Investigation on FBG based optical sensor for pressure and temperature measurement in civil application

Somesh Nandi[1], **Chethana K**[2]*, **T Srinivas**[3], **and Preeta Sharan**[4]

1. *Department of Artificial Intelligence and Machine Learning, Rashtreeya Vidyalaya College of Engineering, Bangalore 560059, India*
2. *Department of Electronics and Communications, Jyothy Institute of Technology, Bangalore 560082, India*
3. *Department of Electrical Communication Engineering, Indian Institute of Science, Bangalore 560012, India*
4. *Department of Electronics and Communications, the Oxford College of Engineering, Bangalore, India*

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Optical fiber Bragg grating (FBG) sensors have advanced significantly in the last several years. The use of innovative FBG in temperature and pressure measurement is examined in this study. The benefits of FBGs, such as their compact size, low weight, resilience to corrosion, immunity to electromagnetic interference, distributed sensing, and remote monitoring, have brought attention to the growing research in this field of structural health monitoring of civil infrastructures. In this investigation, a novel model is proposed and implemented using ANSYS workbench and GratingMOD tool. It is shown that the central wavelength of FBG sensors increased from 1 550 nm to 1 556 nm when the temperature rose from 10 °C to 40 °C. In a similar vein, the central wavelength grew from 1 551.166 7 nm to 1 560.056 nm over a pressure range from 100 MPa to 600 MPa. The claimed work will make it possible to calibrate sensors more precisely, guaranteeing accurate data and being useful in monitoring numerous parameters at once, making them beneficial in a variety of applications.

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Fiber Bragg gratings (FBGs) are fabricated by exposing a single-mode fiber's core laterally to a repetitive pattern of strong laser light. The exposure causes the fiber's core refractive index to permanently rise, resulting in a fixed index modulation that follows the exposure pattern. The term "grating" refers to this fixed index modulation. A tiny amount of light is reflected with each periodic shift in refraction. When the grating time is roughly half the wavelength of the input light, all the reflected light signals combine coherently to one huge reflection at a specific wavelength. The wavelength at which this reflection takes place is known as the Bragg wavelength, and this situation is known as the Bragg condition. Light signals that are not phase matched and have wavelengths other than the Bragg wavelength are effectively transparent. The working principle is explained in Fig.1. An optical fiber, which is often formed of glass, is intended to transmit light along its length entirely internally. Due to the rapid advancement of fiber optics, which allows for data transfer over greater distances and at higher data rates than electronic communication, optical fiber is now the dominating technology in telecommunication. More crucially, the optical fiber can be used to fabricate many sorts of sensors, offering special benefits unmatched by more traditional optical, mechanical, or electrical-based sensors. An optoelectronic instrument can be used to monitor how strain or temperature changes in an optical fiber affect the wavelength or intensity of light that is scattered, reflected, or transmitted. Therefore, there is little signal fluctuation or attenuation as light passes through the grating. Only the Bragg-conforming wavelengths are impacted and powerfully back-reflected. One essential characteristic and benefit of FBGs is their ability to precisely configure and maintain the grating wavelength.

Periodic changes in the refractive index profile of the fiber optical core can be produced using an ultraviolet (UV) powerful source, like a UV laser. These modifications enable the gratings to reflect a particular wavelength of the incoming light. The effective refractive index of the fiber core n_{eff} and the grating pitch Λ both affect the reflected wavelength. The well-known Bragg condition illustrates this dependence as follows

$$\lambda_B = 2n_{\text{eff}}\Lambda. \quad (1)$$

The Bragg wavelength is λ_B. The optical fiber can now operate as a sensor and react to changes in structural

* Chethana K is an associate professor in Department of Electronics and Communications, Jyothi Institute of Technology. She received her Ph.D. degree from Indian Institute of Science in 2018. Her research interests are mainly in integrated photonics and fiber Bragg grating sensors. E-mail: chethana.k@jyothyit.ac.in

characteristics like strain. In Eq.(2), the FBG sensing relation is displayed as

$$\frac{\partial \lambda_B}{\lambda_B} = (1-P_e)\varepsilon + (\alpha+\xi)\Delta T = K_\varepsilon \varepsilon + K_T \Delta T, \quad (2)$$

where α represents the coefficient of thermal expansion as $\alpha = \frac{1}{\Lambda}\left(\frac{\partial \Lambda}{\partial T}\right)$, P_e represents the effective strain-optic coefficient, and $\partial\lambda_B$ denotes variations in Bragg wavelength. The thermo-optic coefficient is represented by ξ, which is described as $\xi = \frac{1}{n_{eff}}\left(\frac{\partial n_{eff}}{\partial T}\right)$. Finally, fluctuations in temperature and strain are related to ε and ΔT, respectively.

