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ANALYTICAL STUDY OF HIGHLY SENSITIVE MEMS BASED BRAGG GRATING PRESSURE SENSOR

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Abstract: A model of MEMS based Bragg Grating Pressure Sensor is analytically proposed in this paper. In MEMS pressure sensor, the shift of wavelength of only one Bragg grating incorporated into a waveguide gives an erroneous outcome because of the cross sensitivity rendered by different parameters including temperature. In this design, the sensor consisting of dual identical Waveguide Bragg Gratings (WBGs) integrated in a curved waveguide in silicon micro-machined circular diaphragm is presented. The pitch of the Bragg gratings changes upon the application of pressure on the diaphragm, and hence, the corresponding wavelength is shifted. As the wavelength shifts because of the temperature, in the two identical waveguide gratings in equal amount, the error occurs due to the change of temperature can be eliminated. So, the Pressure Sensitivity (PS) can be measured correctly. A parametric analysis of this proposed sensor is performed utilizing MATLAB 2015a programming. Pressure sensitivities are found to be 2.0 and 1.8 picometre per Pascal for the two Bragg gratings.

Keywords: Optical MEMS; micro-machined diaphragm; waveguide Bragg gratings; pressure sensor.

1. INTRODUCTION

Optical sensors hold various advantages over other types of sensors as optical sensors are small in size and their weight is comparatively light. These sensors are insusceptible to interference due to radio frequency and additionally interference due to electro-magnetic radiation. They offer great accuracy and data transmission is much more secured [1]. The light is transmitted through optical fibers in Fiber optic sensors and they detect changes in light wavelength, light intensity and phase induced by a disturbing environment. Generally, the measuring parameters of optical fibers are displacement, strain, rotation, temperature, pressure, flow and vibration. In some cases, magnetic and electric fields are also the measurable parameters in optical fibers. Krohn [1] categorized the basic optical fiber sensors- phase-modulated, intensity-modulated [2] and wavelength-modulated [3]. Optical detecting applications have demonstrated numerous potential usages for fiber Bragg gratings (FBGs) because of neatly packed configuration and higher sensitivity. The FBGS are utilized in different detecting applications including pressure, temperature and also strain and furthermore in the fields of medicine and physical checking [4]. The optical sensors which recognize wavelength shift are better than the optical sensors which measure intensity changes as the wavelength shift detectors are less sensitive to noise.

Despite the fact that the FBGs are highly sensitive to strain and temperature, however they have demonstrated lower affectability to pressure. It Is confirmed that a pressure of 70MPa applied to a bare-FBG, the shift of Bragg wavelength was set up to just 0.22 nm, delivering a sensitivity of 0.022 pm/psi confirmed by Xu et al. [5]. The Polymer coated FBG pressure sensor executing as a transducer increased the sensitivity significantly, where Liu et al. [6] refined a sensor which had been established a sensitivity value due to pressure of 0.682 pm/psi . Zhang et al. [7] found the response of the pressure sensitivity (PS) in Fiber Bragg Grating to 0.036 nm/psi where the FBG was embedded in a metal cylinder filled with polymer. The Bragg grating pressure sensor provides significant advantages such as high sensitivity, multiplexing capabilities and resistance to electro-magnetic interference etc. [8, 9]. Henceforth FBGs are extensively used in sensing and telecommunication. The MEMS based optical pressure sensors using single Bragg grating gives an erroneous result owing to the cross-sensitivity impact delivered by different outside variables.

In recent times, the sensitivity of polymer-embedded Fiber Bragg Grating pressure sensor giving 0.06 nm/psi has been informed [10], which is much higher, approximately 2700 times of bare FBG sensitivity. Even though the transducer made of polymer is also suitable with increased sensitivity of the FBG pressure sensor .These sensors are applicable to the sarcastic effects of unrefined petroleum and for that reason, those sensors cannot be applied in the oil industry as well as gas industry. Zhao et al. [11] reported the mathematical description of the sensor completely. The Bragg grating sensor is influenced by thermal expansion effect as well as elasto-optic effect and mechanical distortion simultaneously, when it is subjected to temperature and lateral pressure concurrently. Fragiacomo et al. [12] have ignored measurement errors relating to temperature.

