Fibre bragg grating sensors for measuring spark gap in Micro-EDM in real-time*

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ABSTRACT

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Micro-EDM,
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FBG Sensor

In the phase of Industry 4.0 (I.4) technology, miniaturization has paved the foundation of the smart manufacturing sector and the micromachining processes can be considered as the front end of the I.4 technologies. Micro-Electric Discharge Machining (Micro-EDM) has been considered the most promising micromachining technology for fabrication of microfeatures irrespective to hard and temperature resistive materials. The process characteristics in Micro-EDM is very stochastic in nature, and understanding the proper process characteristics with digitization of data to predict the process for improved capabilities is highly required in this era of Industry 4.0 revolution. The spark discharge between the anode and cathode is envisaged to be very small gap (~10µm) and also an essential parameter for machining performance, but measurement of spark gap of Micro-EDM in real-time is a great challenge. This present work is based on measurement of spark gap with a novel sensing technique based on Fiber Bragg Grating (FBG).

1. Introduction

The I.4 technology summons a SMART manufacturing factory, within which cyber and physical world process together and communicate with people in the real time. The basic formation of this SMART manufacturing sector is the Microsystems technology. Microsystems together form a smart integrated system with mechanical, electronics, and sensing components. They are in use to engineer the miniaturized products in order of few microns, fulfilling every complexity of different geometrical structures. Micro-Electric Discharge Machining (Micro-EDM) is such a considerable micro-manufacturing technology, for fabrication of microstructures. It is a non-conventional machining process [1], where high frequency pulses of low discharge energy (~150µJ) is generated in-between the tiny electrodes of gap less than 10µm, known as spark gap. This electrical spark creates micro-scale craters on the work- piece samples on any conductive or semi conductive materials irrespective of their hardness and with high aspect ratio [2]. The CNC controlled movement of tool/ work pieces is capable of fabricating complex micrometric topographies [3], and is mainly used to produce micro-dies, moulds, surgical tools, ultra fashioned jewelleries, and finishing parts for aerospace and automotive industry [4]. However, the process is lagging in case of batch production of micro parts, due to low Material Removal Rate (MRR) and high Tool Wear Rate (TWR), owing to short-pulsed electric discharge [5]. The current material removal rate i.e. of 0.6-6mm3/hr [6], that leaves a lot from the desired, from the production point of view. Therefore, batch production for micro-parts has been limited.

In this era of Industry 4.0 revolution, understanding the process characteristics and digitization of data to predict the process for improved capabilities is needed. In Micro-EDM processing,

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the parameters are highly stochastic [5], to ensure better machining, high MRR with low TWR is extremely desirable. Accordingly, various parametric studies have been considered, like influence of electro- thermal energy, influence of process variable in formation of crater [7], cold and dense plasma produced in the discharge channel [8], rotation of tool electrode, reversing the polarity of the electrodes, use of additives in dielectric and so on. Among them spark gap plays a very crucial role in Micro-EDM [9]. The spark gap voltage has a direct contribution to the enhancement of material removal rate; it combines with the capacitance level and determines the discharge energy levels during machining [10]. Correspondingly, the quantitative measurement of the spark gap is also very essential parameter for machining performance and but measurement of spark in Micro-EDM which is envisaged to be very small gap between anode and cathode (~10µm) in real-time is a great challenge. In this work, the measurement of spark gap has been accomplished with a novel sensing technique based on Fiber Bragg Grating (FBG) sensors. This is a optical fiber sensor based sensor. FBG has a smaller footprint in the wide range region like structural health monitoring (SHM), coal mining and various biomedical applications, due to its passive nature, multiplexing property [11], and immune to EMI. The fibers are lightweight, small dimension and ease in signal light transmission. The packaged sensor as a whole provides high sensitivity and is pocket friendly [12], [13]. FBG was first fabricated in 1978 [14], and based on the demodulation of the reflected wavelength in response to the applied strain and temperature. The passive device is employed for the measurement of physical quantities such as strain, temperature, displacement, pressure, level, vibration [15]. The application is very prominent in the SHM area, the sensor instrumentation is incredibly resourceful, and they are applied for safety precaution on the assessment of nonlinear properties of the geotechnical structures like Dams and tunnels [16], [17]. Zhao et al. [18] designed a FBG based temperature measurement system in coalmine area for safety preview.

