Jurnal Teknologi

Full Paper

COMPARISON OF WATER LEVEL MEASUREMENT PERFORMANCE FOR TWO DIFFERENT TYPES OF DIAPHRAGM USING FIBER BRAGG GRATING BASED OPTICAL SENSORS

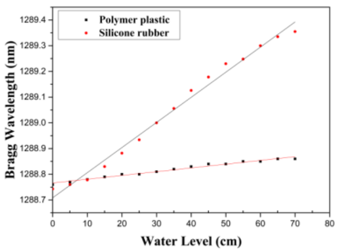
Article history
Received
1 February 2015
Received in revised form
24 March 2015
Accepted
1 August 2015

Odai Falah Ameen, Marwan Hafeedh Younus, RK Raja Ibrahim*, Rosly Abdul Rahman

Laser Center, Physics Department, Faculty of Science, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

*Corresponding author
rkamarulzaman@utm.my

Graphical abstract



Abstract

A sensor head incorporating a diaphragm was designed and fabricated for water level measurement. It operates in the range of 0-70 cm column height, equivalent to a pressure in atmospheric pressure of 0-6.86 kPa. The fiber Bragg grating (FBG) was attached on the two types of diaphragm to detect the change in the hydrostatic pressure caused by water at different levels. The diaphragms performance by comparing the sensitivity in within the mentioned range. Optical spectrum analyzer (OSA) was used to record the shift in the Bragg wavelength λ_B at different water level. The sensitivity of water level measurement using a silicone rubber diaphragm found to be 9.81 pm/cm for 70 cm in water level, while the sensitivity for polymer plastic diaphragm found to be 2 pm/cm at the same level.

Keywords: Fiber Bragg grating, diaphragm, silicone rubber, liquid level, hydrostatic pressure

1.0 INTRODUCTION

Liquid level measurement technologies are very important in many fields such as chemical processors, fuel storage and other industrial environments [1,2,3]. These fields require to employ of sensors has the potential application in explosive liquids with safe environments. Presently there exist many conventional methods to measure the liquid level based on electrical techniques such as, radio frequency, capacitance [4] and resistance [5]. In electronic sensors, there are possibilities of generating of heat and electric spark with its components[6], additionality they suffer from intrinsic safety concerns. Alternatively, the optical sensor such as fiber Bragg grating (FBG) sensor can offer a better solution than conventional sensors. The use of fiber Bragg grating offer many advantages such as, immunity to electromagnetic interference, high sensitivity, wavelength encoded response, linear output, large dynamic range, stability, flexibility, high temperature tolerance, light weight, compact size and resistive to harsh environment [7, 8]. These properties make the FBG possible to be used in potentially flammable environment [9]. The FBG has been used to measure the changes in pressure, strain, temperature, refractive index and others [10]. There are many parameters that can used to monitor the change of the Bragg wavelength such as, generating temperature, tensile or compression on the grating area. There are many techniques were reported to measure the liquid level in the tank by using the FBG. High sensitive liquid-level sensor based on etched area fiber Bragg grating (FBG) [11], a long period fiber grating sensor to measure the liquid level and liquid-flow velocity [12], measuring liquid level based on the bending cantilever rod in the grating region [13, 14], a side polished fiber Bragg grating to detect the liquid level [15], and axial strain along the tapered chirped grating by using buoy hung [16, 17].
In this paper, we proposed a sensor head design to water level measurement utilising an FBG and two

different types of diaphragms. The FBG is placed under a thin layer of polymer or silicone rubber diaphragm which act as a pressure sensor. As a result of pressure generated on the surface of the diaphragm and this lead to Bragg wavelength shifting.

2.0 OPERATING PRINCIPLE

2.1 FBG Sensor

The FBG region is formed by periodic modulation of the refractive index in the fiber optic core along the optical fiber axis, as shown in Figure 1. The periodic modulation in the refractive index is normally produced by exposing the optical fiber to a spatially varying pattern of ultraviolet (UV) light, and these are called gratings. The FBG region can described as a small mirror inside the fiber core, which reflects special wavelengths, because of the periodic changes in the refractive index of the core. When light waves at different wavelengths are transmitted through the optical fiber and passing into the FBG, one of the wavelength λ_B will be reflected back by the FBG and while allowing other wavelengths to transmit through. The Bragg condition can be described by this Eq [17],