Pressure sensing is the key estimation performed enveloping assorted varieties of utilizations. Silicon based MEMS technology is the present-day innovation and is sought because of its reasonable cost and dependable execution. Specially, for constructing MEMS pressure sensors, silicon has proven an excellent material. As opposed to the customary, the piezoresistive effect or capacitive effect is applied in Micro Electromechanical Systems (MEMS) based pressure sensor. The optical MEMS based sensors have many advantages like inherent resistance due to electromagnetic disturbance, mechanical robustness, compactness and simple construction.

Optical MEMS based temperature insensitive Bragg Grating Pressure Sensor is reported in this paper. In this study, the sensor is temperature autonomous, as well as even has straightforward structure of sensing and changeable sensitivity along with measurement range. It has enormous applications including aircraft exhaust pressure measurement. It can also be applied to the medical science like human BP measurement. By utilizing the property that the variation in Bragg wavelength of waveguide Bragg grating (WBG) depends upon temperature and strain, a few sorts of FBG-based sensors have been developed.

In this paper, an Optical MEMS-based pressure sensor using WBG on silicon micro-machined round diaphragm is proposed. It is assumed that for both the gratings, the effect of temperature is same. Here pressure measurement method successfully eliminates the temperature sensitivity. The dimensions of the sensors are modified on the basis of independency of temperature and flexibility of sensitivity along with measurement range.

2. SENSOR CONFIGURATION

Fig. 1 demonstrates the arrangement of the sensor utilizing the round diaphragm. The sensor comprises a bent waveguide where two similar WBGs are placed on a silicon micro machined round diaphragm of 50μm thickness and of 250μm radius. The pitch of the grating changes if pressure is applied to the circular diaphragm. As

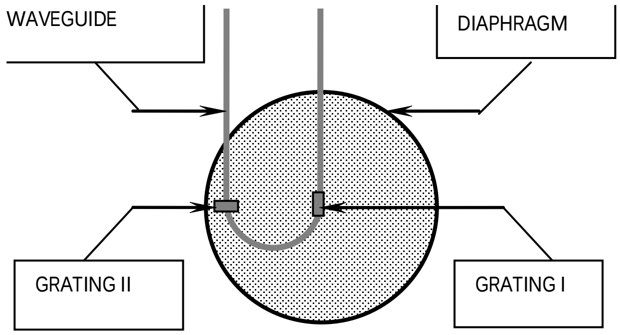

Fig. 1. Schematic diagram of aerial view of round diaphragm based MEMS Dual Bragg Grating pressure sensor

a result, there occurs in the respective Bragg wavelength change. In this configuration, a germanosilicate core with cladding of SiO_2 is formed in the grating structure. **Silica** (pure SiO_2) is doped with germanium (Ge), increasing the index of the doped glass. The resulting homogenous mixture of silica and germanium is referred to as germanosilicate glass. The dual gratings placed in the waveguide are intended for 1550.43 nm Bragg wavelength with 0.5μm line spacing.

3. THEORY

The Fig. 2 shows the schematic diagram of fiber Bragg grating. Bragg's law states that, when a broadband source of light propagates through the fiber, the Fiber Bragg Grating reflects back a thin spectral part of the light at a specific wavelength. This wavelength is known as the Bragg wavelength, which is dependent on the refractive index and also the grating-period of fiber. The equation of Bragg wavelength is expressed by the following equation:

$$\lambda_B = 2 \cdot n_e \Lambda \tag{1}$$

where, λ_B = Bragg wavelength
λ = period of Bragg grating
ne = effective refractive index of the core

The effective refractive index (n_e) is dependent on temperature and strain generated by thermo-optic effect and elasto-optic effect. The Bragg grating period, μ is altered by the longitudinal expansion of Fiber Bragg Grating. The Bragg wavelength is shifted due to the thermal expansion effect of the material of the fiber.

