Hydrostatic pressure based liquid level sensing using FBG : A comparative study

[1,2] D.Sengupta, [1]M.Sai Shankar, [1]K.Srimannarayana,
[1]National Institute of Technology, Warangal, India
[2]Vidya Jyothi Institute of Technology, Hyderabad, India
guuptasengupta@gmail.com

ABSTRACT

The performances of two liquid level sensors based on Fiber Bragg grating are studied. The Fiber Bragg gratings (FBG) are sensitive to strain and temperature. We investigate on enhancement of strain sensitivity of the FBG for liquid level measurement. Two different sensor heads arrangement are fabricated to exploit the strain sensitivity of FBG and use it for the liquid level measurement. The measurement sensitivity of a FBG based fiber optic liquid level sensor can be improved by controlling the parameter such as diameter of the FBG.

1. INTRODUCTION

Sensing of liquid level like measurement of liquid volume in a tank has been intensely studied as a gauging technique because of its essential applications in modern industry like chemical plant or refinery. To monitor the presence of liquid in storage tank a large number of liquid level sensors are employed. Designing of liquid level sensors are dependent on the properties of liquids like being flammable or inert. These sensors are classified by their mechanisms: mechanical, electrical and optical [1]. Among these techniques, optical fiber sensor present some remarkable advantages, such as immune to electromagnetic interference, Electrical insulator, high sensitivity, light weight, and small in size[2]. These sensors are especially attractive for applications in explosive environment and flammable atmosphere because light is confined inside the fiber and does not interact with the surrounding material. The development of Fiber Bragg grating has attracted considerable attention due to its simplicity and reliability. Fiber Bragg Grating (FBG) is a periodic or a quasi-periodic modulation of refractive index inside the core of an optical fiber and manufactured through Ultra Violet (UV) exposure of optical fibers [3]. The grating structure acts like a selective mirror for the wavelength called Bragg wavelength that satisfies the Bragg condition. FBG offers the ability to deploy an array of uniquely identifiable sensors within a single optical fiber, capable of monitoring different physical parameters like temperature, strain, pressure etc.. As the output signal from FBG based system is wavelength encoded, (i.e. their response to the measured parameter has specific wavelength over a specific wavelength range defined for each sensor) they are self-referencing, rendering the information independent of fluctuating intensity of light and with a system immune to source power and connector loss problems which is a limitation of many other optical sensors. The characteristics properties of FBG made it convenient to adopt for sensing liquid level.

When FBG is illuminated by a broadband optical source, a narrow-band spectral component corresponding to the Bragg resonance wavelength of the grating, λ_B, is reflected while all other wavelengths outside the narrow reflection band will be transmitted. The Bragg wavelength, λ_B, is given by

$$\lambda_B = 2n_{eff}\Lambda \qquad (1)$$

where Λ is the grating periodicity and n_{eff} is the effective refractive index of the waveguide mode.

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In this paper we compare the performances of fiber optic liquid level sensor based on fiber Bragg gratings. Two different sensor heads arrangement are fabricated to exploit the strain sensitivity of FBG and use it for the liquid level measurement.

2. PRINCIPLE AND DESIGN DETAILS

Sensing of liquid levels can be done through an indirect process i.e. the hydrostatic pressure at the bottom of the tank containing liquid increases with increase of liquid column in the tank. The FBG experience an axial strain when this hydrostatic pressure applied axially on it. The strain causes a change in grating pitch Λ and effective refractive index n_{eff} of the fiber. The shift in Bragg wavelength λ_B is

$$\Delta\lambda_B = \lambda_B(1 - p_e)\epsilon_z \quad (2)$$

The term ϵ_z is axial strain experienced by the fiber in micro-strain($\mu\epsilon$) along the axis, and p_e is the effective strain – optic constant, which is defined as

$$p_e = \frac{n_{eff}^2}{2}[p_{12} - \upsilon(p_{11} + p_{12})] \quad (3)$$

Where p_{11} and p_{12} are components of the strain-optic tensor, and υ is poisons ratio. For a typical germanosilicate optical fiber, p_{11}=0.113, p_{12}=0.252 and $\upsilon = 0.16$ and n_{eff} = 1.482. The strain sensitivity using these parameters of the fiber Bragg grating at 1550nm is 1.2pm of wavelength shift for 1$\mu\epsilon$ applied to the grating [3].

