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Carbon conductive coated fiber Bragg grating sensor for voltage detection

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A novel temperature stable fiber Bragg grating (FBG) electrical sensor is proposed and demonstrated. The FBG is coated with conductive carbon paint of approximately 3 mm in thickness, with electrode clips were attached approximately 8.0 mm apart within the conductive paint region. The sensor was exposed to increasing and decreasing voltages between 0 V and 4.0 V, and was determined to have sensitivity of 1.8196 nm/V for increasing voltages and a sensitivity of 1.8455 nm/V for decreasing voltages. The response time for increasing voltages is at an average of 150.9s while for decreasing voltages is at an average of 204.7s.

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1. Introduction

Breakthroughs in material research have led to the development of new materials with high electrical conductivity. These materials, also known as conductive polymers, are fabricated by adding conductive materials such as carbon nanotubes (CNTs) into a polymer host, giving the polymer host conductive capabilities while at the same time allowing them to maintain their polymer characteristics. Furthermore, the use of CNTs and other such nanomaterials also gives these polymers increased sensing capabilities, due to the larger surface area that the CNTs provide for interaction with various stimuli [1]. In this regard, CNTs coated on rigid substrate films have already been proven to be highly capable sensors for mechanical [2] or chemical and biological sensors [3].

Similarly, CNTs can also be added to paint to form electrically conductive paint. The conduction of electricity is made possible by having a functional material, a carrier and a binder [4]. CNTs, along with other carbon-based materials such as graphite, carbon black, and also activated carbon powder serve as the functional material [5], and enhance the paint with significant electrical and heat conductivity capabilities. By combining electrically conductive paint with optical devices, a new generation of optical sensors can be realized [6]. Bare FBG cannot be used as a suitable option for temperature sensing due to its very low thermal expansion coefficient [7,8] Typical temperature sensitivity of these bare FBGs is about 10 to 13 pm/°C in which these values can be increased through methods of pre- and post-treatments of the fiber as well as coating and packaging it. Coating bare FBGs with materials having higher thermal coefficients than silica can improve the sensitivity of temperature sensing of the FBGs [9-11]. This temperature sensitivity of the coated FBG can be correlated with the electrical magnitude applied to the FBG sensor, making it a highly capable optical technology for physical measurements in comparison to conventional electronic sensors [12]. Commonly, digital voltmeter is used as the measurement tools to measure voltage. However, this tool happens to have certain limitations during measurement. Digital voltmeters are prone to damage given the voltage is increased beyond a certain limit. Any fluctuations that occur in a circuit may disrupt the ability of the voltmeter to read and display the value of the voltage measurement. There are also chances of the digital voltmeter getting heated up during measurement, resulting in inaccurate readings. FBG based sensors have an upper hand as compared to these conventional voltmeters due to their inherent immunity to electromagnetic interference as well as being able to withstand much higher temperature limits. They are also lightweight, cost-effective and generate no sparks, making them suitable for use in hazardous areas [13-15], and primarily for temperature and strain measurement [16,17].

In this work, a temperature stable electrical sensor using FBGs, coated with conductive carbon paint is proposed and demonstrated. The carbon conductive paint is easily applied onto the surface of the FBG by brushing method, with a layer of approximately 3 mm thick. The proposed FBG is subjected to electrical inputs of varying voltages value and the responses of the sensor are obtained. The sensor is also tested for its stability and sensitivity.

2. Experimental setup

Fig. 1 shows the setup for the proposed conductive carbon coated FBG based electrical tuneable sensor. An erbium-doped fibre (EDF) amplified spontaneous emission (ASE) source is used to generate a C-band ASE spectrum, and is connected to Port 1 of a three-port optical circulator (OC). Port 2 of the OC is connected to the coated FBG, while Port 3 of the OC is connected to an Optical Spectrum Analyser (OSA) with a resolution of 0.06 nm. The carbon coated FBG has a centre wavelength of 1552.40 nm, with the 3-dB bandwidth of 0.6 nm at ambient temperature and a reflectivity of 95% and 5%, respectively. A power sources is also connected to the coated part of the FBG using electrode clips set at a distance 0.8 mm apart. The reason behind this distance is that the grating size of the FBG itself spans 0.8 mm, in which the conductive carbon paint is applied along this grating. The power source is used to provide the test current for the FBG based electrical sensor.