Consequently, the applied pressre is measured by the shift in Bragg wavelength. As this sensor is stressed by pressure and temperature concurrently in several realistic applications, the value of Bragg wavelength $ë_B$ depends on the pressure (P) and temperature (T).

The Bragg wavelength shift can be stated in terms of strain variation and temperature change in the following equation:

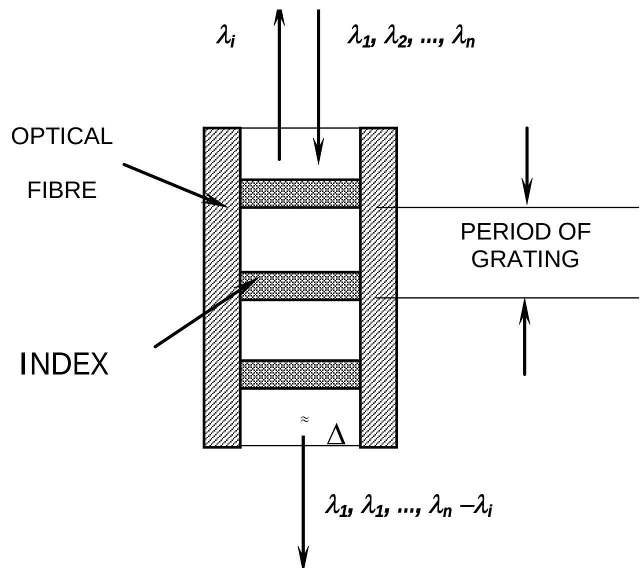

Fig. 2. Schematic diagram of Fiber Bragg Grating

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\varepsilon + (\alpha + \xi)\Delta T \tag{2}$$

where,

ε is the strain due to applied pressure,

ΔT is the variation in temperature,

P_e is the effective photoelastic constant at room temperature (for a germanosilicate fiber, $P_e \approx 0.22$)

α is the thermal expansion coefficient,

ξ is the thermo-optic coefficient

For circular diaphragm-configuration, the shift of Bragg wavelength and the values of sensitivities due to applied pressure are analyzed productively.

3.1. CIRCULAR DIAPHRAGM

It is supposed that the applied pressure is taken as ΔP. In polar co-ordinate system, the strain components are r and θ [12]: the radial component of strain is given by

$$\varepsilon_r = \frac{-(\sigma_r - \nu\sigma_\theta)}{E} \tag{3}$$

$$\varepsilon_r = -\frac{3}{8}\cdot\frac{(3r^2 - r_0^{\ 2} + \nu^2 r_0^{\ 2} - 3r^2\nu^2)\Delta P}{t^2 E} \tag{4}$$

Similarly, the tangential component of strain is expressed by

$$\varepsilon_\theta = \frac{-\left(\sigma_\theta - \nu\sigma_r\right)}{E} \tag{5}$$

$$\varepsilon_\theta = -\frac{3}{8}\cdot\frac{\left(r^2 - r_0^{\ 2} + \nu^2 r_0^{\ 2} - r^2\nu^2\right)\Delta P}{t^2 E} \tag{6}$$

where, Poisson ratio, cross radial component of stress, stress component along radius, Young's modulus, diaphragm radius and diaphragm thickness are ν, $\sigma_{è,}$ σ_r, E, r_0 and t respectively. Since ε_r and $\varepsilon_è$ are small for Grating II and Grating I respectively, so they are neglected.

It is found that from Eqn. (4) and Eqn. (6), for a specific value of pressure, strain decreases with the increase of diaphragm thickness. Substituting Eqn. (4) and Eqn. (6) into Eqn. (2), the Bragg wavelength shift can also be stated using:

$$\frac{\Delta\lambda_{B1}}{\lambda_{B1}} = \left(1 - P_e\right)\left[-\frac{3}{8}\cdot\frac{\left(3r^2 - r_0^{\ 2} + \nu^2 r_0^{\ 2} - 3r^2\nu^2\right)\Delta P}{t^2 E}\right] + \left(\alpha_1 + \xi_1\right)\Delta T \tag{7}$$

$$\frac{\Delta\lambda_{B2}}{\lambda_{B2}} = \left(1 - P_e\right)\left[-\frac{3}{8}\cdot\frac{\left(r^2 - r_0^{\ 2} + \nu^2 r_0^{\ 2} - r^2\nu^2\right)\Delta P}{t^2 E}\right] + \left(\alpha_2 + \xi_2\right)\Delta T \tag{8}$$

where, $\Delta\lambda_{B1} \rightarrow$ Bragg wavelength shift for WBG1

$\Delta\lambda_{B2} \rightarrow$ Bragg wavelength shift for WBG2.

