Performance of Etched Silica FBG for Simultaneous Strain Temperature Measurement

Koustav Dey 1 · B. Ramesh 2 · Sourabh Roy 1

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Abstract
In this paper, we have proposed an etched silica Fiber Bragg Gratings (FBGs) based interrogation technique using an optical spectrum analyser (OSA). The efficiency of the proposed system has extensively been investigated for measuring the temperature and strain simultaneously with higher sensitivity and accuracy covering a larger measurement range. A Single mode-Multi mode-Single mode fiber (SMS) which acts as a bandpass filter is employed in the circuitry for an efficient and fast interrogation technique. We recorded a remarkable enhancement in sensitivity of 20.30 pm/°C and 2.89 pm/με over the temperature and strain range of 25–225 °C and 50–2050 με, respectively. These data were recorded with the strain resolution of ±10 με whereas the resolution for the temperature is ±0.50 °C. The experimental results show the capability of the sensor for measuring the strain and temperature simultaneously with higher intrinsic sensitivity and resolution. The performance of the proposed sensor has been compared with various reported techniques.

Keywords Fiber Bragg gratings (FBGs) · Silica Fiber · Chemical etching · Interrogation technique · Strain measurement · Temperature measurement

1 Introduction
Fiber Optic Sensors (FOSs) have been come up as a promising sensing element owing to their unique features over other conventional sensors for various applications in the last few decades [1–4]. Measuring different parameters simultaneously mostly strain and temperature in many practical applications became a research hotspot for more than a decade. However, crosstalk is the main issue in the case of measuring several parameters simultaneously, which is undesirable in common sensing applications. So far, numerous configurations are available and they are investigated to address the issue of cross-sensitivity in the case of simultaneous measurement of strain and temperature. Several intrinsic optical devices such as Polarization maintaining (PM) fiber [5, 6], Fabry-Perot (FP) [7–10], Long Period Gratings (LPGs) [11, 12] are incorporated with FBG based sensing techniques to offer possible solutions for cross-sensitivity effect. Employing PM fiber will be expensive for a common fiber sensing system. Additionally, inscribing an FBG in a PM fiber is a robust and efficient method for strain-temperature measurement simultaneously. FP based techniques could be employed for high-temperature measurement along with high-resolution detection. But the main drawback is in the fabrication which needs complicated and expensive process including the laser-micromachinery technique. Furthermore, laser-irradiated fiber is much more delicate, attributed to fiber profile deformation. Recently, Dan Su et al. [13] proposed compact dual FBGs inscribed over SMF, Thin Core Fiber (TCF) and the interface of them with splicing technology by high peak power femtosecond laser to measure strain and temperature simultaneously. This scheme has its limitations due to being expensive and complicated fabrication technique. Also achieving special resonance at the splicing point is not so easy task. An FBG sensor embedded with a Multi-Mode Fiber (MMF) has been reported for measuring the temperature and strain with higher accuracy [14, 15]. But the main bottleneck of this technique is to have the equivalent sensitivity of both the components, which is quite difficult to achieve. Silicon Carbide (SiC) has emerged as an excellent semiconductor for Micro Electro Mechanical Systems (MEMS) sensing applications owing to its excellent chemical inertness, superior...
mechanical properties, and outstanding radiation tolerance in the harsh environment [16, 17]. Nevertheless, the SiC MEMS are limited due to its lower sensitivity, lower accuracy, less mechanical stability and miniaturization issue.

For certain applications, a miniaturized sensor with higher intrinsic sensitivity is required. Therefore, any technique that offers miniaturization and the capability of simultaneous measurement will be highly promising than previously reported techniques. Z. Kang et al. [18] demonstrated an up-taper based Mach-Zehnder interferometer technique for simultaneous measurement. Although this technique offers higher temperature sensitivity, it limits due to a special and precise fabrication technique and the small strain sensitivity (0.74 pm/με). Q. Liu et al. [10] integrated an FBG and FP for simultaneous measurement. This scheme has its limitations due to its high cost and complicated fabrication process. Although LPG based method [12] offers higher sensitivity than other photonic sensors, the main bottleneck in using LPG is cladding mode nature which makes it more vulnerable to the external perturbations such as bending and/or temperature change of the surrounding medium, which affects the performance of the sensor system.