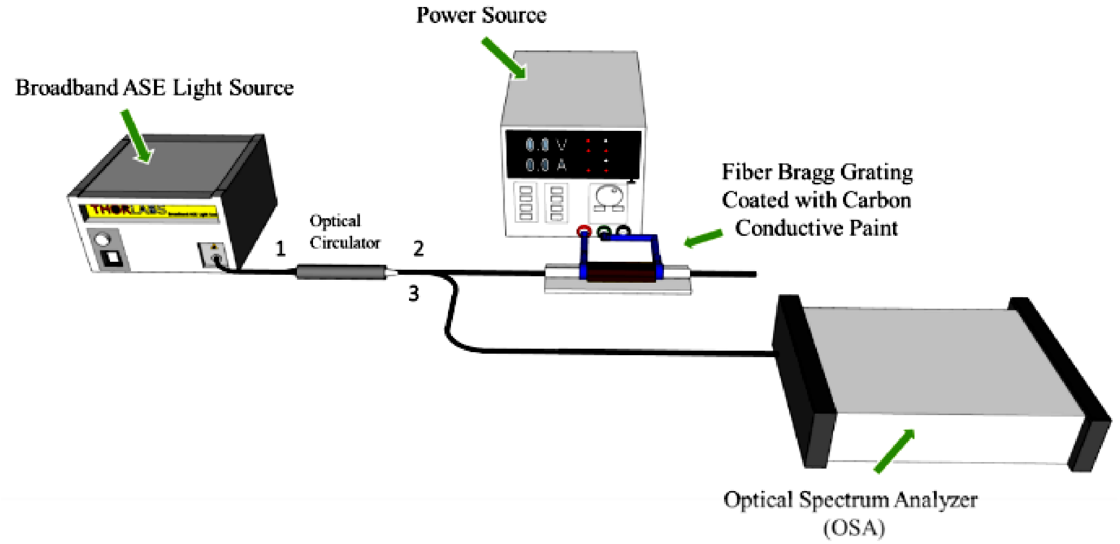

Fig. 1. Configuration setup for the analysis of FBG coated with carbon conductive fiber with electrical power source (color online)

The conductive carbon paint used to coat the FBG is a combination of carbon black and graphite in a water-soluble solution, which gives better performance in terms of electrical conductivity [18]. The carbon paint is water soluble, electrically conductive, non-toxic as well as solvent free and safe. The paint is flexible and can be applied onto most non-conductive materials using any stencil such as brush, roller or even sprayer. It has a density of 1.2 to 1.25 g/ml at 25°C with a sheet resistance of 55 ohm/sq at a film thickness of 50 microns. However, the sheet resistance drops to approximately 32 ohm/sq when the paint is applied on the surface of any material. The carbon conductive paint layer applied on the FBG is left to dry for at least 5 minutes to ensure the paint is completely dried and thus, will not affect the accuracy of the experiment. To coat the FBG, the fiber polymer jacket as well as the cladding is first removed. Then, the carbon conductive paint is brushed onto the grating region to form a thickness of 3 mm. Electronic Vernier callipers are used to measure the thickness of the coating and ensure the desired thickness is obtained. This thickness has been determined to be the optimum thickness to produce the highest sensitivity in the FBG sensor [6]. The schematic diagram of the coated FBG and attached to the electrodes is shown in Fig. 2.

To test the sensor, a low voltage current is injected by the power sources, and the voltage is slowly increased from 0 V to 4.0 V at a steady increment of 0.5 V. The voltage is then decreased in the same increments from 4.0 V to 0 V. For stability testing, the voltage of the power source is set at 1.5 V and the output spectrum data was taken at 2, 5, 10, 15 and 20 minutes respectively. The experiment was done in a closed compound with a controlled air circulation to prevent temperature fluctuations from affecting the FBG. The experimental set up was also arranged on a vibration-free table by Thorlabs to reduce mechanical vibration and thus errors.