$\lambda_{B1} \rightarrow$ Bragg wavelength of WBG1

$\lambda_{B2} \rightarrow$ Bragg wavelength of WBG2

$\alpha_1 \rightarrow$ coefficient of the thermal expansion of Grating I

$\alpha_2 \rightarrow$ coefficient of the thermal expansion of Grating II

$\xi_1 \rightarrow$ thermo-optic coefficient of Grating I

$\xi_2 \rightarrow$ thermo-optic coefficient of Grating II

As the waveguide and material are common in both the gratings, so, $\alpha_1 = \alpha_2$ and $\xi_1 = \xi_2$. The temperature effect on pressure measurement can be removed by subtracting Eqn. (7) and Eqn. (8). In the event that only one grating is taken, the wavelength moves because of pressure cannot be resolved definitely. If sensitivities due to pressure and as well as temperature of the gratings, using dual Bragg grating configurations, then the pressure can be traced accurately. Mathematically, this can be represented as:

$$\frac{\Delta\lambda_{B1}}{\lambda_{B1}} = S_{11}\Delta P + S_{12}\Delta T \qquad (9)$$

$$\frac{\Delta\lambda_{B2}}{\lambda_{B2}} = S_{21}\Delta P + S_{22}\Delta T \qquad (10)$$

where, S_{11}, S_{12}, S_{21}, and S_{22} are coefficient of pressure sensitivity and coefficient of temperature sensitivity of grating I and grating II respectively for the round diaphragm configuration. Eqns. (7) and (9) are compared, authors get

$$S_{11} = \frac{\Delta\lambda_{B1}}{\Delta P} = (1 - P_e) \left[-\frac{3}{8} \cdot \frac{(3r^2 - r_0^{\,2} + v^2 r_0^{\,2} - 3r^2 v^2)}{t^2 E} \right] \qquad (11)$$

$$S_{12} = \frac{\Delta\lambda_{B1}}{\Delta T} = (\alpha_1 + \xi_1) \qquad (12)$$

$$S_{21} = \frac{\Delta\lambda_{B2}}{\Delta P} = (1 - P_e) \left[-\frac{3}{8} \cdot \frac{(r^2 - r_0^{\,2} + v^2 r_0^{\,2} - r^2 v^2)}{t^2 E} \right] \qquad (13)$$

$$S_{22} = \frac{\Delta\lambda_{B2}}{\Delta T} = (\alpha_2 + \xi_2) \qquad (14)$$

The equations (11) and (13) describe that the PS of the sensor can be balanced by changing the estimation of 'r_0' and 't'.

According to the equations (7) and (8), as the wavelengths of Waveguide Bragg Gratings are about 1550.43 nm, their deviations have slight impact on the sensor sensitivity. Hence, it can be concluded that the diaphragm-thickness and diaphragm radius basically control the sensitivity.

4. SIMULATION STUDY AND RESULTS

In this study, MATLAB2015a is used for the simulations. Owing to the application of pressure on the round diaphragm, the grating - pitch has been changed and correspondingly shift of Bragg wavelength is observed, the shift- values are recorded. It is explicitly visualized that the PS changes with the diaphragm thicknesses. Initially, 1550.43 nm as the Bragg grating wavelength for Grating-I and Grating-II is considered.

Due to the applied pressure in the range 0kPa to 10MPa on the circular diaphragm, the shifts of Bragg wavelength of these two gratings are observed in Fig. 3 and Fig. 4. For an applied pressure of 10MPa, the Bragg wavelength shift for grating I is around 0.35 nm and for grating II is around 0.6 nm, and it is shown that the plots show good linearity.

