Simultaneous measurement of temperature and pressure sensorfor oceanography using Bragg gratings

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Pressure and temperature are fundamental properties of the oceanic water. They have varying effects on the processes that take place in oceans be they biological, physical or chemical while pressure always increases with respect to surface when you go down, temperature has a more complex variation with respect to the depth. Various tools and techniques are available to measure these properties. A combination sensor with high accuracy and response time would enable better measurements of these two parameters.
This paper presents a novel structure based on simultaneous measurement of temperature and pressure sensing using Fiber Bragg grating (FBG) sensors. For this, proposed sensor heads for both temperature and pressure. Temperature measurement, two different types of sensor heads has been designed for this implementation. The first sensor head consists of a FBG which is fixed between ceramic block on one side and a bimetallic strip made up of aluminum and copper on the other. The second sensor head consists of the FBG which is fixed between two bimetallic strips. For pressure, in first type the FBG is fixed between silicon rubber foil and sensor head wall. In second method the FBG is fixed between two silicone rubber foils. The pressure on walls of silicon rubber foils elongates FBG, which results in shift of wavelength. Theoretical studies carried out on these proposed sensor heads resulted in an increase in temperature sensitivity of about six times greater than that of bare FBG sensor and pressure sensitivity of about eight times greater than that of bare FBG. Further, the proposed sensors have shown good linearity and stability.

Key words: Fiber Bragg gratings, silicone rubber, Bimetallic strip, Thermal response and oceanography.

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Introduction

Over the last two decades, optical fiber sensors have seen an increased acceptance as well as widespread use for structural sensing and monitoring applications in civil engineering, aerospace, marine, oil & gas, composites and smart structures [1-2]. Optical fiber sensor operation and instrumentation have become well understood and well developed. FBG sensors key research areas include FBG fabrication, FBG demodulation and practical applications [3-5]. Optical fiber sensors, especially FBGs, show distinguishing advantages like immunity to electromagnetic interference and power fluctuations along the optical path, high precision, durability, compact size, ease of multiplexing a large number of sensors along a single fiber, resistance to corrosion, reduced cable dimensions and so on [6-8]. FBGs have become the most prominent sensors and are being increasingly accepted by engineers, as they are particularly attractive to perform strain and temperature measurements under harsh environment areas, like in the presence of electrical noise, EM interference and mechanical vibrations, where conventional sensors cannot operate.

In recent years, various FBG-type sensors have constantly been developed and their uses have expanded rapidly into such applied fields as measurement of strain, displacement, torsion angle, torque, electric current, and gas. Moreover, FBGs can also be used to sense pressure. Enhancing the pressure sensitivity of a FBG is significant not only for pressure sensing but also for expanding applications of FBGs in fiber communication. Therefore to advance the practical applications of FBGs, it is necessary to design a device to enhance the pressure sensitivity.

Fiber optic pressure sensors have wide applications in field of oceanography. It has small size, prolonged life time, anti-corrosive nature, dia-magnetic properties, accuracy, resolution etc. These are all positives of FBG pressure sensor.

Theory

To make a sensor which measures both temperature and pressure simultaneously we need to study their individual performances first. Their individual performances are as follows:

1. <u>Temperature sensor:</u>

For a uniform fiber Bragg grating, both the temperature and strain dependences are linear, and hence, in principle, the strain response of FBG arises due to both the physical elongation of the grating corresponding fractional change in grating pitch, thereby causing a change in fiber index due to photo-elastic effects; as well as on the thermal response of the grating that arises due to the inherent thermal expansion of the fiber material and the temperature dependence of the refractive index. Therefore, the relative change in Bragg wavelength with strain and temperature can be expressed as [9-10].

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e)\varepsilon + (\alpha_s + \zeta_s)\Delta T \tag{1}$$

$$\Delta\lambda_B = [(1 - p_e)\varepsilon + (\alpha_s + \zeta_s)\Delta T]\lambda_B \tag{2}$$

where ε is the axially applied strain, p_e is the effective photo-elastic constant (≅0.22) of the fiber material, ΔT is the temperature change, $\alpha_s$andζ_s are the thermal expansion ($\sim 5 \times 10^{-7} K^{-1}$) and thermo-optic ($\sim 7 \times 10^{-6} K^{-1}$) coefficients of the fiber material, respectively.

