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Fiber-optic liquid level monitoring system using microstructured polymer fiber Bragg grating array sensors: performance analysis

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ABSTRACT

A highly sensitive liquid level monitoring system based on microstructured polymer optical fiber Bragg grating (mPOFBG) array sensors is reported for the first time. The configuration is based on five mPOFBGs inscribed in the same fiber in the 850 nm spectral region, showing the potential to interrogate liquid level by measuring the strain induced in each mPOFBG embedded in a silicone rubber (SR) diaphragm, which deforms due to hydrostatic pressure variations. The sensor exhibits a highly linear response over the sensing range, a good repeatability, and a high resolution. The sensitivity of the sensor is found to be 98 pm/cm of water, enhanced by more than a factor of 9 when compared to an equivalent sensor based on a silica fiber around 1550 nm. The temperature sensitivity is studied and a multi-sensor arrangement proposed, which has the potential to provide level readings independent of temperature and the liquid density.

Keywords: Fiber Bragg gratings; Polymer optical fiber sensors; Liquid level monitoring systems, High sensitivity.

1. INTRODUCTION

Liquid level monitoring is of great importance in many industrial applications, such as aircraft fuel systems, flood warning, water supplies or biochemical processing, etc. Most traditional liquid level sensors are based on mechanical and electrical techniques. However they suffer from intrinsic safety concerns in explosive environments, such as fuel storage facilities. In recent years, to overcome this problem, many optical fiber liquid level sensors have been investigated, which are based on different operating principles [1,2]. Amongst these, many types of liquid level sensors based on fiber Bragg gratings have been demonstrated [3-7]. However, these sensors exhibit some drawbacks, such as low sensitivity [2,7], limited range [3,5-7], long-time instability [4] limited resolution [1] expensive cost [1], weakness [1-3], and complicated manufacture [1,3-7]. In this paper, a simple liquid level monitoring system based on mPOFBG array sensors showing high sensitivity is investigated. The new configuration is based on five mPOFBGs inscribed in the same fiber in the 850 nm spectral region, providing the potential to interrogate liquid level by measuring the strain induced in each mPOFBG embedded in a silicone rubber (SR) diaphragm. The performance of this sensor is compared with a similar sensor incorporating an FBG inscribed in silica fiber and shown to exhibit a factor of 9 improvement in sensitivity, resulting from the much lower Young's modulus of POF compared to silica fiber. Compared with other devices in the literature, the proposed configuration displays much greater sensitivity (more than four times that of the best sensitivity published [8]), a highly linear response, good stability and repeatability. Also, the temperature behavior and measurement resolution were studied in detail.

2. DESIGN OF SENSOR ARRAY

2.1 Fabrication of mPOFBGs and diaphragm preparation

Five identical mPOFBGs were inscribed in a doped mPOF fabricated from poly(methyl methacrylate) (PMMA) – for details of the fabrication see [9]. The mPOF has a core diameter of ~6 μm and an outer diameter of ~125 μm. This fiber has been chosen to benefit from its relatively low loss of 7 dB/m in the 850 nm spectral region in order to optimize the reflectivity of all gratings whilst having a long length of polymer fiber. Furthermore, with this configuration (strong FBGs in series configuration) we only need to use one optical coupler to interrogate the five FBGs inscribed in the same mPOF. Using a single 75 cm long fiber, the five multiplexed mPOFBGs are inscribed spatially separated by 15 cm. A CW He–Cd laser with an output power of 30 mW at 325 nm was used to inscribe the grating array in the doped mPOF. This fiber has an optimum inscription time of 11 minutes [9]. The inscription process was monitored using a superluminescent diode from Superlum centered at 830 nm (with a spectrum width of 40 nm) and an optical spectrum analyzer (OSA) connected to an 850 nm single-mode silica coupler. To obtain five gratings with different wavelengths, we used two different phase masks (itches of 557.5 and 580 nm) and made use of the thermal annealing process to

change their wavelengths [10]. Following grating inscription, the 75 cm long mPOF containing FBGs was UV-glued (Norland 78) to one 8° angled silica fiber pigtail. Thereafter, the SR solution was prepared by mixing homogeneously two liquids (SILASTIC® T-4 Base and Catalyst from DowCorning Corporation) in a ratio of 100:10 by volume. The prepared SR solution was poured in a 50 mm diameter plastic container with a height of 1.1 mm (see Fig. 1(a)), in which was also placed the POF containing the FBG. It shall be noted that the key element of the sensor is the diaphragm fabrication and additional care was taken to ensure the mPOFBG was at the center of each diaphragm (Fig. 1 (a)). With regard to uniformity, the diaphragms obtained had thicknesses around 1.080 ± 0.005 mm. The mold was kept undisturbed for 24 hours at room temperature to allow the SR to set.