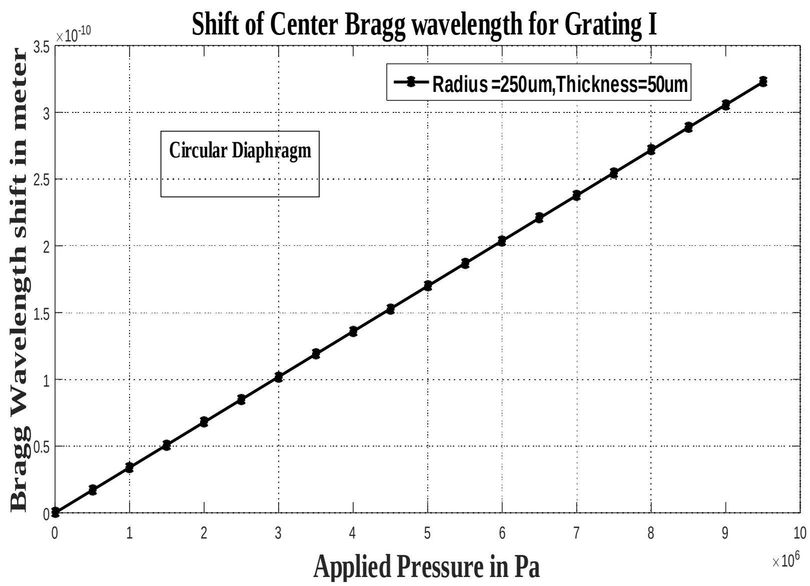

Fig. 3. Graph for shift of Bragg Wavelength vs. applied pressure for Grating

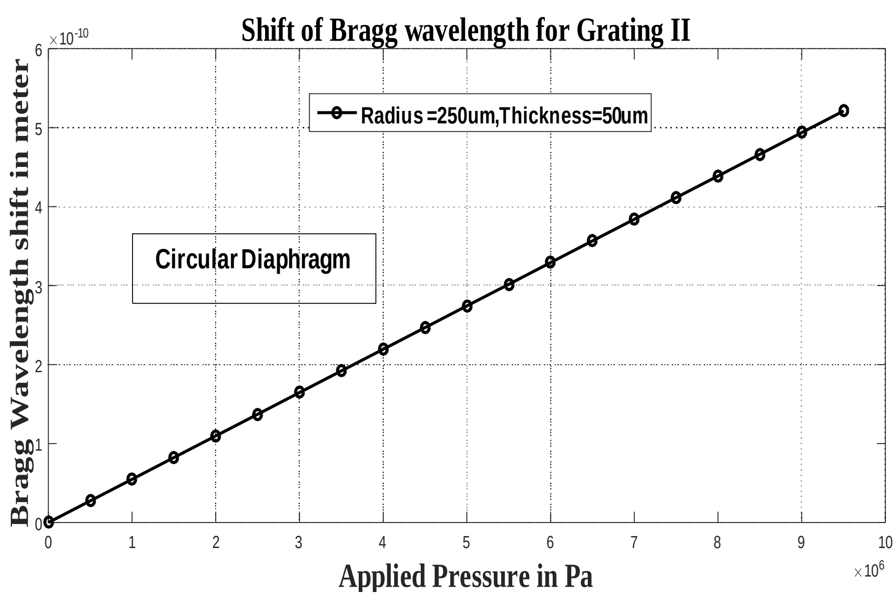

Fig. 4. Graph for shift of Bragg Wavelength vs. applied pressure for Grating II.

