DEVELOPMENT OF TEMPERATURE-INSENSITIVE FIBRE BRAGG GRATING BASED PRESSURE TRANSDUCER

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SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science.

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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ABSTRAK

Penderia tekanan adalah peralatan penting dalam bidang pengukuran tekanan. Dalam kajian ini, penderia tekanan dengan diafragma aluminium yang berasaskan penderia fiber Bragg grating (FBG) dengan strategi pampasan suhu dibentangkan. Penderia yang berasaskan FBG adalah baik untuk aplikasi tertentu seperti dalam bidang biomedikal, dalam kebuk pembakaran dan kebuk tekanan; terutamanya yang melibatkan persekitaran yang kasar dan gangguan elektromagnetik yang tinggi. Salah satu cabaran terbesar dalam penggunaan penderia berdasarkan FBG adalah paparan spektrum yang tidak stabil kerana wujudnya variasi suhu persekitaran. Fenomena ini menghasilkan perubahan besar dalam bacaan tekanan, dan seterusnya menyumbang kepada masalah ketepatan dalam pengukuran. Untuk mengatasi masalah ini, kajian ini memperkenalkan satu pendekatan untuk menyelesaikan ketidakseragaman paparan keluaran penderia dengan mengaplikasikan dua FBGs, yang mana salah satu dilekatkan pada pusat diafragma (sensor FBG) dan satu lagi pada tapak transduser tekanan (rujukan FBG). Ketidakseragaman paparan keluar spektrum dapat dihapuskan dengan menggunakan normalisasi variasi panjang gelombang Bragg dari sensor FBG ($\Delta\lambda_{FBG1}$) dengan variasi panjang gelombang Bragg dari rujukan FBG ($\Delta\lambda_{FBG2}$). Hasilnya, menunjukkan bahawa transduser tekanan FBG ini mempunyai sensitiviti 2.8485 nm/MPa pada suhu bilik dalam linkungan 22.9°C hingga 27.8°C dan pekali pemasangan linear 99.97% dalam julat tekanan dari 0 MPa hingga 0.5 MPa. Penderia tekanan FBG ini dengan teknik pampasan suhu terbukti sesuai untuk pengukuran tekanan gas dengan ralat purata 2.32% berbanding dengan tolok tekanan konvensional yang terdapat di pasaran.

ABSTRACT

Pressure sensors are the essential equipment in the field of pressure measurement. In this study, an aluminium diaphragm-based fibre Bragg grating (FBG) pressure transducer with temperature compensation strategy is presented. FBG-based sensors are good for certain applications, such as biomedical, combustion chamber and pressure vessel; particularly those involving harsh enviroment and high electromagnetic disturbance. One of the greatest challenges for utilising an FBG-sensor based transducer is the unstable output spectrum due to temperature variations. This phenomenon results in a huge variation in pressure readings, thus contributing to accuracy problem. To overcome the problem, this study introduced an approach to solve the inconsistency of sensor output by utilising two FBGs that were bonded at the centre of the diaphragm (FBG sensor) and at the base of the pressure transducer (FBG reference). The inconsistency of wavelength was eliminated by normalising the Bragg wavelength variation from the FBG sensor ($\Delta\lambda_{FBG1}$) with respect to Bragg wavelength variation from the FBG reference ($\Delta\lambda_{FBG2}$). The results indicated that the FBG pressure transducer had a sensitivity of 2.8485 nm/MPa at room temperature within the range of 22.9°C to 27.8°C and a linear fitting coefficient of 99.97% in a pressure that ranged from 0 MPa to 0.5 MPa. This FBG pressure transducer with temperature compensation technique was proven to be suitable for the pressure measurement of gas with an average error of 2.32% as compared to the conventional pressure gauge available in market.

