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Two Applications of FBG Temperature Sensor for Environmental Safety

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Abstract –Detection and monitoring of temperature in fire sensitive areas, high temperature zones such as underground coal mines and smelting plant applications is a crucial requirement in order to ensure safety of working personnel and to avoid unnecessary damage to life and infrastructure. Smoldering combustion is most often responsible for underground coal mine fire. A commonly used method for detection of underground fire can be done through temperature gradient. Similarly smelting plants as mandated in various stages of aluminium production starting from the mixing stage typically having 160ºC-180ºC to the alumina electrolysis process that is characterized by about 1000°C.Therefore, detection and subsequent monitoring of temperature change in underground coal mines as well as smelting plants is an important concern. A four channel FBG temperature sensor based system is proposed in this paper that demonstrates multiple FBG sensors. These four sensors sense different temperatures and a single channel making use of wavelength division multiplexing (WDM) is used thereafter to send the sensed data. A WDM demultiplexer is used to retrieve the originally transmitted signal at the receiver. Three different channels such as Optical fiber cable (OFC), Free Space Optics (FSO) and Optical Wireless communication (OWC) channels have been simulated here to assess and compare the performance of the proposed WDM-FBG sensor system.

Keywords– FBG; Optical Sensor; Temperature; OFC; FSO; OWC.

I. INTRODUCTION

Temperature sensing is an important concern for the environmental safety. Detection of increase in temperature before any exposure is required. Accurate timely temperature detection prevents any life loss and industrial damage in areas where in temperatures can go beyond some safety limits due to a slew of reasons. Conventional temperature sensors like Thermocouple, resistance temperature detector (RTDs), pyrometers and thermistors do exist to sense temperature in different applications. Although these are in practice, however different temperature ranges mandate the use of different temperature sensors and may not lead to multiplexing easily. From the point of view of electromagnetic interferences, electric sparks, an optical Fiber Bragg Grating (FBG) sensor is better than these electrical sensors. Also it can be used in a multiplexed configuration to sense temperature at several locations and sensing mechanism which is optical in nature avoiding the need for expensive electrical isolation. Such sensors are immune to environmental changes and passive in nature. It is with these constraints that we make use of an optical Fiber Bragg Grating (FBG) sensor to detect different changes in temperature [1-2] as point sensors. The same type of sensor can be used to detect different temperature ranges with different thermo-optic coefficients and the system designer need not worry about different sensors for a host of temperature ranges. Besides offering immunity to electromagnetic interference that is widespread in industrial applications and ease of deployment in inflammable, hazardous areas such aluminium smelting plant and underground coal mines, these sensors are also easily amenable to multiplexing. Typically the Hall-Héroult process [3] is used for aluminium smelting in the process of extracting aluminium from its oxide, alumina. This is done in many stages with particular temperature scaling. During aluminium production, temperature sensing is required in various stages [4]. A temperature in the range of 160-180°C [4-5] is required in the mixing stage. The hot green paste coming out of the mixer has to be cooled to about 110-120°C before it is fed into the block press in the Block Forming stage. This is done in order for the finished blocks to retain their shape [5]. The furnace used for baking needs to be slowly heated up to the range of 1100 – 1120°C and slowly cooled down again [5-6] for the green blocks. Baking of the green blocks is carried out above 1000ºC [5-6]. An exothermic reaction resulting due to the natural oxidization of coal over time leads to underground coal mine fire [7]. This is one of the terrible hazards that must be taken care of without or as less as possible human intervention. The smouldering combustion occurs by self-heating due to an increase in temperature because of exothermic internal reactions leading to explosion. The forthcoming mine fire always leads to gradual rise in temperature. The heat produced determines the energy transfer between the coal and its surroundings due to the temperature changes [8-9]. The heat produced leads to coal mine fire which is a risky hazard in underground coal mines.