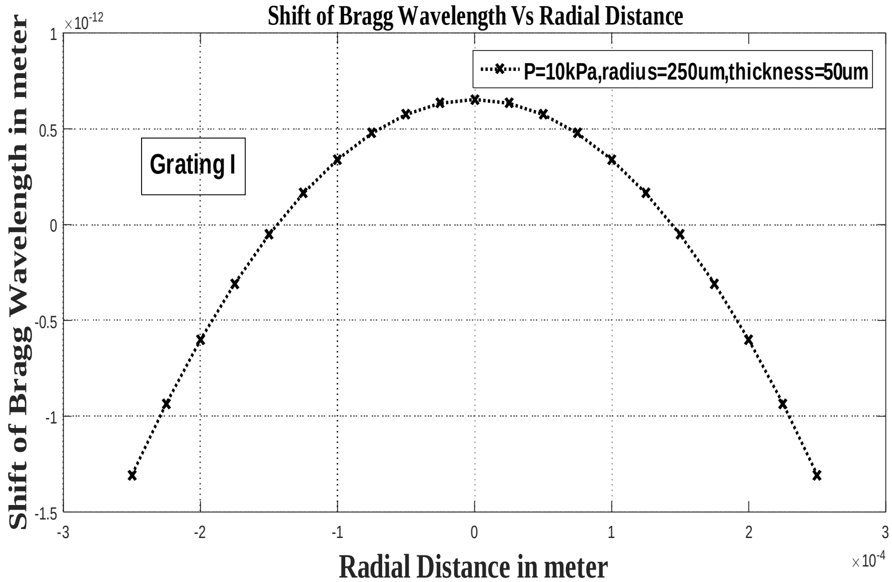

Fig. 5. Graph for Bragg Wavelength shift vs. distance along radius for grating I

The Fig. 5 and Fig. 6 depict the graphs of the deviation in Bragg wavelength of the Bragg Gratings-I and Bragg Grating II vs radial distance on the circular diaphragm configuration respectively. The Fig. 7 and Fig. 8 show sensitivities due to the pressure for the grating-I and II with the variations in the thicknesses in the diaphragm respectively. It is noted that the PS increases with the decrease in diaphragm thickness. The Pressure sensitivities are observed to be 2 pm/Pa and 1.8 pm/Pa in the round diaphragm.

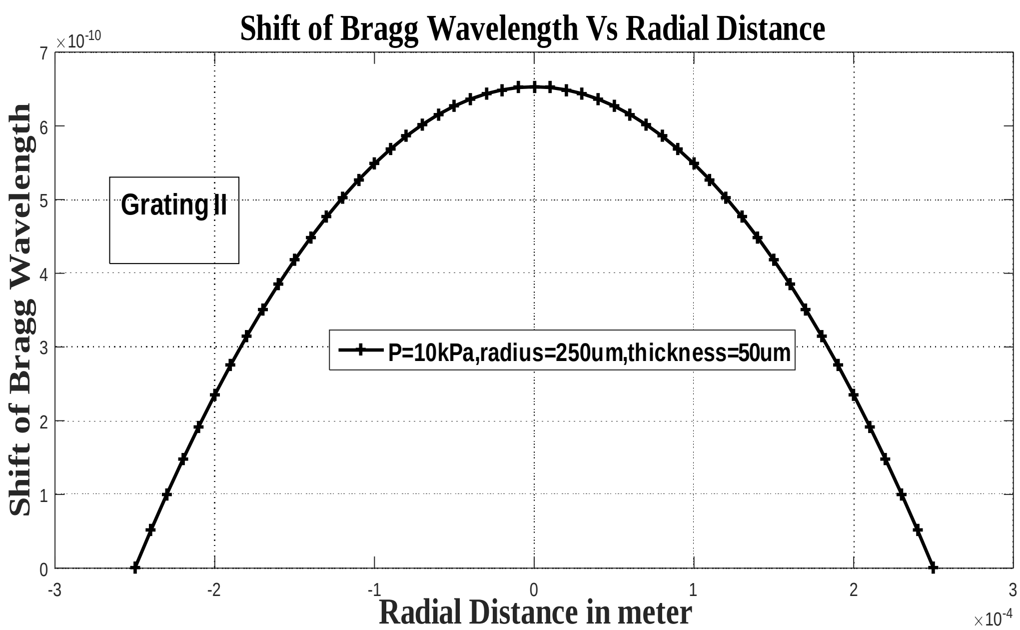

Fig. 6. Graph for Bragg Wavelength shift vs. distance along radius for grating II.

