Design of optical fibre based highly sensitive acoustic sensor for underwater applications

Jincy Johny*, Thomas Smith, Kaushalkumar Bhavsar, Radhakrishna Prabhu
School of Engineering
Robert Gordon University, Aberdeen, United Kingdom
*j.johny@rgu.ac.uk

***Abstract*—Fibre optic sensing is a key technology for a variety of underwater sensing and monitoring applications. Fibre optic acoustic sensors are mainly based on interferometric detection approach where the acoustic pressure-induced phase shift of light has been used as sensing principle. Recently, fibre optic acoustic sensors based on speciality fibres like Photonic Crystal Fibre (PCF) were reported. However, interferometry based detection approaches amongst all these fibre optics sensors are intensity based and therefore susceptible to light power fluctuations and require a complex instrumentation related to signal detection. Besides, wavelength based detection approach using FBG (Fibre Bragg Grating) offers significant advantages over the conventional approach. FBG sensors were reported to have higher performance for underwater acoustic sensing applications. This paper reports a novel design of an underwater acoustic pressure sensor using a combination of PCF and FBG to provide high sensitivity. Theoretical investigations were carried out on the PCF-FBG sensor to study the effect of applied pressure and induced strain on the FBG inscribed in the core of PCF. Effect of light confinement in PCF was studied for different geometrical parameters and 4-ring PCF structure was reported. Further, sensitivity enhancement was proposed utilizing air hole structure of the PCF to enhance the impact of acoustic pressure on the induced strain in FBG.**

Keywords*— acoustic sensors; optical fibre; interferometry; PCF; FBG

I. INTRODUCTION

Subsea sensing and monitoring are gaining new focus in recent years. The subsea/underwater sensing applications include diverse areas such as seismic monitoring, detection of marine objects (such as submarines) and marine animals (such as whales), ocean current monitoring, pollution monitoring. [1-2]. Traditional underwater monitoring approaches using conventional instruments had many limitations. Real-time monitoring was impossible, communication between the sensors and the control systems operating onshore was not possible, any malfunction or failure of the sensor system was not detected until the instruments were recovered from the monitoring mission and the sensor data that can be collected was limited by the onboard memory space [3]. These limitations of conventional instruments can be overcome by using fibre optic sensors. Optical fibre sensors can perform real-time remote sensing and offer many advantages like larger bandwidth, immunity to electromagnetic interference (EMI), electrical isolation, the ability to operate in harsh environmental conditions, etc [4].

Over the past 30 years, optical fibre based sensors have been exploited to detect acoustic signals based on the interferometric approach where the pressure-induced phase shift of light has been used as detection principle [5-6].

An acoustic or sound wave normally consists of mechanical vibrations of their propagating medium [7]. These vibrations induce a pressure, which leads to change in fibre length and effective mode index. This effect directly relates to the property of the fibre material such as Young's modulus. Conventional silica fibres have relatively high Young's modulus which makes the conventional fibre incompressible. Therefore, the sensitivity of fibre optic acoustic sensors can be increased either by coating them with a material of low Young's modulus [8] or improving the acoustic pressure effect by wrapping the fibre around a properly designed mandrel structure [9]. Fig. 1 shows a fibre optic Mach-Zehnder interferometer (MZI) wherein, two optical fibres are wound on separate sensing structures, called the mandrels (sensing and reference mandrels). The signals from sensing and reference arms results in an interference pattern called fringes, which depends on the frequency of the received acoustic signal [9]. MZI can detect sound waves or vibrations by analyzing the signal interference between the two separate fibre sensors [10].

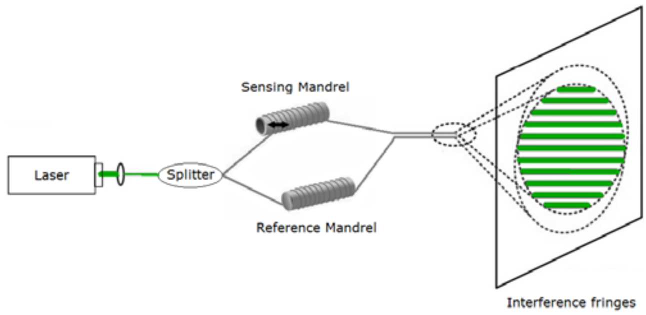

Fig. 1. Typical fibre optic interferometric setup to detect acoustic signal based on interference fringes.

