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Characterization of Bragg Grating Lengths in Single-Mode Fibre for Strain Sensor Applications

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ABSTRACT

This study presents the successful fabrication of Fibre Bragg Gratings (FBGs) using a 248 nm KrF Excimer Laser combined with the optical phase mask technique. The research focuses on investigating the effects of stress on Bragg grating length in single mode fibres (SMFs). A total of five FBGs, each with different grating lengths, were analysed for strain sensitivity. The findings reveal a linear relationship between strain and Bragg grating length for all tested FBGs. Notably, the FBG with a grating length of 2.50 cm exhibited the highest strain sensitivity, however the strain sensitivity for all FBG grating lengths were found to be consistent. These results suggest the potential for optimizing FBG grating length in multimode fibre to enhance performance in strain-sensitive applications.

1. Introduction

Over the last two decades, the telecommunication industry has experienced significant growth, particularly with the development of fibre optics communication, which stands out for its superior performance [1]. This development has sparked increased interest in using optical fibre sensors [2,3] as an alternative to traditional sensors in various engineering applications [4], including dynamic strain [5], temperature [6,7], pressure [8], viscosity, acceleration, chemical measurements and humidity detection [9,10].

In recent years, there has been considerable focus on applying Fibre Bragg Grating (FBG) for microwave photonics sensor system [11] and also to monitor civil and structural engineering projects [12]. Studies on infrastructures such as highway bridges [13], roadways, aircraft [14], dams and watercrafts have demonstrated the need for improved technology to detect structural degradation and provide more accurate instrumentation [15]. FBG-based optical fibre sensors offer an attractive solution, particularly for strain sensing. Some FBG based sensors and systems [16] have already been deployed in real-world civil infrastructure projects. For instance, several sensors were installed on a

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steel girder in a bridge, as developed by Todd MD and Johnson GA at the US Navy Research Laboratory, to demonstrate FBG's capabilities as a sensor [17].

Recent studies highlight how tilted fibre Bragg gratings (TFBGs) are being used to improve sensitivity and signal clarity. These sensors, which involve modifying the angle of grating inscription, are especially useful in noisy environments, offering significant improvements in applications such as aerospace and structural health monitoring [18]. FBG sensors are being increasingly deployed in challenging environments, such as nuclear or high-radiation areas and for interrogation monitoring [19] conditions in railway systems [20] and composite materials. These developments reflect a growing trend toward multi-functional, robust FBG sensor systems that can operate reliably in extreme conditions [21]. Recent findings also emphasize how modern FBG sensors [22] continue to show a variety of sensitivity ranges depending on the application and environmental conditions. In some cases, the experimental sensitivities significantly diverge from theoretical predictions, similar to the discrepancies noted in this study [23].

A previous study examining the influence of grating length on FBG performance yielded promising results. The study involved modelling five fibres with different grating lengths and analysing the simulated results by calculating each fibre's bandwidth, as well as its transmission and reflection spectra. The researchers solved couple mode equations using the Transfer Matrix method [24]. The results showed a correlation between grating length and bandwidth: longer gratings were associated with narrower bandwidths, indicating better performance. It can be concluded that longer grating lengths provide superior performance and are, therefore, more desirable for use. A direct proportionality between a fibre's sensitivity and its reflectivity was also highlighted. However, there has been limited experimental research on the effect of grating length on the performance of FBG sensors. Therefore, this paper aims to experimentally verify this correlation by testing five FBGs with varying Bragg grating lengths. Based on prior research, it is expected that longer grating lengths will result in increased sensitivity.

The study demonstrates a clear, almost linear relationship between the Bragg grating length of FBGs and their strain sensitivity. This confirms earlier research that suggested a correlation between these parameters, but the study goes further by quantifying the sensitivity across multiple grating lengths. The finding that the FBG with a 2.5 cm grating length exhibits superior strain sensitivity contributes new data, suggesting that optimizing grating lengths can enhance sensor performance.