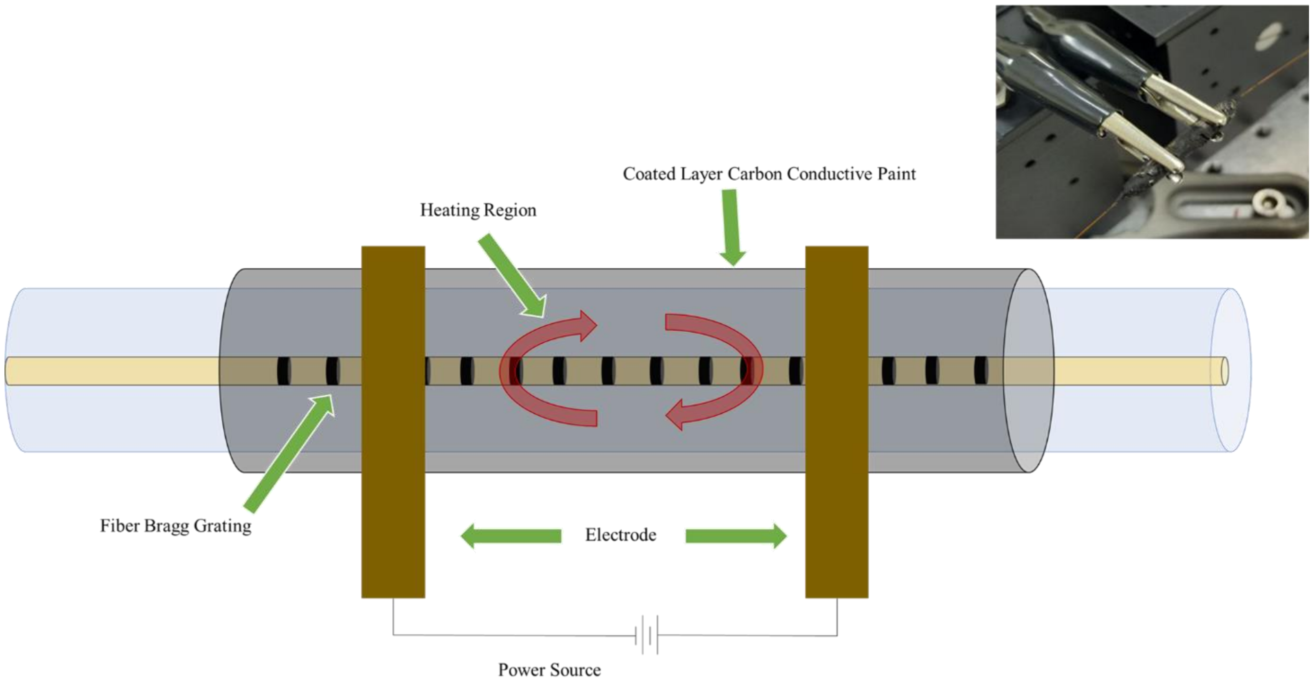

Fig. 2. Schematic diagram of the FBG coated with carbon conductive paint attached to electrodes (color online)

3. Result and discussion

Fig. 3 shows the change of the spectrum as the voltage applied is increased from 0.0 V to 4.0 V at 0.5 V increments and reduced from 4.0 V to 0.0 V at decrements of 0.5 V. Over the voltage range from 0.0 V to 4.0 V, the spectrum peak wavelength is observed to shift from 1547.78 nm to 1554.52 nm, with a total shift of 6.74 nm. The spectrum of the FBG sensor has an average shift of 1.8196 nm/V against an increasing voltage, with the spectrum shifting to the longer wavelength. This is attributed to the current flow along the body of the coating which produces heat, and in turn causes the coating to expand, forcing the grating region of the FBG to stretch and producing a wavelength shift towards a longer wavelength [19-21].

It is also observed that initially, although the voltage is slowly being increased, the spectrum does not show a significant wavelength shift. However, at a voltage of 1.5 V and above, the change in the spectral shift starts to become noticeable. This is again attributed directly to the amount of heat generated by the increasing voltage; the lower voltages cannot be able to sufficiently drive the current across the coating, thereby resulting in less resistance and as such less heat generated. In the same manner, at the higher voltages, more heat is generated by the flow of the current, causing the shift to be higher than predicted. Therefore, the obtained graph does not fit exactly onto the theoretical linear relationship of the voltage to the change in the wavelength, but deviates slightly in at the lower and higher voltages.

As for the voltage ranging from 4.0 V to 0.0 V, the spectrum peak wavelength of the FBG sensor produces a total shift of 7.00 nm, from 1555.15 nm to 1548.15 nm with an average shift of 1.8455 nm/V. The lowering voltage causes less heat to be generated by the coating, and in turn shifts the wavelength spectrum back towards the shorter wavelength. However, unlike the case with the increasing voltage, lowering the voltage does not shift the wavelength back to the same point, as the additional heat generated does not dissipate quickly, and thus contributing to some stretching of the FBG.

