Remote Monitoring of Temperature Using Optical Fiber Bragg Grating Sensor

Sagupha Parween(✉) and Aruna Tripathy

College of Engineering and Technology, Bhubaneswar, Bhubaneswar, Odisha, India
atripathy@cet.edu.in

Abstract. Optical sensors are used to sense any change in environmental conditions. They utilize the measurand into changing some attributes of a light ray passing through an optical fiber. This change may be intensity, phase, state of polarization or a wavelength. This change is used for detection at the receiving end according to physical parameters. Fiber Bragg grating (FBG) sensors are one of the most commonly used sensors in optical communication. FBG sensor is mainly used for sensing temperature and strain. This paper focuses mainly on FBG optical sensor used as temperature sensor. The principle of FBG has been explained in detail for temperature sensing. The change in temperature with respect to change in thermo-optic coefficient has been analyzed. The sensed information has been retrieved at the user end using optical fiber cable (OFC) and free space optic (FSO) channels. A beam of light travelling through the OFC cable is called as a wired optical communication, whereas the FSO can be said as wireless communication. The performance of OFC and FSO channels has been compared for sensing the data from the FBG sensor using OptiSystem 16.0 Simulation Software. The contribution of the paper is threefold: (i) determination of the thermo optic coefficient and the range of temperature dependent on this coefficient for the FBG, (ii) comparison of the performances of sensed data transmission over OFC and FSO channel and (iii) evaluation of an analog link used to transmit and receive the measurand.

Keywords: Optical sensor · FBG · Thermo-optic coefficient · OFC · FSO

1 Introduction

An optical sensor has many advantages over electrical sensors such as high sensitivity, small size, no electromagnetic interference, resistance to corrosion, and its light weight [1]. Fibre Bragg Grating (FBG) sensors are mainly used for sensing temperature and strain with the additional advantages of low weight and small size as well as the capability of having multiple sensors in one line. The FBG sensor operates on the principle of Fresnel reflection wherein it uses the reflection and transmission of light when incident on an optical media having different refractive indices [1]. The FBGs or FBG arrays have been widely applied in the measurement of physical, chemical, biomedical, and electrical parameters where the information is usually encoded by the Bragg wavelength shift of

P. K. Behera and P. C. Sethi (Eds.): CSI 2020, CCIS 1372, pp. 36–47, 2021.
https://doi.org/10.1007/978-981-16-2723-1_5

FBGs [2–5].The basic principle of FBG sensors is the measurement of an induced shift in the wavelength of an optical source due to a measurand, such as strain or temperature. A broadband light source i.e. optical spectrum given by a white light source is used to interrogate the grating, from which a narrowband slice is reflected and rest is transmitted [6]. White light source is a broadband light source which contains all the wavelengths [6]. When such a light is given as an input to the FBG sensor, any change in temperature with respect to the reference temperature will lead to reflect back the centre Bragg wavelength and pass the rest of the wavelengths. An FBG sensor thus, is said to work upon wavelength modulation. A basic block diagram of FBG sensor is given in Fig. 1.

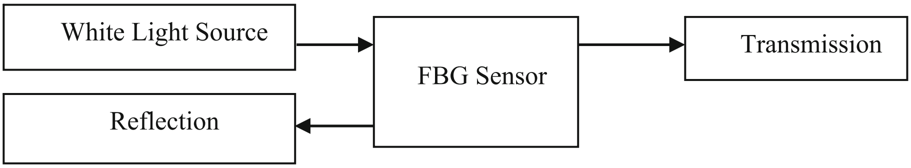


Fig. 1. Basic block diagram of FBG sensor

The sensed information is transmitted and subsequently received over an analog communication link which is realized by Optical Fiber Cable (OFC) and Free Space Optic (FSO) communication in this paper. The analog optical link has three sections: transmitter, optical fiber and receiver [7]. The transmitter basically provides electro-optic conversion; here we have used the sensed information of FBG sensor as an input to the OFC channel. The optical fiber takes the light beam to the destination. The receiver carries out the optoelectronic conversion by using photodiodes/photo detectors such as PIN photodiode and Avalanche photodiode [7, 8]. An FSO channel also has been used to transmit the sensed measurand to the receiver. The working of an FSO is similar to OFC with the only difference that the optical signal is sent through free air in the absence of optical cable [9, 10]. Section 2 describes about the FBG sensor system modeling. The results of experimental layouts for proposed FBG based system are shown in Sect. 3, the results and analysis of experimental arrangements are presented in Sect. 4. Section 5 provides a conclusion of the experimental results obtained.