2.2 mPOFBG array sensors

This is a new development that builds on the idea of determining liquid level by measuring the pressure at the bottom of the liquid container, but with some critical advantages. The system features several FBG-based pressure sensors as described above placed at different depths. Any sensors that are above the surface of the liquid will all read the same ambient pressure. Sensors below the surface of the liquid will read pressures that increase linearly with depth. The position of the liquid surface can therefore be approximately identified as lying between the first sensor to read an above-ambient pressure and the next higher sensor. This level of precision would not in general be sufficient for most liquid level monitoring applications; however a much more precise determination of liquid level can be made by linear regression to the pressure readings from the sub-surface sensors, as shown in Fig. 1(b). There are numerous advantages to this latter multi-sensor approach: first, the temperature induced wavelength shift in the individual sensors, as well as the temperature induced changes in the sensor pressure sensitivity, are automatically compensated; second, the operation of the system is not affected by changes in the density of the liquid and finally, it provides the possibility to detect and compensate for malfunctioning sensors. The design of the prototype multiple sensor configuration consists of a square acrylic tube (800 mm length, with 3.2 mm wall thickness and 38.1 mm outside dimension), with windows drilled at equidistant positions along it as shown in Fig. 1(c). It contains five sensors positioned over 15 mm diameter holes spatially separated by 150 mm. The sensors were then placed and sealed at positions aligned with the window positions such that the FBG center was aligned with the window center. A thin layer of silicone sealant was used to seal effectively the sensing area and a slight strain was applied to the diaphragm when it was sealed to avoid hysteresis effects. With the tube sealed at the bottom, and open at the top, the atmospheric pressure inside the tube remains relatively constant. The system relies on increasing hydrostatic pressure deforming the diaphragms causing the fiber to become elongated, which results in a positive shift in the Bragg wavelength; otherwise, the internal pressure matches the external pressure and the diaphragm is not deformed.

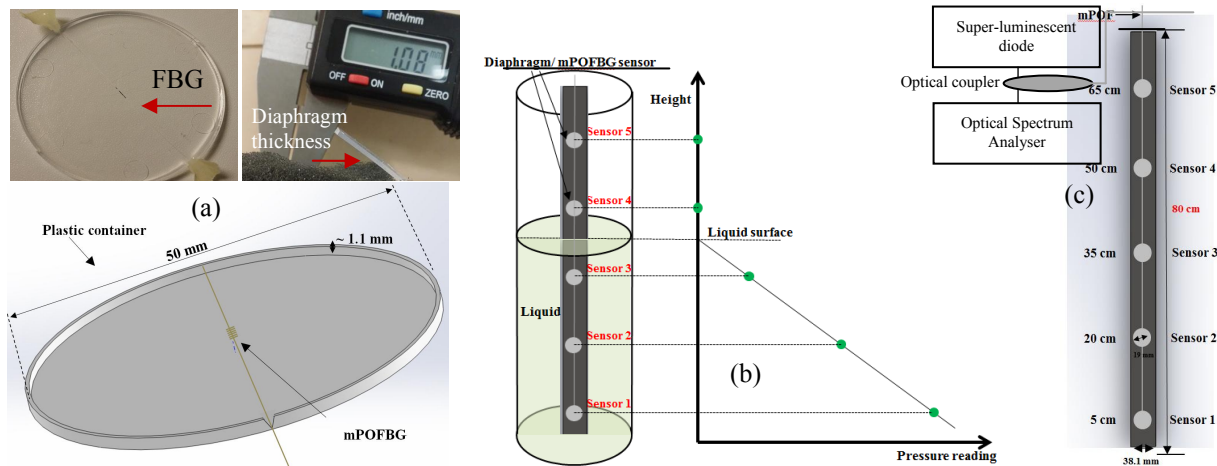


Figure 1. (a) Plastic container used for the diaphragm fabrication and an image of the SR diaphragm. (b) Five discrete pressure sensors with three submerged in liquid: determination of liquid level using linear regression. (c) Experimental apparatus and diagram of the acrylic tube sensor arrangement using mPOFBG array sensors.