Recently, Photonic Crystal Fibre (PCF) based sensors have become the subject of extensive research due to their inherent geometry/structure based light guiding properties. Compared to conventional solid core fibres, higher sensitivity was reported by using hollow core photonic crystal fibre (HC-PCF) for acoustic pressure detection [10]. This is mainly attributed to the many air hole based structure of the fibre which significantly reduces the effective Young's modulus and increases the axial strain. The PCF based acoustic sensor was reported by

Dnyandeo et al. [11] to monitor low-frequency underwater acoustic signal using Mach-Zehnder interferometric approach. A study on the effect of underwater acoustic pressure on the effective refractive index of the fundamental mode propagating in HC-PCF was reported by Abdallah et al. [12]. Photonic crystal based hydrophone using Fabry–Perot interferometric approach was reported for ocean acoustics [13]. However, the interferometric based detection approaches are intensity based and susceptible to light power fluctuations. The instrumentation related to detection of the signal is very complex in nature. On the other hand, wavelength based detection approach using FBG (Fibre Bragg Grating) offers significant advantages such as: high sensing range, multiplexing capability, multi-point and multi-parameter sensing capability, efficient operation in extreme environmental conditions (e.g. harsh marine environment, High-Pressure, High-Temperature (HPHT) field conditions), etc.

FBG is a mature and widely explored technology which finds a wide range of applications in diverse areas. However, intensive researches are still going on to enhance and exploit its capabilities for advanced sensing and monitoring applications. FBG sensors were reported for underwater acoustic sensing applications, which offer better performance than conventional optical fibre sensors [14]. This is because FBG is not distributed over the entire length of the fibre, rather it is localized in a shorter area (few mm), retaining all advantages of fibre optic sensors.

When FBG experiences acoustic pressure, the centre Bragg wavelength is expected to vary in tandem with the sound signal. The photoelastic effect modulates the effective refractive index and pitch of the grating due to the experienced acoustic pressure [15-17]. An underwater FBG based acoustic sensor was reported which equips two FBGs for measurements with differential outputs, enabling improved sensitivity [15]. However, still the sensitivity is limited by the relatively high Young's modulus of the silica fibre commonly used for FBGs. Blending of FBG in PCF can effectively reduce Young's modulus due to many air hole structures. Despite their integration, both PCF and FBG retains its sensing capability and opens up new possibilities (such as air holes can be utilized for incorporating microstructures) to realize highly sensitive sensor systems for underwater monitoring applications. PCF-FBG based acoustic sensor makes the instrumentation much simpler when compared to the existing interferometry based sensors. It greatly reduces the size and the complexity of the optical circuitry and signal processing unit involved [18]. Fibre optic interferometric sensor measurements are intensity based, whereas the PCF-FBG sensor operates in the wavelength domain, which is less susceptible to light power fluctuations.

In this paper, we report a novel design of PCF-FBG based highly sensitive acoustic sensor for underwater applications. Theoretical investigations were carried out on the PCF-FBG sensor using COMSOL Multiphysics, MATLAB and ANSYS software. Study on light confinement in the core of the PCF (where FBGs were inscribed) was carried out. Effect of applied pressure on FBG and a corresponding shift in the Bragg wavelength was studied. Furthermore, the effect of induced strain in FBG and a corresponding shift in wavelength was investigated. The sensitivity of the PCF-FBG sensor can be further enhanced by utilizing the air hole structure of PCF.

Natural frequency response and strain effect upon applied pressure were investigated for a solid cylindrical microstructure using simulations. A novel design by incorporation of micro-structures of different shape and size inside PCF holes is proposed to develop a highly sensitivity PCF-FBG based acoustic sensor.

II. Theory

A. PCF

PCF geometry is characterized by a periodic arrangement of air holes running along the length of the fibre creating a periodic refractive index change [19]. This specialized structure and refractive index contrast result in higher light confinement within the core of PCF sensor.

PCFs guide light by one of the two guiding mechanisms: index-guiding and bandgap-guiding. The operation of index guided PCF is similar to conventional optical fibres where light is confined within the high index core region by modified total internal reflection (M-TIR) principle [20]. Bandgap PCFs guides light in the low-index core region by reflection from the photonic crystal cladding [21].