2 System Model

An FBG is created by engraving periodic patterns of refractive index change inside the core of a single mode fiber. This change in refractive index is typically created by showing the fiber core to an intense interference pattern of UV energy [11]. The exposure produces a permanent increase in the refractive index of the fiber's core, creating a fixed index modulation according to the exposure pattern. This fixed index modulation is called a grating [12]. A small amount of light is reflected at each grating period. All the reflected light signals combine consistently to one large reflection at a particular wavelength. This is referred to as the Bragg condition, and the wavelength at which this reflection occurs is called the Bragg wavelength [12, 13].Only those wavelength are reflected that satisfy the Bragg condition and this wavelength has maximum efficiency [13].

When light from an optical white light source i.e. an optical spectrum is incident, only a specific wavelength which satisfies Bragg condition will be reflected while the remaining wavelengths are transmitted, the wavelength for which the incident light is reflected with maximum efficiency is called the Bragg wavelength. In optical fiber gratings, the phase matching condition is given by [14, 15].

$$\beta_1 - \beta_2 = \Delta\beta = \frac{2\pi}{\lambda} \tag{1}$$

Where β_1 and β_2 are the propagation constants of the modes being coupled and Λ is the grating period. In the case of FBGs, the forward propagating core mode couples to the reverse propagating core mode, it means the propagation constants remain the same but with a negative sign.

$$\beta_2 = -\beta_1 = \beta \tag{2}$$

Then the phase matching condition is given by,

$$\beta - (-\beta) = 2\beta = \frac{2\pi}{\Lambda} \tag{3}$$

But the propagation constant β is given by,

$$\beta = \frac{2\pi}{\lambda} n_{eff} \tag{4}$$

Where n_{eff} is the effective refractive index of fiber core, so Eq. (3) becomes

$$2\left(\frac{2\pi}{\lambda} n_{eff}\right) = \frac{2\pi}{\Lambda} \tag{5}$$

So the Bragg wavelength is given by [16, 17],

$$\lambda_B = 2n_{eff}\Lambda \tag{6}$$

From Eq. (6) we can see that Bragg wavelength will shift with respect to any change in effective refractive index or grating period. The effective refractive index has a value as average of all the periodic refractive indices in the optical fiber. The Bragg wavelength will shift with any change in the environmental conditions. As the Bragg wavelength depends upon effective refractive index n_{eff}, any change in effective refractive index will shift the Bragg wavelength. Any changes in the temperature of the surrounding from a reference level will lead to change in refractive index in the material; it means the effective refractive index will change. The change in effective refractive index is given by [19, 20],

$$n_{eff} = \xi n \Delta T \tag{7}$$

Where ξ is the thermo-optic coefficient, n is the refractive index of fiber, and ΔT is the change in temperature from the reference temperature. Equation (7) gives the change in temperature that will change the n_{eff} which leads to a shift in the Bragg wavelength.

3 Proposed System Using FBG

The layout of the proposed system to measure temperature using an FBG sensor system is shown in Fig. 2. Here the white light source (WLS) is given as an input to FBG sensor. In increasing or decreasing the temperature surrounding the grating from a reference temperature level, the refractive index of the fiber will experience a change as given in Eq. (7). Those wavelengths that satisfy the Bragg condition are reflected and rest is transmitted. The output spectrum of WLS, transmission and reflection can be seen through WDM FBG Sensor Interrogator as shown in Fig. 3(a), Fig. 3(b), and Fig. 3(c) respectively. If we increase or decrease the temperature the grating center wavelength will shift accordingly.