3. EXPERIMENTAL RESULTS AND ANALYSIS

The mPOFBG array sensor system was installed in a liquid container of 80 cm height with an inner diameter of 94 mm. The experimental setup consists of a super-luminescent diode centered at 830 nm, a silica single-mode 850 nm coupler,

and an OSA (see Fig. 1(c)). The sensor performance was tested within a liquid level range of 0 to 75 cm and with a liquid level increment step of 2.5 cm. Three cyclic tests were performed to investigate both increasing and decreasing levels of the liquid. Figure 2(a) shows the first cycle of the sensors 1 and sensor 3. The wavelength shift was extracted and the sensitivity of each sensor was calculated, showing a sensitivity of 98.6 ± 0.3 pm/cm (sensor 1), 98.1 ± 0.2 pm/cm (sensor 2), 98.4 ± 0.6 pm/cm (sensor 3), 97.6 ± 0.8 pm/cm (sensor 4), and 86.1 ± 2.6 pm/cm (sensor 5), respectively. In terms of sensitivity variation between each sensor, one can see that there is a slight discrepancy coming from sensor 5 – we believe that this is due mainly to the fiber thermal annealing process used in the sensors 1, 2, 3 and 4 and not in the sensor 5 [11]. Also, there are some limitations (amount of silicone used and slight strain applied to the diaphragms when they are sealed to the prototype), in terms of the manual assembly which could be significantly reduced in a proper manufacturing process. To guarantee the stability of the sensor, a constant liquid level was maintained for a period of 5 minutes at each step before the reading was taken. Less than 3 pm shift of the central wavelength was observed over each such step period. The temporal response of the liquid-level array sensor system at room temperature is illustrated in Fig. 2(b). With the liquid level varying repeatedly from the top of the container to the bottom and so on, the sensor system has good stability, a good linearity, and is able to provide consistent results. By combining information, the depth of the liquid could be determined with a resolution of better than 1 cm. Our results can be seen to compare very favourably with previous results in terms of range-to-resolution [1-7], which represents the number of effective measurement points.

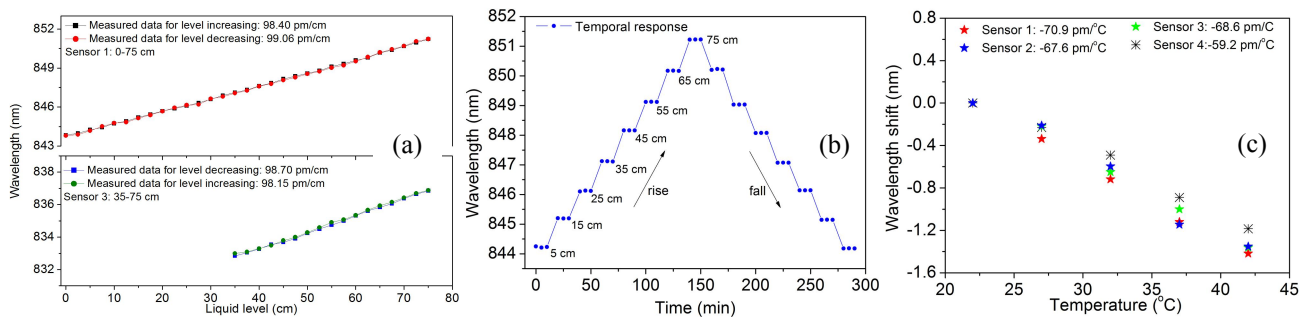


Figure 2. Cyclic response for: (a) sensor 1 and 3. (b) Temporal response during rise and fall of liquid. (c) Wavelength shift vs. temperature variation for submerged sensors (sensor 1, 2, and 3) and the sensor out the liquid (sensor 5).