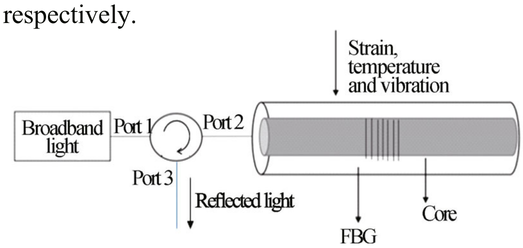


Fig.1 Working principle of FBG sensor[1]

The first term in Eq.(2) denotes the impacts of strain, and the second term is the effect of temperature. For complete strain transmission, when bonding FBG sensors to their host material, various requirements must be met. A theoretical investigation is carried out to get knowledge of the variables that affect strain transmission. The two most important elements that are thought to have the most impact on strain transfer are material property and sensor geometry. Fig.2 depicts a schematic cross section of an optical fiber. The optical interrogation system's role is to find the wavelength shift in proportion to the outside disturbance as depicted in Fig.3. The sensor has an inherent ability to self-reference as a result of the properties of FBG, since the information detected is immediately encoded in accordance with wavelength, which is an absolute parameter and independent of the light power and loss in the transmission fiber. The quasi-distributed sensing of measurands, such as temperature, strain, and pressure, among others, can be arbitrarily placed at any point along the fiber thanks to the wavelength-encoded characteristic.

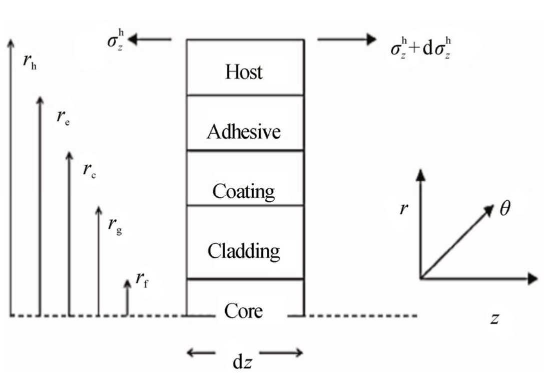


Fig.2 An optical fiber's cross section that has been attached to a host structure[2]

A quasi-distributed FBG sensor array has an individual reflected wavelength for each FBG. The maximum wavelength shift of each individual FBG as a result of external perturbations should be higher than the wavelength distance between two adjacent FBGs. This allows for the simultaneous tracking of the measure's magnitude and its value at any given sensing location along the fiber. In other words, many FBG sensors might be engraved onto a single optical fiber. Comparing this to typical electrical sensors which call for a separate circuit for each sensor is obviously very advantageous. Fig.4 demonstrates how the reflected wavelength responds differently when force is applied to the sensor.

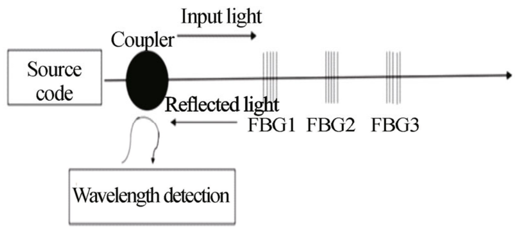


Fig.3 Interrogation principle

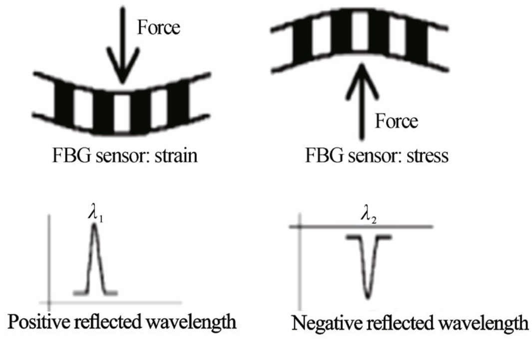


Fig.4 Reflective wavelengths

In fiber grating-based sensor systems, measuring the Bragg wavelength shift of FBGs serves as the fundamental operating principle[3]. Due to the FBG's extremely narrow reflection spectrum (0.2 nm), multiplexing up to 100 of these sensors with various reflection wavelengths onto a single fiber is possible. FBG sensors are popular and employed in a number of applications that call for tens or even hundreds of sensors. At the Bragg wavelength of 1 550 nm, the typical strain and temperature responses of FBG are 1 μm/ε and 13 pm/°C, respectively. Two FBG sensors are typically needed to measure strain since they are sensitive to both temperature and strain. One FBG must be mounted to the structure to measure strain, and the other FBG must be nearby to compensate for temperature.