In both the applications, it is critical to sense and maintain an accurate temperature change to avoid the losses of precious lives as well as infrastructure damage. Multiple FBG sensors are proposed to be distributed in the area of concern to detect the temperature change and to multiplex the sensed data to be sent over a common channel to some remote monitoring unit. Wavelength Division Multiplexing (WDM) is used to multiplex temperature as coming from several sources distributed over a given area [10-11]. Multiplexing reduces the number of components and installation cost within a sensor network. The sensed information is transmitted and subsequently received over an analog communication link. Optical Fiber Cable (OFC), Free Space Optic (FSO) and Optical Wireless Communication (OWC) have been used as the communication link in this work. The sensed measurand is sent to the receiver via an FSO channel. However, in all these, FBG sensor was used as a point sensor over OFC or FSO in a multiplexed configuration. The capability of a multiplexed sensor over an OWC is yet to be explored and the resulting performance needs to be compared with those obtained over OFC and FSO. This particular issue is addressed in the present work. An FSO is similar to OFC in its working with the only difference being the transmission of an optical signal through free air rather an optical cable [12-13]. The OWC is not much different from the FSO except the difference is in the propagation medium. OWC is considered for outer surface where it is assumed to be free from atmospheric attenuation factor [14]. In the receiver a WDM Demultiplexer is used to separate the sensed data that has been transmitted from each FBG sensor. Section II describes the proposed FBG sensor over the three different transmission media. Section III shows the proposed experimental layouts for proposed WDM-FBG system. The results and analysis of experimental arrangements are compared in Section IV followed by a conclusion of the experimental results in Section V.

II. SYSTEM MODEL

The basic principle of FBG sensors is the measurement of an induced shift in the wavelength of an optical source due to the change in temperature. An FBG sensor reflects only one particular wavelength while the transmitting the remaining wavelengths when light from an optical white light source (WLS) is incident upon it. The particular wavelength which is reflected off satisfies the Bragg condition and the corresponding wavelength is called the Bragg wavelength [15]. So the Bragg wavelength is given by [15-16],

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

where n_{eff} is the effective refractive index, Λ is the grating period, and λ_B is the Bragg wavelength. A wavelength shift and the corresponding change in the wavelength w.r.t change in the reference temperature is given as [17]:

$$\Delta\lambda_B = \lambda_B(1+\xi)\Delta T \qquad (2)$$

where, $\Delta\lambda_B$ is the wavelength shift, λ_B is the centre Bragg wavelength, ξ is the thermo-optic coefficient and ΔT is the change in temperature. The change in temperature other than the set reference temperature in the FBG sensor shifts the centre wavelength.

III. PROPOSED SENSOR LAYOUT

Distributed sensors can used to detect the temperature change at different locations in the smelting plants and coal mines as per the requirements. Many FBG sensors are placed to detect the change in temperature and the sensed data is in the form of a wavelength shift from a preset central wavelength. These sensors are said to be

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working upon wavelength modulation. The WLS sends the optical spectrum having all the wavelengths between 1.5430μm to 1.5600μm, in which 1.5499μm is the centre wavelength. With any change in temperature other than reference temperature, the wavelengths that satisfy the Bragg condition in Eq. (1) will be reflected at each grating period and these small wavelengths that are reflected is omitted from the incident optical spectrum and form a notch having Bragg wavelength [18]. The Any increase or decrease of the temperature from a reference value results in shifting the grating centre wavelength accordingly. At the transmitter side, the WDM combines multiple sensed data simultaneously with high data rate at a time from different sensors over a common communication channel and send it to the receiver side [19-20]. This paper illustrates transmission of the sensed data over both wired and wireless channels. The sensed data is transmitted to the receiver via OFC for wired channels and for the wireless, FSO and OWC channels have been simulated. The block schematic of a 4-channel WDM-FBG system with OFC, FSO and OWC as communication channels is shown in Fig.1, Fig.2 and Fig.3respectively. Each FBG is used to sense a different temperature as it is located at a different location. A WDM demultiplexer is used to separate the sensed data from each FBG sensors at the receiver.