Additionally, experiments were carried out to explore the temperature response of the sensors. For this experiment three sensors (sensor 1, 2, and 3) were submerged and sensor 4 was kept out of the liquid to compare the temperature behavior. The entire prototype was then placed in an environmental chamber (Sanyo Gallenkamp) under varying temperatures to study its response. The temperature was increased from 22°C up to 42°C with steps of 5°C. In each step, the temperature was kept constant over 2 hours to ensure thermal equilibrium was achieved. Fig. 2(c) shows the measured wavelength shift of each sensor at different temperatures. From Fig. 2(c), the change in Bragg wavelength over the 20 temperature variation was obtained for sensors 1 to 4 giving -1.42 nm, -1.35 nm, -1.36 nm and -1.18 nm, respectively. It may be seen that the sensor out of the water (sensor 4) shows significantly less sensitivity (see Fig. 2 (c)) to temperature when compared to the submerged sensors; this topic is currently under investigation.

From Fig. 1(b), the determination of liquid level can be made by linear regression to the wavelength shift from sub-surface sensors at different depths. Two cases are presented for liquid surface level analysis using linear regression: first, when the liquid surface level, $L_{surface}$, is at 60 cm and secondly when the $L_{surface}$ is at 47 cm. Initially the container was emptied of liquid and kept undisturbed during 15 minutes at room temperature, after which the Bragg wavelength of each sensor was recorded. Next liquid was added up to a specific level and kept undisturbed for a time of 15 minutes at room temperature. Then, the Bragg wavelength of each sensor was again recorded to determine the wavelength shift caused by the hydrostatic pressure. The results are depicted in Figs. 3(a) and (b), showing for each case the equations of linear fit. For each equation, the position of the $L_{surface}$ will be estimated through the interception of the linear fit with the y-axis. From the first equation presented in Fig. 3(a), we achieved an intercept value of 60.24 ± 0.54 cm, being a value very close to the real value – 60 cm of liquid level. For the equation shown in Fig. 3(b), we achieved a value of 46.16 ± 0.72 cm. The temperature response has an impact on the accuracy of the system. As shown in Fig. 2(c), a temperature rise of 10°C induces a wavelength shift of approximately 0.6 nm. In the case of a single sensor, such a wavelength shift is equivalent to a level change of about 7 cm - from Fig. 2(a) - and so this represents the error that would result from a 10°C rise in temperature. In the case of the multiple sensor system employing linear regression, the slightly different temperature sensitivities of the submerged sensors compared to those above the liquid mean that

temperature changes still cause an inaccuracy in the recovered level, but in this case a 10°C rise is equivalent to an error of just under 0.6 cm in the liquid level.

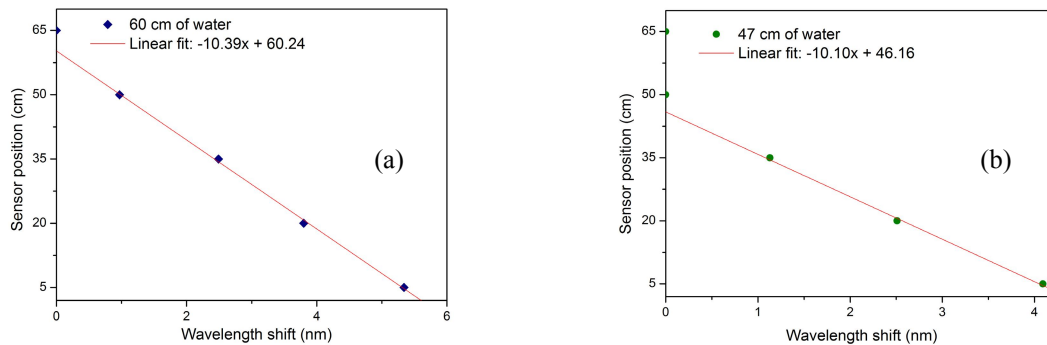


Figure 3. Determination of liquid level using linear regression for a position of the liquid surface at (a) 60 cm and (b) 47 cm.

4. CONCLUSION

For the first time a highly sensitive liquid level monitoring sensor based on mPOFBG array sensors embedded in SR is designed and its performance studied. The experimental results show that the proposed system has a high sensitivity to liquid level, great repeatability, a high resolution, and exhibits a high linear response. This mPOFBG sensor, when compared with a similar sensor based on a silica fiber grating, exhibits 9 times sensitivity, due to the fiber's much lower elastic modulus. A multi-sensor level monitoring system is proposed to enable operation insensitive to temperature, liquid density and even effective gravitational force. This new configuration can be a useful tool in many applications, such as aircraft fuel monitoring, biochemical and environmental sensing.

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