Bimetallic strip (consisting of aluminum and copper) will normally be made straight at some reference temperature. If the temperature is hotter than the reference , aluminum expands more and its greater length puts it on the outside of the curve while aluminum contracts more and its shorter length puts it on the inside of the curve if the temperature is cooler than the reference [11].

1.1 Sensor head fabrication

The required FBG of length 2 cm with Bragg reflected peak at 1550.7 nm and having bandwidth of 0.102 nm at temperature 30 ^{o}C, is written in photosensitive fiber with 248 nm UV laser assisted grating writing facility at CSIO, Chandigarh using phase mask technique. Bimetallic strip of length 32 mm and width 4.6 mm, with thicknesses of copper and aluminum as 0.023 mm, 0.85 mm respectively has been employed for the fabrication of the sensor head. The sensor head consisting of bare FBG glued between the surfaces of the bimetallic strip and ceramic block is shown in fig.1.The separation between the bimetallic strip and ceramic block used in this sensor head is 4 cm (2cm length of the FBG + one cm each on either side of it).

1.2 <u>Experimental Setup and discussion</u>:

The experimental setup consisting of a broadband source (BBS) with 40 nm spectral width (1525-1565 nm), connected to port-1 of a 3-port fiber optic circulator, is used to launch light into the grating inscribed fiber that is connected to port-2 of the circulator. The back reflected wavelength shifts were monitored by an optical spectrum analyzer (86142B, Agilent Inc.) via port-3, as shown in Fig.1.

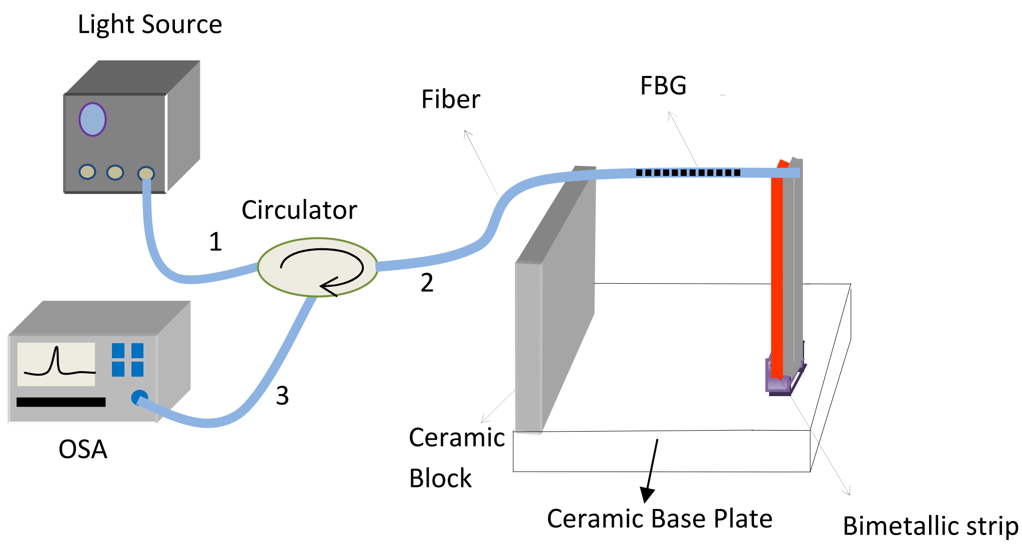

Fig. 1FBG fixed between metal block and one bimetallic strip.