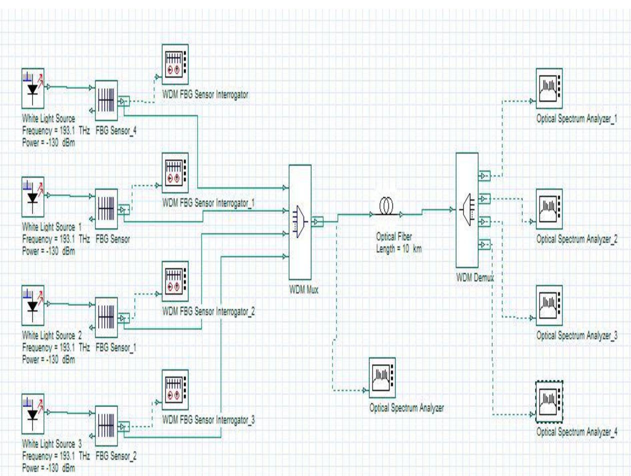

Fig. 1 Layout of the proposed 4-channel WDM-FBG System over OFC channel

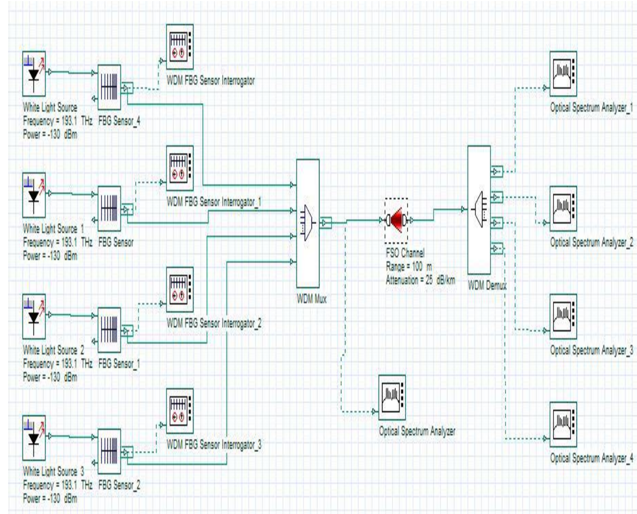

Fig. 2 Layout of the proposed 4-channel WDM-FBG System over FSO channel

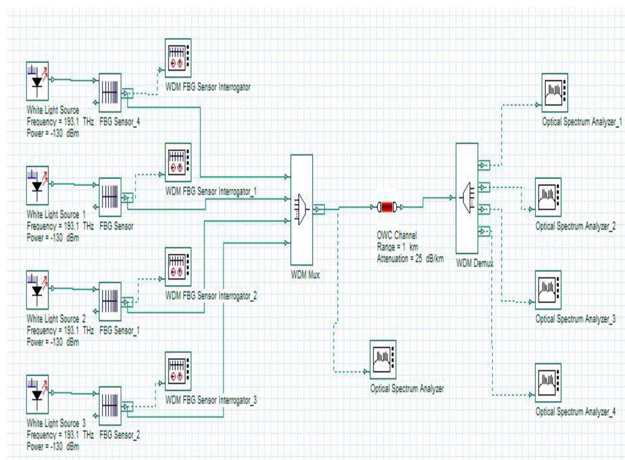

Fig. 3 Layout of the proposed 4-channel WDM-FBG System over OWC channel

IV. RESULTS AND ANALYSIS

OptiSystem 16.0 software has been used here to perform all the simulations. The graphs are obtained using MATLAB R2016b. In 4-Channel WDM-FBG system, four number of FBG sensors are used to sense 4 different temperature ranges, i.e. between 200ºC, 350ºC, 600ºC and 1000ºC with respect to a reference temperature of 0ºC that has a centre Bragg wavelength 1.54999 nm. The thermo-optic coefficient ξ used for temperature sensing of 200ºC and 350ºC is10^{-4}/ºC and for 600ºC and 1000ºC the ξ value is 10^{-5}/ ºC. The change in temperature will shift the centre 1.5499 μm wavelength into four different wavelengths for four different temperatures; these wavelengths are multiplexed using WDM which is shown in

Fig. 4 and passed through a 1 km OFC that has a typical channel attenuation of 0.2 dB/km.

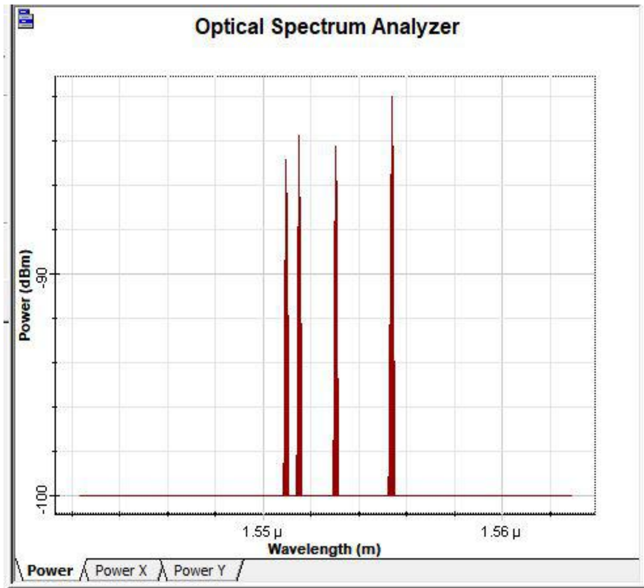

Fig. 4 4x1 WDM Mux output OFC channel

At the receiver side WDM demultiplexer is used to retrieve the data from each transmitter. We have assessed the capability of FSO and OWC channels to send out and receive the multiplexed data in as to be used in these two applications also. An FSO channel is 100m range with 25dB/Km attenuation and OWC with a range of is 1Km with 25dB/Km has been used in the schematic. The Bragg wavelength shift according to the change in temperature as transmitted through OFC, FSO, and OWC channels is compared in TABLE I.

