of liquid gradually replaces the surrounding air medium of the fibre. Initially, evanescent field from the uncladded regions of the fibre interacts with the surrounding air medium (refractive index $n_{\text{air}} = 1.000$). However, with the rise of liquid level air is gradually replaced by high refractive index medium (e.g. for water $n_{\text{water}} = 1.331$) and thus affects the evanescent field absorption locally at the sensing region of the fibre. With the sensor designed by us, liquid-level variation as small as 2.5 cm can be measured with high accuracy and repeatability.

For a step-index multimode optical fibre with core radius a, core refractive index n_1, cladding refractive index n_2 and operating at a wavelength of λ, the number of modes supported by the fibre is given by[13]

$$N = \frac{4V^2}{2}, \tag{1}$$

The V-parameter is again given by

$$V = \frac{2\pi a}{\lambda}(\text{NA}), \tag{2}$$

where NA is the numerical aperture of the fibre. The output light intensity from the fibre depends on the number of guided modes supported by the optical fibre and for a fixed optical source wavelength this can be varied by either changing the core diameter ($2a$) or the NA of the fibre. In the sensor designed here, we primarily vary the NA of the optical fibre locally by changing the refractive index of the surrounding medium in a periodically uncladded optical fibre. This would affect the output optical power. A step-index multimode optical fibre is uncladded at a regular intervals so that the core region of the fibre is directly exposed to the air medium. For a fixed length of optical fibre with all its uncladded regions exposed initially to air medium, the number of light modes supported by the fibre would be fixed. However, with the rise of liquid level along the fibre length, the surrounding air medium would be replaced by the liquid medium causing a local change in V-parameter in the sensing region of the fibre. This would modulate the output light signal intensity. Equation (2) implies that output light intensity from the fibre would decrease with the rise of liquid medium and vice versa.

Schematic of the experimental set-up of FOLLS is shown in Figure 1. It consists of a laser diode (LD; 650 nm, 2 mW output), an objective lens, plastic clad silica (PCS) step-index multimode optical fibre, 2×1 fibre coupler, a silicon photodetector and a liquid container. Light signal from the LD is coupled to the optical fibre of diameter 980/1000 μm, numerical aperture 0.37. The other end of this fibre is connected to the input port of the coupler. The output port is coupled to the sensing fibre of length 1.5 m, diameter 980/1000 μm and NA 0.37, which is uncladded at a regular spacing of 2.5 cm in 1 m length. The plastic clad of the fibre is removed by burning it in oxygen-rich LPG flame at a temperature of ~500–600°C. In order to remove equal length of clad region from the fibre, we used a pointed flame and the fibre was kept firmly on the holder so that it did not move or bend during uncladding process. Approximately 2–3 mm length plastic clad of the fibre at a spacing of 2.5 cm in 40 numbers was uncladded to sense 1 m length of liquid-level variation with the sensor. The advantage of the PCS fibre is that the core region consists of silica material which is hydrophobic in nature and thus water molecules would not stick to the side wall when there is a fall in level in the container. The end port of the fibre is silver-coated to a thickness of ~200 nm, so that it acts as a reflecting mirror for the forward propagating light signal. The fibre is placed inside a cylindrical tube of length 1 m and diameter 15 cm, where liquid can be filled by pouring it from the outside. The back-reflected signal from this fibre propagates in the reverse direction to reach to the Si-photo detector.

To study the sensor characteristics, initially the container was kept empty and then water was poured slowly to note the responses of the sensor. For every 2.5 cm rise of liquid level, it touched an unclad region of the sensing fibre and thus modulated the intensity of the output light signal. Figure 2 illustrates the sensor response rise and the present sensor. Figure 2 also includes a zoomed in view data of the sensor during rise of liquid level in the container in the length scale 30–38 cm. The step-response characteristics clearly indicate that the sensor responds to the rising level of liquid periodically in the length interval of 2.5 cm and remains insensitive within this length. The unequal step-response which has been observed in this length scale is attributed to uneven decladding of the sensing fibre during fabrication process and deposition of external micro particles on the sensing region and might interact with evanescent field form the optical fibre. The zoomed in view data of the entire response curve, in fact, reveal that sensing regions of the fibre were not equally uncladded during fabrication process, which resulted in unequal step-response curve almost all along its length. For falling mode of level a small deviation has been observed in the sensor responses, which is attributed to the fact that water molecules might be placed at the edge of the plastic clad and the core fibre and thus perturb the sensor reading.