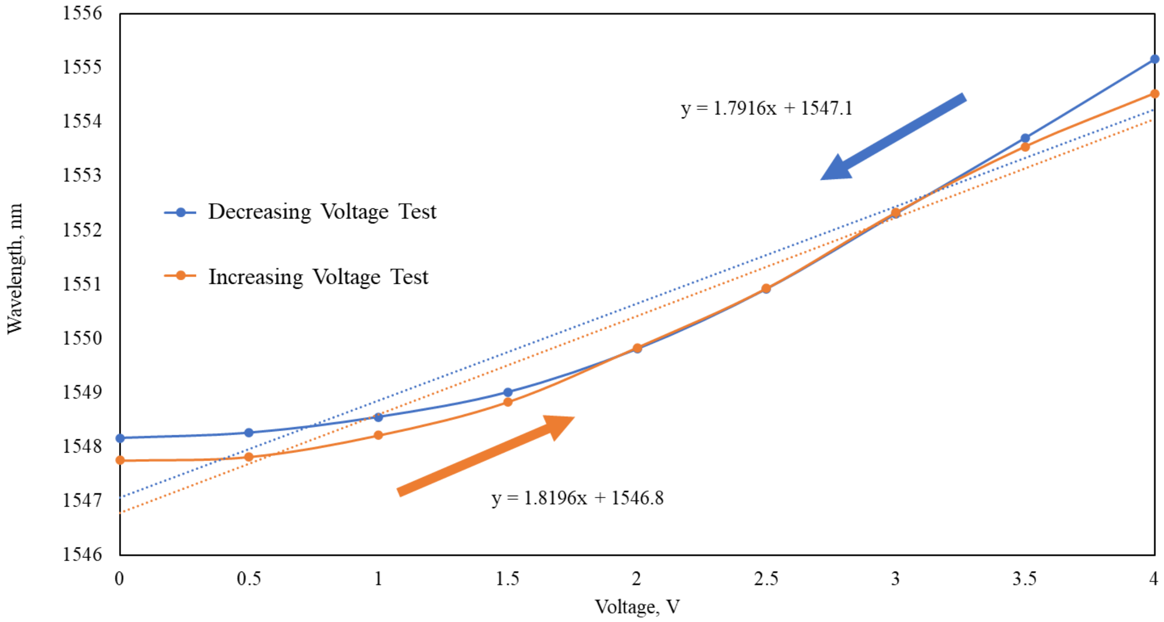

Fig. 3. Peak wavelength of FBG coated with carbon conductive paint for different applied voltages from 0.0 V to 4.0 V with 0.5 V increment and from 4.0 V to 0.0 V with 0.5 decrement (color online)

Fig. 4 shows the wavelength response against time at different voltages ranging from 0.0 V to 4.0 V with an increment of 0.5 V. It can be seen that the time taken for the wavelength to shift in accordance to the new voltage is more or less consistent at about 150s. The initial injection of the current at a voltage of 0.5 V results in the shortest time required for the wavelength shift to stabilize, which is attributed to the smaller amount of heat generated by the current. It is also observed that for each increment in the voltage, the wavelength shift rises almost exponentially before stabilising. This can be attributed to the jump in the voltage causing a spike in the temperature, explaining the quicker shift, before the temperature stabilises and the expansion of the FBG stops. This trend is observed for all voltages above 1.0 V.