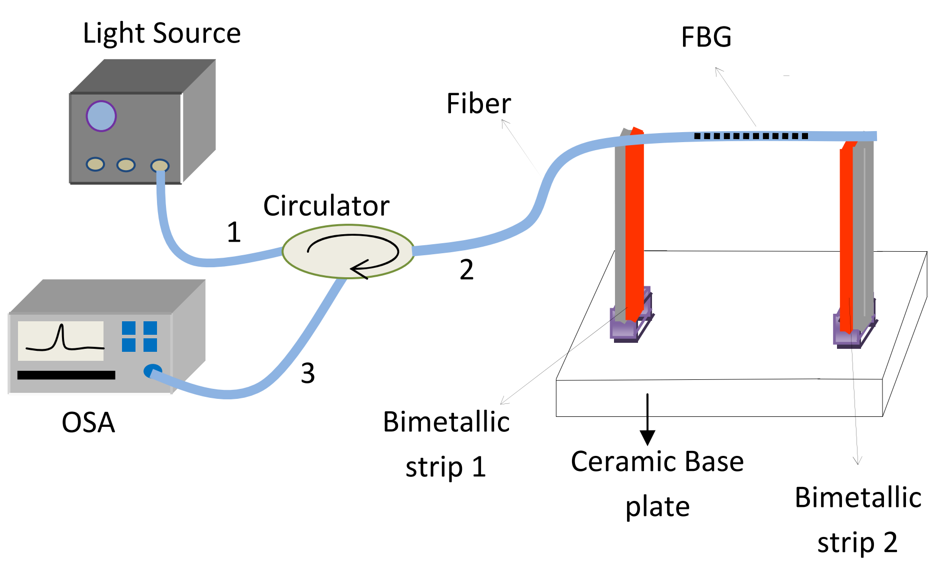

Fig. 2FBG fixed between two bimetallic strips.

The experiment consists of placing the sensor heads in the hot chamber whose temperature can be varied with an accuracy of ±1°C. The sensor is heated from room temperature to 100°C and the Bragg reflected wavelength is noted. During the process of heating from room temperature to 100 °C, each sampling temperature was stabilized at least 10 minutes before the wavelength shift is noted. The corresponding temperature response of the bare FBG has also been noted separately for the above temperature range.

The total Bragg wavelength shift when the FBG, fixed between a ceramic block and single bimetallic strip, is subjected to a temperature change [12].

$$\Delta\lambda_{B1} = \left[\left((1-p_e)\frac{1}{L}\frac{(T-T_0)L^2}{2.s} \times k\right) + (\alpha_s + \zeta_s)\Delta T\right]\lambda_{\boldsymbol{B}} \tag{3}$$

The FBG is fixed between two bimetallic strips as shown in Fig.4, the total Bragg wavelength shift is[12]

$$\Delta\lambda_{B2} = \left[2 \times \left((1-p_e)\frac{1}{L}\frac{(T-T_0)L^2}{2.s} \times k\right) + (\alpha_s + \zeta_s)\Delta T\right]\lambda_B \tag{4}$$

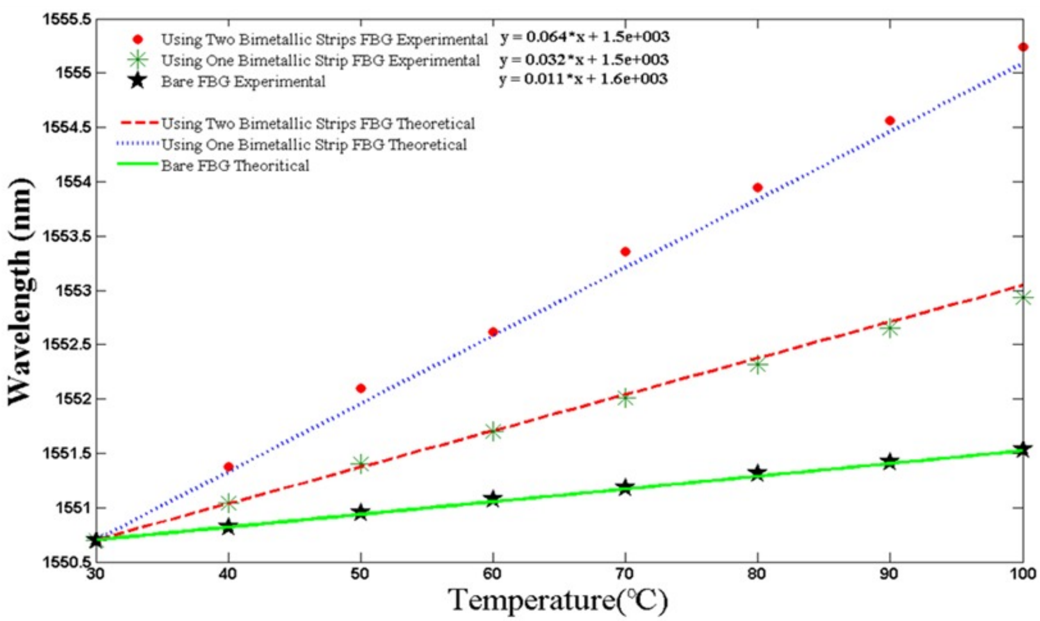

Fig. 3 Experimental and Theoretical measured wavelength versus temperature.