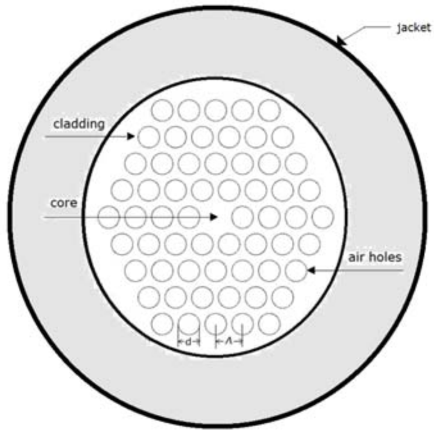

Fig. 2. Cross sectional view of a typical PCF fibre showing the characteristic structural features including air holes

Fig. 2 depicts the cross section of a solid core PCF. Conventional single mode fibre size is 9/125/250 μm. Optical fibre size is commonly referred to by the outer diameter of its core, cladding and coating. Light confinement within the PCF depends on its structural parameters such as: pitch (Λ), which is the cladding hole center to center distance; d, which is the diameter of the air holes in the cladding; the number of air hole rings, etc.

B. FBG

FBGs are constructed within a short segment of the optical fibre core, which reflects particular wavelengths of light and transmits all others. They are characterized by permanent periodic refractive index change, known as fibre Bragg grating. The fundamental principle of FBG depends on Bragg condition which states that any changes in physical parameters such as pressure, temperature, strain etc modifies the refractive index or grating period of the fibre grating, which in turn changes the Bragg reflected wavelength (λ_b) [22].

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

Where n_{eff} is the effective refractive index and Λ is the period of the grating or spatial period.

FBG strain sensitivity, which is the fractional change in Bragg wavelength [23] for applied strain $\left(\varepsilon = \frac{\Delta\Lambda}{\Lambda}\right)$ is given by:

$$\frac{\Delta\lambda_b(\varepsilon)}{\lambda_b} = (1 - \rho_e)\Delta\varepsilon \qquad (2)$$

Where ρ_e is the photo-elastic coefficient and $\Delta\varepsilon$ is the variation in strain value.

Axial strain along FBG due to applied pressure is given by [24]:

$$\varepsilon = -\frac{P(1-2v)}{E} \qquad (3)$$

Where ε is the strain, P is applied pressure, v is Poisson's ratio and E is the young's modulus.

C. PCF-FBG sensor

In PCF-FBG sensor configuration, the FBG is written on to the core of the photonic crystal fibre. Fig. 3 shows the cross-sectional and lateral view of the PCF-FBG sensor. PCF-FBG combination improves the capabilities of the fibre optic sensor system in terms of power, energy scaling and discrimination of cross-sensitivities [25]. They have the potential to differentiate the effects of different physical parameters like temperature and strain [26]. Furthermore, the strong light confinement characteristics of PCF returns strong sensing signals from the sensor. Hence, the PCF-FBG sensor is expected to have higher Signal to Noise Ratio (SNR).

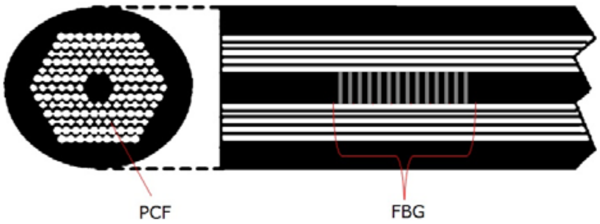

Fig. 3. PCF-FBG sensor configuration

Quasi-distributed FBGs with multi-wavelength based detection further enhances the capabilities of the PCF-FBG combo. This configuration consists of a series of FBGs inscribed into the core of the transmission fibre (PCF) (Fig. 4), each with a different Bragg wavelength (λ_1, λ_2, λ_3,..,λ_n) [27] and reflected light can be detected using optical spectrum analyzer (OSA). Multiple FBGs within the PCF enables multi-point multi-parameter sensing capabilities. [28].

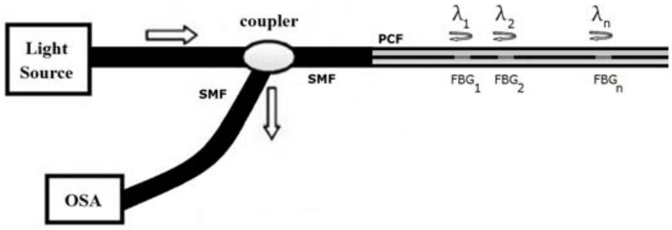

Fig. 4. Configuraiton of PCF-FBG acoustic sensor array for multipoint sensing.