The reported sensitivity values, ranging between 24.2 pm/με and 27.9 pm/με, are over 20 times higher than the known sensitivity of a bare fibre strain sensor (~1 pm/με). This discrepancy suggests that modifications in the fabrication process, such as the use of a 248 nm KrF Excimer laser and phase mask technique, can greatly influence sensor performance. This challenges the established sensitivity benchmarks in FBG literature, opening avenues for further exploration into the impact of fabrication techniques.

By providing detailed data on the strain-induced wavelength shifts and their relationship to grating length, the study contributes practical insights into the design of more accurate and sensitive FBG-based strain sensors. These findings can be applied in industries that rely on fibre optic sensors for monitoring mechanical stress, structural health and environmental conditions.

2. Methodology

The following experiment consists in characterizing five bare FBGs with different grating lengths; 1cm, 1.5cm, 2cm, 2.5cm and 3cm is shown in Figure 1. The FBG has been successfully fabricated by using 248nm KrF Excimer Laser with optical phase mask technique as discussed in our previous work [25,26].

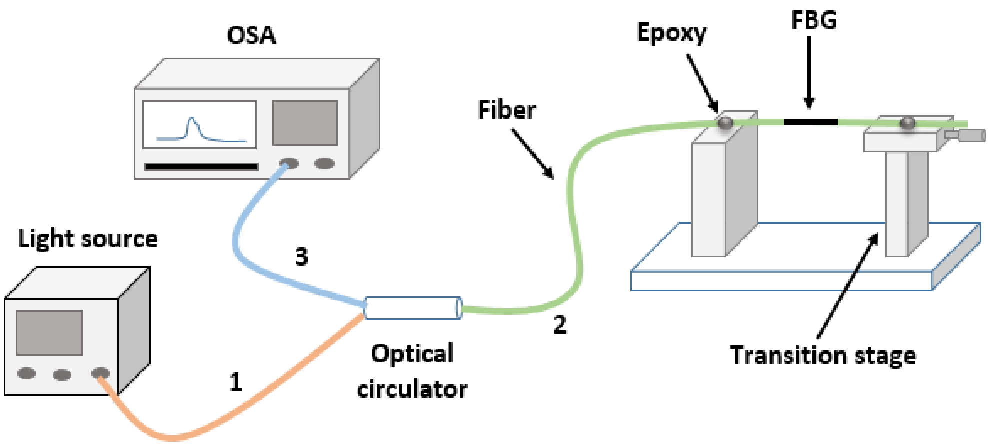

Fig. 1. Schematic experimental setup of strain sensor

In the experimental setup, strain was applied to the FBGs with different grating lengths. The FBGs were fixed onto a transition stage with epoxy. One end of the fibre was securely held in place, while the other end was connected to a micrometric adjustment screw. This screw was used to precisely apply strain to the fibre. By turning the screw, the fibre was gradually stretched, increasing the strain on the FBG. The strain was incrementally applied in steps of 10 µm, starting from 0 µm and going up to 100 µm, which corresponds to two full rotations of the screw.

To measure the resulting wavelength shift caused by the applied strain, a broadband light source with a spectral range of 1400 nm to 1600 nm was used to emit light through the fibre containing the FBG. Then, the light signal passed through an optical circulator that directed it toward the FBG. The circulator ensures the proper flow of light and reflects the Bragg wavelength back toward the detection system. The Optical Spectrum Analyzer (OSA) monitored the behaviour of the Bragg wavelength by measuring the wavelength shift in response to the applied strain. As strain was applied to the FBG, the reflected Bragg wavelength shifted due to changes in the fibre's grating period.

The OSA provided precise readings of the reflected wavelength at each strain increment. Since the strain was increased in fine increments of 10 µm using the micrometric screw, the OSA was able to detect the corresponding shift in the Bragg wavelength with high accuracy. This enabled the researchers to plot the wavelength shift as a function of the applied strain for each grating length. By using this setup, the experiment ensured controlled and accurate application of strain, allowing for precise measurement of the Bragg wavelength shift, which was key to determining the strain sensitivity of the FBGs.

As shown in Figure 2, the optical circulator regulates the path taken by the signal; it first transmits the signal from the light source to the FBG, then receives the reflected wavelength and guides it towards the OSA. The strain applied on the fibre was gradually increased from 0µ to 100µm, which corresponds to two whole turns of the micrometric screw and with an increment of 10µm.