Factively, an etched FBG can be employed for this purpose due to its simpler fabrication approach, lower loss, miniaturized size and absence of frail splicing point, which made it more attractive towards the aforesaid applications. Sridevi. S et al, [19] have proposed an etched FBG based sensor with enhanced sensitivity and higher measurement range.

In this paper, an improved sensor configuration with higher sensitivities and measurement range compare to the previously reported methods is proposed using an etched silica FBG. An edge filtering technique using an optimized SMS has also been included to avoid the cross-sensitivity issue. Using the proposed etched silica-based edge-filtering method and a transfer matrix method, the capability for simultaneous measurement of strain and temperature has been demonstrated. It shows a higher sensitivity for temperature and strain of 20.30 pm/°C and 2.89 pm/με, respectively. A comprehensive comparative table has been provided to emphasize the performance of our proposed method with respects to the other similar reported methods.

2 Experimental Setup and Working Principle

The configuration of the proposed sensor is given in Fig. 1.

As shown in Fig. 1, the proposed experimental set-up consists of a super-luminescent light-emitting diode (SLD, 1300–1800 nm) as the light source, a circulator, SMS integrated with an FBG, an optical spectrum analyser (OSA, Agilent 86142B) as a detector whose wavelength resolution is ~0.01 pm, an oven (0 to 250 °C) connected with a dimmer-stat and a one-dimensional micro-translational stage with the minimum adjustable displacement of 0.01 mm. A calibrator thermometer (CL3515R, OMEGA) was kept inside the oven for accurate measurement of the temperature.

At first, light from the SLD source will be coupled to the FBG and will get reflected. The reflected light from the FBG will be filtered by the SMS and reaches the detector through the circulator.

The sensor scheme demonstrated here is based on the principle of the interrogation technique between the FBG and the SMS. A fast and effective interrogation is usually referred to as an edge filtering technique. It works on frequency-to-amplitude conversion based on the convolution between both the FBG and the edge filter i.e., SMS spectra. For this, an unstrained FBG is placed along with one of the falling slope edges of the SMS. When the external perturbation i.e., temperature and strain will be applied onto the grating, the shift in the wavelength along with the change in output optical power of the FBG will follow the slope region of the SMS, which is a typical edge filter. Then strain and temperature change can be measured by utilizing the well-known characterization matrix as shown below. Here the coefficient is related to the measurement of the power and wavelength shift with external perturbations [20]:

\[
\begin{bmatrix}
\Delta T \\
\Delta \varepsilon
\end{bmatrix} = \frac{1}{D} \begin{bmatrix}
K_{\varepsilon P} & -K_{\varepsilon \lambda} \\
-K_{\lambda P} & K_{T \lambda}
\end{bmatrix} \begin{bmatrix}
\Delta \lambda \\
\Delta P
\end{bmatrix}
\]

(1)

Where the determinant is \( D = K_{TP}^*K_{\varepsilon \lambda}K_{\varepsilon P}K_{T \lambda} \); Where \( K_{TP}, K_{\varepsilon \lambda}, K_{\varepsilon P} \) and \( K_{T \lambda} \) are the matrix coefficients for power/temperature, wavelength/strain, power/strain and wavelength/temperature. Thus, by exploiting their different strain and temperature sensitivities and using this simple configuration, the strain and temperature can be simultaneously measured with high sensitivity.