$$\lambda_B = 2n_{eff}\,\Lambda \tag{1}$$

where n_{eff} is the effective refractive index of the core of the single-mode fiber, and Λ is the periodicity of the grating. The relationship between the Bragg wavelength and the applied strain is given by Eq. (2) [18],

$$\Delta\lambda_B/\lambda_B = (1-P_e)\varepsilon \tag{2}$$

where ε is the strain applied to the grating, P_e is the strain-optic constant defined as in Eq. (3) [18],

$$P_e = (n_{eff}^2/2)\left[P_{12} - \nu\left(P_{11}+P_{12}\right)\right] \approx 0.22 \tag{3}$$

where $P_{11} = 0.113$ and $P_{12} = 0.252$ are two components of the strain-optic tensor, $\nu = 0.16$ is the Poisson's ratio. Thus Eq.(2) can be simplified,

$$\Delta\lambda_B = 0.78\lambda_B\varepsilon \tag{4}$$

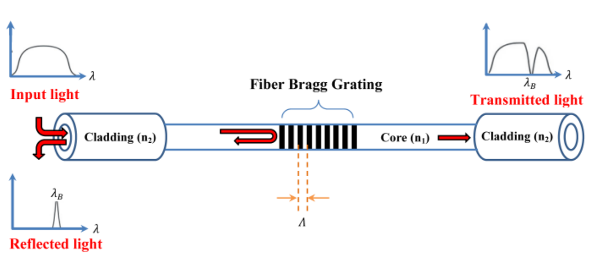


Figure 1 Operation of FBG optical sensor

2.2 Sensor Head

All pressure sensors operate on the basis of the same principle for the detection of physical force that arise as a result of pressure. The sensor depends on the form the diaphragm sealed over a cavity containing air at atmospheric pressure. In this study, the sensor head will be used to detect hydrostatic pressure of different water level. Hydrostatic pressure is generated by a column of liquid at the bottom of the tank as a result of the force of gravity, which is a function of the height and density of the liquids. The pressure difference ΔP across the diaphragm is given by Eq. (5) [19,20],

$$\Delta P = \rho . g . h \tag{5}$$

where ρ is the density of the liquid (kg/m^3), g is the acceleration gravity (m/s^2) and h is the height of liquid level.

The diaphragm disk of diameter $2r$ and thickness t is deflected when loaded with lateral hydraulic pressure, which increases whenever the liquid level increased. The deformation of the diaphragm will generate pressure on the grating region, this lead to the shift in Bragg wavelength. Eq. (2) shows the relationship between the Bragg wavelength shifting and strain.

The center deflection δ for a clamped circular diaphragm, as shown in Figure 2 and given by the following equation as [20],

$$\delta = (3/16)(1-\nu^2)(\Delta \mathrm{P} r^4/Et^3) \tag{6}$$

where r is the radius of the diaphragm, E and ν are the Young's modulus and Poisson's ratio of the diaphragm respectively.

The maximum strain on this thin circular diaphragm under uniform pressure can be calculated by this Eq. (7)[19],

$$\varepsilon = (3\Delta P/8t^2E)\left(1-\nu^2\right)r^2 \tag{7}$$

Combining Eq. (7) and Eq.(4), we can derive

$$\Delta\lambda_B = (2.34\lambda_B\Delta P/8t^2E)\left(1-\nu^2\right)r^2 \tag{8}$$

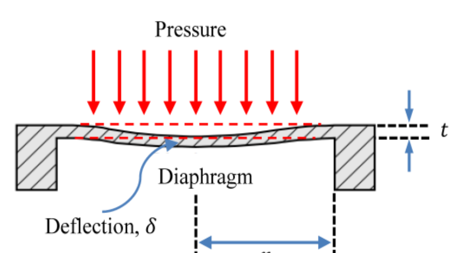


Figure 2 The deformation of the diaphragm under the front of pressure

3.0 SENSOR HEAD STRUCTURE

The sensor head consists of five layers (sandwich layers), as shown in Figure 3(a). The layer 1 is the FBG sensor. The layer 2 is a diaphragm with a diameter (4.4 cm). The layer 3 is a hemisphere shape of plastic with a groove. The layer 4 is a stainless steel screw. The layer 5 is a diaphragm with a diameter (5.5 cm), this diaphragm is placed at the top-end of the cavity cylinder.

