An FBG based hydrostatic pressure sensor for liquid level measurements

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ABSTRACT

A small and simple hydrostatic pressure sensor using fiber Bragg grating sensor for liquid level sensing is reported. The working principle of the sensor head design is based on transferring hydrostatic radial pressure to axial strain to the FBG. An FBG written in a fiber of diameter 50μm has been used for the measurement. The experimental result shows that sensitivity of the sensor can reach 23pm/cm of liquid column. The sensor can be useful in applications that involved with less hydrostatic pressure, like a tank with inflammable liquid in a fuel gas station.

Keywords: Hydrostatic pressure, Liquid level, Silicone rubber, Strain, FBG

1. INTRODUCTION

Hydrostatic pressure and temperature measurement is essential in many industrial applications such as liquid level monitoring in oil storage tank, downhole pressure measurement and other applications. In many harsh environments like high EMI, existence of toxic or corrosive agents, electrically conductive and inflammable conventional electronic sensors are not suitable. The fiber optic sensors are proved to be a substitute and give better result than the conventional sensors for the measurement of temperature, pressure, strain, salinity, rotation and flow rate etc. because of their passivity, dielectric nature and immune to EMI etc [1, 2]. Fiber optic sensors utilizing fiber Bragg gratings have received considerable attention recently due it wavelength encoded response, linear output, high sensitivity, large dynamic range, self referencing, inline optical connectivity, compatibility with fiber optical networks [3]. Many techniques have been developed to improve the liquid level sensing range using FBG. An FBG embedded on a cantilever for liquid level measurement is proposed [4, 5]. Attempt also being made to sense liquid level through hydrostatic pressure using FBG [6,7]. FBG shows poor sensitivity to sense pressure. But to enhanced this pressure sensitivity of FBG many technique has been adopted [8, 9]. An FBG pressure sensor is developed using a hollow metal cylinder filled with polymer with a pressure sensitivity $2.2\text{x}10^{-2}$MPa [10]. A small dimension of the sensor head is required for hydrostatic pressure measurement along with temperature. Since the FBG has temperature cross sensitivity.

This paper presents a small, simple technique of sensing hydrostatic pressure using an FBG as sensor in the sensor head which is a hollow cylinder partially filled by silicone rubber is proposed for liquid level measurement. The proposed sensor scheme using FBG sensor for liquid level measurement along with temperature is focused.

2. THE WORKING PRINCIPLE OF HYDROSTATIC PRESSURE SENSOR

FBG is a periodic or a quasi-periodic modulation of refractive index varying several millimeters inside the core of a photosensitive optical fiber. When light from a broad band source propagate through the grating, the wavelength that satisfies the Bragg resonance condition is reflected. The Bragg condition is

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

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Where λ_B is the Bragg wavelength, n_{eff} is the effective refractive index of the guided mode and Λ is the grating pitch of the grating.

Pressure can be sensed using bare FBG, but the pressure sensitivity of bare FBG is very small [11]. To enhance the pressure sensitivity, the diameter of the fiber where FBG_1 is written in the core of the optical fiber reduced using chemical etching. The FBG_1 is mounted inside a metal cylinder and filled cylinder with Silicone rubber (SR) forming the hydrostatic pressure sensing head shown in part 1 of the sensor head fig.1.