III. Results And Discussions

A. Modeling of PCF-FBG sensor

Light confinement effect in the PCF-FBG sensor was investigated using a computational software. Modeling of the PCF was carried out using the wave optics module of COMSOL Multiphysics. Fig. 5 shows the electric field mode profile of the designed 4-ring PCF. A very strong light confinement within the PCF core was observed. This strong light confinement within the PCF core enhances the light propagation range and therefore, enables long distance remote sensing and monitoring suitable for underwater marine applications. In the previous study, it was found that tighter optical mode field confinements can be achieved for the PCF-FBG sensor, by optimising its various parameters such as air hole size, pitch and number of rings. [29]. It was observed that the effect of outer hole ring structures has a negligible effect on the light confinement and therefore, the outer ring holes can be utilized to enhance the imparted strain on FBG due to external pressure on PCF.

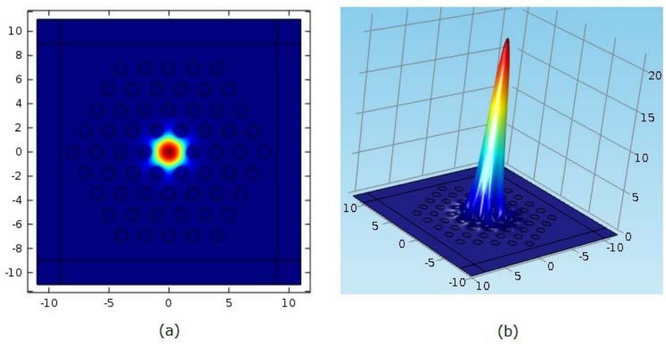

Fig. 5. (a) 2D and (b) 3D view of the electric field distribution profile of a 4-ring PCF.

A computational study was carried out using MATLAB to study the effect of applied pressure on the FBG Bragg wavelength. Fig. 6 shows the change in Bragg wavelength ($\Delta\lambda$) due to applied pressure to the FBG. It was observed that Bragg wavelength varied linearly with applied pressure. This study provides information about the applied pressure effect on the PCF-FBG sensor.

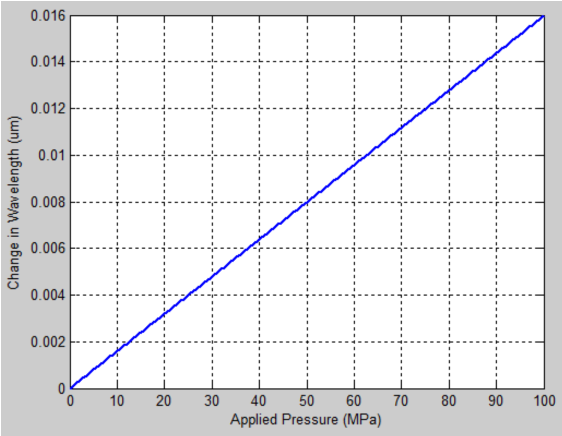

Fig. 6. Change in centre wavelength with applied pressure

Furthermore, the effect of induced strain due to applied pressure was studied using numerical modeling. Fig. 7 shows the strain sensitivity graph of FBG, which is the plot of a shift in Bragg wavelength to change in applied strain. FBG strain sensitivity factor calculated theoretically varies linearly with applied strain. This sensitivity analysis, helped in understanding how the PCF-FBG sensor would respond to the strain imparted by the external pressure.