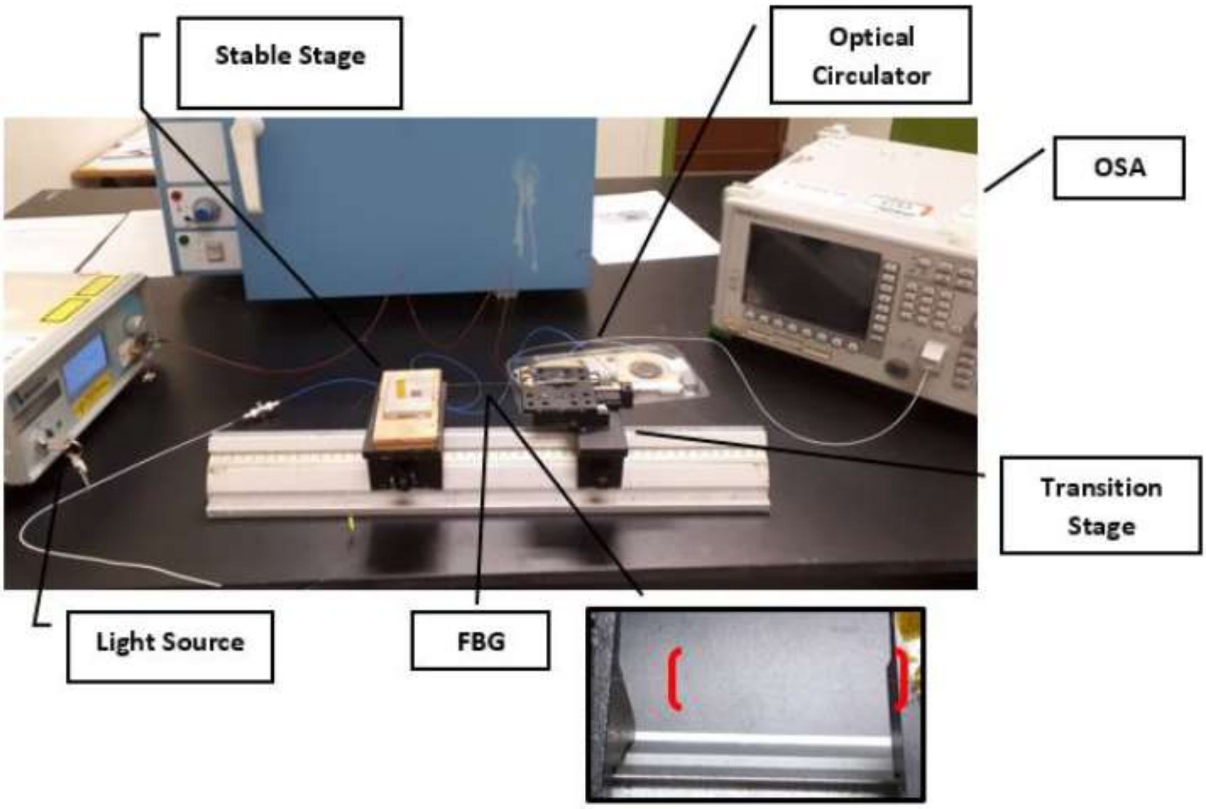

Fig. 2. Actual experimental setup of strain sensor

3. Results

Figure 3 shows the intensity of the signal received by the OSA for each fibre when they're not under strain. From these results, it can be observed that the fibre with 2.5 cm of grating length gives highest intensity.