3 Fabrication Details

3.1 Design of SMS Fiber Structure and its Role as an Edge Filter

The SMS fiber structure has been constructed by sandwiching an optimized section of the step-index MMF (50/125 μm) between two SMFs (8.2/125 μm). For this, at first, the fibers were cut using a high-quality fiber cleaver. After careful cleaning, the fiber sections were spliced using a fusion splicer (Fujikura-60s). A negligible change in the power was observed before and after sandwitching the fibers. This change may be due to the improper splicing, mismatching of the two connectors etc. which have not been considered in our analysis. All the fiber sections are in-line so that there is no offset between the fiber interfaces.
SMS fiber structure has been employed as an edge filter in our proposed sensing technique. A fast and effective interrogation is usually referred to as an edge filtering technique. It works on frequency-to-amplitude conversion based on the convolution between both the FBG and the edge filter i.e., SMS spectra and the same is presented here. When the light travels through the SMS, the output power changes linearly with the wavelength of the input light, which is a typical edge filter. Due to the Multi-Mode Interference (MMI) phenomena, the wavelength dependence transmission spectrum can be observed. By proper selection of the MMF length [21], the SMS structure can have a spectral response with falling and rising edges in the desired wavelength range. Thus, one of the steep edges has been implemented by convoluting with FBG in the edge filtering technique for achieving higher sensitivity in our experiment.

### 3.2 Preparation of Etched Silica FBG

The etching was performed on the silica-based FBG using hydrofluoric acid. The overall chemical reaction involved is normally understood as:

\[
\text{SiO}_2 + 6\text{HF} = 2\text{H}_2\text{O} + \text{SiF}_6^{2-} + 2\text{H}^+ 
\]

The etching rate solely depends on the concentration of the solution and the temperature.

To control the etching of the FBG inscribed in the SMF-28e + corning fiber (https://www.corning.com/optical-communications/in/en/home/products/fiber/optical-fiber-products/smf-28e-.html) in an effective way, firstly the etching rate evaluated using the SMF-28e + fiber. For this purpose, a dozen of samples was taken and immersed into a 40% HF solution. The samples were taken out every 5 min and the diameter of the etched section in various positions were measured by optical microscopy after careful cleaning and drying. It is found that the etching rate is 1.61 μm/min at 25 ± 1 °C (room temperature). The FBG of length 1 cm is dipped into 40% HF solution to reduce its cladding diameter to around 10 μm, which has been optimized to sustain an above-mentioned range of strain and just to get the effective and stable “Evanescent field wave (EFW)” to improve the sensing quality of the FBG probe.

An inverted optical microscope was used to confirm the effectiveness of the etching throughout the length of the grating. The obtained images are shown in Fig. 2. Figure 2(a) depicts the image for the un-etched FBG whereas the etched FBG with 10 μm diameter of the fiber is shown in Fig. 2 (b). By removing the cladding diameter adequately, the EFW gets strengthen which in turns increases the device sensitivity [22, 23].

### 4 Results and Discussions

In this section, the experimental validation for simultaneous measurement has been carried out.

To determine the temperature co-efficient, a temperature change was applied over the range of 25 °C to 225 °C with an interval of 5 °C (at zero strain) onto the etched grating. The change of the optical power was monitored using the OSA. Similarly, the peak wavelength shift of the FBG peak was monitored and noted down during the change of the temperature over the aforementioned range.

To evaluate the strain co-efficient, the applied strain was increased from 50 μɛ to 2050 μɛ with an interval of 110 μɛ at a constant temperature (~23 °C). The shift of the central wavelength of the FBG peak due to applied strain was also monitored. The results are shown in Fig. 3. A good linearity was observed for all the measurements. Fig. 3 (a) & (b) present the linear fittings of variation of the power loss at the time of applying the temperature and strain individually at zero strain and 23 °C of temperature respectively. Whereas, Fig. 3 (c) & (d) depicts the wavelength shift of the FBG upon the application of the temperature and strain over the range of 25–225 °C of temperature and 50–2050 μɛ of strain at zero strain and constant room temperature, respectively.

