Research Article

Simple Pressure Sensor with Highly Customizable Sensitivity Based on Fiber Bragg Grating and Pill-Shaped 3D-Printed Structure

Van Quyet Nguyen,1,2 Chia-Chin Chiang,1 and Liren Tsai1

1Department of Mechanical Engineering, National Kaohsiung University of Science and Technology, Kaohsiung 807, Taiwan
2Faculty of Mechanical Engineering, Nha Trang University, Khanh Hoa 57000, Vietnam

Correspondence should be addressed to Liren Tsai; liren@nkust.edu.tw

Received 5 May 2022; Revised 8 June 2022; Accepted 25 June 2022; Published 19 July 2022

Academic Editor: Marco Consales

Copyright © 2022 Van Quyet Nguyen et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

This study presents a simple pill-shaped pressure sensor fabricated by fused deposition modelling (FDM) technology. A fiber Bragg grating (FBG) sensor was embedded inside the structure during the 3D printing process. The dimension of the sensor was simulated by the finite element method to explore the customizability of the pressure sensor. The proposed pill-shaped pressure sensor showed great linearity and achieved high sensitivity with a total Bragg-shifted wavelength of 1.44 nm in the pressure range between 0 and 0.35 MPa, corresponding to a pressure sensitivity of 4.11 nm/MPa. The measured pressure change matched closely with finite element simulation, and the sensitivity could easily increase five times by a thirty percent increase in structure size. The results showed that the pill-shaped pressure sensor had high linearity and great feasibility and could be easily customized to a wide pressure range for static and dynamic pressure measurements in industrial applications.

1. Introduction

In recent years, fiber Bragg grating (FBG) sensors have had a vigorous development because of their outstanding advantages such as compactness, light configuration, high stability, high-reliability multiplexing, and immunity to electromagnetic interference. FBG is commonly used to measure diverse industrial and structural parameters, such as strain, pressure, temperature, humidity, liquid level, and even detect specific chemical compounds [1–3]. In the field of pressure sensors, sensitivity is an important parameter because it determines the resolution and accuracy of the sensing system. The pressure sensitivity measured with bare FBG is $3.04 \times 10^{-3}$ nm/MPa [4]. There are many ways to improve the sensitivity of sensors in general and pressure sensors in particular, as shown in Figure 1. It can improve from internal factors as well as external factors.

About improving external factors, many studies have been published and proposed. First, improve the sensor's sensitivity without embedding the FBG, i.e., not directly affecting the FBG segment, but attaching it to a structure to increase the sensitivity of the FBG, as some studies have previously published. For example, the FBG put in a glass-bubble housing achieves a sensitivity of 0.0278 nm/MPa [5], or it was glued on a Bourdon tube with a sensitivity of 1.414 nm/MPa [6], etc. Second, the sensitivity is improved by embedding the bare FBG in another material with an elastic structure, i.e., acting directly on the FBG segment. This approach is more complicated and takes more time to prepare and fabricate the sensor. There are many published research papers such as embedding a single polymer FBG into a silicone rubber diaphragm [7] or embedding into an epoxy resin diaphragm [8], etc., and the sensitivity has also been improved such as the measured pressure sensitivity is found to be 0.08 nm/MPa by polymer-coated fiber Bragg grating [9], and the pressure sensitivity improved up to 39.6 nm/MPa by using polymer packaged fiber grating pressure sensor [10]. Next, the pressure sensitivity has been reported to be 2.0 nm/MPa [11] or a shielded polymer-coated fiber Bragg grating increased the pressure sensitivity as high as 5.277 nm/MPa [12]. The FBG encapsulated in a
Their application is in a medium and low pressure measurement, the pill-shaped sensor will be tested in the pressure chamber. The deformation on the polymer diaphragm leads to the deformation such as the FBG was putted in resin cylinder with a sensitivity of 2.08 nm/MPa [18], and several other FBG pressure sensors embedded in 3D-printed materials have also been proposed [19–23].