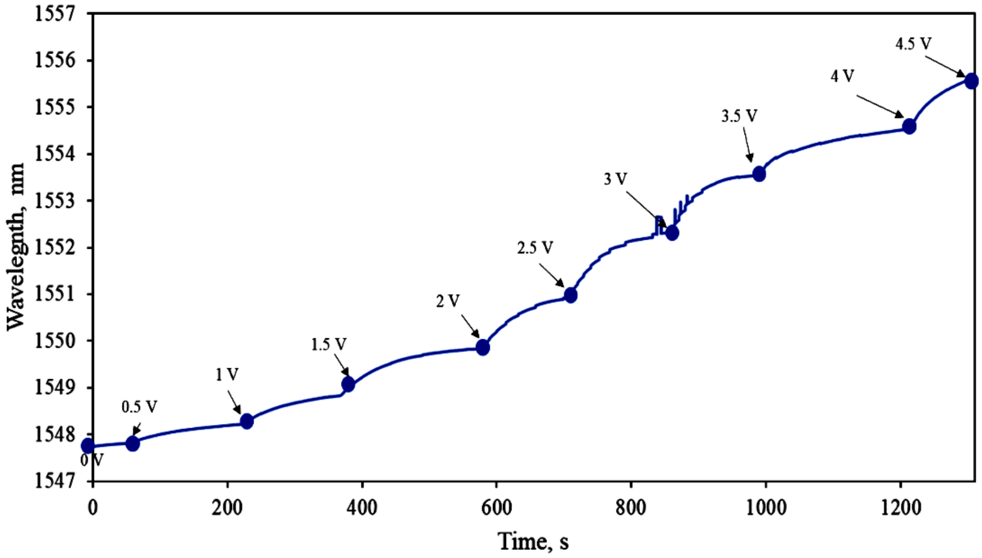

Fig. 4. Wavelength response against time for different applied voltages from 0 V to 4.0 V with 0.5 V increment (color online)

Fig. 5 shows the response time of the FBG sensor for applied voltage ranging from 0 V to 4.0 V with an increment of 0.5 V. The average response time of the FBG sensor is approximately 150.9 seconds with the lowest response time being approximately 54.8 seconds at an applied voltage of 0.5 V. On the other hand, the highest response time is approximately 217 seconds at the applied voltage of 4.0 V. The values of the response time are not consistent and fluctuate at certain points of the applied voltage. These fluctuations of the response time are attributed to the distribution of heat throughout the coating of the FBG sensor. The region between 123 seconds until

160 seconds shows that the FBG can provide a good response to the changing voltage between the range of 1.0 V to 3.5 V. This is possible as this region does not show substantial fluctuations in the response time.

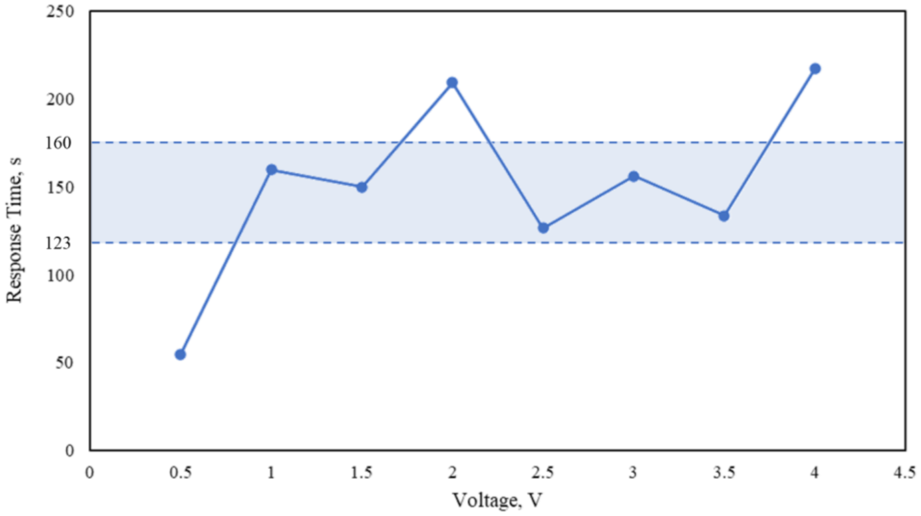

Fig. 5. Response time for different applied voltages from 0 V to 4.0 V with 0.5 V increment (color online)

Fig. 6 shows the wavelength response against time for different voltages applied from 4.0 V to 0.0 V with a decrement of 0.5 V. The time taken for a certain value of voltage to increase to another value is apparently consistent. This is due to the heat generated from the flowing current, based on the value of applied voltage towards the coating body. The heat at the coating body tends to dissipate, leaving out the remaining heat from the flowing current based on the specific value of the applied voltage. The observed consistency of the wavelength response time indicates that the amount of heat dissipated at every decrement of 0.5 V is somehow consistent. Similar to Fig. 4, a negative exponential curve is observed during each drop in the voltage, with the sudden drop being a result of the reduction in the voltage, while the stabilization of the heat causes the curve to the plateau.