To sense the hydrostatic pressure for the liquid level measurement using FBG's two sensor heads are fabricated and tested.

In the first sensor head design a bourdon tube is used as a pressure sensing device. A bourdon tube consists of a thin walled tube that is flattened diametrically on opposite sides to produce a cross sectional area elliptical in shape, having two long flat sides and two short round sides and its free end is sealed as shown in Fig.1.

When the air pressure is applied at the opening end of the bourdon tube, it tends to straighten out and the angular deflection of the free end is taken as a measure of the pressure.

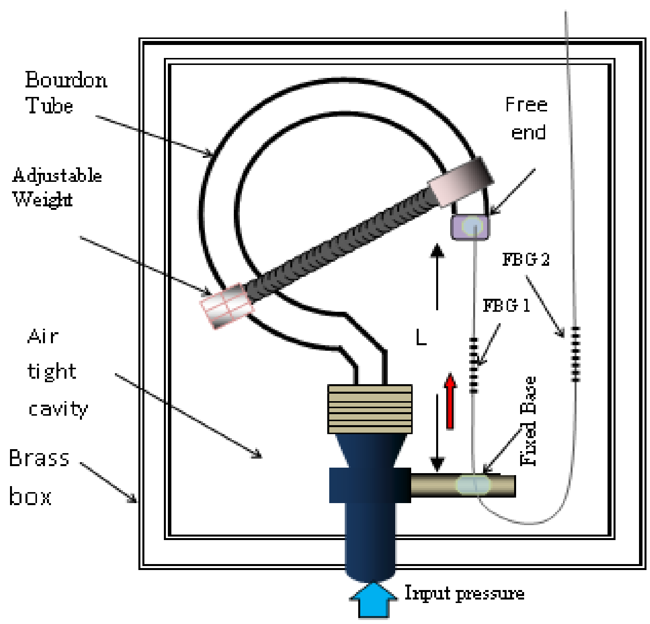

Fig. 1 Schematic arrangement of hydrostatic pressure sensor head

When pressure P is applied the displacement Δl for the free end tip of the bourdon tube is empirically given by[4].

$$\Delta l = 0.05\left(\frac{S\,P}{\mathrm{E}}\right)\left(\frac{D}{t}\right)^{0.2}\left(\frac{w_1}{w_2}\right)^{0.33}\left(\frac{w_1}{t}\right)^{3} \tag{4}$$

Where w_1, w_2, t, D, S and E are the major and minor axis of elliptical cross section of the bourdon tube, thickness of the bourdon tube, diameter of the 'C' shaped bourdon tube, circumferential length and Young's modulus of the bourdon tube material respectively.

An attachment is made to the bourdon tube (fixed base) to fix the FBG. The length between the free end and the fixed base is 4cm (L). Two FBG's (FBG_1 and FBG_2) written inline in a 9/125µm photosensitive fiber were used in the sensor head. The FBGs used in the experiment were fabricated using phase mask technique. The resonant peaks of FBG_1 and FBG_2 used are 1545.83nm (λ_{B1}) and 1543.01nm (λ_{B2}) respectively. The portion of the fiber where FBG_1 is written is glued in between the tip of the free end and the fixed base of the bourdon tube. The remaining portion of the fiber where FBG_2 is written is free from strain and is part of the sensor head. The FBG_2 is used for compensate the effect of temperature during the liquid level measurement. The bourdon tube arrangement is now enclosed in a sealed box made of Brass to isolate it from surrounding atmosphere and is the sensor head.

The displacement of the free end due to change in pressure in the bourdon tube induces axial strain in the FBG_1. The strain response of FBG_1 depends on the physical elongation of the grating (fractional change in grating pitch), and the change in effective refractive index due to photo elastic effect.

The Bragg wavelength shift of FBG_1 due to applied pressure to the bourdon tube is

$$\frac{\Delta\lambda_{B1}}{\lambda_{B1}} = (1 - P_e)\frac{\eta}{L}0.05\frac{SP}{\mathrm{E}}\left(\frac{D}{t}\right)^{0.2}\left(\frac{w_1}{w_2}\right)^{0.33}\left(\frac{w_1}{t}\right)^{3} \tag{5}$$

Where 'η' is a rational factor that correlates ΔL and the displacement of the free end of the bourdon tube, Δl.