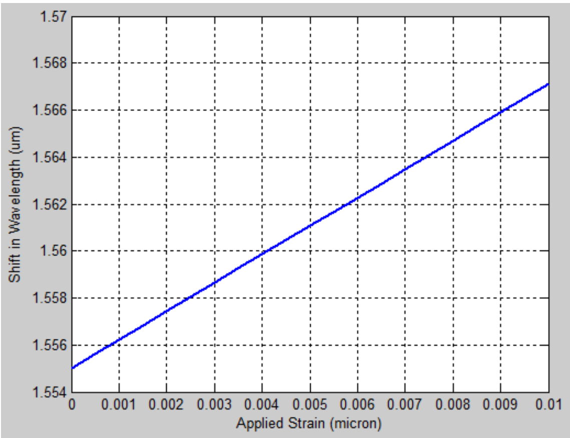

Fig. 7. Shift in Bragg wavelength for applied strain

B. PCF-FBG Micro-structure

To further enhance the sensitivity, air holes in the PCF can be utilized to incorporate micro-structures inside. Various micro-structures can be designed with appropriate shape and size to match their natural resonant frequency with the incoming acoustic signal. By incorporating the micro-structures in the air holes, the effect of induced strain due to acoustic pressure can be increased by their natural resonant effect. This, in turn, led to higher strain imparted on the FBG in the core of PCF. The increased strain effect observed by the FBG will lead to high sensitivity. A micron-sized solid cylinder structure was designed to resonate in the acoustic frequency range. A natural vibrational frequency response of the designed micro-structure was investigated using simulations in ANSYS software. Fig. 8 shows the observed longitudinal strain with natural resonant frequency response for the applied pressure. It was observed that designed cylindrical structure gives higher strain response at different resonant frequencies with highest observed around 12000 Hz. Therefore, incorporating this structure inside PCF holes can provide higher strain values for the same applied pressure on PCF which can lead to increased sensitivity. Furthermore, the stronger light confinement in the core (where the FBGs are inscribed to measure the strain) and flexibility to design different geometries of PCF will support the incorporation of various micro-structures of different shape and size inside the air holes of PCF.

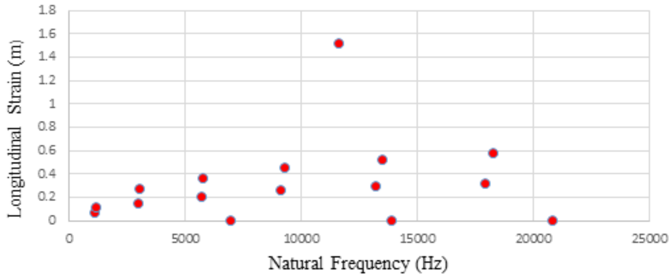

Fig. 8. Longitudinal strain for each natural frequency of solid cylinder.

IV. Conclusion

A design of a novel PCF-FBG based highly sensitive fibre optic acoustic sensor was carried out. Several theoretical investigations were carried out on the PCF-FBG sensor design. The shift in the Bragg wavelength of FBG with applied pressure was studied. The result shows that change in wavelength was linear with applied pressure. This means that acoustic waves with variable pressure can be detected as a linearly varying wavelength. Furthermore, the plot of induced strain over FBG vs shift in wavelength due to applied pressure on PCF has shown a linear change. Furthermore, a strong light confinement in the core of 4-ring PCF enables a long distance light propagation. Wavelength-based acoustic signal detection using FBG simplifies instrumental complexity and susceptibility towards light power fluctuations. An air hole based geometric structure of the PCF significantly reduces the effective Young's modulus and increases the axial strain which leads to higher sensitivity. Sensitivity can be further enhanced by incorporating micro-structures to resonate at acoustic frequencies.

References

[1] Felemban E, Shaikh FK, Qureshi UM, Sheikh AA, Qaisar SB. Underwater sensor network applications: A comprehensive survey. *International Journal of Distributed Sensor Networks.* 2015; 11(11):896832.

[2] Barlow J, Gisiner R. Mitigating, monitoring and assessing the effects of anthropogenic sound on beaked whales. *Journal of Cetacean Research and Management.* 2006; 7(3):239-249.

[3] Akyildiz IF, Pompili D, Melodia T. Underwater acoustic sensor networks: research challenges. *Ad hoc networks.* 2005; 3(3):257-279.

[4] Gholamzadeh B, Nabovati H. Fiber optic sensors. *World Academy of Science, Engineering and Technology.* 2008; 42(3):335-340.

[5] Cole J, Johnson R, Bhuta P. Fiber-optic detection of sound. *The Journal of the Acoustical Society of America.* 1977; 62(5):1136-1138.

[6] Bucaro J, Dardy H, Carome E. Fiber-optic hydrophone. *The Journal of the Acoustical Society of America.* 1977; 62(5):1302-1304.

[7] Lurton X. An introduction to underwater acoustics: principles and applications. : Springer Science & Business Media; 2002.

[8] Hughes R, Jarzynski J. Static pressure sensitivity amplification in interferometric fiber-optic hydrophones. *Applied Optics.* 1980; 19(1):98-107.