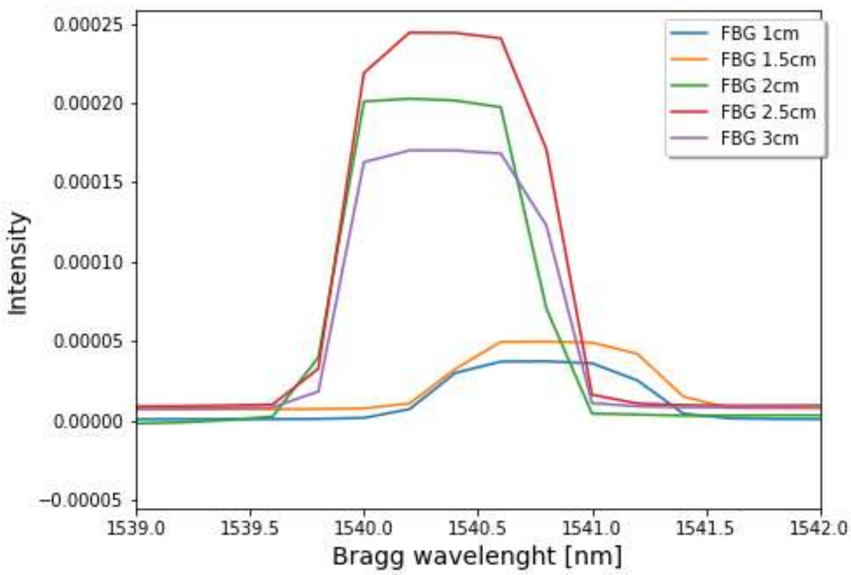

Fig. 3. Intensity for different grating length without strain

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Volume 140 Issue 1 (2026) 1-9

To observe the strain's influence on the fibre, the reflected Bragg wavelength is plotted every 10µm for each fibre. The wavelength shift, as a response to the increase of the strain on the FBG, can be clearly seen in Figure 4 for every grating length.

This experiment's objective is to define whether there is a correlation between the sensor's sensitivity, its Bragg grating length and the signal's intensity. The sensitivity can be deducted, for each grating length, by drawing the Bragg wavelength shift versus the strain. Each curve has a linear trend line whose slope corresponds to the value of the sensitivity.