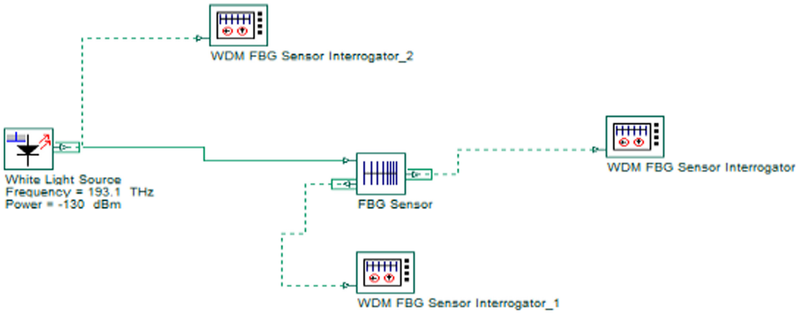


Fig. 2. Proposed system layout using an FBG sensor

We need to sense the temperature at the receiver through both the OFC and FSO link. The FBG output is transmitted over an analog link. In order to cover a large distance some suitable analog or digital modulation schemes may be employed. We have used amplitude modulation (AM) in our work here. The layouts of an OFC based link without and with AM are shown in Figs. 4 and 6 respectively. Similar schematic diagrams for an FSO based analog link are illustrated in Figs. 5 and 7 respectively.

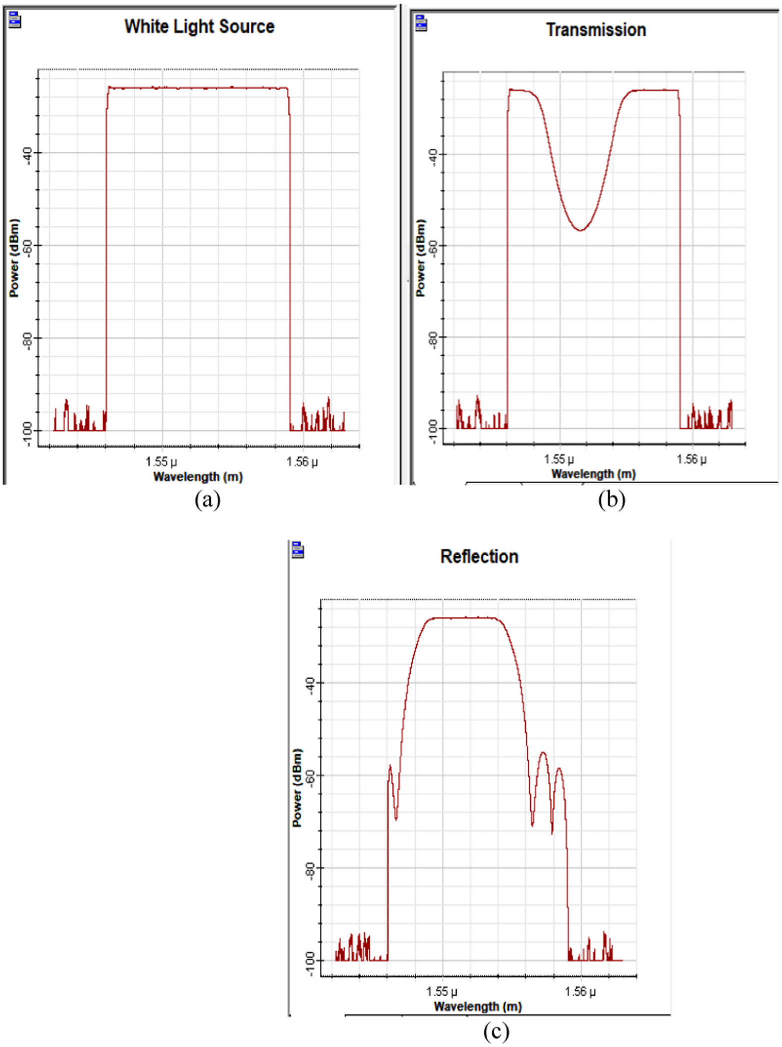


Fig. 3. (a) White light source signal spectrum; (b) Transmission signal spectrum; (c) Reflection signal spectrum