Figure 3(b) shows the structure of the sensor head, the casing is made from hard plastic material. Two cylindrical cavities, the top cavity with an outer diameter of 5.5 cm and an inner diameter of 4.4 cm while the bottom cavity has an inner diameter of 2.5 cm. Two small holes with a diameter of 1 mm are drilled at both sides on the top of the bottom cavity to allow the insertion of FBG sensor. Two different types of diaphragm, polymer plastic and silicone rubber were used in this work.

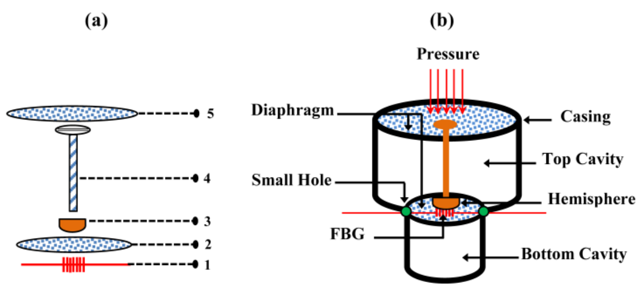


Figure 3 (a) The main layers (sandwich layers) of the sensor head body (b) The sensor head structure

4.0 EXPERIMENTAL SET-UP

The sensing set-up consists of a broadband light source (BBLS) emitting light in the range of 1200-1400 nm, SLD Light Source, optical spectrum analyser (OSA) and a sensor head, as shown in Figure 4. The tank is made from an acrylic cylinder with a height of 75 cm and 10 cm in outer diameter. The FBG used in this work is a single-mode optical fiber, with core diameter is 9 µm and the cladding is 125µm. Bragg wavelength $\lambda_B = 1288.025nm$, grating length is 3mm and the reflection is 90%.

The water level was increased in step of 5 cm up to 70 cm. This change in water level by 5 cm increased or decreased causes a shift in the Bragg wavelength. The shift in Bragg wavelength will be recorded by using the OSA device. From the results we can form calibration curve, to find out the water level displacement relationship with Bragg wavelength shift.

Figure 5 shows the transmission spectrum and the shift in Bragg wavelength as a result of the high liquid level in the tank by using OSA. The Figure shows a transmission spectrum, as a result of hydrostatic pressure generated on the silicone rubber diaphragm, for different height of water level.

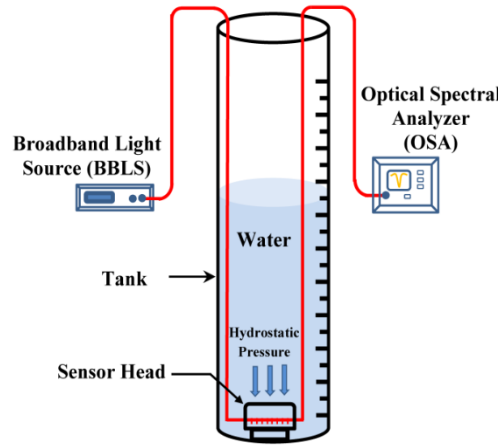


Figure 4 The experimental set-up for measure water level

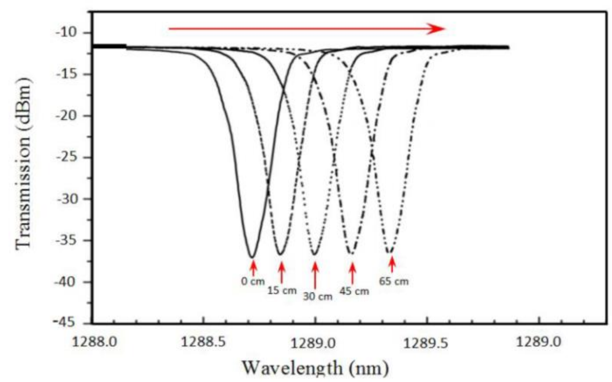


Figure 5 The spectrum of the FBG sensor as a function of increasing the water level

5.0 RESULTS AND DISCUSSION

The experimental results depicted in Figure 6 show the comparison of response from the sensor head for two types of the diaphragm with increase the water level. Similarly the shift in Bragg wavelength of FBG was recorded with an increment of 5 cm. The results showed that the shift in Bragg wavelength was linear in both types of diaphragm. From the curve fitting of the experimental result, it is evaluated that the sensitivity of the water level sensor was for the polymer plastic diaphragm is 2 pm/cm, and the sensitivity for silicone rubber diaphragm 9.81 pm/cm. In addition the resolution of the Bragg wavelength shifting by using polymer plastic diaphragm was 0.1 nm, whereas it was 0.612 nm by using a silicone rubber diaphragm. This result is due to the high flexibility owned by silicon rubber diaphragm [21].