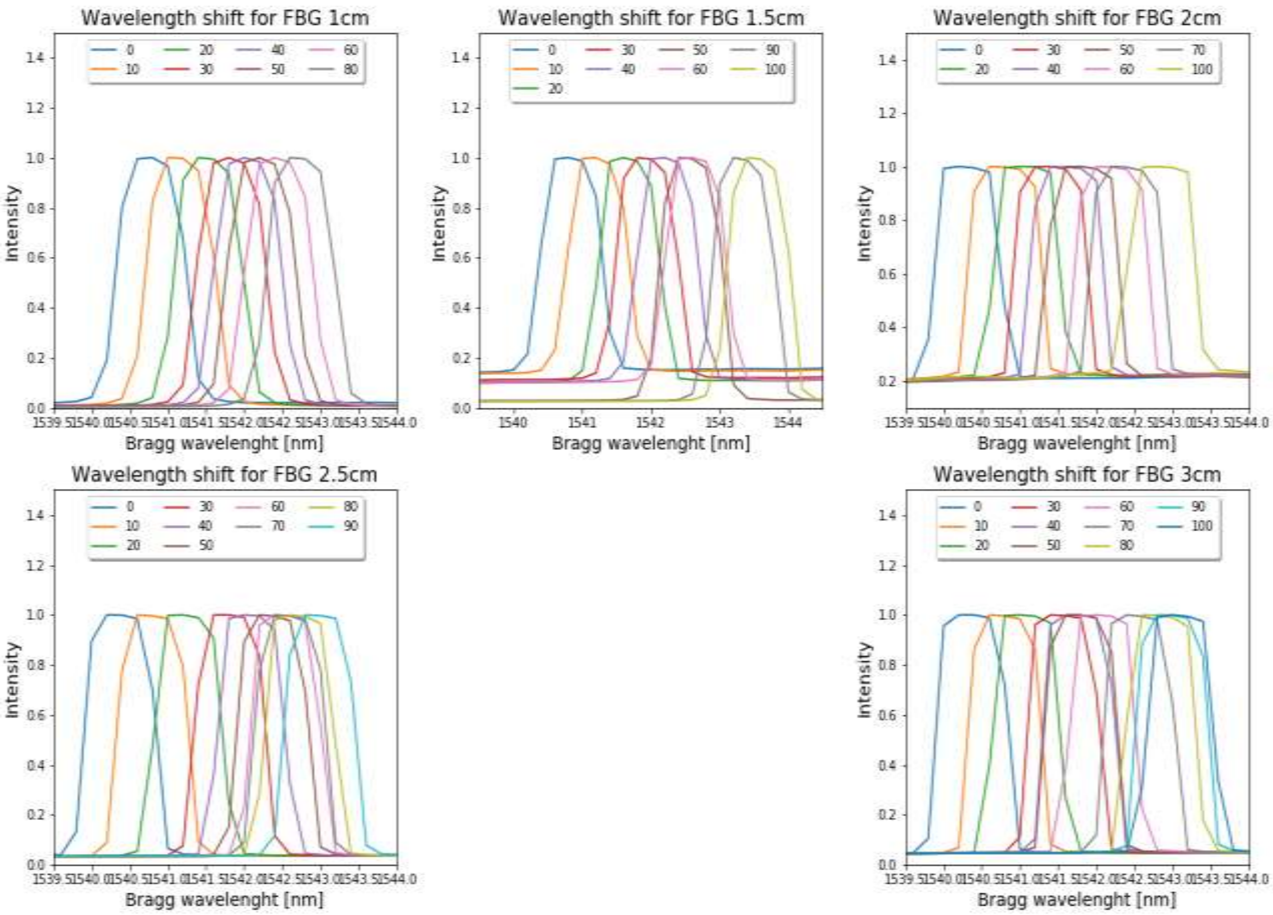

Fig. 4. Wavelength shift as a response to the increase of the strain on the FBGs

Figure 5 shows the plot of the sensitivity of each fibre versus their grating length. Overall, with the exception of the results for the 3cm FBG, it appears that there is a slight correlation between the fibres' grating length and its sensitivity; the longer the grating length is, the better the sensitivity. Moreover, the same observations can be made regarding the correlation between the signal's intensity and the sensitivity. From these results, it appears that the FBG with a grating length of 2.5cm is better that the others as it has the best sensitivity and intensity. However, the values of the sensitivity range between 24.2pm/µε and 27.9 pm/µε. This is more than 20 times higher than the known value of the sensitivity for a bare fibre strain sensor, which is around 1 pm/µε [27].

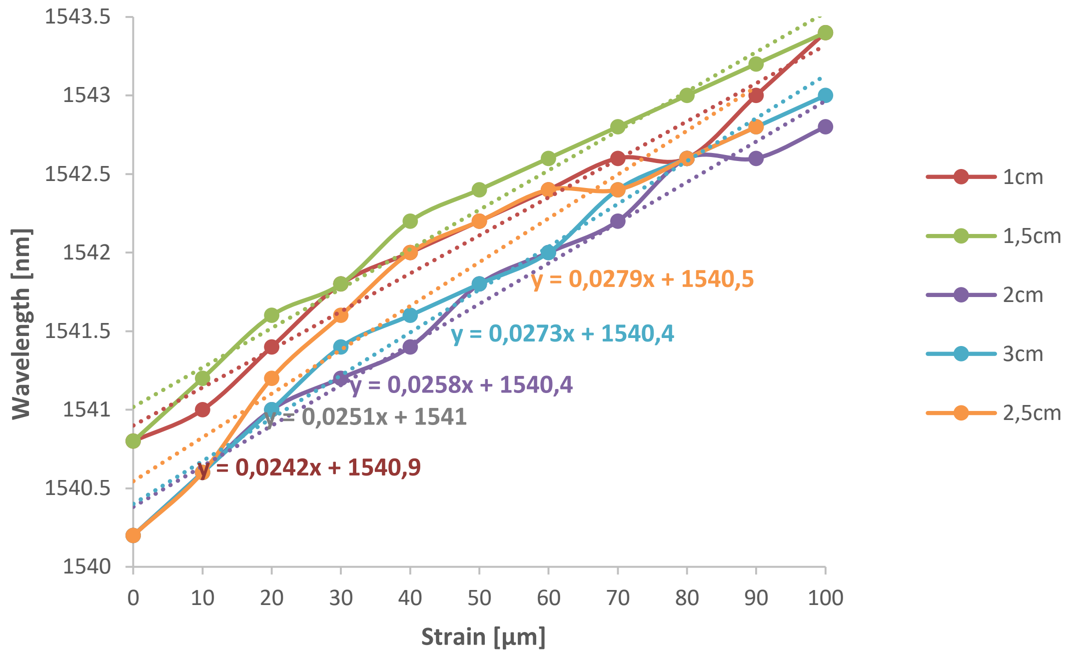

Fig. 5. Wavelength shift *vs*. strain for different grating lengths

The sensitivity of a Fibre Bragg Grating for a strain sensor is shown in Eq. (1):