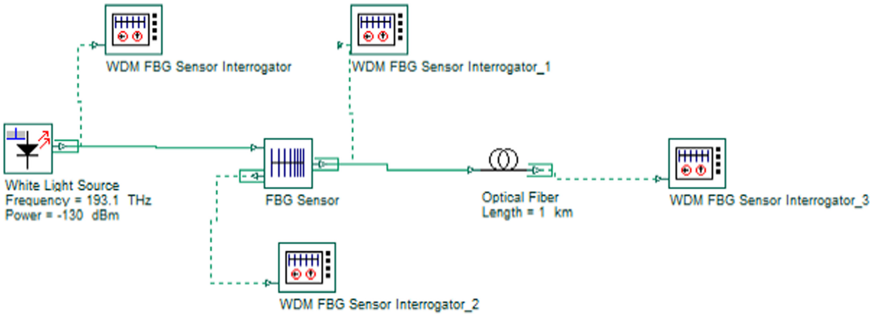


Fig. 4. Layout of FBG sensor system data sent through an OFC channel

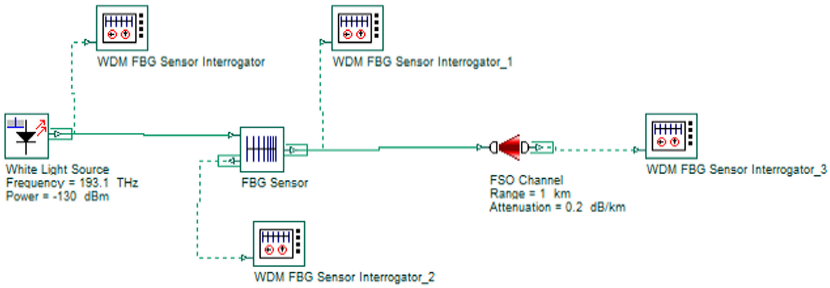


Fig. 5. Layout of FBG sensor system data sent through an FSO channel

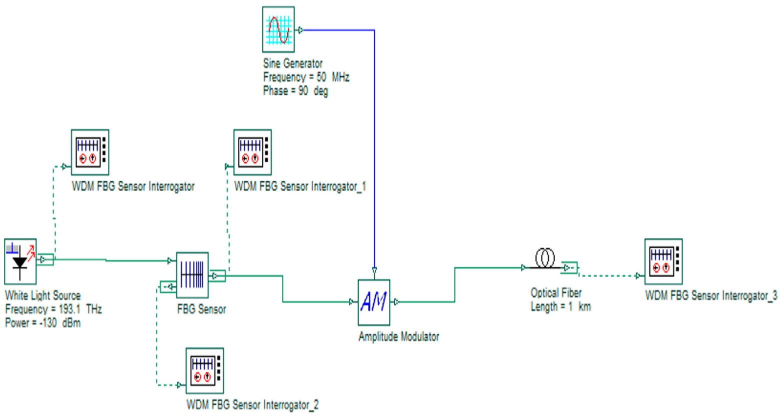


Fig. 6. Layout of FBG sensor system data sent via an analog link through a OFC channel

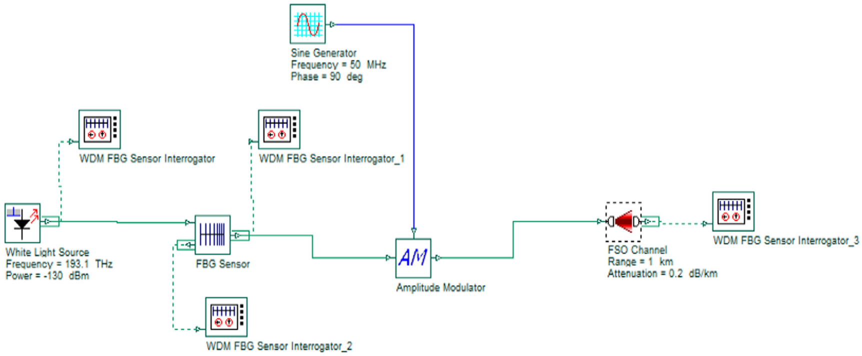


Fig. 7. Layout of FBG sensor system data sent via an analog link through a OFC channel