The displacement parameter is measured indirectly by FBG, with its strain sensing property. Displacement is an important parameter in the measurement field, thus packaging and design of displacement sensor is important assignment, mainly in the field of structural monitoring of civil infrastructures [19], tunnel construction engineering [20] and in roadways [21]. Therefore, FBG displacement sensor is favorable than active displacement sensor for its high sensitivity, easy integration and remote transmission without any signal loss. This paper presents the novel technique of the FBG displacement sensor adopted for spark gap measurement in Micro-EDM, so introduction of FBGs in micrometer gap displacement measurement is recognized as a novel technology.

2. Material and Methods

2.1. Micro EDM

The Micro-EDM experimental setup has been built in-house MST laboratory as shown in Figure (1). Three-axis travel linear motorised stages of 1µm resolution, Holmarc make- Model No. TSV 75 Mu01-01 has been used for the actuation of x, y and z movement of the workpiece. The Tungsten carbide tool electrode of 400µm diameter has been used to create the micro craters on the work-piece electrode immersed in the dielectric (EDM oil). The work- piece electrode is made up of brass material; both the electrodes are highly conductive in nature. The RC-circuit based controller is developed in lab to regulate the pulsed electric discharge, whose resultant feedback is obtained in digital phosphor oscilloscope DPO7104 of Tektronix make.

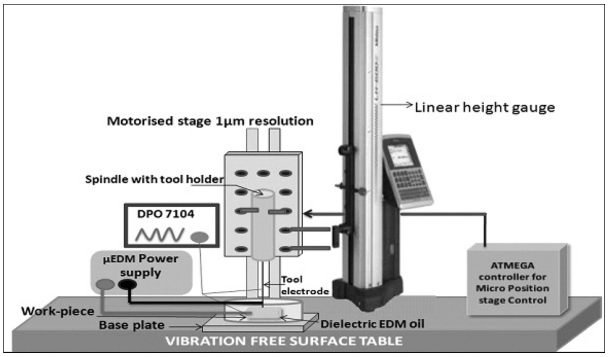


Fig. 1. Micro-EDM setup

2.2. Fiber bragg gratings

Fiber Bragg gratings is an optical fiber sensors, this optical fiber consist of inner core, clad and outer the buffer coating. On the core of the fiber, gratings are formed by inscribing a periodic modulation on the refractive index (R.1)[22]. There is a permanent change in the increased R.I in the core. As a result, a small amount of incident light is reflected at each period, and the coherent combination of the reflected light signals to one large reflection at a particular wavelength is referred to as the Bragg wavelength, satisfying the Bragg's condition [23]. λ_b is the Bragg wavelength. The equation is as follows,

$$\lambda_b = 2n\Lambda \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

"n" is the effective refractive index of the fiber core, and "Λ" is the spacing between the gratings, known as the grating period. The pitch "Λ" of the grating is altered on excitation with strain and temperature. This in turn changes the reflected Brag wavelength (λ_b). The FBG sensor used in this particular experiment have been fabricated in LASER R&D laboratory in RRCAT, Indore, with copper vapour laser at 255.3 nm using phase mask technique [24], with 90% reflectivity at 1546nm and strain coefficient of 1.22με/pm.