Figure 7 shows the relationship between the change in Bragg wavelength with increased water pressure in both types of diaphragm. The sensitivity of the curve fitting for the polymer plastic diaphragm is 15 pm/kPa, while the sensitivity for silicone rubber diaphragm was 100.185 pm/kPa, for the water column pressure of 0 to 6.86 kPa. In absence case the water in the tank, the internal pressure will match with the external pressure, so there will not be a deformation of the diaphragm. The sensitivity is compared with other liquid level sensor, the sensor head proposed with a silicone rubber diaphragm is displayed much greater sensitivity. There are many researchers has been used the FBG as hydrostatic pressure sensor, and conversion of hydrostatic pressure value to liquid column using the factor (1 MPa = 102 meters). Joseph, S., *et al*. reported that the sensitive is 0.185 nm/m [19], and Sengupta, D. and K. Srimannarayana were the sensitivity 71 pm/m [22]. Sengupta, D. and P. Kishore the sensitivity is 23 pm/cm [6].

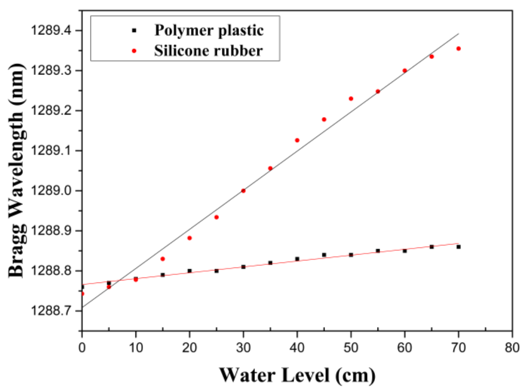


Figure 6 The response of the sensor head with increasing the water level for two types of the diaphragm

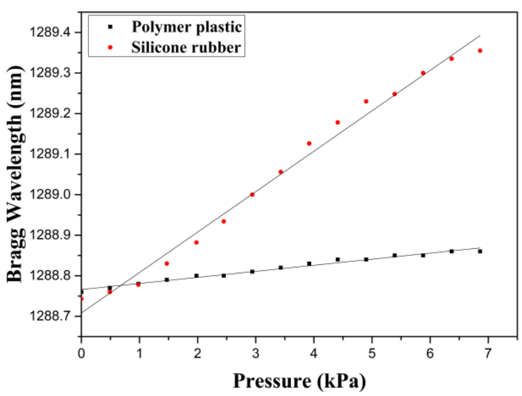


Figure 7 The response of the sensor head with increasing hydrostatic pressure for two types of the diaphragm

6.0 CONCLUSIONS

In this study, a new sensor head based on the FBG was designed to monitor water level. It incorporates a diaphragm which will serve as a source of pressure detector as the water level changes. The performance of the sensor head was achieved by putting an FBG on the different diaphragms for sensitivity improvement. The operating mechanism of this sensor head is based on the hydrostatic pressure, and the role of the diaphragm is to transfer the hydrostatic pressure on the FBG. The sensor was tested to measure the water level in a tank to maximum 70 cm column height which equivalent maximum pressure 6.86 kPa. The pressure on the FBG is increased gradually with an increase in the curvature radius of the diaphragm, leading to the shift in Bragg wavelength, which was recorded via OSA. The results show that the sensitivity of silicone rubber is 9.81 pm/cm and its larger than the sensitivity of the polymer plastic that equal 2 pm/cm at the same level.

Acknowledgment

The author would like to thank the staff at the Laser Center, University Technology Malaysia (UTM) for providing research facilities required to complete this study, and for financial support research of Grant No. 08448. Odai is grateful to the Ministry of Higher Education and Scientific Research, Iraq for providing PhD scholarship.