4 Results and Analysis

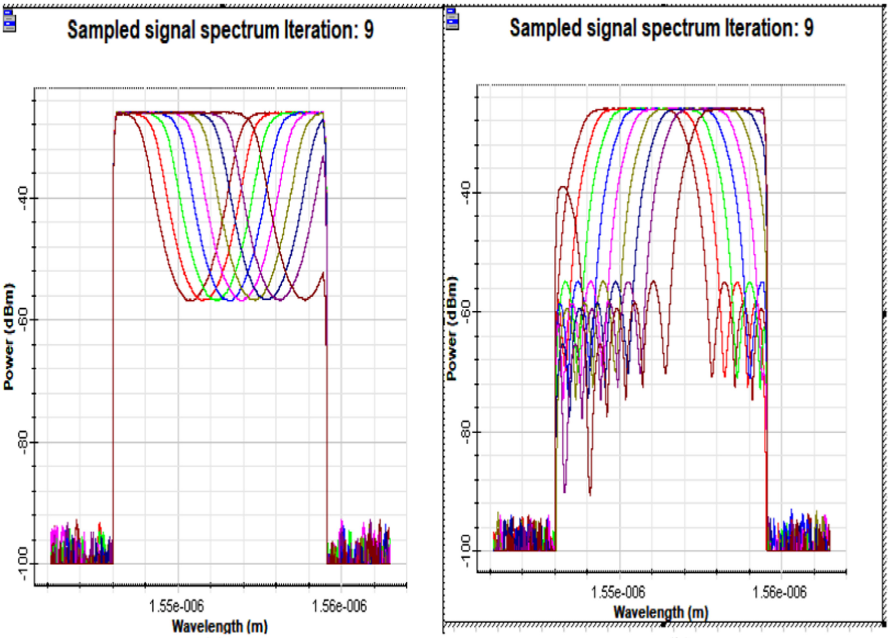
All the experimental block schematics are implemented in OptiSystem 16.0. The change in temperature varies up to a certain range according to the Thermo-optic coefficient shown in Table 1.

Table 1. Range of temperature vs. thermo-optic coefficient

Thermo-optic coefficient (/°C)	Range of temperature (°C)
0.0001	−12 to 40
0.00001	−120 to 400
0.000001	−1200 to 4000

The Thermo-optic coefficient (ξ) is kept to 0.0001/°C, reference temperature is 0°C, effective refractive index n_{eff} is 1.45, and the temperature surrounding the grating has been changed. There will be a shift in center Bragg wavelength (i.e. 1550 nm) with change in temperature in transmission and reflection of FBG sensor is shown in Fig. 8(a) and Fig. 8(b) respectively. Table 2 shows the colour summary of Fig. 8 w.r.t temperature. It can be observed that at the change of temperature in 50 °C with ξ value 0.0001, the FBG sensor is unable to reflect the center Bragg wavelength. If we increase the thermo-optic coefficient to 0.00001/°C the change of temperature in 50 °C can reflect the center wavelength.

The Bragg wavelengths will be shifted if we increase or decrease the temperature in the FBG sensor and send through OFC and FSO channel. The shift in Bragg wavelengths sensed by both OFC and FSO channel for layouts as shown in Figs. 4 and 5 for a length of 1 km with channel attenuation of value 0.2 dB/Km is compared and shown in Table 3. Table 4 shows the difference in Bragg wavelength shift with respect to center Bragg wavelength (i.e. 1.54999 µm) for reference temperature 0 °C, keeping ξ value 0.0001 and the temperature is changed according to the Table 3.



(a) (b)

Fig. 8. (a) Transmission signal spectrum shift w.r.t change in temperature; (b) Reflection signal spectrum shift w.r.t change in temperature

Table 2. Colour summary of Fig. 8 w.r.t temperature

Colour	Temperature(°C)
	5
	10
	15
	20
	25
	30
	35
	40
	50

The change in wavelength w.r.t temperature is given by [21], the sample observation of theoretical and experimental wavelength shift is shown in Table 5.

$$(\Delta\lambda_B)_{temp} = \lambda_B(1 + \xi)\Delta T \tag{8}$$

Figure 9 shows the comparative plot for temperature verses Bragg wavelength shift through OFC and FSO channels with respect to reference temperature 0 °C and $\lambda_B =$ 1.54999 μm (i.e. the center Bragg wavelength found experimentally).

Table 3. Comparative summary of Bragg wavelength sensed through OFC and FSO channel

Temperature (°C)	Bragg wavelength through OFC (μm)	Bragg wavelength through FSO (μm)
−5	1.54926	1.54923
0	1.54999	1.54999
5	1.55073	1.55069
10	1.55155	1.55154
15	1.55234	1.55229
20	1.55306	1.55311
25	1.55419	1.55427
30	1.55463	1.55465
35	1.55541	1.55535
40	1.55632	1.55621

Table 4. Comparative summary of shift in Bragg wavelength sensed through OFC and FSO channel with respect to center Bragg wavelength at reference temperature 0 °C

Temperature (°C)	Bragg wavelength through OFC (nm)	Bragg wavelength through FSO (nm)
−5	0.72	0.76
5	0.75	0.7
10	1.57	1.55
15	2.36	2.3
20	3.08	3.11
25	4.2	4.28
30	4.65	4.66
35	5.43	5.36
40	6.34	6.24

Table 5. Summary of theoretical and practical wavelength shift w.r.t temperature

Temperature (°C)	Theoretical ($\Delta\lambda_B$) (nm)	Experimental ($\Delta\lambda_B$) in OFC (nm)	Experimental ($\Delta\lambda_B$) in FSO (nm)
40	6.2	6.34	6.24
35	5.4	5.43	5.36
30	4.6	4.65	4.66

Figures 10(a) and 10(b) shows the attenuation verses distance to sense the transmitted data through OFC and FSO channel respectively.