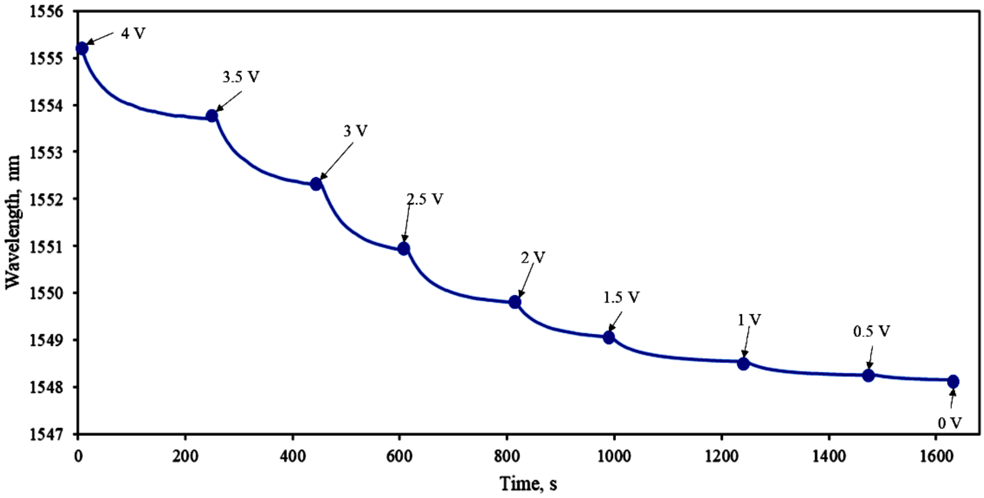

Fig. 6. Wavelength response against time for different applied voltages from 4.0 V to 0 V with 0.5 V decrement (color online)

Fig. 7 shows the response time of the FBG sensor for applied voltage ranging from 4.0 V to 0 V with a decrement of 0.5 V. The average response time of the FBG sensor is at approximately 204.7 seconds. The lowest response time and highest response times are approximately 149 seconds at 0.5 V and 252 seconds at 1.0 V respectively. The overall values of the response time are not consistent and fluctuate at certain point of applied voltage. Similar as in Fig. 5, the region between 180 seconds and 255 seconds shows the least fluctuations in the response time. Furthermore, the decreasing in applied voltage results in a larger response time is due to the process of heat dissipation which commonly consumes a lot more time as compared to the heat distribution as the applied voltage is increased.

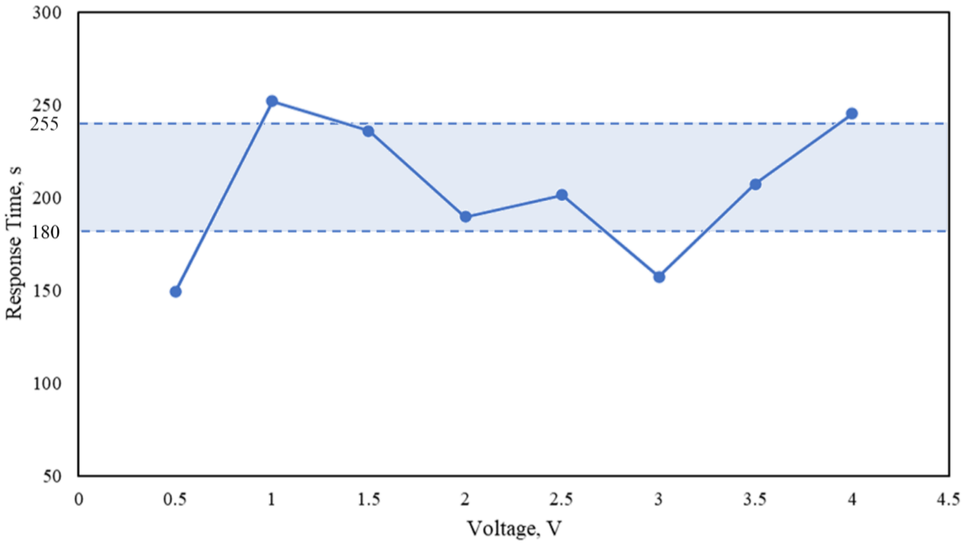

Fig. 7. Response time for different applied voltages from 4.0 V to 0 V with 0.5 V decrement (color online)

Table 1 summarises the FBG sensor performance in terms of sensitivity, average response time and accepted range of response time for increasing and decreasing applied voltage.