$$\Delta\lambda\Delta\varepsilon=0.79\ \lambda B\ pm/\mu\varepsilon \quad (1)$$

Where, λB is the Bragg Wavelength of the fibre and ε is the grating's strain. The fibres used in this experiment have two different Bragg wavelengths; 1540.5 nm for the grating lengths 2, 2.5 and 3cm and 1541 nm for 1 and 1.5cm. Thus, the theoretical value of the sensitivity for both Bragg wavelengths is 1.217 pm/με. From the previous figure, the experimental values were deducted and listed in Table 1.

Table 1
The sensitivity of strain sensor at different grating length

Grating Length (cm)	Sensitivity (pm/με)
1.0	24.2
1.5	25.1
2.0	25.8
2.5	27.9
3.0	27.3

As shown in Figure 6, these results show a strong, almost perfect, linear relationship between a FBG's Bragg Wavelength and its grating length, confirming the previous reflection stating that the sensor responds correctly to the strain applied on it. However, the obtained sensitivities do not match at all with the ones that were calculated previously. Furthermore, contrary to what was obtained for the strain sensor, it appears that that there is slight correlation between the fibre's grating length and its sensitivity; the longer the former, the better the latter. This correlation is even stronger if the data for the 3 cm grating length is not taken into consideration. It also appears from that the 2.5 cm grating length gives a better performance overall. The anomaly at 3 cm, where the correlation between grating length and sensitivity breaks down, raises questions about potential upper limits to grating length optimization. While the general trend suggested that longer grating lengths increase sensitivity, the 3 cm FBG showed lower sensitivity compared to the 2.5 cm FBG.

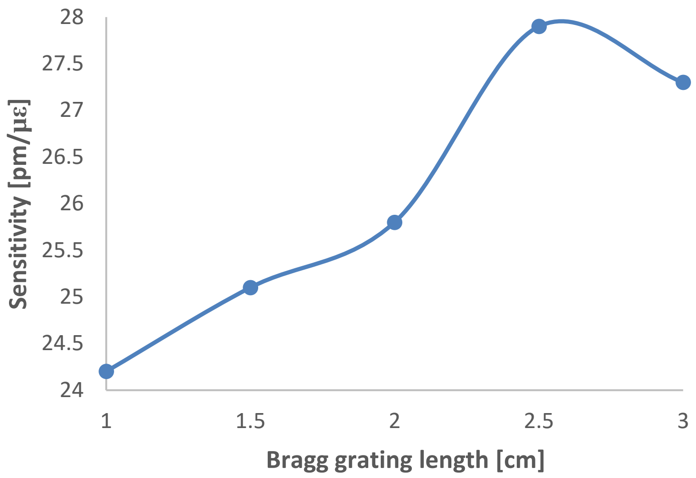

Fig. 6. Sensitivity *vs.* Bragg grating length

Based on our experimental results for strain sensors, this hypothesis was proven incorrect. The strain sensitivity for all FBG grating lengths were found to be consistent, with values of approximately 24-27 pm/με for strain sensitivity, due to the use of the same type of fibre, which was a single-mode fibre. For future investigations, we recommend exploring FBG-based multimode fibres. These fibres are expected to exhibit higher sensitivity compared to single-mode fibres, due to their larger core diameter and the advanced technology involved in doped glass.

4. Conclusions

The strain sensitivities for all FBG grating lengths were found to be consistent, with values of approximately 24-27 pm/με for strain sensitivity, due to the use of the same type of fibre, which was a single-mode fibre. For future research, we suggest investigating FBG-based multimode fibres, which are anticipated to offer greater sensitivity compared to single-mode fibres. This is due to their larger core diameter and the advanced doped glass technology.

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