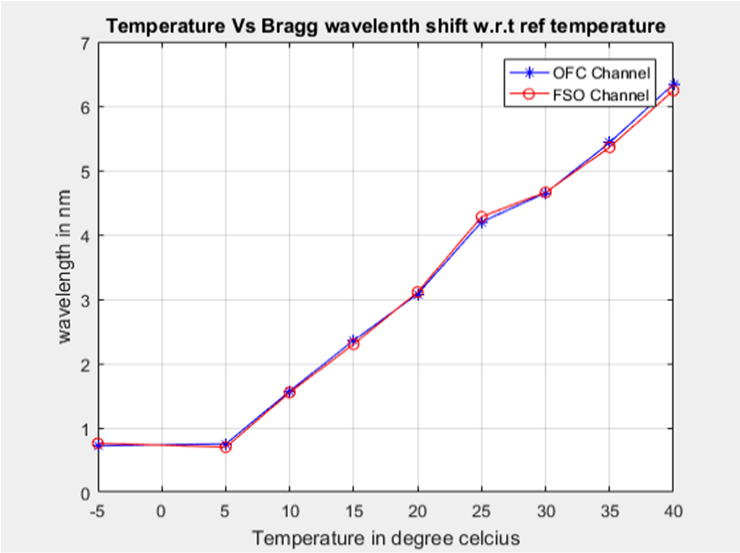
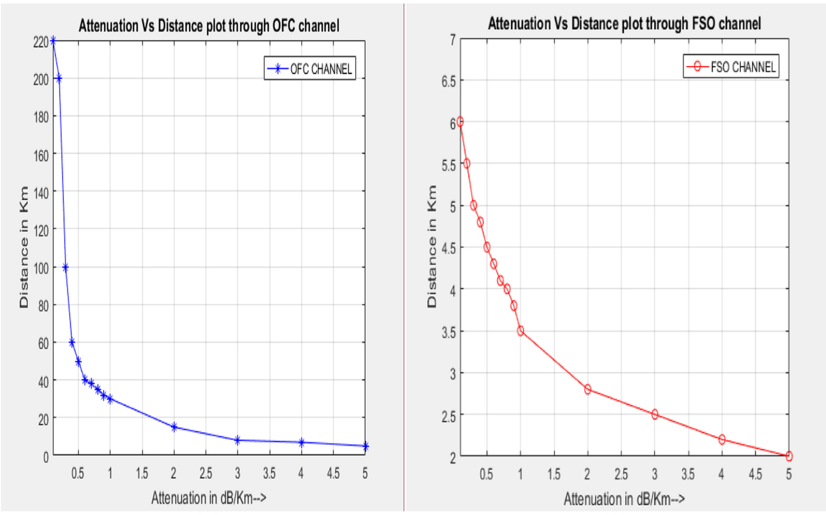


Fig. 9. Comparative plot of temperature vs. Bragg wavelength shift for OFC and FSO channel



(a) (b)

Fig. 10. (a) Attenuation verses distance plot to sense the transmitted data through OFC channel; (b) Attenuation verses distance plot to sense the transmitted data through FSO channel

5 Conclusion

The proposed layouts are implemented in OptiSystem 16.0 and the graphs are plotted using MATLAB R2016b. We have obtained the characteristics of FBG sensor by changing the temperature from −5 °C to 40 °C. Thermo-optic coefficients for different range of temperatures to sense the Bragg wavelength have been determined experimentally. The sensed data from FBG Sensor has been sent through wired and wireless channel (i.e. through OFC and FSO) to assess their suitability as transmission media for low data rate applications like temperature. It is found that the difference between Bragg wavelength shifts in OFC and FSO is not very significant. This implies it is possible to send the sensed data of a measurand wirelessly in order to increase the data transmission rate and to avoid the presence of fiber cable. Experimentally, it has also been found that the sensed data of an FBG sensor can be retrieved reliably for longer distances up to 220 Km for attenuation of 0.1 dB/Km through an OFC cable whereas the coverage is limited to 6 Km distance only for the same value of attenuation through an FSO channel. The use of multiple FBG sensor based multiplexed system is currently under investigation.