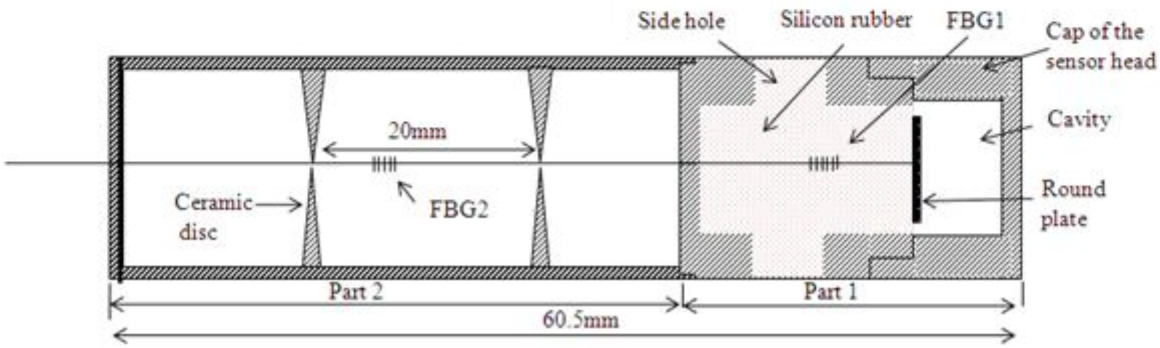

Fig.1 Schematic of the sensor head.

One end of FBG_1 is glued to the center of a round plate attached to the SR surface and the other end is glued to the center hole at the base of the cylindrical metal structure. A cap made up of metal, cover the opening end of the cylinder to form a cavity. The wall of the cylinder has two side holes opposite to each other and perpendicular to the axis of the cylinder. When the sensing head is immersed in the liquid, hydrostatic pressure P_r is applied to side hole the sensor head, the SR is pressurized in all radial directions corresponding to an axial force acting on the round plate because of a pressure difference created between cavity and outside the sensor head and thereby producing axial strain on the FBG_1.

The relationship between applied pressure and strain in the fiber is expressed as [10]

$$\varepsilon_{fiber} = \frac{2\nu_p P_r A}{aE_f + (A-a)E_p} \qquad (2)$$

Where P_r is the radial pressure around the fiber and silicone rubber, ε_{fiber} the axial strains of the optical fiber, ν_f and E_f denote the Poisson's ratio(0.17) and elasticity coefficient($7x10^{10}$ N /m^2) of the fiber, and ν_p and E_p denote the poisson's ratio (0.4) and elasticity coefficient ($1.8x10^6$ N /m^2) of the Silicon rubber respectively. 'a' is the cross sectional area of the FBG_1, 'A' is the surface area of the round plate attached to the silicone rubber at the opening end of the sensor head. The shift in Bragg wavelength due to the increasing in strain can be expressed by

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\frac{2\nu_p P_r A}{aE_f + (A-a)E_p} \qquad (3)$$

Using of the relationship of pressure and water depth given as 1MPa = 102m, the Bragg wavelength shift related to the sensing pressure P_r and water level is obtained as

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\frac{204\nu_p H A}{aE_f + (A-a)E_p} \qquad (4)$$

Where 'H' represents the water level in meters. FBGs are sensitive to strain and temperature, so for continuous monitoring of liquid level along with temperature an arrangement has been made in the sensor head (part 2) for sensing the temperature of the liquid only. Liquid level and temperature sensitivity of FBG_1 and temperature sensitivity of FBG_2 can be written in matrix form and inverted to yield liquid level detection and temperature from the $\Delta\lambda_{B1}$ and $\Delta\lambda_{B2}$ of FBG_1 and FBG_2.

$$\begin{pmatrix}\Delta H\\ \Delta T\end{pmatrix} = \frac{1}{Z}\begin{pmatrix}K_{T2} & -K_{T1}\\ -K_{H2} & K_{H1}\end{pmatrix}\begin{pmatrix}\Delta\lambda_{B1}\\ \Delta\lambda_{B2}\end{pmatrix} \qquad (5)$$

Where $Z = K_{H1}K_{T2} - K_{T1}K_{H2}$, K_{H1}, K_{T1} and, K_{H2}, K_{T2} are the liquid level and temperature sensitivity coefficients of FBG_1 and FBG_2 respectively. In practice the elements of the matrix $K_{H(i)}$ and $K_{T(i)}$ (i=1,2) can be determined experimentally by measuring separately the Bragg wavelength shifts with liquid level and temperature.