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LIST OF SYMBOLS

A	Area
λ_B	Bragg wavelength
t	Diaphragm thickness
p_e	Effective photoelastic
n_{eff}	Effective reflective index
F	Force
λ_o	Laser output
y_{max}	Maximum deflection
Λ	Period of Bragg grating
v	Poisson's ratio
P	Pressure
P	Pressure applied
r	Radius of diaphragm
ε	Strain applied
ΔT	Temperature changes
α	Thermal coefficient
ξ	Thermo-optic coefficient
x	Value of pressure
y	Value of wavelength
$\Delta\lambda_B$	Wavelength changes
E	Young's modulus

LIST OF ABBREVIATIONS

ABS	Acrtlonitrile butadiene styrene
ASE	Amplified spontaneous emission
CRC	Canadian Communication Research Centre
CFRP	Carbon fibre reinforced polymer
EMI	Electromagnetic interference
EOM	Electro-optic modulator
FP	Fabry-Perot
FBG	Fibre Bragg grating
FEA	Finite element analysis
nm	Nanometre
N	Newton
OFS	Optical fibre sensor
OSA	Optical spectrum analyzer
Pa	Pascal
PD	Photodetector
SHM	Structural health monitoring
SLD	Superluminescent diode
SLED	Superluminescent light emitting diode
OTF	Tunable optical filter
UV	Ultra violet

REFERENCES

Al-Fakih, E. A., Osman, N. A. A., Adikan, F. R. M., Eshraghi, A., & Jahanshahi, P. (2015). Development and validation of fiber Bragg grating sensing pad for interface pressure measurements within prosthetic sockets. *IEEE Sensors Journal, 16*(4), 965-974.

Albert, J., Shao, L. Y., & Caucheteur, C. (2013). Tilted fiber Bragg grating sensors. *Laser & Photonics Reviews, 7*(1), 83-108.

Allwood, G., Wild, G., Lubansky, A., & Hinckley, S. (2015). A highly sensitive fiber Bragg grating diaphragm pressure transducer. *Optical Fiber Technology, 25*, 25-32.

Alwis, L., Sun, T., & Grattan, K. (2016). Developments in optical fibre sensors for industrial applications. *Optics & Laser Technology, 78*, 62-66.

Baldwin, C. S., Yu, M., Miller, C. E., Sirkis, J. S., Chen, S., & Balachandran, B. (1999). *Bragg grating based Fabry-Perot sensor system for acoustic measurements.* Paper presented at the Smart Structures and Materials 1999: Sensory Phenomena and Measurement Instrumentation for Smart Structures and Materials.

Balkanli, H. (1981). Bourdon tube transducer: Google Patents.

Bremer, K., Leen, G., Lewis, E., Moss, B. J., Lochmann, S., & Mueller, I. (2014). Pressure sensor with an interferometric sensor and an in-fiber Bragg grating reference sensor: Google Patents.

Casas, J. R., & Cruz, P. J. (2003). Fiber optic sensors for bridge monitoring. *Journal of bridge engineering, 8*(6), 362-373.

Chang, C.-C., Johnson, G., Vohra, S. T., & Althouse, B. (2000). *Development of fiber Bragg-grating-based soil pressure transducer for measuring pavement response.* Paper presented at the Smart Structures and Materials 2000: Sensory Phenomena and Measurement Instrumentation for Smart Structures and Materials.

Chen, C., Yu, Y.-S., Yang, R., Wang, C., Guo, J.-C., Xue, Y., . . . Sun, H.-B. (2013). Reflective optical fiber sensors based on tilted fiber Bragg gratings fabricated with femtosecond laser. *Journal of Lightwave Technology, 31*(3), 455-460.

Chen, H. (2010). Fiber optic pressure sensor based on a single-mode fiber F–P cavity. *Measurement, 43*(3), 370-374.

Cui, L.-Q., Long, X., & Qin, J.-M. (2015). A bellow pressure fiber optic sensor for static ice pressure measurements. *Applied Geophysics, 12*(2), 255-262.

Di Sante, R., & Bastianini, F. (2015). Temperature compensated fibre Bragg grating based sensor with variable sensitivity. *Optics and Lasers in Engineering, 75*, 5-9.

Díaz, C. A., Leal-Junior, A. G., André, P. S., da Costa Antunes, P. F., Pontes, M. J., Frizera-Neto, A., & Ribeiro, M. R. (2018). Liquid level measurement based on FBG-embedded diaphragms with temperature compensation. *IEEE Sensors Journal, 18*(1), 193-200.

Edwards, A. T. (2000). *Comparison of strain gage and fiber optic sensors on a sting balance in a supersonic wind tunnel.* Virginia Tech.

Ferreira, L., Antunes, P., Domingues, F., Silva, P., & André, P. (2012). Monitoring of sea bed level changes in nearshore regions using fiber optic sensors. *Measurement, 45*(6), 1527-1533.