In order to overcome the sensitivity limitation of the previously proposed bare FBG sensors, this study made external factor changes to improve the sensor’s sensitivity by creating a 3D-printed diaphragm structure. It showed that certain efficiency saves a lot of fabrication time. Specifically, the structure is fabricated based on the principle of the pressure difference between spatial regions in order to create a reaction on the polymer diaphragm leading to deformation in the sensor fiber and its named pill-shaped structure. Here, the pill-shaped sensor will be tested in the pressure chamber. Their application is in a medium and low pressure measuring range with good sensitivity.

2. Sensor Design

2.1. Fabrication and Package. The optical fiber used in this study has an inner core diameter of 9.6 μm and an outer glass (SiO2) coating diameter of 124.9 μm, made by Fibercore Ltd. (Southampton, UK). Bragg gratings were written into the fiber using a pulsed KrF-laser system (Coherent Xantos, 248 nm wavelength, 12 mJ/cm², Coherent, USA). The FBG was fabricated using the B7 masker, and a peak wavelength at 1541.705 nm is used to sense the pressure.

Sensor design has been implemented in many different ways; it depends on the material parameters, geometry, and thickness. The design in our test was fabricated via 3D printing using polylactic acid (PLA) material which was considered in the numerical analysis. The print material selected in the digital simulation is PLA with the following parameters: Young’s modulus of 3.45 GPa, Poisson ratio of 0.35, and density of 1290 kg/cm³.

These parameters have also been included in the numerical simulation by the ANSYS software. In this study, the pill-shaped structure is fabricated using PLA material in the 3D printer, INFINITY X1E, with a coating density of 100% and a smooth thickness of 0.2 mm. The print head temperature is 215 degrees Celsius, and the bedplate temperature is 65 degrees Celsius, both within the allowable range. The modeling has a design shown in Figure 2. The 3D-printed model was then coated with waterproof paint (Ming Shing spray paint, Taiwan) to prevent leaks. The optical fiber (with the original FBG in the middle, no coating) is attached to the structure and fixed with high-quality adhesive (MXBON super glue, Taiwan).

2.2. Analyze by Numerical Methods. The pill-shaped sensor will be tested in the low-pressure range. Hence, only numerical simulations (e.g., using the finite element method) can accurately represent the strain distribution across the diaphragms and, more importantly, the strain transferred to the FBG. In this study, before the experiment’s sensor structure was carried out, we used the ANSYS 2020R1 software to analyze the sensor’s response with a pill-shaped structure made of PLA material. About the structural meshing, the sensor body made of 3D-printed material has meshed with finite elements of 0.5 mm for the entire structure. The finite element model has 153665 nodes and 89362 elements. In the sensor structure, the main deformation component under the action of pressure is the diaphragm on both sides of the structure. Both of these diaphragms are 1 mm thick.

Figure 3 shows that, at an applied pressure of 0.35 MPa, the maximum axial strain (με) reached 1948 at the center of the diaphragm, and with each change in pressure, the strain in the diaphragm has a linear response to the static pressure, and with larger diaphragm size, it is obvious that the resulting axial strain is also larger. Thus, the basis for placing optical fiber in this area is completely reasonable. Based on this numerical analysis, we experiment with the fabricated sensor.

2.3. Working Principle. The relation between the shift of the Bragg wavelength of FBG (Δλb/λb) and the axial strain ε applied to a fiber grating is [24]

$$\frac{\Delta \lambda_b}{\lambda_b} = (1 - p_e) \varepsilon,$$  

(1)

where $p_e = 0.5 n_{eff}^2 \left[ P_{12} - \nu (P_{11} + P_{12}) \right]$ is the effective photoelastic coefficient of the glass fiber with Poisson ratio $\nu$, $P_{11}$ and $P_{12}$ denote the photoelastic coefficients, and $n_{eff}$ represents the effective refractive index of the guide mode. For a typical fused-silica fiber, $\nu = 0.16$, $n_{eff} = 1.46$, $P_{11} = 0.12$, $P_{12} = 0.27$, and thus, $p_e = 0.22$ [25].