Fig.3 shows the plot of the temperature response of bare FBG and the proposed FBG sensor head. The sensitivity of bare FBG $\left(\frac{d\lambda_B}{dT} = 11\ \mathrm{pm}/°\mathrm{C}\right)$ is found to be very low compared to that of $\left(\frac{d\lambda_B}{dT} = 32\ \mathrm{pm}/°\mathrm{C}\right)$ the proposed first. The sensitivity is also found three times more than that of bare FBG in case of first sensor head and six times more than that of bare FBG with the second sensor head.

2. Pressure Sensor head Fabrication:

The sensor head is a hallow cylinder with dimensions of 4cm x 2cm which can be held in palm. It is made of stainless steel so that sensor head is anti-corrosive. The diaphragm is made of silicon rubber with maximum Young's modulus of 5Mpa. A small copper foil is placed to fix the fiber. Two 0.3cm holes made on the side wall allows water inside the sensor head and the sensor head can be maintained under varying hydrostatic pressure. Due to the pressure variations FBG gets strained and Bragg wavelength shift is noticed. This shift is used to measure the pressure at that particular place.

2.1Experimental setup and discussion:

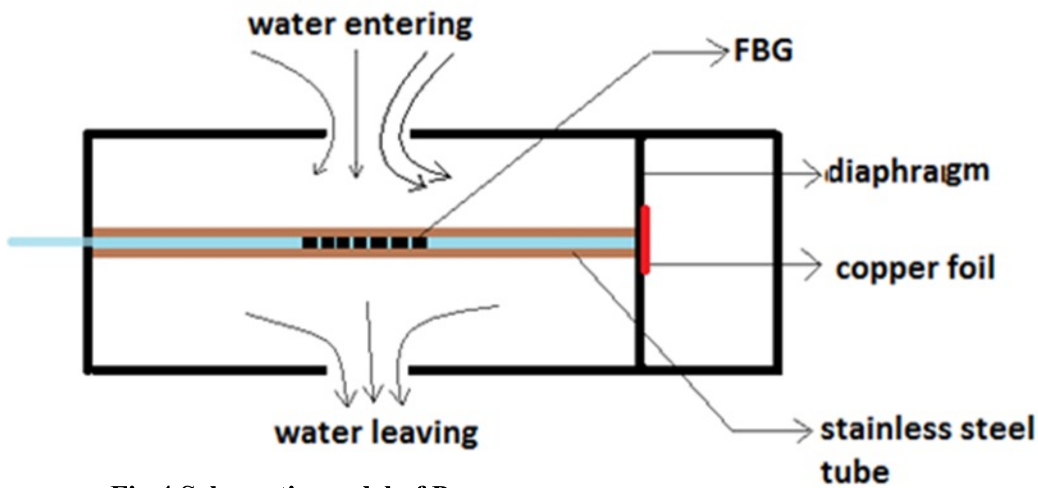

Fig.4 Schematic model of Pressure sensor

When the Sensor head is immersed into ocean water, the water exerts pressure on diaphragm and diaphragm elongates. This elongation will further elongate the fiber by which a shift in wavelength is observed. The corresponding equations are as follows [13]:

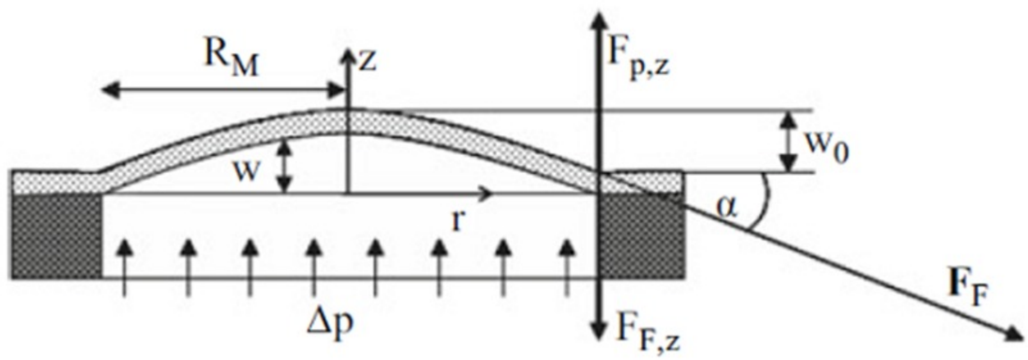

Fig.5 Elongation of silicon membrane

Force on the membrane is calculated as follows:

$$\Delta p.\pi.R_m^2 \approx -\sigma_m.d_m.2\pi R_m.\tan(\alpha) = -\sigma_m.d_m.2\pi R_m.\frac{\partial w}{\partial r}|_{r=R_m} \tag{5}$$

$$\Delta p.\pi.R_m^2 = -\sigma_m.d_m.2\pi R_m.w_o.\frac{2}{R_m} = 4\pi.w_o.d_m.\sigma_m \tag{6}$$

$$\Delta p = \frac{4w_0 d_m}{R_m^2}.\sigma_M \tag{7}$$

According to Hooke's law, the radial strain is calculated as follows:

$$\varepsilon_R = \frac{\sigma_R}{E_m} + v_m.\frac{\sigma_T}{E_m} = \frac{1}{E_m}(\sigma_R + v_m.\sigma_T) \tag{8}$$

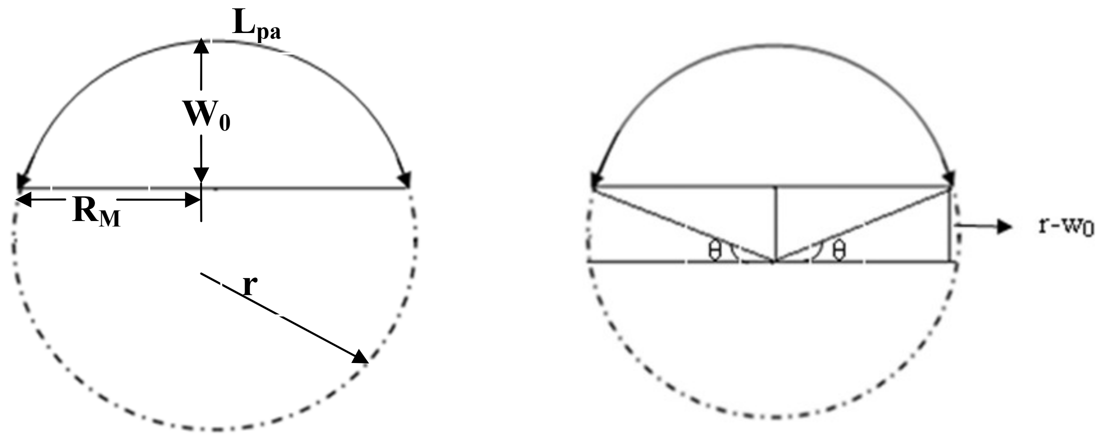

Fig.6 Cross section of diaphragm

The tangential strain is calculated accordingly:

$$\varepsilon_T = \frac{\sigma_T}{E_m} + v_{m.}\frac{\sigma_R}{E_m} = \frac{1}{E_m}(\sigma_T + v_m.\sigma_R) \tag{9}$$

From fig.6

$$r = \frac{R_m^2 + w_0^2}{2w_0} \tag{10}$$

$$\theta = \sin^{-1}\frac{r - w_0}{r} \tag{11}$$

By approximating $\sin\theta \cong \theta$ we get

$$\theta = \frac{r-w_0}{r} \tag{12}$$

The length of the arc of the circle is

$$L_{pa} = \pi r - 2r + 2w_o \tag{13}$$

Now strain produced in silicone rubber is calculated as follows:

$$\varepsilon_R = \frac{\pi r - 2r + 2w_o - 2R_m}{2R_m} \tag{14}$$

If tangential strain is assumed to be zero everywhere, we obtain:

$$\sigma_R = \varepsilon_R \frac{E}{1-v_m^2} \tag{15}$$

The total stress σ_M of the thin circular membrane is obtained from the sum of the residual stress σ_o and the stress generated by the deflection of the membrane σ_R

$$\sigma_M = \sigma_0 + \sigma_R$$

From (14) & (15)

$$\sigma_M = \sigma_0 + \left(\frac{\pi r - 2r + 2w_o - 2R_m}{2R_m} X \frac{E}{1-v_m^2}\right) \tag{16}$$