2.3. Experimental setup of FBG based displacement sensing system

FBG based displacement sensing device has been designed and developed for measurement of spark gap in Micro- EDM. A cantilever structure is used to generate a strain on the FBG sensor [25], as FBG is directly responsive to strain and temperature. FBG is bonded on the cantilever beam, and the other end of the cantilever is subjected to external displacement. Strain is induced on the FBG, as the load is applied to beam. This variation of strain corresponds shift in wavelength, known as Bragg's wavelength. NI 4844 interrogator has been used to monitor the wavelength shift. In case of spark gap measurement in Micro-EDM, gap is that micrometer displacement to be measured by the FBG. The sensor system is integrated with the Micro EDM setup as shown in Figure 2. The packaged FBG based displacement sensor is highly compact and it is ability to be easily dismantled to accommodate easy replacement of the sensor and to vary the sensor position on the cantilever beam for altering the strain/displacement sensitivity.

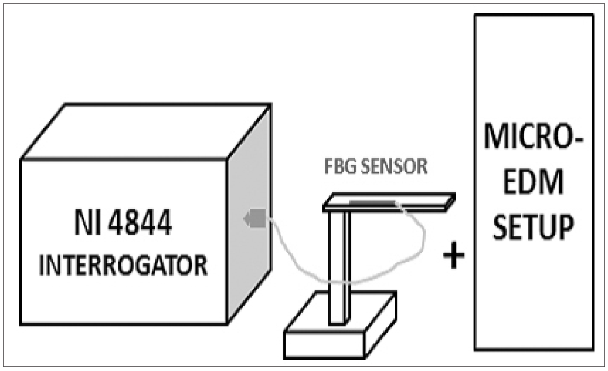


Fig. 2. Integration of the sensor system and the Micro-EDM setup.

3. Experimental Methodology

3.1. Calibration of FBG based displacement sensor

FBG in the basic form is responsive to strain and temperature. For measuring displacement, the strain sensing property of FBG has been adopted to measure the spark gap in between the tool and work piece. The concept is, displacement the primary measurand, and strain has been the secondary direct measurable parameter. The block diagram in fig. (3) represent the concept of developed FBG based displacement sensor. The schematic of experimental setup for calibration is shown in Fig. (4).

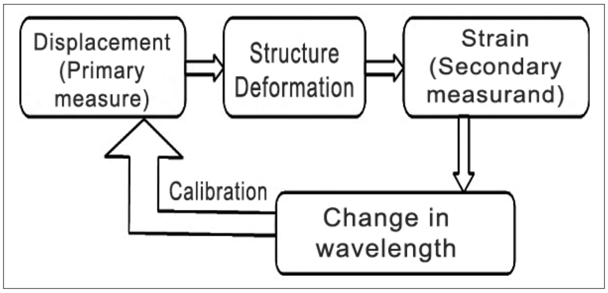


Fig. 3. Concept of displacement measurement by FBG.

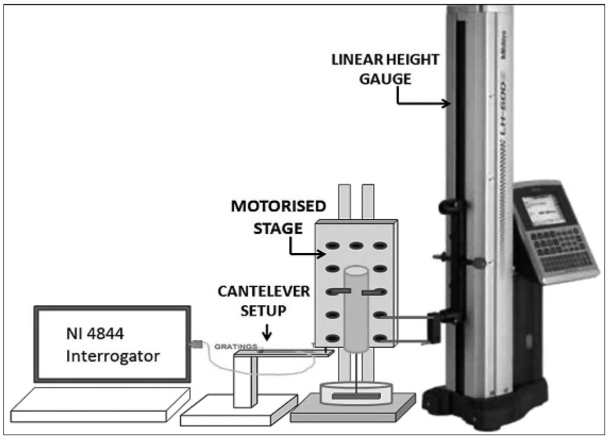


Fig. 4. Schematic of experimental setup.

The developed displacement device has been calibrated against a precision measuring instrument of 100nm resolution. In the unstrained condition, the FBG sensor is with 1546.740nm centre wavelength, as observed in the interrogator. With applying external displacement, the beam is deflected with the generation of strain in the FBG. On a consequence, there is a shift in central wavelength. The schematic of the calibrated setup has been shown in figure (4). The five different experimental trials have been conducted, each time for every trial the primary measurand is different, and as a result, there is a uniform shift in wavelength detected from the interrogator. The calibration table (1) is given below.