3. RESULTS AND DISCUSSION

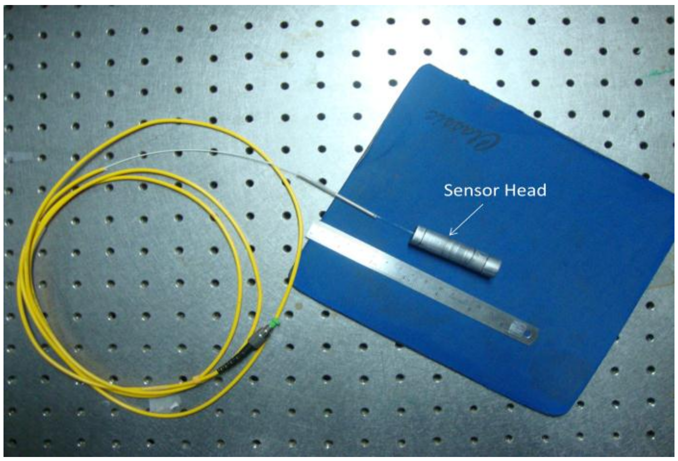

Fig.2. Sensor head

Figure 2. represent the sensor head used in the work presented in this paper. The sensor head for simultaneous measurement of liquid level and temperature is installed at the bottom of the tank of height 150cm. As the water level in the tank raises the hydrostatic pressure at the bottom of the tank increases. The sensor performance was tested within a liquid level range of 0 to 100cm and the response of the sensor is recorded with every 5cm increment of liquid level Fig. (3).

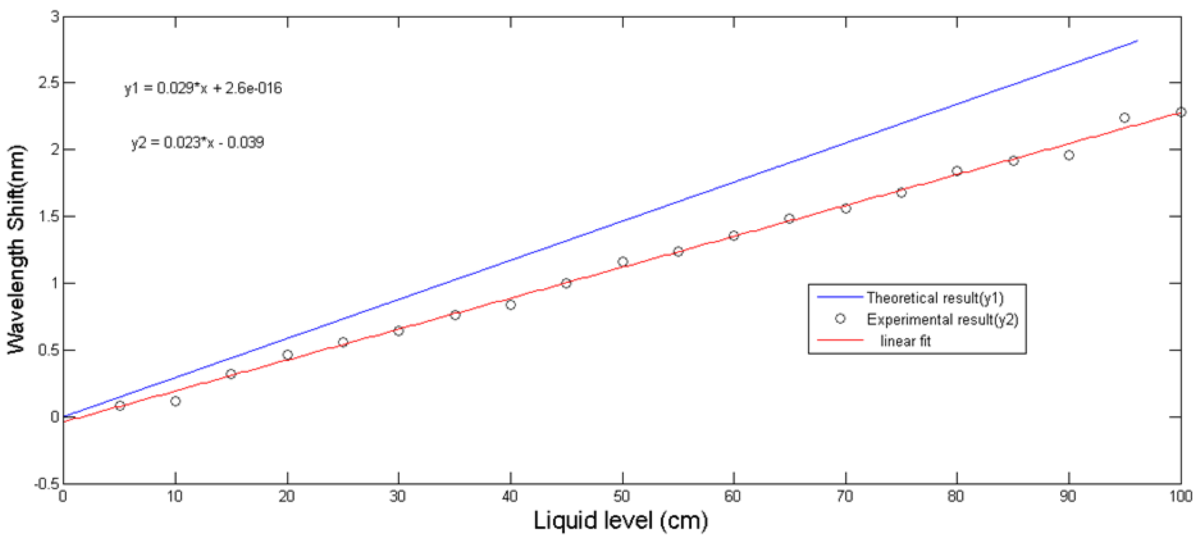

Fig.3. Response of FBG_1 to the rise in liquid level

The shift in Bragg wavelengths varies linearly (99%) with rise in water level. The sensitivity of the sensor is 23pm/cm.