As shown in Fig.5, simple optical sensors work by emitting light, interacting with a target, detecting the response of the light interaction, and converting it into an electrical signal for further processing and analysis. The sensing element in an optical sensor can be a photodetector (e.g., photodiode or phototransistor) or other optical components, like prisms, lenses, or interferometers. These sensors find applications in various fields, including proximity detection, object recognition, and environmental monitoring. Multiplexing multiple optical sensors can be challenging, as they may interfere with each other. This can limit the number of sensors that can be used in a single fiber or optical system.

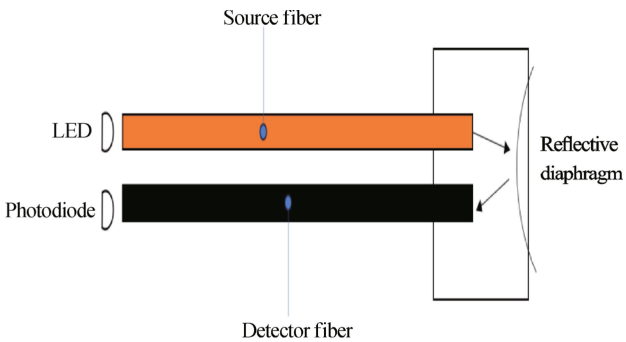


Fig.5 A simple optical sensor

It goes without saying that the effectiveness of an FBG sensor system greatly hinges on its capacity to precisely and adequately quantify the Bragg wavelength shift of FBGs. High-speed detection may be required in some applications, such as the train's velocity monitoring. The wavelength shift of FBG sensors may be determined using a variety of techniques. Broadband optical light sources are necessary to illuminate FBG sensors because they are passive devices. Utilizing linear optical filters, tunable bandpass optical filters, or optical spectrum analyzers, the reflected wavelength can be determined.

FBG sensors are specialized optical sensors made especially to measure strain, temperature, and other physical characteristics. While optical sensors have a wider variety of applications, they are not just confined to fiber-based systems. One major advantage in applications needing dispersed sensing is their ability to be multiplexed via a single optical fiber, which can be achieved by FBG based sensors.

One of the most crucial variables for monitoring structural safety in engineering applications is pressure. In several industries, like the oil and chemical industries, the development of precise and efficient sensors for the monitoring of liquid level or pipe pressure is crucial. To assess pressure and liquid level, several sensing strategies based on mechanical, electrical, and optical techniques have been created. In challenging situations such as those with electromagnetic interference, high temperatures and pressures, hazardous compounds, or explosive substances conventional electrical or mechanical pressure sensors have limited capabilities. The classic electrical and mechanical pressure sensors' uses are further constrained by single-point measurement, incapacity for remote transmission, and lack of online monitoring.

Due to their evident benefits such as compact size, low weight, corrosion resistance, immunity to electromagnetic interference, distributed capability, and remote sensing, optical fiber sensors offer an appealing alternative. Fabry-Perot cavity, FBG, and intensity-based optical fiber pressure sensors are the three main categories. Since FBG pressure sensors' measurements are based on the Bragg wavelength and independent of the light intensity, connection, or fiber loss, they have recently received a great deal of attention and have been widely used[4]. Additionally, multiplexing FBG sensors on a single optical fiber enables on-line and quasi-distributed monitoring. A diaphragm-cantilever-based FBG pressure sensor with a sensitivity of 258.28 pm/MPa in the range of 0—2 MPa was proposed by ZHAO et al[5]. An FBG pressure sensor was fabricated using a fused deposition modelling method. An FBG sensor embedded in polymer was fabricated by LEAL-JUNIOR et al[6] for the simultaneous detection of pressure and temperature. With resolutions of 6 kPa, 0.1 °C, and 0.17 m^3/h, respectively, ZHAO et al[7] developed an integrated FBG sensor for the measurement of pressure, temperature, and flow rate.