Table 1. Summary of coated FBG sensors performance for increasing and decreasing applied voltage

Voltage range (V)	Sensitivity (nm/V)	Average response time (s)	Accepted range of response time (s)
0 – 4.0 (increasing)	1.8196	150.9	54.8 – 217.0
4.0 – 0 (decreasing	1.8455	204.7	149.0 – 252.0

The sensor shows a better sensitivity during the voltage decreasing as compared to during the voltage increasing. In terms of average response time, it is quickest during the increasing of voltage applied rather than the decreasing voltage applied. This is the same with the accepted range of response time in which the sensor has a better accepted range of response time during voltage increasing than during decreasing.

Fig. 8 shows the reflection spectra of the stability test conducted at 1.5 V at the period of 2, 5, 10, 15 and 20 minutes respectively. From the figure, it can be seen that there is a slight shift for each of the spectrum due to the heating effect from the flowing current that dynamically changes the physical behaviour of the coating. While this change can affect the spectral shift of the FBG sensor coated with the conductive carbon paint, it can be considered insignificant due to its small amount of shift seen in the spectrum and thus indicates that the proposed sensor is stable for voltage measurements.

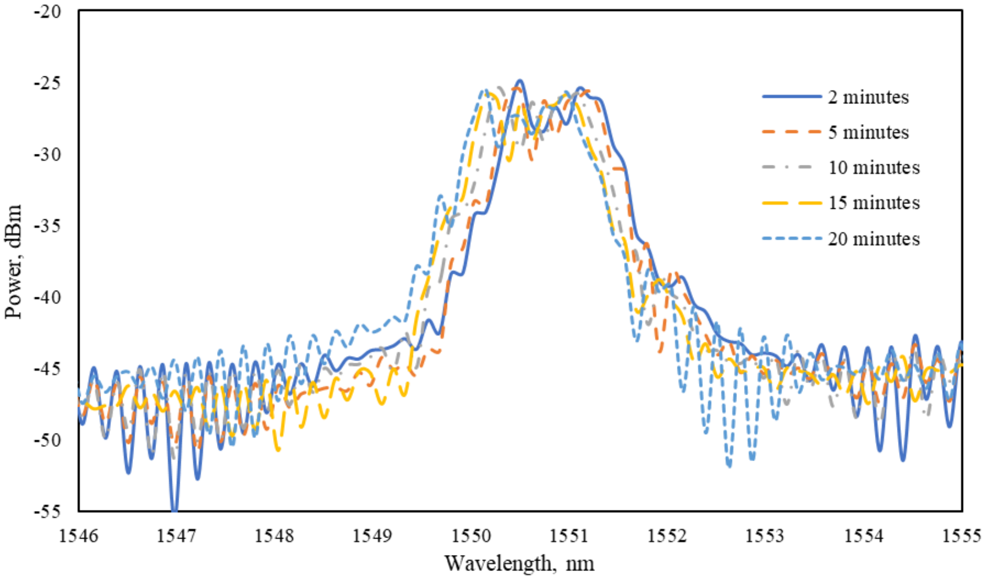

Fig. 8. Reflection spectra of the conductive carbon coated FBG sensor for different period of time at a constant voltage of 1.5 V (color online)

4. Conclusion

A novel electrical tuneable and temperature control sensor by using fiber Bragg grating (FBG) coated with conductive carbon paint is demonstrated. The FBG sensor is coated through using brushing method with the thickness of 3 mm. A pair of electrode clips were attached at the ends of the conductive paint region approximately 8.0mm apart. The experiment is done in two parts; (1) tuneable electrical voltage in the increasing and decreasing ranging in between 0 V and 4.0 V; (2) temperature control given constant value of voltage applied to the FBG sensor. The sensor has a sensitivity of 1.8196 nm/V for increasing voltage and a sensitivity of 1.8455 nm/V for decreasing voltage, both at the range of between 0 V and 4.0 V. The response time of the FBG sensor in the increasing voltage is at an average of 150.9 s with the accepted quickest response time is 54.8 s and the slowest response time is 217.0 s. The response time of the FBG sensor in the decreasing voltage is at an average of 204.7 s with the accepted quickest response time is 149.0 s and the slowest response time is 252.0 s. For the temperature control test, the spectrum shift of the FBG sensor shows only the slightest fluctuation given the voltage is constant during the test. Therefore, this FBG sensor can be a good electrical tuneable as well as temperature control system with high sensitivity.

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