In the second sensor head design a small hollow steel cylinder with one side open, and is filled with silicone rubber embedding an etched FBG in it as shown in Fig. 2. At the opening end of the cylinder, one end of the fiber having FBG is glued to the center of a hard core (surface area = A).

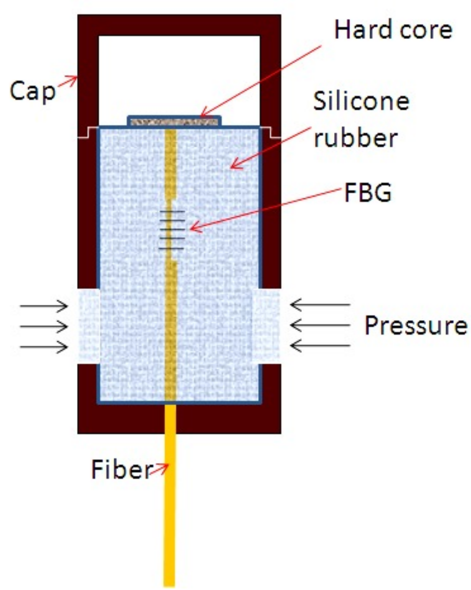

Fig. 2 Schematic arrangement of hydrostatic pressure Sensor head

The hard core is attached to the silicone rubber surface and the other end of the fiber is glued to the center hole present at the base of the steel cylinder. To create an air tight cavity at the opening end a steel cap is used. The wall of the cylinder has two side holes opposite to each other and perpendicular to the axis of the cylinder. When this arrangement (pressure sensing head) is immersed in the liquid, hydrostatic pressure P_r at the bottom of the tank is applied to the side hole of the sensor head. The silicone rubber present in the sensor head is pressurized in all radial directions leading to an axial force on the hard core [5]. This force on the hard core results in an axial strain in the FBG. The relationship between applied pressure and strain experienced by the FBG is

$$\varepsilon_f = \frac{2\nu_{SR}P_rA}{a\mathrm{E_f}+(A-a)\mathrm{E_{SR}}} \quad (6)$$

where P_r is the radial pressure on the silicone rubber, ε_f the axial strain, a is the area of cross-section , E_f is the elasticity coefficient ($7\mathrm{x}10^{10}$ N/m^2) of the fiber and ν_{SR} and E_{SR} denote the Poisson's ratio (0.4) and elasticity coefficient ($1.8\mathrm{x}10^6$ N/m^2) of the silicon rubber, respectively.

The pressure sensitivity of the sensor is given by

$$\frac{\Delta\lambda_B}{\lambda_B} = (1-P_e)\frac{2P_rA\nu_{SR}}{a\mathrm{E_f}+(A-a)\mathrm{E_{SR}}} \quad (7)$$

Expressing hydrostatic pressures (Pr) in terms of water column height (H), Eqn.7 modifies to

$$\frac{\Delta\lambda_\mathrm{B}}{\lambda_\mathrm{B}} = (1-\mathrm{P_e})\frac{2\mathrm{P_r}\mathrm{A}\nu_\mathrm{SR}}{\mathrm{aE_f}+(\mathrm{A}-\mathrm{a})\mathrm{E_{SR}}} \quad (8)$$

The above Eqn. 8 shows that the variation in the sensitivity of the sensor for a given water column depends on the physical parameters of the sensor arrangements i.e Poisson's ratio and elasticity coefficient of silicone rubber, hard core surface area, elasticity coefficient and cross-sectional area of the fiber respectively.

3. RESULTS AND DISCUSSIONS

The experimental result from the first sensor head design shows a pressure sensitivity of the FBG_1 is 50.05×10^{-3} nm/psi. This corresponds to a pressure sensitivity of $0.0032\mathrm{x}10^{-2}$/psi. The axial strain experienced by FBG_1 in the sensor head due to variation in the pressure is around 2388 times higher than that experienced by the bare FBG. The sensitivity of the sensor in terms of water column is found to be 71pm/meter upto 21meters. The recorded data indicates no shift in λ_{B2} with the change in pressure.