References

[1] Sarath, T. M., SubhaHency, J. P. and Daniel, F. 2013. *Level Measurement Using MEMS Pressure Sensor*. *International Journal of Advanced Research in Computer Science and Software Engineering*. 3: 118-121.
[2] Bukhari, S. F. A. and Yang, W. 2006. *Multi-Interface Level Sensors And New Development In Monitoring And Control Of Oil Separators. Sensors*. 6: 380-389.
[3] Krishnamurthy, L., Adler, R., Buonadonna, P., Chhabra, J., Flanigan, M., Kushalnagar, N., Nachman, L. and Yarvis, M. 2005. Design and Deployment of Industrial Sensor Networks:Experiences from a Semiconductor Plant and the North Sea. *In Proceedings of the 3rd International Conference On Embedded Networked Sensor Systems*. ACM. 64-75.
[4] Drechsel, M., Rediske, S., Pulvermacher, R. and Peters, D. 2015. Capacitive Liquid Level Sensor. U.S. Patent 8,936,444, issued January 20.
[5] Albin, R. and Cacciola, J. A. 1998. Liquid Level Sensor Utilizing Ac And Resistance. U.S. Patent 5,719,556, issued February 17.
[6] Sengupta, D. and Kishore, P. 2014. Continuous Liquid Level Monitoring Sensor System Using Fiber Bragg Grating. *Optical Engineering*. 53(1): 017102-017108.
[7] Iwamoto, K. and Kamata, I. 1992. Liquid-Level Sensor With Optical Fibers. *Applied optics*. 31(1): 51-54.
[8] Chen, Q. and Lu, P. 2008. Fiber Bragg Gratings And Their Applications As Temperature And Humidity Sensors. *Atomic, Molecular and Optical Physics*. 235-260.
[9] Yang, H. Z., Qiao, X. G., Luo, D., Lim, K. S., Chong, W. and Harun, S. W. 2014. A Review Of Recent Developed And Applications Of Plastic Fiber Optic Displacement Sensors. *Measurement*. 48: 333-345.
[10] Cusano, A., Cutolo, A. and Albert, J. 2011. *Fiber Bragg Grating Sensors: Recent Advancements, Industrial Applications And Market Exploitation*. Bentham Science Publishers.
[11] Yun, B., Chen, N. and Cui, Y. 2007. Highly Sensitive Liquid-Level Sensor Based On Etched Fiber Bragg Grating. *Photonics Technology Letters, IEEE*. 19(21): 1747-1749.
[12] Wang, J.-N. and Luo, C.-Y. 2012. Long-Period Fiber Grating Sensors For The Measurement Of Liquid Level And Fluid-Flow Velocity. *Sensors*. 12(4): 4578-4593.
[13] Guo, T., Zhao, Q., Dou, Q., Zhang, H., Xue, L., Huang, G. and Dong, X. 2005. Temperature-Insensitive Fiber Bragg Grating Liquid-Level Sensor Based On Bending Cantilever

Beam. *Photonics Technology Letters, IEEE*. 17(11): 2400-2402.

[14] Sohn, K.-R. and Shim, J.-H. 2009. Liquid-Level Monitoring Sensor Systems Using Fiber Bragg Grating Embedded In Cantilever. *Sensors and Actuators A: Physical*. 152(2): 248-251.

[15] Xiaowei, D. and Ruifeng, Z. 2010. Detection Of Liquid-Level Variation Using A Side-Polished Fiber Bragg Grating. *Optics & Laser Technology*. 42(1): 214-218.

[16] Dong, X., Liu, W. and Zhao, R. 2013. Liquid-Level Sensor Based On Tapered Chirped Fiber Grating. *Science China Technological Sciences*. 56(2): 471-474.

[17] Sengupta, D., Sai Shankar, M., Saidi Reddy, P., N Sai Prasad, R. L. and Srimannarayana, K. 2010. Axial Strain Based Bragg Grating Level Sensor. *Optoelectronics and Advanced Materials*. 4(12): 1933-1936.

[18] Kashyap, R. 2009. *Fiber Bragg Grating*. 2nd ed. USA: Elsevier.

[19] Song, D., Zou, J., Wei, Z., Chen, Z. and Cui, H. 2011. Liquid-Level Sensor Using A Fiber Bragg Grating And Carbon Fiber Composite Diaphragm. *Optical Engineering*. 50(1): 014401-014405.

[20] Ashby, M. F. 1999. *Materials Selection in Mechanical Design*. 2nd ed.

[21] http://www.dowcorning.com/content/rubber/.

[22] Sengupta, D. and Srimannarayana, K. 2013. Hydrostatic Pressure Based Liquid Level Sensing Using FBG: A Comparative Study. *International Conference on Optics in Precision Engineering and Nanotechnology (icOPEN2013)*. International Society for Optics and Photonics. 87691X-87696X.