Fidanboylu, K., & Efendioglu, H. (2009). *Fiber optic sensors and their applications.* Paper presented at the 5th International Advanced Technologies Symposium (IATS'09).

Figliola, R. S., & Beasley, D. (2006). *Theory and design for mechanical measurements*: John Wiley & Sons.

Filloux, J. (1969). Bourdon tube deep-sea tide gauges. *Tsunamis in the Pacific Ocean, edited*.

Frieden, J., Cugnoni, J., Botsis, J., Gmür, T., & Ćorić, D. (2010). High-speed internal strain measurements in composite structures under dynamic load using embedded FBG sensors. *Composite Structures, 92*(8), 1905-1912.

Fu, H., Liu, H., Dong, X., Tam, H., Wai, P., & Lu, C. (2008). High-speed fibre Bragg grating sensor interrogation using dispersion-compensation fibre. *Electronics Letters, 44*(10), 618-620.

Fuller, L. (2005). *Bulk micromachined pressure sensor.* Rochester Institute of Technology.

Hill, K., Fujii, Y., Johnson, D. C., & Kawasaki, B. (1978). Photosensitivity in optical fiber waveguides: Application to reflection filter fabrication. *Applied Physics Letters, 32*(10), 647-649.

Hill, K. O., & Meltz, G. (1997). Fiber Bragg grating technology fundamentals and overview. *Journal of lightwave technology, 15*(8), 1263-1276.

Hong, C., Zhang, Y., Yang, Y., & Yuan, Y. (2019). A FBG based displacement transducer for small soil deformation measurement. *Sensors and Actuators A: Physical, 286*, 35-42.

Hsu, Y., Wang, L., Liu, W.-F., & Chiang, Y. (2006). Temperature compensation of optical fiber Bragg grating pressure sensor. *IEEE Photonics Technology Letters, 18*(7), 874-876.

Huang, J., Zhou, Z., Wen, X., & Zhang, D. (2013). A diaphragm-type fiber Bragg grating pressure sensor with temperature compensation. *Measurement, 46*(3), 1041-1046.

Isago, R., & Nakamura, K. (2009). A high reading rate fiber Bragg grating sensor system using a high-speed swept light source based on fiber vibrations. *Measurement Science and Technology, 20*(3), 034021.

Jones, D. (1998). Introduction to fiber optics. *Naval Education and Training Professional Develeopment and Technology Center*.

Jones, R. T., & Dunphy, J. R. (2006). Optical differential pressure transducer utilizing a bellows and flexure system: Google Patents.

Kang, D., Park, S., Hong, C., & Kim, C.-G. (2005). The signal characteristics of reflected spectra of fiber Bragg grating sensors with strain gradients and grating lengths. *NDT & E International, 38*(8), 712-718.

Kennedy, G. C. (1954). Pressure-volume-temperature relations in CO2 at elevated temperatures and pressures. *Amer. J. Sci, 252*(4).

Kersey, A. D., Davis, M. A., Patrick, H. J., LeBlanc, M., Koo, K., Askins, C., . . . Friebele, E. J. (1997). Fiber grating sensors. *Journal of lightwave technology, 15*(8), 1442-1463.

Khakpour, R., Mansouri, S. R., & Bahadorimehr, A. (2010). *Analytical comparison for square, rectangular and circular diaphragms in MEMS applications.* Paper presented at the Electronic Devices, Systems and Applications (ICEDSA), 2010 Intl Conf on.

Knute, W. L., & Bailey, W. H. (1992). Fiber-optic transducer apparatus: Google Patents.

Krohn, D. (1988). Fiber Optic Sensors—Fundamentals and Applications (Instrument Society of America, Research Triangle Park, NC): Chapters.

Kumar, V. (1983). An Instrument for the Measurement of Infrasounds and Subsonic Disturbances in the Atmosphere. *IETE Journal of Research, 29*(1), 30-32.

Kumar, V., & Narayana, K. Development of an ANN-based Pressure Transducer.

Leal-Junior, A. G., Díaz, C. A., Frizera, A., Marques, C., Ribeiro, M. R., & Pontes, M. J. (2019). Simultaneous measurement of pressure and temperature with a single FBG embedded in a polymer diaphragm. *Optics & Laser Technology, 112*, 77-84.

Lee, B. (2003). Review of the present status of optical fiber sensors. *Optical fiber technology, 9*(2), 57-79.