References

1. Jonathan, O., et al.: Fiber optic measurement system for fresnel reflection sensing: calibration, uncertainty, and exemplary application in temperature-modulated isothermal polymer curing. J. Lightwave Technol. **36**, 939–945 (2018)
2. Ugis, S., Sandis, S., Vjaceslavs, B.: Evaluation and research of FBG optical temperature sensors network. In: Conference in Advances in Wireless and Optical Communications (2017)
3. Ecke, W., Latka, I., Willsch, R., Reutlinger, A., Graue, R.: Fibre optic sensor network for spacecraft health monitoring. Measur. Sci. Technol. **12**, 974–980 (2001)
4. Schroeder, K., Ecke, W., Apitz, J., Lembke, E., Lenschow, G.: Fibre Bragg grating sensor system monitors operational load in a wind turbine rotor blade. Measur. Sci. Technol. **17**, 1167–1172 (2006)
5. Li, H.-N., Li, D.-S., Song, G.-B.: Recent applications of fiber optic sensors to health monitoring in civil engineering. Eng. Struct. **26**, 1647–1657 (2004)
6. Sunita, P.U., Vivekanand, M.: Fiber Bragg grating modeling, characterization and optimization with different, index profiles. Int. J. Eng. Sci. Technol. **2**(9), 4463–4468 (2010)
7. Giallorenzi, T.G.: Optical communications research and technology: fiber optics. Proc. IEEE **66**, 744–780 (1978)
8. Arun, G., Bhawana, S.: Optical fiber: the new era of high speed communication (technology, advantages and future aspects). Int. J. Eng. Res. Dev. **4**, 19–23 (2012)
9. Piyush, S., Priyanka, G., Prashant, R.: Basic concept of free space optics communication (FSO): an overview. In: IEEE International Conference on Communication and Signal Processing (ICCSP), pp. 439–442 (2015)
10. Akhil, G., Pankaj, A., Rohit, K., Sonam, B.: A survey of free space optical communication network channel over optical fibre cable communication. Int. J. Comput. Appl. **105**, 32–36 (2014)
11. Bennion, I., Williams, J.A.R., Zhang, L., Sugden, K., Doran, N.J.: UV written in fiber Bragg gratings. Opt. Quantum Electron. **28**, 93–135 (1996). https://doi.org/10.1007/BF00278281
12. Hill, K.O., Meltz, G.: Fiber Bragg grating technology fundamentals and overview. J. Lightwave Technol. **15**, 1263–1276 (1997)
13. Sunita, P.U., Vivekanand, M.: Optimization of apodized fiber Bragg grating for sensing applications. Int. J. Comput. Appl. Electron. Inf. Commun. Eng. (ICEICE) **3** (2011)
14. Raman, K., Jose, M.L.H.: Handbook of Optical Fiber Sensing Technology; Fiber Grating Technology: Theory, Photosensitivity, Fabrication and Characterization, pp. 349–377. Wiley (2002)
15. Raman, K.: Fiber Bragg Gratings, 2nd edn. Academic Press, Cambridge (2010)

16. Carlo, E.C., Antonello, C., Clarissa, C., Abdulkadir, Y., Vittorio, M.N.P.: Fibre Bragg Grating Based Strain Sensors: Review of Technology and Applications. Sensors **18**, 1–27 (2018)
17. Cong, J., Zhang, X., Chen, K., Xu, J.: Fiber optic Bragg grating sensor based on hydrogels for measuring salinity. Sens. Actuators B Chem. **87**(9), 487–490 (2002)
18. Turan, E.: Fiber grating spectra. J. Lightwave Technol. **15**, 1277–1294 (1997)
19. Manish, S., Anubhuti, K.: Fiber Bragg Grating (FBG) is used as modeling and simulation for temperature sensor. Orient. J. Comput. Sci. Technol. **3**(1), 103–107 (2010)
20. Lun, K.C., Remco, N., Kevin, A.: Fiber Bragg grating sensors. In: Proceedings of the Symposium on IEEE Photonics Benelux, Netherlands (2010)
21. Khare, R.P.: Fiber Optics and Optoelectronics. Oxford University Press, Oxford (2004)