Using equation 4 the sensitivity of the FBG_1 i.e. 29pm/cm is obtained using the parameters value used in this experiment. The experimental result shows that liquid level sensitivity of the FBG_1 calculated theoretically is more than experimental one. This may be due to the silicone rubber stick to the inner wall of the sensor head and leads to decrease in axial force acting on the round plate. The liquid level measurement range is restricted to the maximum axial strain sensed by the fiber Bragg grating. The liquid level detection range can be enhanced using different diameter of FBG_1 in compensation with liquid level sensitivity and with the E_p values of silicone rubber (Equation 4).

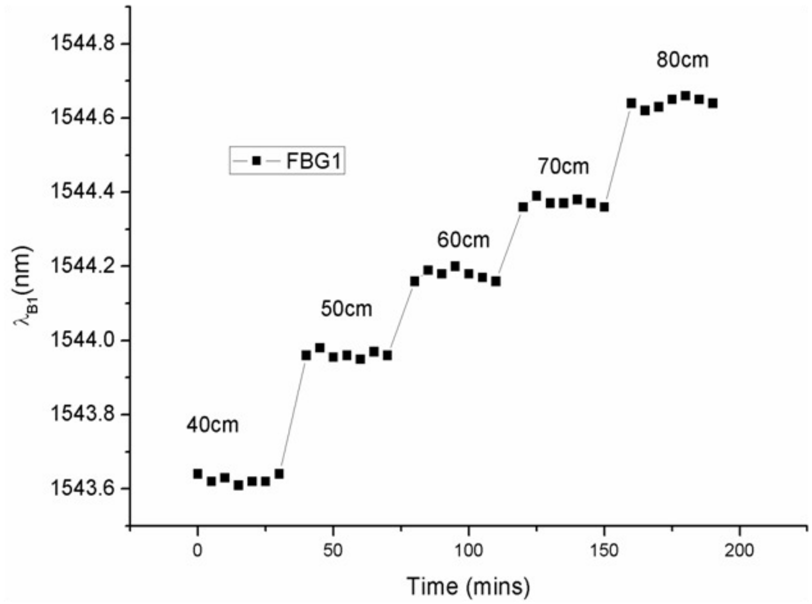

Figure 4. Temporal response of the FBG_1 during rise of liquid level

The temporal response of the hydrostatic pressure sensor on rise in liquid level is shown in the figure 4. The stability of the sensor at different liquid level kept for 30mins and a tolerance of ±0.01nm is observed. This fluctuation is probably due to vibrations in the tank used in the prototype experimental setup.

The temperature sensitivity of FBG_1 is approximately 13pm/^{0}C which is confirmed by obtaining a Bragg wavelength shift of 525pm in the range from 30 to 70 ^{0}C. Thus, the temperature effect really affects the accuracy of the liquid-level measurement of this sensor and it is improved by employing another FBG (FBG_2) in the part 2 of the sensor head. FBG_2 is insensitive to hydrostatic pressure of the liquid. The temperature sensitivity of the FBG_2 is 13pm/^{0}C. The measurement of Temperature of liquid present in the tank is also necessary because hydrostatic pressure depends on density of the liquid and density varies with temperature. In order to compensate the effect of temperature on liquid level measurement equation (4) can be used for the correct measurement of liquid level as well as temperature.

4. CONCLUSION

A small and high sensitive encapsulated hydrostatic pressure sensor (sensing head of length 60.5mm) for liquid level detection along with temperature is presented. The sensor shows a water level sensitivity of 23pm/cm within a 100cm liquid level range. FBG has temperature and strain cross sensitivity so it is necessary to measure the temperature of the liquid. Another FBG_2 with 13pm/^{0}C temperature sensitivity is used for simultaneous measurement of liquid level and temperature. The small and rigid structure of the sensor head is ideal in applications that involved with less hydrostatic pressure, like a tank with inflammable liquid in a fuel gas station.

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