Lee, B., & Jeong, Y. (2002). Interrogation techniques for fiber grating sensors and the theory of fiber gratings. *Optical Engineering-New York-Marcel Dekker Incorporated, 76*, 295-382.

Li, C., Ning, T., Zhang, C., Wen, X., Li, J., & Zhang, C. (2016). Liquid level and temperature sensor based on an asymmetrical fiber Mach–Zehnder interferometer combined with a fiber Bragg grating. *Optics Communications, 372*, 196-200.

Li, T., Shi, C., Tan, Y., Li, R., Zhou, Z., & Ren, H. (2016). A diaphragm type fiber Bragg grating vibration sensor based on transverse property of optical fiber with temperature compensation. *IEEE Sensors Journal, 17*(4), 1021-1029.

Liang, M., Fang, X., & Ning, Y. (2018). Temperature compensation fiber Bragg grating pressure sensor based on plane diaphragm. *Photonic Sensors, 8*(2), 157-167.

Liang, M., Fang, X., Wu, G., Xue, G., & Li, H. (2017). A fiber bragg grating pressure sensor with temperature compensation based on diaphragm-cantilever structure. *Optik-International Journal for Light and Electron Optics, 145*, 503-512.

Liang, R. (2015). *Piezoelectric Pressure Sensors Based On Flexible PZT Thick-Film Composite Device.* University of Pittsburgh.

Lin, W., & Zhang, X. (2006). *A novel approach for dynamic pressure transducer based pipeline leak detection.* Paper presented at the Intelligent Control and Automation, 2006. WCICA 2006. The Sixth World Congress on.

Ling, H.-y., Lau, K.-t., Cheng, L., & Jin, W. (2006). Viability of using an embedded FBG sensor in a composite structure for dynamic strain measurement. *Measurement, 39*(4), 328-334.

Liu, L., Zhang, H., Zhao, Q., Liu, Y., & Li, F. (2007). Temperature-independent FBG pressure sensor with high sensitivity. *Optical fiber technology, 13*(1), 78-80.

López-Amo, M., & López-Higuera, J. M. (2011). Multiplexing techniques for FBG sensors. *Chapter, 6*, 99-115.

Luo, D., Ismail, Z., & Ibrahim, Z. (2013). Added advantages in using a fiber Bragg grating sensor in the determination of early age setting time for cement pastes. *Measurement, 46*(10), 4313-4320.

Luo, J., Hao, Y., Ye, Q., Hao, Y., & Li, L. (2013). Development of optical fiber sensors based on Brillouin scattering and FBG for on-line monitoring in overhead transmission lines. *Journal of lightwave technology, 31*(10), 1559-1565.

Madhavi, K., Sumithradevi, K., Krishna, M., & Vijayalakshmi, M. (2011). *Analysis of Square and Circular diaphragms for a MEMS pressure sensor using a Data Mining tool.* Paper presented at the Communication Systems and Network Technologies (CSNT), 2011 International Conference on.

Marick, S., Bera, S. K., & Bera, S. C. (2014). A Modified Technique of Flow Transducer Using Bourdon Tube as Primary Sensing Element. *Sensors Journal, IEEE, 14*(9), 3033-3039.

Marques, C. A., Peng, G.-D., & Webb, D. J. (2015). Highly sensitive liquid level monitoring system utilizing polymer fiber Bragg gratings. *Optics Express, 23*(5), 6058-6072.

Meltz, G., Morey, W. W., & Glenn, W. (1989). Formation of Bragg gratings in optical fibers by a transverse holographic method. *Optics letters, 14*(15), 823-825.

Mihailov, S. J. (2012). Fiber Bragg grating sensors for harsh environments. *Sensors, 12*(2), 1898-1918.

Mishra, D. (2014). *Experimental combustion: an introduction*: Crc Press.

Neeharika, V., & Pattnaik, P. K. (2016). Optical MEMS pressure sensors incorporating dual waveguide Bragg gratings on diaphragms. *IEEE Sens. J, 16*(3), 681-687.

Pachava, V. R., Kamineni, S., Madhuvarasu, S. S., & Putha, K. (2014). A high sensitive FBG pressure sensor using thin metal diaphragm. *Journal of Optics, 43*(2), 117-121.