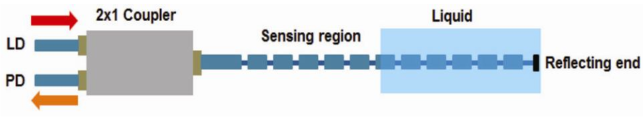

Figure 1. Schematic set-up of the proposed liquid-level sensor.

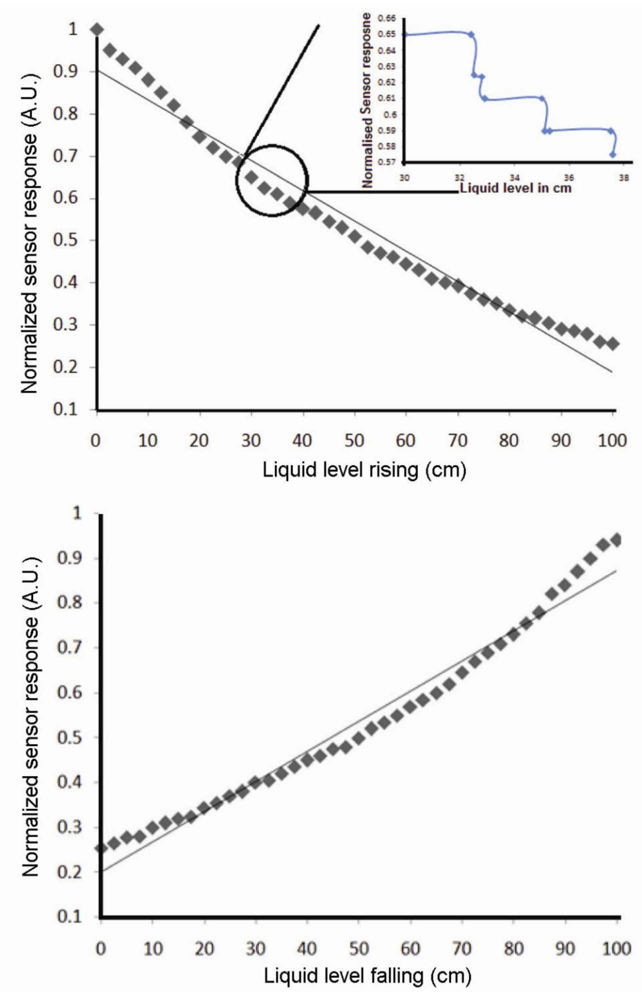

Figure 2. Normalized sensor response for rise and fall in water level in the container. In the top panel zoomed-in view shows the step-like response of the sensor.

The characteristics of the sensor have also been studied for other liquid media. For this we chose propylene as a test sample. Propylene has a refractive index of 1.36, which is higher than the water (1.33) and thus, effective NA of the fibre in the unclad region would be smaller for propylene when it replaces the surrounding air medium. We compared our sensor responses for this liquid medium with the earlier obtained data for water in the container. Figure 3 illustrates the sensor responses for both media for liquid level rising in the container.

It is evident from eq. (2), that the V-parameter of the optical fibre depends on its core diameter ($2a$). For small core diameter fibre, the V-parameter would be less and therefore light signal intensity at the output port of such sensing fibres would be less. The normalized value of the sensor responses for 1000 and 600 µm diameter fibre is shown in Figure 4.

Owing to the nature of the sensing scheme, we observed similar trend in the characteristic curve. However, for smaller core diameter fibre the output light signal voltage received by the detector was found to be smaller than the bigger core diameter fibre. Similarly, for optical fibre of

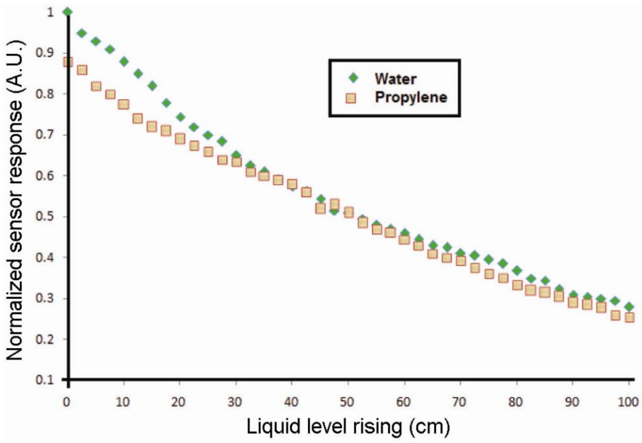

Figure 3. Comparison of sensor responses for water and propylene solution rising in the container.