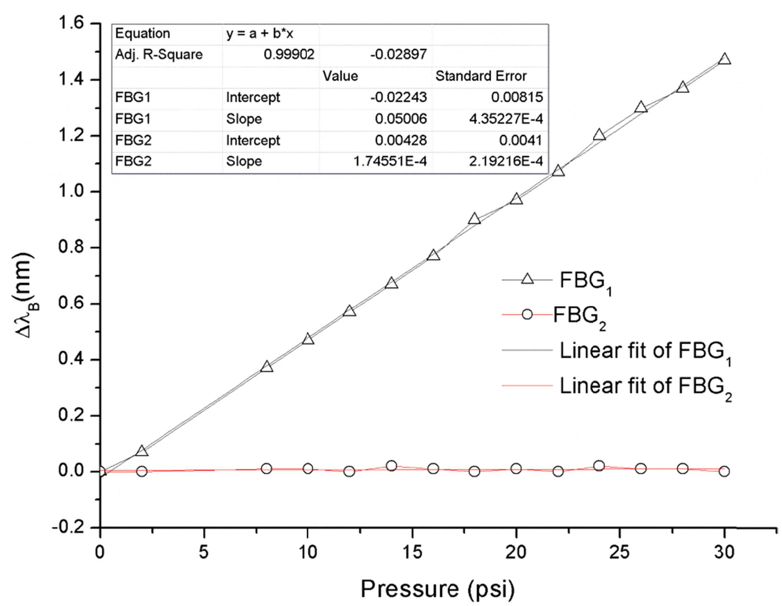

Fig. 3 Response of FBG_1 and FBG_2 at different hydrostatic pressures

The response of the FBGs is plotted by changing the temperature from 30^0C to 100^0C. The temperature response of FBG's was found linear with sensitivity of 10.5pm/^{0}C and 10.2pm/^{0}C for FBG_1 and FBG_2 respectively. The hydrostatic pressure sensitivity of the FBG_1 is low but can be enhance after replacing it with another FBG written in4.2/80µm fiber. The result is shown in Table.1.

Table 1: Sensitivity of the FBG at different pressure and temperature

Sensitivity	FBG_1(9/125µm)	FBG(4.2/80µm)	FBG_2(9/125µm)
Pressure	0.050nm/psi	0.101nm/psi	------
Temperature	0.010nm/°C	0.013nm/°C	0.010nm/°C

To find the second sensor head response with the liquid level the Liquid present in the tank is increased at a step of 5cm to a height of 100cm. The shift in Bragg wavelength of FBG_1 was recorded and the results plotted as shown in Fig. 4. The shift in Bragg wavelength was linear and the sensitivity of the sensor was found 23pm/cm. The shift in Bragg wavelength corresponding to rise in liquid level is theoretically determined and plotted. The theoretical sensitivity of the sensor is found to be 29pm/cm.