Table 1
Calibration Data.

Sl no.	Displacement	Frequency	Wavelength Shift (λ)
1	10 mm	10 Hz	1 nm
2	5 mm	10 Hz	0.5 nm
3	1 mm	10 Hz	0.1 nm
4	200 µm	10 Hz	0.02 nm
5	100 µm	10 Hz	0.01 nm

From the figure, it is evident that the displacement to be measure and strain on the FBG sensor is linear and hence the following relation can be formulated.

$$D\,(\mu m) = 0.1\,(\mu\varepsilon) + C \qquad \text{....................(2)}$$

Where D is the displacement measured, ε is the strain, and C is the proportional constant, which is zero in this case. As this calibration test has been conducted under controlled laboratory environment, the drift due to temperature effect is neglected. The observed sensitivity factor is 1pm/10µm.

3.2. Experiment on spark gap measurement

The FBG based displacement sensor has been calibrated, i.e. offering good sensitivity. The wavelength shift shares a linear relation with the displacement as shown in figure (5). The experimental setup is similar to the calibration setup as shown below in the schematic and in the pictorial view. Only the tool electrode is attached with a tool holder to the motorized stage, and the work-piece is dipped in the di-electric EDM oil. During the experiment for measurement of the spark gap, initially the tool is in contact position with the work-piece at no power condition; the interrogator reflects the central the wavelength of the FBG sensor “λ_1 nm”, i.e. reference wavelength without any excitation. Now the tool electrode is retracted from the work piece with a delay of 10secs to further proceed it towards the work-piece for the next condition. In the next phase, power mode is switch on i.e. active state, for high frequency pulse generation within the tiny gap of electrodes. The tool is advances towards the work-piece, when it reaches the optimum gap between the tool and work-piece, the spark is generated with the electric discharge, the wavelength noted in the interrogator is “λ_2 nm”.

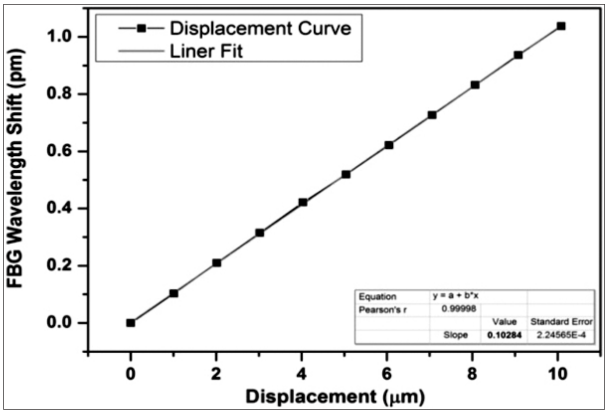


Fig. 5. Wavelength shift Vs displacement curve (linear fit Curve).

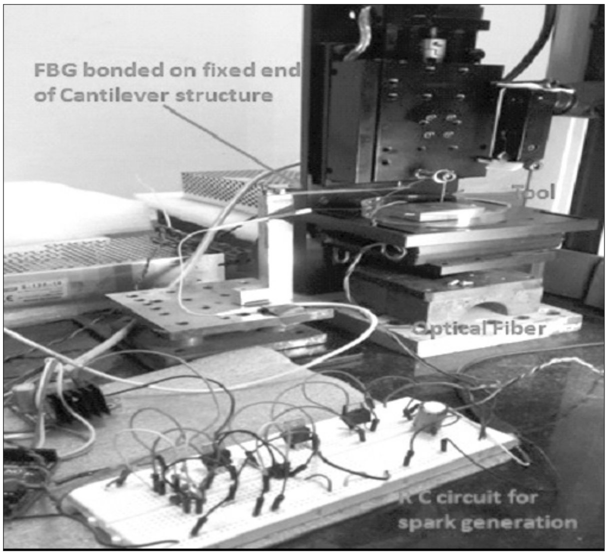


Fig. Pictorial view of the experimental setup.