For an FBG with two ends fixed by two polymer diaphragms located opposite each other, so the axial strain along the FBG due to an applied pressure $P$ is given by

$$\varepsilon = \frac{-P(1-2\nu)}{E},$$  

(2)
where ν and E are the Poisson ratio and Young’s modulus of the polymer (PLA material), respectively. The sensor’s operation principle is that the pill-shaped structure’s deformation leads to tension in the FBG fiber during a change in applied pressure, resulting in a change in the Bragg wavelength, which the OSA records.

3. Experiment Set-Up

The experimental layout for this study is shown in Figure 4. The sensor is placed in a well-controlled pressure chamber to test the pressure response. The pressure inside the chamber is changed using a compressor that pushes water into the chamber and is controlled with an accurate pressure gauge. The experimental temperature was well controlled at laboratory temperature (25°C ± 0.5°C), and the effect of temperature was considered to be within control. The light from a diode laser source (Model DL-BP1-CS5169A) is launched into the FBG through the 1×2 optical coupler. The reflectance spectrum of the FBG is then transferred to an optical coupler and fed to the optical spectrum analyzer (OSA, Model-MS9740A, Anritsu). The connector is an FC/UPC connector (FC/UPC FC/UPC SM SX 9/125, 3.0 mm, 2 m).

The pressure applied in the pressure chamber compresses the polymer diaphragm on either side where air pressure is available. This results in the two diaphragms being pulled on both sides, producing axial strain in the FBG. The test pressure was increased up to 0.35 MPa in steps of 0.01 MPa, and the corresponding change in the Bragg wavelength of the FBG was recorded using the OSA.

4. Results and Discussions

Figure 5 shows the recorded OSA spectra of the Bragg wavelength shift of the FBG corresponding to the pressure from 0 to 0.35 MPa with a step of 0.05 MPa. In the first experiment, the applied pressure went from 0 to 0.35 MPa; but in the second, the pressure decreased from 0.35 to 0 MPa and then increased again to 0.35 MPa for the 3rd test. The total Bragg wavelength shift over the applied pressure range was recorded as 1.44 nm, corresponding to a pressure sensitivity of 4.11 nm/MPa.

To study the repeatability response of the sensor, the experiment was repeated in three tests under laboratory conditions (at room temperature). Figure 6 shows a comparison of three pressure tests against the rise and fall of the pressure, indicating that the pressure sensitivity is 4.25, 4.06, and 4.15 nm/MPa, respectively. A linear analysis showed that the linear values of the data obtained in the three experiments were 0.9935, 0.9996, and 0.9933, respectively, all of which exceeded 0.99. Therefore, the mean standard deviation of the sensitivity of the pressure sensor in the repeated experiment is 0.055 nm/MPa. The smaller the standard deviation, the closer the value is to the mean sensitivity, and thus, higher accuracy and the corresponding Bragg wavelength shift of the FBGs were recorded. As a result, the sensor possesses outstanding linearity and cycle repeatability. It can be used as a highly stable pressure sensor.

Regarding the sensor’s sensitivity, it can be seen from Table 1 that the pill-shaped sensor in this study has a much higher sensitivity than the bare FBG sensor. It is 1334 times more than the bare FBG sensor mentioned in [4], respectively; 125 times more than the FBG sensor mentioned in [5]; and 2.9 times, two times, 12 times, 108 times, and almost four times that of the sensitivity of FBG sensors mentioned in [6, 18, 26–28], respectively. On the other hand, when compared with the FBG sensors embedded in other structures, the sensor in this study shows good and much higher sensitivity than some types of sensors, as indicated in the methodology above. Of course, it is not the highest; for example, the polymer-coated sensor mentioned in [10, 12, 13] (Table 1) is more sensitive than the sensor in this study. However, it is clear that it is easier and faster to fabricate the structure for 3D-printed sensors than the above-compared structures. The sensitivity can improve drastically by altering the structure size, shape, or material.