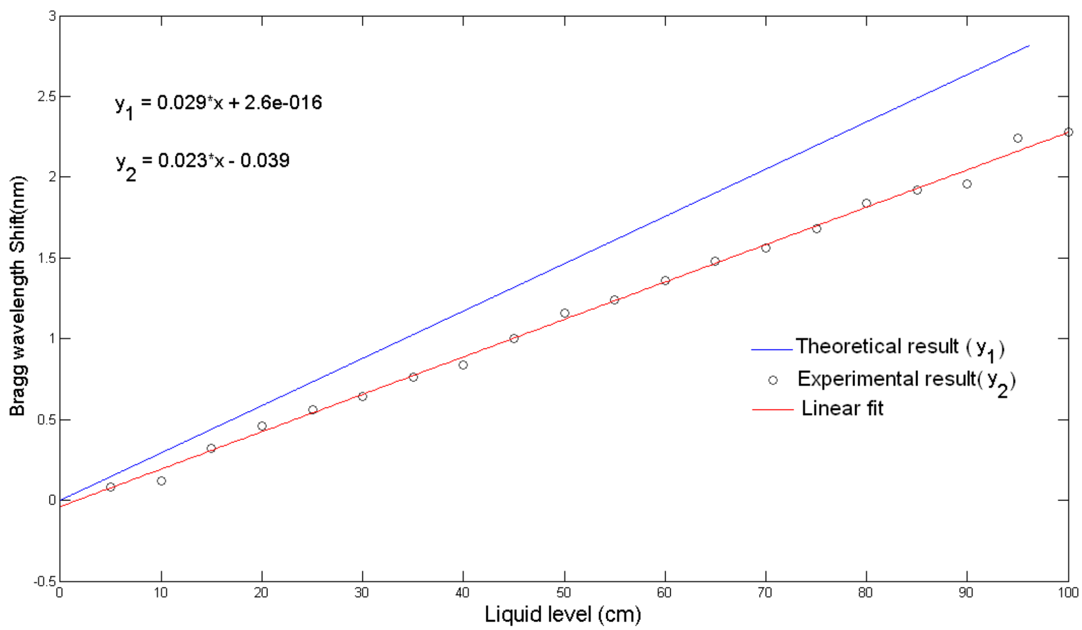

Fig. 4 Bragg wavelength response of FBG_1 during rise in liquid level

The liquid level measurement range is restricted by the maximum axial strain that can be tolerated by FBG. This may be overcome by using different diameters of FBG to balance the sensitivity and agree with E_{SR} values of silicone rubber. Study conducted with an FBG written in 9/125µm fiber used in the same arrangement, within one meter water column pressure was found very low.

For this, the sensor head with this FBG was placed inside the pressure chamber and the response of the sensor in terms of Bragg wavelength shift with the applied pressure was recorded upto 140psi (which is equivalent to 98.5 meter water column pressure) and the observations are shown in Fig. 5. The water column pressure sensitivity was found to be

25pm/meter. This shows that an increase in the diameter of the fiber where FBG is written can be useful for the measurement of high liquid column pressure (Eqn. 8). At the same time it shows low sensitivity on short range of liquid column pressure measurement.

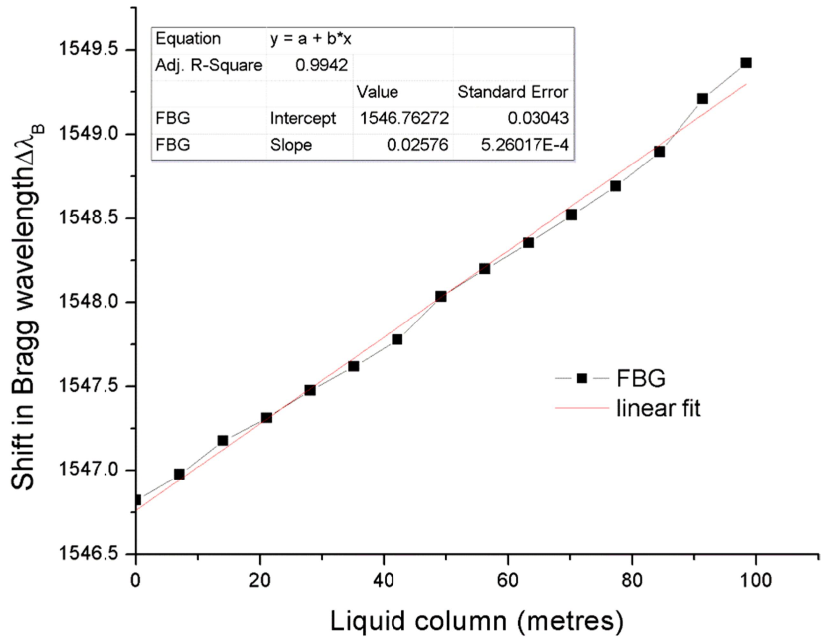

Fig. 5 Response of FBG (9/125µm) at different liquid column height

The temperature sensitivity of FBG_1 before encapsulating it in the sensor head is 13pm/^{0}C which is confirmed by obtaining a Bragg wavelength shift of 525pm in the range of 30^{0}C to 70 ^{0}C. But the temperature sensitivity of the FBG_1 after encapsulating it was found to be 11pm/^{0}C. This decrease in temperature sensitivity is due to the contact of FBG_1 with silicone rubber. Another FBG named as FBG_2 is incorporated inline and kept free from any kind of strain. The FBG_2 used for compensating the effect of temperature during the liquid level measurement.

CONCLUSION

In conclusion, we demonstrate two different Liquid level sensors using fiber Bragg gratings used in two different sensor head. The performances of the two liquid levels sensor head arrangement are compared. The Experimental result show that fiber parameters, such as the diameter of the FBG have significant effects on the Bragg wavelength shift and can be used for enhancing the sensitivity of the sensor and sensing range.

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