Thus, the resultant wavelength corresponds the difference in the touch wavelength and spark wavelength,

$$\text{i.e.} \quad \lambda_1 - \lambda_2 = \Delta\lambda \text{ nm} \qquad \text{....................(3)}$$

Since, from the calibrated factor, 1pm wavelength shift = 10µm displacement of stage.

Therefore, Δλ pm is the resultant spark wavelength.

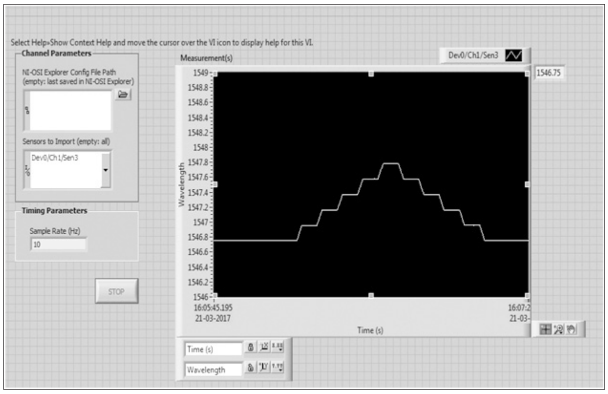
4. Result & Discussion

The experiment has been conducted under

controlled environment condition, free temperature interference, as FBG is highly responsive to temperature. During the experiment, at the initial condition: passive state; λ_1 nm (central wavelength) is noted for the touch value i.e. the tool is in contact with the work-piece. At the final condition: active state; λ_2 nm (wavelength shift) during the time of spark. Therefore, the resultant shift in wavelength ($\Delta\lambda$) nm is the spark wavelength corresponds the measure of spark gap. The least spark gap measured is the 0.5 µm and maximum gap obtained is 8.8 µm. The experimental table (2) is given below.

Table 2
Experimental table for spark gap measure.

Exp. No.	**Touch Value**	**Spark Value**	**Difference of wavelength shift λ_1-λ_2 = λ_B i.e. the spark gap measure; 1pm =10µm (calibrated factor)**		
1.	**λ_1**	**λ_2**	**$\lambda_1 - \lambda_2 = \lambda_B$**	**Wave-length shift**	**Spark gap**
2.	1547.48568	1547.48533	3.50E-04	0.35	3.5
3.	1547.51447	1547.51393	5.40E-04	0.54	5.4
4.	1547.4359	1547.43566	2.40E-04	0.24	2.4
5.	1547.2982	1547.29779	4.10E-04	0.41	4.1
6.	1547.28036	1547.28031	5.00E-05	0.05	0.5
7.	1547.27938	1547.2785	8.80E-04	0.88	8.8
8.	1547.28061	1547.28008	5.30E-04	0.53	5.3



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Channel Parameters
NI-OSI Explorer Config File Path (empty: last saved in NI-OSI Explorer)
Sensors to Import (empty: all): Dev0/Ch1/Sen3
Timing Parameters
Sample Rate (Hz): 10

Fig. 6. Real time plot of the FBG sensor in the interrogator.

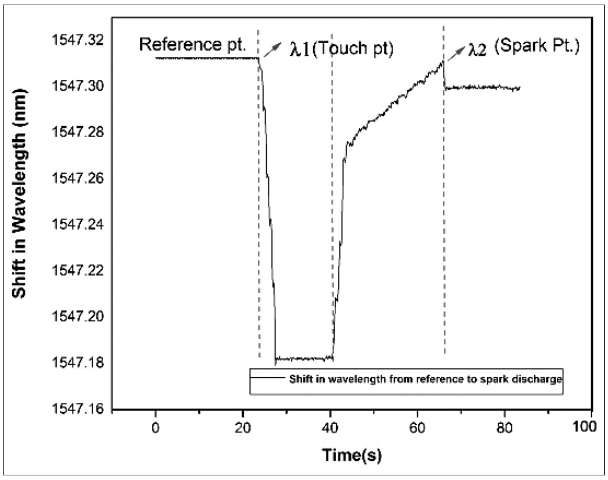

Fig. 7. Spark gap measure in real time.