In addition, in this experiment, pressure is applied to the diaphragm on both sides, so it will be more efficient and achieve better sensitivity than the one-sided response on FBGs. The experimental sensitivity is also close to the theoretical calculation. With this new sensor structure, we can completely change the thickness of the diaphragm to adapt...
Figure 4: The experimental layout.

Figure 5: Measured reflection spectra of FBGs: (a) 1st test, increase pressure; (b) 2nd test, decrease pressure; (c) 3rd test, increase pressure.
Figure 6: (a) Measured Bragg wavelength as a function of the applied pressure. (b) Linear fit of wavelength and standard deviation.

Table 1: Comparison of the sensitivity of several reported FBG pressure sensors.

| Method                                             | Pressure range | Sensitivity (wavelength shift) | References   |
|----------------------------------------------------|----------------|--------------------------------|--------------|
| Bare FBGs were put in the pressure chamber         | 70 MPa         | $3.04 \times 10^{-3}$ nm/MPa   | [4]          |
| FBGs were put in a glass-bubble housing            | 14 MPa         | $27.8 \times 10^{-3}$ nm/MPa   | [5]          |
| FBGs were glued on Bourdon tube                    | 1 MPa          | 1.414 nm/MPa                   | [6]          |
| FBGs were put in a resin cylinder                  | 0.4 MPa        | 2.08 nm/MPa                    | [18]         |
| FBGs based on the diaphragm-cantilever             | 10 MPa         | 0.34 nm/MPa                    | [26]         |
| FBGs based on the plane diaphragm                  | 50 MPa         | $37.48 \times 10^{-3}$ nm/MPa  | [27]         |
| FBGs based fixed guided beam                       | 2 MPa          | 1.03 nm/MPa                    | [28]         |
| FBG encapsulated in a partially polymer-filled metal cylinder | 0.1 MPa | 39.6 nm/MPa                  | [10]         |
| FBG embedded in a polymer-filled metal cylinder     | 0.45 MPa       | 5.277 nm/MPa                   | [12]         |
| FBG encapsulated in a polymer-half-filled metal cylinder | 0.2 MPa | 33.5 nm/MPa                   | [13]         |
| FBGs were put in the pill-shaped 3D-printed structure | 0.35 MPa | 4.11 nm/MPa | This study |
to the required pressure ranges. We can also increase the safety of FBGs by creating a protective layer on the two sides of the pill-shaped structure. This could make it a bit more difficult to implant FBG fiber into the structure and will probably alter the pressure range.

A numerical analysis method is used to evaluate the sensor structure’s customizability. Figure 7 shows that the applied pressure from 0 to 0.35 MPa results in a wavelength shift from 0 to 1.44 nm. It is pretty close to the numerical simulation analysis results. It demonstrates the high reliability and potential of the sensor in this study. For this, the two structural dimensions of the sensor are compared. The entire structure’s size is $62 \times 25 \times 20$ mm ($L \times H \times W$), and the larger size for comparison in numerical simulation is $80 \times 25 \times 44$ mm. Figure 8 shows that when the sensor size was increased by 30%, the sensitivity can improve almost five times. It also demonstrates the outstanding feature of 3D printing technology: the flexibility, easy adjustment, and fabrication of different sizes and thicknesses of the sensor corresponding to the value to be measured. In other words, using 3D printing technology in the fabrication of the sensor’s structure shows a very high degree of customization to the desired applied pressure range.
5. Conclusion

A highly sensitive and linear FBG pressure sensor is designed and demonstrated. Pressure sensitivity is enhanced by connecting the two ends of the FBGs to the two diaphragms in the 3D printer-printed structure, which operates on the principle of differential pressure resulting in a tensile response of the diaphragm. Therefore, it directly induces tensile strain in the optical fiber. The test results show that the designed sensor has high linearity and good repeatability in pressure measurements with negligible standard deviation. As mentioned above, this pill-shaped sensor has much better sensitivity than other sensors in its class. Although it is not the most sensitive sensor, it excels in its simplicity of construction, high customization, and saving time and economy manufacturing. This sensor can measure pressure in technological processes with a suitable pressure range and can be calibrated to accommodate lower or higher pressure ranges.