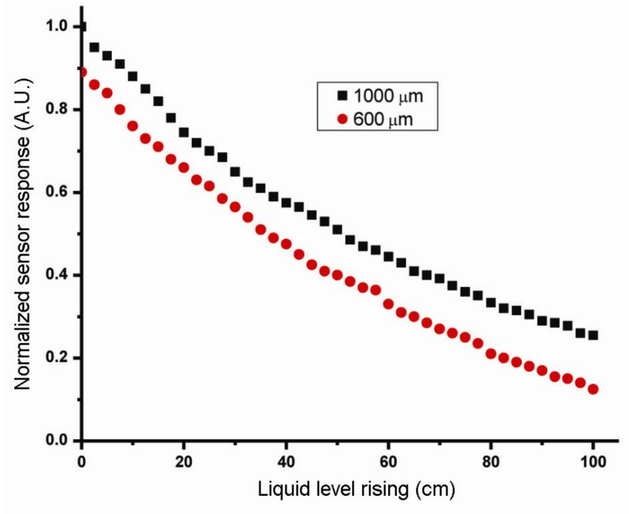

Figure 4. Sensor characteristic curves for 1000 and 600 μm diameter sensing optical fibres when water level rises in the container.

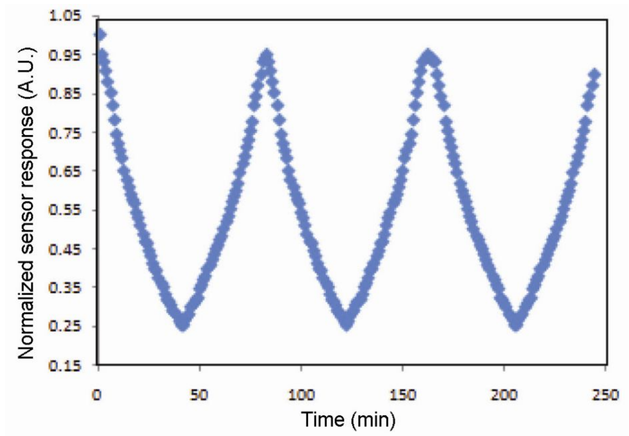

Figure 5. Repeatable characteristic of the proposed sensor.

larger core diameter (>1000 μm), it can be presumed that the V-parameter would be more and hence larger amount of light signal intensity would be carried by the sensing fibre to the detector section of the sensor.

We also studied the repeatability characteristic of the sensor. For three continuous cycles of water-level variation in the container, the sensor responses have been noted. Figure 5 illustrates the characteristic curve. The periodic variation of the sensor response signal with the level variation indicates that the proposed design is highly reproducible in nature. This characteristic has been observed for six weeks and we noticed similar response curves each time.

Because of the nature of the modulation scheme and the type of optical fibre (PCS) used in the present work, the proposed technique is robust and can be useful for monitoring liquid-level variation of any solution which is non-corrosive and non-reactive with the fibre. The unique advantage of the quasi-continuous liquid-level sensor is that output modulated light signal can be easily digitized by connecting simple electronic circuit to the detector section of the sensor. For completely uncladded optical fibre, although, continuous liquid-level variation and better sensitivity can be achieved, digital conversion of the modulated light signal would not be possible. In the sensor designed by us, the minimum liquid-level variation that can be measured is 2.5 cm, which is the spacing between two adjacent uncladded regions of the fibre.

In summary a robust, inexpensive, quasi-continuous fibre-optic liquid level sensor has been designed by us. Liquid-level variation as small as 2.5 cm can be detected with accuracy and repeatability, which can be further enhanced by reducing the periodicity of the unclad region of the fibre. As the response of the sensor is dependent on the refractive index of the surrounding medium, we can estimate the refractive index of an unknown medium (higher or lower than the reference medium, e.g. water) from the characteristic response of the sensor. The performance of sensor for long dynamic range (>2 m) application will be studied in the future.

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