An FBG sensor was integrated into a sensing pad by AL-FAKIH et al[8] to monitor the interface pressure inside prosthetic sockets. Using a phase signal analysis, GUTIERREZ-RIVERA et al[9] suggested a low-pressure optical fiber sensor based on a thin polyester layer. A temperature-insensitive FBG pressure sensor with a temperature cross-sensitivity of 0.33 Pa/°C in the pressure range of 0—1.2 kPa was fabricated by LEAL-JUNIOR et al[10]. For pressure measurement with temperature adjustment, WANG et al[11] integrated an FBG with a diaphragm-assisted Fabry-Perot interferometer.

A raw FBG sensor has a pressure sensitivity of 3.04 pm/MPa[12], which is too low to be used in practical applications. Many mechanical systems using FBG sensing technology have been presented, including FBG embedded in a polymer, metal coated FBG on a cylinder, and FBG bonded on a triangular cantilever[13], to enhance the FBG pressure sensitivity. Some of the solutions, however, call for the preparation and multiplexing of highly complex structures that are difficult to produce in a single optical fiber.

Finding the peak shift of the Bragg wavelength that corresponds to that temperature is the fundamental component of FBG temperature sensing. The temperature sensitivity of the FBG sensor is approximately 11.5 pm/°C.

A finite element model (FEM) is implemented. The modelling of the FBG sensor attached to its host structure is shown in Fig.6. This model is interested in how the fiber responds to applied pressure in terms of strain. The ANSYS software suite was used to create the model.

Every layer between the fiber's core and the structure has been modelled, and its material properties are taken into account. Using advanced solver options including linear dynamics, nonlinearities, thermal analysis, materials, composites, hydrodynamic, explicit, and more the proposed structure is modelled and analyzed.

The vibration frequency of the objects under observation can span a wide range due to the widespread use of FBG sensors in numerous fields. For instance, whereas the vibration frequency of aircraft structures can reach up to 11 kHz, that of civil structures is frequently below 100 Hz.

FBG sensors are frequently mounted on the surface of the host material, as shown in Fig.6, to concurrently measure the strain and cause no perturbation on the mechanical properties of the monitored structure. L denotes the bonded length in half. The dynamic strain of the structure is communicated to the sensing fiber through the interfacial shear forces when the structure is activated by external fatigue loads. Three fundamental presumptions are stated prior to the theoretical analysis in accordance with the mechanical characteristics of the construction and the operational principle of FBG sensors. Only axial vibration is taken into account, with the potential coupling effects of vertical and transverse vibration on axial vibration being disregarded. The interfaces are well contacted, with no debonding, slippage, or microvoids. Materials with linear elastic properties make up the sensor fiber, sticky layer, and monitored structure. Fig.7 establishes a three-layered testing model made up of an optical fiber, an adhesive layer, and a host material.

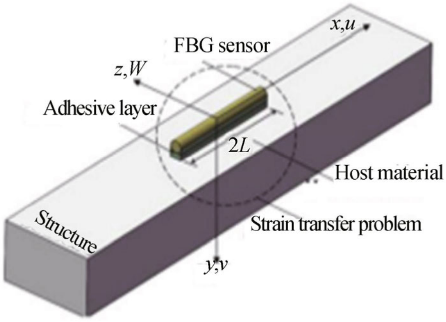


Fig.6 FBG sensor

Using the ANSYS Multiphysics program, the strain distribution of a structure is examined. Fig.8 shows equivalent stress generated, total deformation and directional deformation, respectively. The study's findings showed that the temperature and pressure applied to the structure's apex resulted in a significant deformation. The structure's shape may change due to the deformation brought by the point defections.

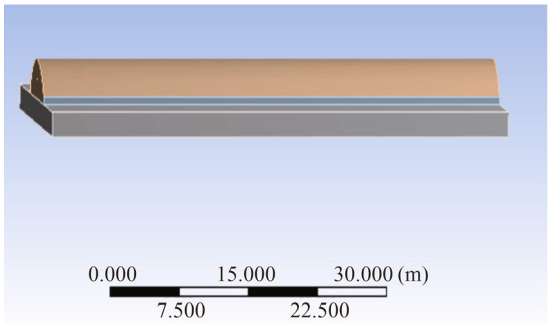
Strain dependence of an FBG sensor can be determined by

$$\Delta\lambda_{\mathrm{B}} = \lambda_{\mathrm{B}}(1-P_{\mathrm{e}})\Delta\varepsilon, \tag{3}$$