Pan, H., Dong, H., Zhang, G., & He, J. (2013). Research on fiber grating pressure/temperature monitoring device of distinguish range and double sensitivity. *Zhongguo Jiguang(Chinese Journal of Lasers), 40*(2), 0205005-0205006.

Pevec, S., & Donlagic, D. (2012). Miniature all-fiber Fabry–Perot sensor for simultaneous measurement of pressure and temperature. *Applied optics, 51*(19), 4536-4541.

Pinet, É. (2011a). *Pressure measurement with fiber-optic sensors: commercial technologies and applications.* Paper presented at the 21st International Conference on Optical Fibre Sensors (OFS21).

Pinet, É. (2011b). *Pressure measurement with fiber-optic sensors: commercial technologies and applications.* Paper presented at the Proc. SPIE.

Poeggel, S., Tosi, D., Duraibabu, D., Leen, G., McGrath, D., & Lewis, E. (2015). Optical fibre pressure sensors in medical applications. *Sensors, 15*(7), 17115-17148.

Rajanna, K., Nayak, M., Krishnamurthy, R., & Mohan, S. (1997). Low-cost thin film pressure transducer. *Vacuum, 48*(6), 521-524.

Rao, P. V., Srimannarayana, K., Shankar, M. S., Kishore, P., & Prasad, S. R. (2012). *Enhanced sensitivity of FBG pressure sensor using thin metal diaphragm.* Paper presented at the Fiber Optics and Photonics (PHOTONICS), 2012 International Conference on.

Rao, Y.-J. (1997). In-fibre Bragg grating sensors. *Measurement science and technology, 8*(4), 355.

Ren, G., Li, T., Hu, Z., & Zhang, C. (2019). Research on New FBG Soil Pressure Sensor and Its Application in Engineering. *Optik*.

Sengupta, D., Sai Shankar, M., Saidi Reddy, P., Sai Prasad, R., & Srimannarayana, K. (2012). Sensing of hydrostatic pressure using FBG sensor for liquid level measurement. *Microwave and Optical Technology Letters, 54*(7), 1679-1683.

Sharma, A. K., & Ojha, A. K. (2012). A Study on Micro-Electro-Mechanical Systems (MEMS) Sensors & their Applications *International Journal of Engineering and Advance Technology (IJEAT), 1*(5).

Sheng, H.-J., Liu, W.-F., Lin, K.-R., Bor, S.-S., & Fu, M.-Y. (2008). High-sensitivity temperature-independent differential pressure sensor using fiber Bragg gratings. *Optics express, 16*(20), 16013-16018.

Shu, Y., Chen, W., Zhang, P., Wu, J., Liu, H., & Zhang, W. (2013). Non-destructive testing of stress distribution in cable anchor.

Snyder, M. D., & Chen, Y. F. (2014). *Development of Aluminum Diaphragms for Concrete Bridges.*

Srimannarayana, K., & Kishore, P. (2013). *Diaphragm based high sensitive FBG pressure sensor.* Paper presented at the International Conference on Optics in Precision Engineering and Nanotechnology (icOPEN2013).

Thony, J.-L., & Vachaud, G. (1980). Automatic measurement of soil-water pressure using a capacitance manometer. *Journal of Hydrology, 46*(1), 189-196.

Tsuda, H. (2006). Ultrasound and damage detection in CFRP using fiber Bragg grating sensors. *Composites science and technology, 66*(5), 676-683.

Tsuda, H. (2010). Fiber Bragg grating vibration-sensing system, insensitive to Bragg wavelength and employing fiber ring laser. *Optics letters, 35*(14), 2349-2351.

Urban, F., Kadlec, J., Vlach, R., & Kuchta, R. (2010). Design of a pressure sensor based on optical fiber Bragg grating lateral deformation. *Sensors, 10*(12), 11212-11225.

von Beckerath, A. (1998). *WIKA-handbook: Pressure and Temperature Measurement*: WIKA Instrument Corporation.

WANG, H.-l., SONG, J., FENG, D.-q., & WU, H.-c. (2011). High temperature-pressure FBG sensor applied to special environments [J]. *Optics and Precision Engineering, 3*, 010.

Wang, Q. (1998). *Touch mode capacitive pressure sensors and interface circuits.* Case Western Reserve University.

Wang, Q., & Ko, W. H. (1999). Modeling of touch mode capacitive sensors and diaphragms. *Sensors and Actuators A: Physical, 75*(3), 230-241.