The spark gap experiment has been performed in real time; the gap measure is calculated from the resultant wavelength, obtained from interrogator. The real time plot from the interrogator has been given in below in Fig. (6), and the spark gap measure indicating the touch value and the spark value with the time scale has been given below in Fig. (7).

5. Conclusion

In Micro-EDM process the spark gap play critical role on the machining performance. It has been noted from literatures, different methods like average gap voltage, pulse discrimination circuit and various servo controllers have been used for controlling of spark gap between tool electrode and work piece. The actual size of the spark gap is in order of few microns, measuring it is a daunting task. So, interference of the sensor system made it knowledgeable about the actual gap size. FBG sensor is the ideal with a miniature size of (~100µm diameter) and less immune to electromagnetic interference.

This research work describes the design and development of a FBG-based displacement sensor. Accordingly, the cantilever structure has been designed on which FBG sensor is bonded for submicron spark gap measurement. The calibration of the displacement sensor package has been carried out under controlled environmental conditions in the laboratory, using a high-precision motorized linear motion controller. The strain exerted on FBG as a result of deflection of cantilever beam causes the wavelength change. This data interrogated using NI based DAQ has been calibrated to conclude that 1 picometer change in wavelength shift represents 10µm displacement of tool i.e. a resolution of 10µm/pm. The experimental results on Micro- EDM setup determine an average spark of 3.5µm. The results obtained revealed good linearity of FBG sensor. Further, it can be used to measure the spark gap across multi electrode, which is very required for the enhancement of MRR. This FBG sensor package is advantageous to electrical sensors respect EMI, less wiring, large measurement range with no data loss, standalone usage, easy sensor replacement, portable package, lightweight, multiplexing capability, and temperature compensation. In the further work, this data acquired from FBG sensor will be used for Micro-EDM process analytics carried out using IIoT enabled devices to predict the micro-EDM process and also to control the movement of electrodes compensated for every pulse discharge such that the spark gap in successive discharges remains consistent even across multiple electrode in parallel sparks across multi-electrodes.