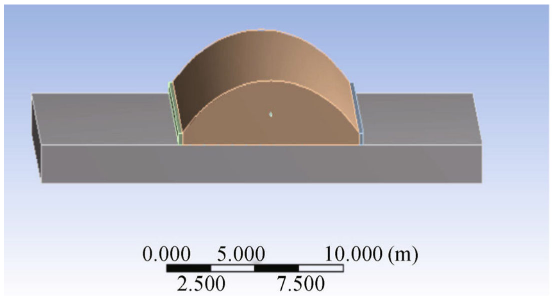
$$P_{\mathrm{e}} = \left(\frac{N_{\mathrm{eff}}^2}{2}\right)[P_{12} - v(P_{11}+P_{12})], \tag{4}$$

where ε is equivalent strain, P_{e} is photo elastic coefficient, n_{eff} is effective refractive index, λ_{B} is central wavelength, Bragg equals a shift in wavelength, Poisson's ratios are P_{11}=0.113 and P_{12}=0.252, and the strain optic constant is v=0.33.

Fig.9(a) gives the segment of FBG in GratingMOD tool and (b) explains the gratings in FBG, XZ mode of FBG

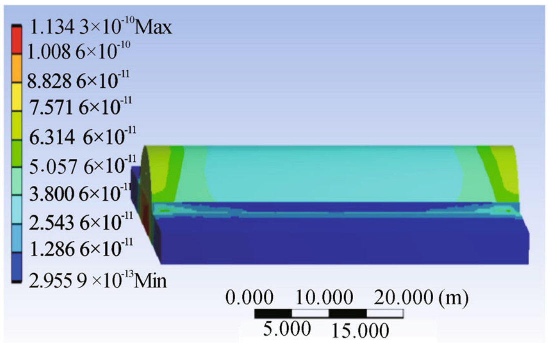


(a)

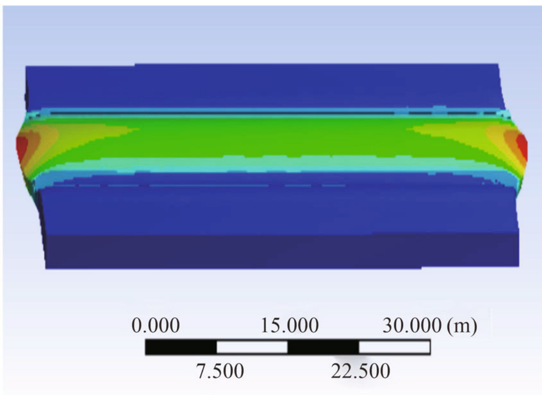


(b)

Fig.7 (a) FBG integrated structure; (b) Side view of the structure



(a)



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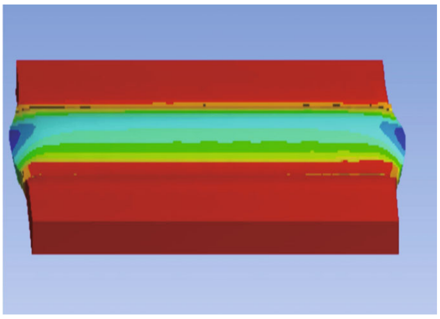

(c)

Fig.8 (a) Equivalent stress generation in the structure; (b) Total deformation in the structure; (c) Directional deformation in the structure

sensor. Bragg's wavelengths for varying pressures from 100 MPa to 600 MPa and temperature from 10 °C to 40 °C have been generated for the structure as shown in Figs.10 and 11. Obtained values are used in R soft GratingMOD tool. The two main tools for simulation, analysis and synthesis of gratings in GratingMOD, facilitate complete light wave field information inside the fiber core with gratings. The Bragg wavelengths obtained from pre-analysis for different temperatures are used as parameters for the simulation in R soft GratingMOD tool to find the grating period, wavelength spectrum and the propagating mode. Parameters considered are shown in Tab.1.