Wang, T., Yuan, Z., Gong, Y., Wu, Y., Rao, Y., Wei, L., . . . Wan, F. (2013). Fiber Bragg grating strain sensors for marine engineering. *Photonic Sensors, 3*(3), 267.

Wang, W., Jiang, X., & Yu, Q. (2012). Temperature self-compensation fiber-optic pressure sensor based on fiber Bragg grating and Fabry–Perot interference multiplexing. *Optics communications, 285*(16), 3466-3470.

Wang, X. X., & Wu, C. Y. (2012). *Pressure sensitivity researched on the metal-coated FBG sensors.* Paper presented at the Advanced Materials Research.

Wang, Y., Wang, M., & Huang, X. (2010). High-sensitivity fiber Bragg grating transverse force sensor based on centroid measurement of polarization-dependent loss. *Measurement Science and Technology, 21*(6), 065304.

Webb, D. J., Surowiec, J., Sweeney, M., Jackson, D. A., Gavrilov, L., Hand, J., . . . Bennion, I. (1996). *Miniature fiber optic ultrasonic probe.* Paper presented at the Fiber Optic and Laser Sensors XIV.

Wild, G., & Hinckley, S. (2010). *Optical fibre Bragg gratings for acoustic sensors.* Paper presented at the Proc. 20th International Congress on Acoustics.

Xiong, Y., He, J., Yang, W., Sheng, L., Gao, W., & Chen, Y. (2012). *Research on FBG pressure sensor of flat diaphragm structure.* Paper presented at the Measurement, Information and Control (MIC), 2012 International Conference on.

Xu, M., Reekie, L., Chow, Y., & Dakin, J. P. (1993). Optical in-fibre grating high pressure sensor. *Electronics letters, 29*(4), 398-399.

Yang, Y., Annamdas, V. G. M., Wang, C., & Zhou, Y. (2008). Application of multiplexed FBG and PZT impedance sensors for health monitoring of rocks. *Sensors, 8*(1), 271-289.

Yin, G., Dai, Y., Karanja, J., & Dai, J. (2015). Optimization design for medium-high frequency FBG accelerometer with different eigenfrequency and sensitivity. *Sensors and Actuators A: Physical, 235*, 311-316.

Yin, S., & Francis, T. (2002). *Fiber optic sensors*: CRC press.

Yunus, A. C., & Cimbala, J. M. (2006). *Fluid mechanics: fundamentals and applications*.

Zhang, W., Fang, L., & Liu, Y. (2009). Fiber Bragg grating pressure sensor with ultrahigh sensitivity and reduced temperature sensitivity. *Optical Engineering, 48*(2), 024402.

Zhang, W., Li, F., & Liu, Y. (2009). FBG pressure sensor based on the double shell cylinder with temperature compensation. *Measurement, 42*(3), 408-411.

Zhang, Y.-n., Peng, H., Qian, X., Zhang, Y., An, G., & Zhao, Y. (2017). Recent advancements in optical fiber hydrogen sensors. *Sensors and Actuators B: Chemical, 244*, 393-416.

Zhao, Y., Chen, M.-q., Xia, F., & Lv, R.-q. (2018). Small in-fiber Fabry-Perot low-frequency acoustic pressure sensor with PDMS diaphragm embedded in hollow-core fiber. *Sensors and Actuators A: Physical, 270*, 162-169.

Zhao, Y., Wu, Q.-l., & Zhang, Y.-n. (2018). Theoretical analysis of high-sensitive seawater temperature and salinity measurement based on C-type micro-structured fiber. *Sensors and Actuators B: Chemical, 258*, 822-828.

Zhao, Y., Yu, C., & Liao, Y. (2004). Differential FBG sensor for temperature-compensated high-pressure (or displacement) measurement. *Optics & Laser Technology*, *36*(1), 39-42.

Zhao, Y., Zheng, H.-k., Lv, R.-q., & Yang, Y. (2018). A practical FBG pressure sensor based on diaphragm-cantilever. *Sensors and Actuators A: Physical*.

Zhu, Y., & Wang, A. (2005). Miniature fiber-optic pressure sensor. *IEEE Photonics Technology Letters*, *17*(2), 447-449.

Zohari, M. (2014). *The applications of near infra-red fibre Bragg grating sensors for wave propagation based structural health monitoring of thin laminated composite plates.* University of Southern Queensland.