Data Availability

Data is available on request.

Conflicts of Interest

The authors declare no conflict of interests.

Acknowledgments

This work was supported by the Ministry of Science and Technology, Taiwan, under Grant MOST 110-2221-E-992-054-MY3.

References

[1] E. Vorathin, Z. Hafizi, N. Ismail, and M. Loman, “Review of high sensitivity fibre-optic pressure sensors for low pressure sensing,” Optics & Laser Technology, vol. 121, p. 105841, 2020.
[2] R. He, C. Teng, S. Kumar, C. Marques, and R. Min, “Polymer optical fiber liquid level sensor: a review,” IEEE Sensors Journal, vol. 22, no. 2, 2021.
[3] R. Min, Z. Liu, L. Pereira, C. Yang, Q. Sui, and C. Marques, “Optical fiber sensing for marine environment and marine structural health monitoring: a review,” Optics & Laser Technology, vol. 140, p. 107082, 2021.
[4] M. Xu, L. Reekie, Y. Chow, and J. P. Dakin, “Optical in-fibre grating high pressure sensor,” Electronics Letters, vol. 29, no. 4, pp. 398-399, 1993.
[5] M. Xu, H. Geiger, and J. Dakin, “Fibre grating pressure sensor with enhanced sensitivity using a glass-bubble housing,” Electronics Letters, vol. 32, no. 2, pp. 128-129, 1996.
[6] J. Huang, Z. Zhou, D. Zhang, and Q. Wei, “A fiber Bragg grating pressure sensor and its application to pipeline leakage detection,” Advances in Mechanical Engineering, vol. 5, 2013.
[7] C. A. Marques, G.-D. Peng, and D. J. Webb, “ Highly sensitive liquid level sensor using a polymer optical Bragg grating for industrial applications,” in In CLEO: Applications and Technology, 2015: Optical Society of AmericaOptica Publishing Group.
[8] C. A. Díaz, A. G. Leal-Junior, P. S. Andre et al., “Liquid level measurement based on FBG-embedded diaphragms with temperature compensation,” IEEE Sensors Journal, vol. 18, no. 1, pp. 193–200, 2017.
[9] Y. Liu, Z. Guo, Y. Zhang, K. S. Chiang, and X. Dong, “Simultaneous pressure and temperature measurement with polymer-coated fibre Bragg grating,” Electronics Letters, vol. 36, no. 6, pp. 564–566, 2000.
[10] V. Pachava, S. Kamineni, S. Madhuvarasu, and K. Putha, “Polymer packaged fiber grating pressure sensor with enhanced sensitivity,” International Journal of Optoelectronic Engineering, vol. 4, no. 1, pp. 1–5, 2014.
[11] Q. Wen, J. Zhu, S. Gong, J. Huang, H. Gu, and P. Zhao, “Design and synthesis of a packaging polymer enhancing the sensitivity of fiber grating pressure sensor,” Progress In Natural Science, vol. 18, no. 2, pp. 197–200, 2008.
[12] Y. Zhang, D. Feng, Z. Liu et al., “High-sensitivity pressure sensor using a shielded polymer-coated fiber Bragg grating,” IEEE Photonics Technology Letters, vol. 13, no. 6, pp. 618-619, 2001.
[13] H.-J. Sheng, M.-Y. Fu, T.-C. Chen, W.-F. Liu, and S.-S. Bor, “A lateral pressure sensor using a fiber Bragg grating,” IEEE Photonics Technology Letters, vol. 16, no. 4, pp. 1146–1148, 2004.