The simulation results show that the refractive index of materials may be accurately predicted using mathematical models that account for variations in temperature and pressure. With the use of these models, the refractive index under particular pressure and temperature settings can be determined. Equations like Cauchy's equation or

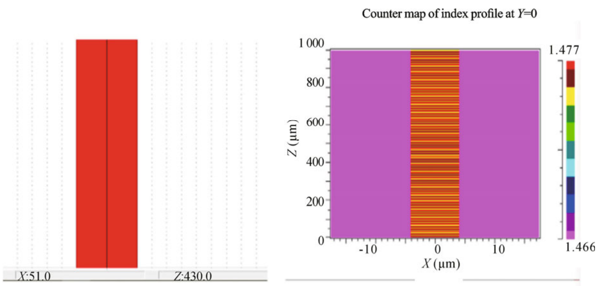

Fig.9 Refractive index profile of the FBG sensor

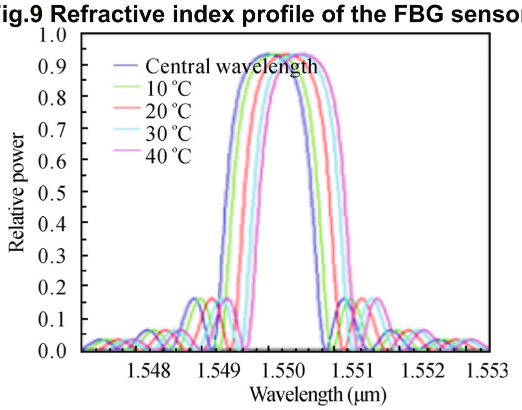

Fig.10 Variation in Bragg's wavelength for temperature ranging from 10 °C to 40 °C

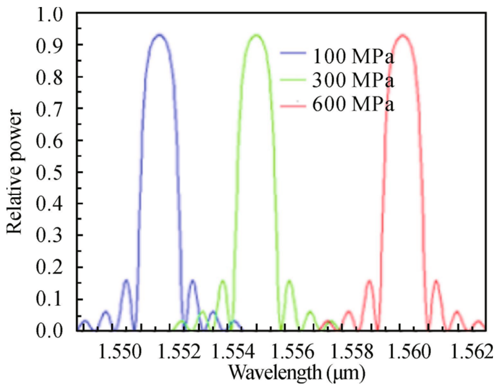

Fig.11 Variation in Bragg's wavelength for pressure ranging from 100 MPa to 600 MPa

Tab.1 Parameters for R soft GratingMOD tool

Parameter	Detail
Simulation tool	R soft GratingMOD
Structure type	3D fiber
Profile type	Step index
Free space wavelength	1.55 μm
Waveguide width and height	8.2 μm

Tab.2 Comparison of previous works with present work

Work	Objective	Observations
Ref.[14]	Strain analysis	This work has investigated the strain transmission mechanism of surface attached FBG sensors under fatigue stress.
Ref.[15]	Computation of temperature, deformation and pressure	Fiber-optic Bragg sensor with tilted grating is implemented in this work, with temperature from 20 °C to 100 °C.
Ref.[16]	Modelling of strain, temperature and vibration	The shift in the Bragg wavelength of π-PSFBG due to the various ranges of temperature (−40—100 °C), strain (0—1 500 με), and vibration (0—14 με·Hz)
Ref.[17]	Comparative tests of concrete beam integrated FBG sensors	The test proved the applicability of FBG sensors for strain/load measurement integrated in the beam.
Ref.[18]	Strain-temperature cross-sensitivity	Temperature varies from –50 °C to 100 °C, with temperature sensitivity between 1.088 nm/°C and 1.099 nm/°C.
Proposed work	Pressure and temperature measurement	Structure is modelled and results of wavelength from 1 550 nm to 1 556 nm are obtained for temperature from 10 °C to 40 °C, and central wavelength changes from 1 551.166 7 nm to 1 560.056 nm over a pressure range from 100 MPa to 600 MPa.

the Sellmeier equation, adjusted to incorporate temperature-dependent coefficients, can be used to analyze temperature dependency. Eqs.(2), (3) and (4) connect wavelength, temperature, pressure and refractive index. When utilizing photonics software, it is often customary for the software packages to include integrated libraries or databases containing material properties, including refractive index data under different temperature and pressure conditions. This feature simplifies the process of performing these conversions and facilitates the utilization of temperature and pressure sensor effects within R soft photonic simulations. Tab.2 shows the comparative study of the proposed work with exiting published articles.

FBG sensors prove invaluable for obtaining precise temperature and pressure measurement when configured to withstand challenging conditions. Their applications span across various domains, including the assessment of bridge loads, short-term structural evaluations, vibration monitoring, seismic responses, and inspections of civil infrastructure. For scenarios marked by substantial temperature or pressure fluctuations, fiber optic sensing emerges as the most suitable choice. Notably, alterations in temperature and pressure prompt shifts in the central wavelength, as evidenced in this study, transitioning from 1 550 nm to 1 556 nm and from 1 551.166 7 nm to 1 560.056 nm, respectively.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

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