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Reference

1. Katz, Z and Tibbles, CJ: Analysis of micro-scale EDM process, 'Int. J. Adv. Manuf. Technol'., vol. 25, no. 9-10, 2005, 923-928.
2. Rajurkar, KP; Yu, ZY: 3D micro-EDM using CAD/ CAM, 'CIRP Ann. - Manuf. Technol.', vol. 49, no. 1, 2000, 127-130, .
3. Yu, ZY; Masuzawa, T; Fujino, M: Micro-EDM for Three-Dimensional Cavities - Development of Uniform Wear Method-, 'CIRP Ann.', vol. 47, no. 1, 2007, 169-172, .
4. Masuzawa, T: State of the Art of Micromachining, 'CIRP Ann.', vol. 49, no. 2, 2000, 473-488.
5. Pham, DT; Dimov, SS; Bigot, S; Ivanov, A; Popov, K: Micro-EDM - Recent developments and research issues, 'J. Mater. Process. Technol.', vol. 149, no. 1-3, 2004, 50-57.
6. Uriarte, L; et al., Comparison between microfabrication technologies for metal tooling, 'Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.', vol. 220, no. 11, 2006, 1665-1676.
7. Hanumaiah, N; Mitra, S; Paul, G; Roy, S; Sarkar, S: Investigations on influence of process variables on crater dimensions in micro-EDM of γ-titanium aluminide alloy in dry and oil dielectric media, 'Int. J. Adv. Manuf. Technol.', vol. 65, no. 5-8, 2012, 1009-1017, .
8. Nagahanumaiah, J; Ramkumar, N; Glumac, S; G, Kapoor; Devor, RE: Characterization of plasma in micro-EDM discharge using optical spectroscopy, 'J. Manuf. Process.', vol. 11, no. 2, 2009, 82-87.
9. Yeo, SH; Kurnia, W; Tan, PC: Electro-thermal modelling of anode and cathode in micro-EDM, 'J. Phys. D. Appl. Phys.', vol. 40, no. 8, 2007, 2513–2521.
10. Jahan, MP; Ali Asad, ABM; Rahman, M; Wong, YS; Masaki, T: Micro-Electro Discharge Machining (μEDM), 'Micro-Manufacturing Des. Manuf. Micro-Products', 301–346, 2011.
11. Davis, MA; Kersey, AD; Sirkis, J; Friebele, EJ: Shape and vibration mode sensing using a fiber optic Bragg grating array, 'Smart Mater. Struct.', vol. 5, no. 6, 1996, 59-765.
12. Lee, B: Review of the present status of optical fiber sensors, 'Opt. Fiber Technol.', vol. 9, no. 2, 2003, 57-79.
13. Tomas, R: Optical fibre sensory technology, Opt. Lasers Eng., vol. 23, no. 4, 2003, 260.
14. Hill, KO; Fujii, Y; Johnson, DC; Kawasaki, BS: Photosensitivity in optical fiber waveguides: Application to reflection filter fabrication, 'Appl. Phys. Lett.', vol. 32, no. 10, 1978, 647-649,
15. Allwood, G; Wild, G; Lubansky, A; Hinckley, S: A highly sensitive fiber Bragg grating diaphragm pressure transducer, 'Opt. Fiber Technol.', vol. 25, 2015, 25-32.
16. Pei, H; Teng, J; Yin, J; Chen, R: A review of previous studies on the applications of optical fiber sensors in geotechnical health monitoring, 'Measurement, vol. 58, 2014, 207-214.
17. Ho, Yen-Te; Huang, An-Bin; Lee, Jui-Ting: Development of a fibre Bragg grating sensored ground movement monitoring, 'Meas. Sci. Technol.' vol. 17, 2006, 1733-1740.
18. Zhao, Q; Zhang, Y, hua; Ji, Y, cheng; Huang, Z, an; Gao, Y, kun: Mechanism research and application on distributed optical fibre temperature measurement in coalmine goaf area based on the sensor network, 'Int. J. Sens. Networks', vol. 20, no. 2, 104, 2016.
19. Chong, KP: Health Monitoring of Civil Structures, 'J. Intell. Mater. Syst. Struct.', vol. 33, no. 10, 928-940, 9AD.
20. Ye, XW; Ni, YQ; Yin, JH: Safety Monitoring of Railway Tunnel Construction Using FBG Sensing Technology, 'Adv. Struct. Eng.', vol. 16, no. 8, 2013, 1401- 1409.
21. Liang, M; Fang, X: Application of Fiber Bragg Grating Sensing Technology for Bolt Force Status Monitoring in Roadways, 'Appl. Sci.', vol. 8, no. 1, 2018, 107.
22. 'Fiber Gratings : Basic Theory and Sensing Principle', book chapter -2, 20-79.
23. Chen, J; Liu, B; Zhang, H: Review of fiber Bragg grating sensor technology, 'Front. Optoelectron. China', vol. 4, no. 2, 2011, 204-212.
24. Mizunami, T; Gupta, S; Shimomura, T: KrF-laser-induced fiber Bragg gratings: Formation characteristics and cutback measurement, 'Japanese J. Appl. Physics, Part 1 Regul. Pap. Short Notes Rev. Pap.', vol. 35, no. 8, 1996, 4349- 4352, .
25. Dong, X; Liu, Y; Liu, Z; Dong, X: Simultaneous displacement and temperature measurement with cantilever- based fiber Bragg grating sensor, 'Opt. Commun.', vol. 192, no. 3–6, 2001, 213–217 ◘

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