[14] C.-W. Lai, Y.-L. Lo, J.-P. Yur, W.-F. Liu, and C.-H. Chiang, “Application of Fabry–Pérot and fiber Bragg grating pressure sensors to simultaneous measurement of liquid level and specific gravity,” Measurement, vol. 45, no. 3, pp. 469–473, 2012.
[15] X. Liu, L. Liang, K. Jiang, and G. Xu, “Sensitivity-enhanced fiber Bragg grating pressure sensor based on a diaphragm and hinge-lever structure,” IEEE Sensors Journal, vol. 21, no. 7, pp. 9155–9164, 2020.
[16] Y. Zhao, H.-k. Zheng, R.-q. Lv, and Y. Yang, “A practical FBG pressure sensor based on diaphragm-cantilever,” Sensors and Actuators A: Physical, vol. 279, pp. 101–106, 2018.
[17] Q. Fan, D. Feng, and Z. Yong, “Highly sensitive FBG pressure sensor based on square diaphragm,” Optik, vol. 225, p. 165559, 2021.
[18] Y.-K. Lin, T.-S. Hsieh, L. Tsa, S.-H. Wang, and C.-C. Chiang, “Using three-dimensional printing technology to produce a novel optical fiber Bragg grating pressure sensor,” Sensors Mater, vol. 28, no. 5, pp. 389–394, 2016.
[19] C. Hong, Y. Zhang, and L. Borana, “Design, fabrication and testing of a 3D printed FBG pressure sensor,” IEEE Access, vol. 7, pp. 38577–38583, 2019.
[20] P. C. Liacouras, G. T. Grant, K. Choudhry, G. F. Strouse, and Z. Ahmed, “Fiber Bragg gratings embedded in 3D-printed scaffolds,” NCSLI Measure, vol. 10, no. 2, pp. 50–52, 2015.
[21] C. Hong, Y. Yuan, Y. Yang, Y. Zhang, and Z. A. Abro, “A simple FBG pressure sensor fabricated using fused deposition modelling process,” Sensors and Actuators A: Physical, vol. 285, pp. 269–274, 2019.
[22] L. Schenato, Q. Rong, Z. Shao et al., “Highly sensitive FBG pressure sensor based on a 3D-printed transducer,” Journal of Lightwave Technology, vol. 37, no. 18, pp. 4784–4790, 2019.
[23] M. Fajkus, J. Nedoma, R. Martinek et al., “Pressure membrane FBG sensor realized by 3D technology,” Sensors, vol. 21, no. 15, p. 5158, 2021.
[24] W. W. Morey, G. Meltz, and W. H. Glenn, “Fiber optic Bragg grating sensors,” in In Fiber optic and laser sensors VII, vol. 1169, pp. 98–107, International Society for Optics and Photonics, 1990.
[25] G. Hocker, “Fiber-optic sensing of pressure and temperature,” *Applied Optics*, vol. 18, no. 9, pp. 1445–1448, 1979.

[26] M.-F. Liang, X.-Q. Fang, G. Wu, G.-Z. Xue, and H.-W. Li, “A fiber Bragg grating pressure sensor with temperature compensation based on diaphragm-cantilever structure,” *Optik*, vol. 145, pp. 503–512, 2017.

[27] M. Liang, X. Fang, and Y. Ning, “Temperature compensation fiber Bragg grating pressure sensor based on plane diaphragm,” *Photonic Sensors*, vol. 8, no. 2, pp. 157–167, 2018.

[28] M. Manuvinakurake, U. Gandhi, U. Mangalanathan, and M. Nayak, “Design, fabrication and testing of fiber Bragg grating based fixed guided beam pressure sensor,” *Optik*, vol. 158, pp. 1063–1072, 2018.