TABLE I Bragg wavelengths shift vs. Temperature change over OFC, FSO and OWC

Temperature (ºC)	Bragg Wavelength over OFC (µm)	Bragg Wavelength over FSO (µm)	Bragg Wavelength over OWC (µm)
200	1.55304	1.55309	1.55301
350	1.55539	1.5556	1.55536
600	1.55096	1.55097	1.55094
1000	1.55151	1.55149	1.55147

We have considered the centre Bragg wavelength as 1.54999µm in obtaining TABLE I. The difference in Bragg wavelength shift for OFC, FSO, and OWC communication channels as a function of temperature as obtained by using Eq. (2) is shown in TABLE II where we have taken the reference temperature as 0ºC and n_{eff} is considered to be 1.45.

TABLE II Difference between Bragg wavelengths shift and centre Bragg wavelength

Temperature (ºC)	Theoretical ($\Delta\lambda_B$) (nm)	Simulated ($\Delta\lambda_B$) (nm) in OFC	Simulated ($\Delta\lambda_B$) (nm) in FSO	Simulated ($\Delta\lambda_B$) (nm) in OWC
200	30.1	31.06	31.061	31.0602
350	54.24	54.43	54.44	54.43
600	92.1	93.05	93.058	93.056
1000	154.1	155.15	155.14	155.147

A look at TABLE II clearly shows that the simulated temperature shifts over the three different channels follow the theoretical shifts closely. The comparative plot of temperature vs. both theoretical and simulated Bragg wavelength shifts as a function of the ambient temperature as observed over OFC, FSO and OWC channels are compared in Fig. 5. All the results show the detection and sensing capability of the proposed scheme over three different channels as the same result is observed to be obtained in each case.

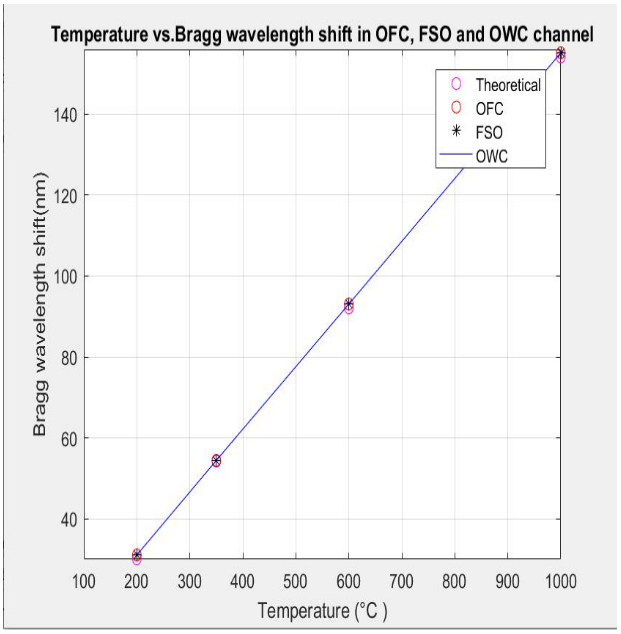

Fig.5 Graph depicting Temperature as a function of Bragg wavelength shift observed over OFC, FSO and OWC communication channels

The FBG sensor can reliably transmit the sensed temperature up to a certain range through the OFC, FSO and OWC communication channels. TABLE III shows the reliable distance to detect the sensed temperature at the receiver. Here an attenuation of 0.2 dB/Km is considered for all the three channels.

TABLE III Communication range over OFC, FSO and OWC channel for the 4 channel WDM FBG Sensor

Communication Channel	Range
OFC	75 Km
FSO	520 m
OWC	30 Km

V. CONCLUSIONS

Two applications of FBG sensor in fire related hazardous areas like underground coal mines and smelting plant applications are presented through computer simulations that demonstrate the multiplexing capability offered by fibre based temperature sensing and subsequent monitoring. The maximum range is observed to be obtained for OFC which is 75 km while OWC is pretty restricted in its range to 520m for a temperature range of 200^{0}C to 1000^{0}C. Results obtained show promise for the use of such sensors in avoiding mishaps due to unmonitored sharp temperature changes as well as providing environmental safety in both of the areas.

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