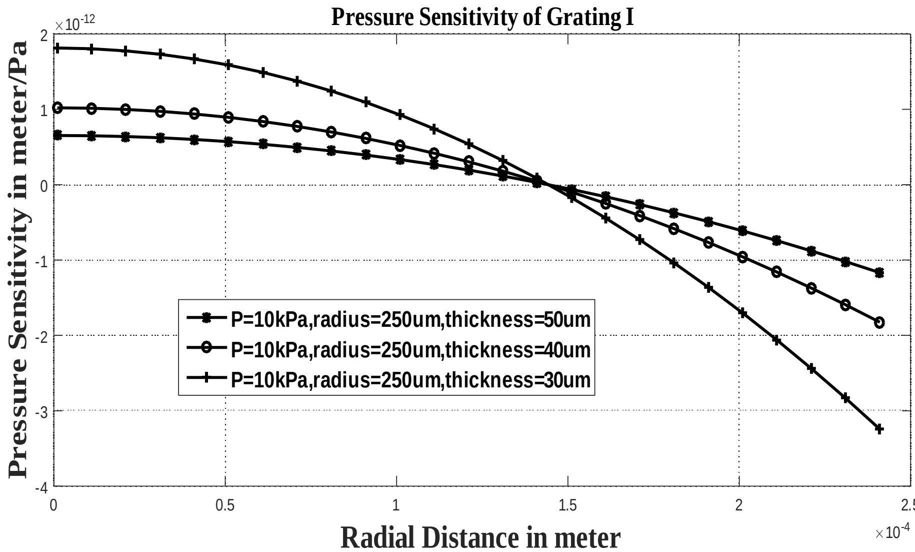

Fig. 7. Plot of Pressure Sensitivity vs. radial distance for grating I

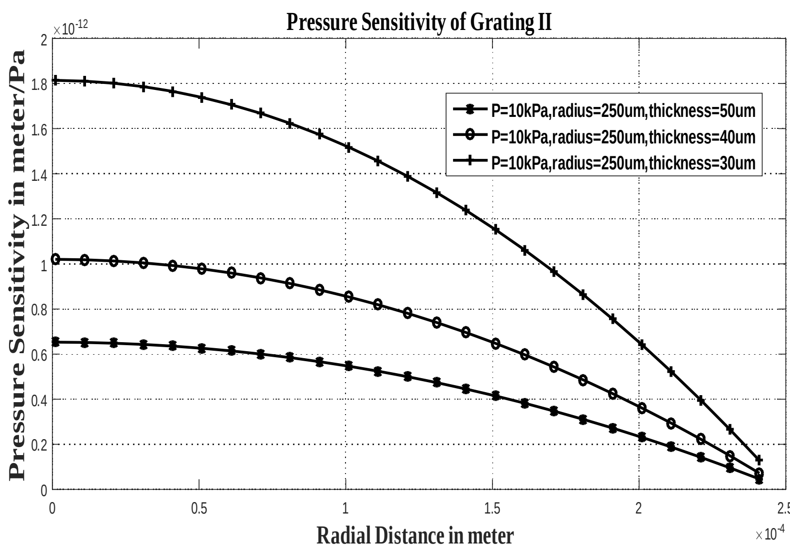

Fig. 8. Plot of pressure sensitivity vs. radial distance for grating II

5. CONCLUSION

In this parametric study, the investigations using the MATLAB programming clearly indicate that Dual Waveguide Bragg Grating Pressure sensor with circular diaphragm configuration removes the temperature sensitivity effect. This effect on temperature sensitivity can be minimized by taking into account the changes in the shift of the Bragg Wavelength when both the gratings are in appropriate scaling. It is observed that if the diaphragm thickness is decreased, the PS increases. The Pressure sensitivities are observed to be 2 pm/Pa for the Grating I and 1.8 pm/Pa for Grating II for the round diaphragm configuration. This configuration is adapted due to its high-PS values. Moreover, the range of measurement and sensitivity can be adjusted by altering the proportions of the device. The sensors have a huge prospect of using in the field of industrial and commercial applications.

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