[9] McDearmon G. Theoretical analysis of a push-pull fiber-optic hydrophone. *Journal of Lightwave Technology.* 1987; 5(5):647-652.

[10] Pang M, Jin W. Detection of acoustic pressure with hollow-core photonic bandgap fiber. *Optics express.* 2009; 17(13):11088-11097.

[11] Pawar D, Rao CN, Choubey RK, Kale S. Mach-Zehnder interferometric photonic crystal fiber for low acoustic frequency detections. *Applied Physics Letters.* 2016; 108(4):041912.

[12] Abdallah A, Chaozhu Z, Zhi Z. Investigation on the effect of underwater acoustic pressure on the fundamental mode of hollow-core photonic bandgap fibers. *International Journal of Optics.* 2015; 2015.

[13] Kilic O, Digonnet MJ, Kino GS, Solgaard O. Miniature photonic-crystal hydrophone optimized for ocean acoustics. *The Journal of the Acoustical Society of America.* 2011; 129(4):1837-1850.

[14] Takahashi N, Hirose A, Takahashi S. Underwater acoustic sensor with fiber Bragg grating. *Optical Review.* 1997; 4(6):691-694.

[15] Ni X, Zhao Y, Yang J. Research of a novel fiber Bragg grating underwater acoustic sensor. *Sensors and Actuators A: Physical.* 2007; 138(1):76-80.

[16] Kersey AD, Davis MA, Patrick HJ, LeBlanc M, Koo K, Askins C, et al. Fiber grating sensors. *Journal of Lightwave Technology.* 1997; 15(8):1442-1463.

[17] Spillman W, McMahon DH. Multimode fiber-optic hydrophone based on the photoelastic effect. *Applied Optics.* 1982; 21(19):3511-3514.

[18] Kim H, Sampath U, Song M. Multi-Stress Monitoring System with Fiber-Optic Mandrels and Fiber Bragg Grating Sensors in a Sagnac Loop. *Sensors.* 2015; 15(8):18579-18586.

[19] Pinto AM, Lopez-Amo M. Photonic crystal fibers for sensing applications. *Journal of Sensors.* 2012; 2012.

[20] Wehrspohn RB, Kitzerow H, Busch K. Nanophotonic Materials: Photonic Crystals, Plasmonics, and Metamaterials. : John Wiley & Sons; 2008.

[21] Xiao L, Jin W, Demokan M. Photonic crystal fibers confining light by both index-guiding and bandgap-guiding: hybrid PCFs. *Optics express.* 2007; 15(24):15637-15647.

[22] Hill KO, Meltz G. Fiber Bragg grating technology fundamentals and overview. *Lightwave Technology, Journal of.* 1997; 15(8):1263-1276.

[23] Othonos A. Fiber bragg gratings. *Review of scientific instruments.* 1997; 68(12):4309-4341.

[24] Mondal B, Sharan P, Hussain Z. Modelling and Simulation of Pressure Sensitivity of Bragg Grating Sensor for Structural Health Monitoring Application.

[25] Jollivet C, Guer J, Hofmann P, Schulzgen A. Monolithic Fiber Lasers Combining Active PCF With Bragg Gratings in Conventional Single-Mode Fibers. *Selected Topics in Quantum Electronics, IEEE Journal of.* 2014; 20(5):36-41.

[26] Martelli C, Canning J, Groothoff N and Lyytikainen K. Bragg gratings in photonic crystal fibers: strain and temperature chacterization. Bragg gratings in photonic crystal fibers: strain and temperature chacterization. *Bruges, Belgium-Deadline Past*International Society for Optics and Photonics; 2005. 302-305.

[27] Fu H, Liu H, Chung W, Tam H. A novel fiber Bragg grating sensor configuration for long-distance quasi-distributed measurement. *IEEE sensors Journal.* 2008; 8(9):1598-1602.

[28] Paladino D, Quero G, Caucheteur C, Mégret P, Cusano A. Hybrid fiber grating cavity for multi-parametric sensing. *Optics express.* 2010; 18(10):10473-10486.

[29] Johny J, Prabhu R, Fung WK. Investigation of structural parameter dependence of confinement losses in PCF–FBG sensor for oil and gas sensing applications. *Optical and Quantum Electronics.* 2016; 48(4):1-9.