Here residual stress is neglected as it is very low for silicone rubber and if it seems to matter we can eliminate it by coating with very small amount of copper and by this the equation is reduced to:

$$\sigma_M = \left(\frac{\pi r - 2r + 2w_o - 2R_m}{2R_m} X \frac{E}{1-v_m^2}\right) \tag{17}$$

By substituting from eqn. (7)

$$\Delta p = \frac{4w_0 d_m}{R_m^2} X \left(\frac{\pi r - 2r + 2w_o - 2R_m}{2R_m} X \frac{E}{1-v_m^2}\right) \tag{18}$$

If it is assumed that tangential strain is zero throughout the membrane, then equation is as follows:

$$\Delta P = \frac{E_M d_M}{1-v_m^2} X \frac{(\pi+2)w_o^2 - 4R_M w_o + (\pi-2)R_M^2}{R_M^3} \tag{19}$$

If we neglect the approximation $\sin\theta \cong \theta$ we get the following equation:

$$\Delta P = \left(\frac{(\pi-2\theta)w_0^2 - 4R_M w_0 + (\pi-2\theta)R_M^2}{R_M^3(1-v_m^2)}\right).d_M.E \tag{20}$$

In correspondence to equation (20) we get:

$$W_0 = \frac{4R_m \pm \sqrt{16R_m^2 - 4(\pi+2)Y}}{2(\pi+2)} \tag{21}$$

where

$$Y = \left[\left((\pi-2)R_M^2\right) - \left(\frac{(1-v_m^2)XR_m^3 X\Delta P}{E_M.d_M}\right)\right]$$

From equation (1) $\in = \frac{W_0}{L}$

$$\Delta\lambda_B = \left[(1-p_e)\frac{W_0}{L} + (\alpha_s + \zeta_s)\Delta T\right]\lambda_B$$

And hence

$$\Delta\lambda_B = \left[(1-p_e)\frac{4R_m \pm \sqrt{16R_m^2 - 4(\pi+2)Y}}{2(\pi+2)L} + (\alpha_s + \zeta_s)\Delta T\right]\lambda_B \tag{22}$$

The shift in wavelength can be increased by factor of 2 if there are two diaphragms. The equation is same except that shift increases.

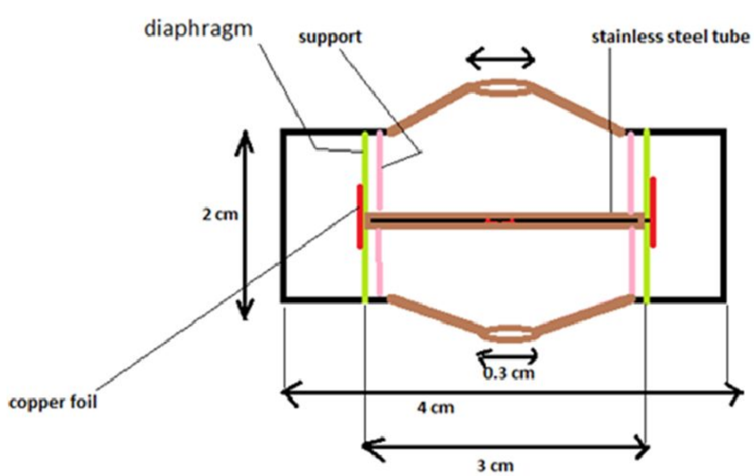

Fig.7 Pressure sensor with two diaphragms and increased shift in wavelength

In correspondence to Fig.7 the overall equation for shift in wavelength:

$$\Delta\lambda_B = \left[2(1-p_e)\frac{4R_m \pm \sqrt{16R_m^2 - 4(\pi+2)Y}}{2(\pi+2)L} + (\alpha_s + \zeta_s)\Delta T\right]\lambda_B \quad (23)$$

2.2THEOROTICAL SIMULATION:

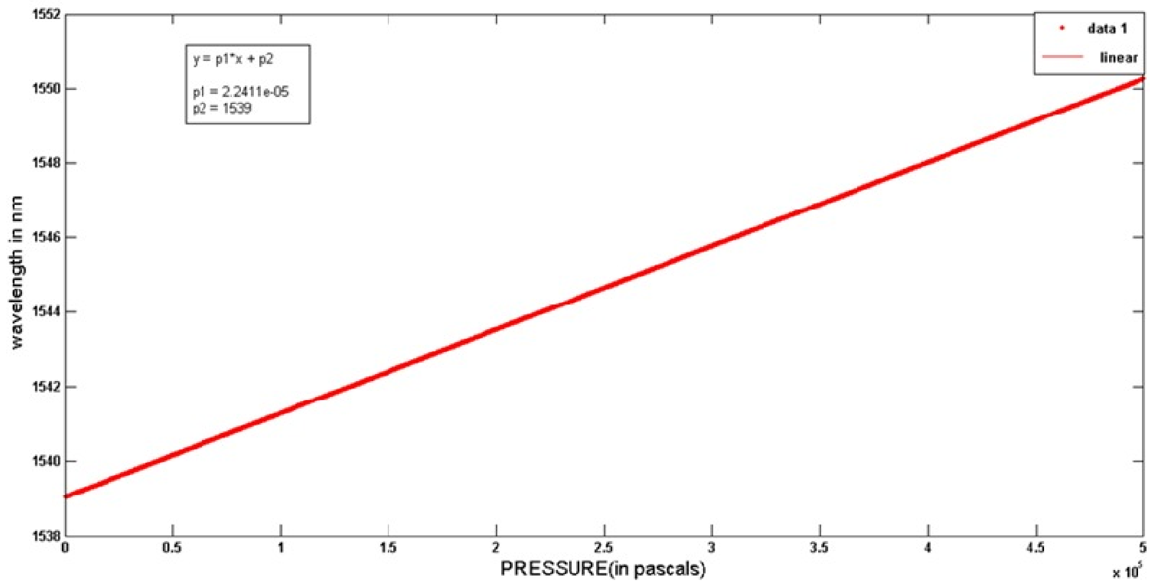

Fig. 8 MATLAB simulation of shift in wavelength

Fig.8 shows the plot of the pressure response of FBG.

The theoretical sensitivity of FBG observed is approximately$\left(\frac{d\lambda_B}{dP} = 11 \text{ nm}/Pascal\right)$.The graph we got shows that linearity is achieved by the pressure sensor. For a depth of 50m there is a shift of 11nm (app.) and shift of more than 22nm cam be achieved by alignment of two sensor heads.

Combined sensor:

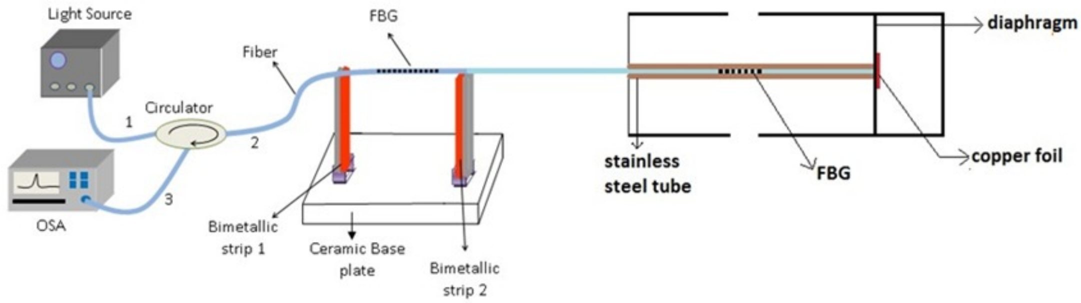

Fig.9 Combined sensor for temperature and pressure measurement

This is the proposed combined sensor head which can measure both temperature and pressure simultaneously with good accuracy.

Conclusion:

A novel sensor structure for enhancing and controlling temperature and pressure sensitivity simultaneously, has been designed using two FBG sensor heads and the theoretical and experimental results of Temperature sensor and theoretical results of Pressure sensor have been presented. The sensitivity of this arrangement can be enhanced and controlled with good linearity, stability and repeatability by using the bimetallic strips and diaphragms.

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