With increasing the temperature, a redshift can be observed in the spectrum due to the increase in the refractive index of the cladding and the core mode. In our proposed method, the measurement in temperature and strain is restricted to 225 °C.
and 2050 με respectively, due to the measurement limit of the instruments.

To find the temperature sensitivity, the wavelength shifts during rising as well as for lowering the temperature has taken into consideration. From the experimental result, it can be inferred that there is no evidence of hysteresis due to the high repeatability and overlapping of the data. The higher temperature sensitivity is mainly due to the EFW. As EFW strengthens, the sensitivity of the device increases. Furthermore, a decrease in Young’s modulus of the etched fiber was observed which increases its thermal expansion co-efficient and having a considerable influence on the thermal sensitivity of the sensor and the EFW which leads to the decrease of the thermo-optic coefficient of the fiber. In the case of strain measurement, when an axial force/stress is applied onto a grating, there will be a resulting shift in the central Bragg wavelength mainly due to a change in the grating period. This effect becomes enriched when the fiber diameter is reduced. As a result, a prominent shift in the Bragg wavelength can be observed as shown in Fig. 3 (d).

In order to find out the sensitivities, the aforementioned transfer matrix has been used and a linear fit was applied to each measured characteristic in Fig. 3.

$$\frac{\Delta T}{\Delta \varepsilon} = \frac{1 - 0.077}{1.68} dB/\mu\varepsilon \quad \frac{2.89 pm/\mu\varepsilon}{0.93 dB/^\circ C} \quad \frac{20.30 pm/^\circ C}{\Delta P}$$ (2)

The obtained higher value of the matrix co-efficient overcomes the problem of noise sensitiveness [24].
The achieved temperature sensitivity of the proposed sensor 20.30 pm/°C, is roughly double to the theoretical value (w.r.to the FBG with reflected Bragg wavelength value ~1550 nm) i.e., ~10 pm/°C, whereas, the strain sensitivity of the FBG is 2.89 pm/με, which is 2.45 times higher compared to the theoretical value i.e., ~1.2 pm/με.

Bragg gratings are made on silica fiber whose maximum strain limit is around 4.8GPa [25]. But due to the unavailability of the facilities in our lab, the maximum strain limit that the sensing probe can sustain has not reported.

To measure the temperature for a fixed strain value or vice versa, a random value of temperature and strain has to be applied to the sensor head. After that, a particular parameter has to be increased by fixing the other parameter. Finally, the corresponding wavelength shift and change in the power level of FBG has to be incorporated in eq. 2, from this, the change in temperature and strain could be evaluated simultaneously.

5 Performance Analysis and Metrics of the Designed Sensor

To analyse the performance of this proposed scheme for simultaneous measurement, the sensor head underwent strain variations up to 1806 με at 300 με step interval at a constant temperature (T = 90 °C). Similarly, the temperature was varied over the range 35 °C–185 °C at 30 °C intervals for a specific applied strain (ε = 606 με). Putting the values of the wavelength shift exhibited by the sensor head using eq. (2), temperature and strain changes are calculated. The results are shown in Fig. 4. The deviation with respects to the applied values have shown here.

The sensor’s outputs for a particular temperature and strain are shown in Fig. 4. Figure 4(a) depicts the strain changes over the range 0–1806 με at 90 °C while Fig. 4(b) shows the variation of the temperature over the range of 35–185 °C at 606 με.

From these plots, the maximum deviation for temperature and strain are ±0.7 °C and ±32 με respectively.

5.1 Performance Metrics of the Proposed Sensor

Performance metrics of the proposed sensor system such as a limit of detection (LoD) and resolution are obtained for the etched FBG based temperature and strain sensor.

5.1.1 Limit of Detection (LoD)

Here, we have used the method of determination of the limit of detection (LoD) from the instrumental resolution limit [26]. Hence in our formula, ‘σ’ is defined as the standard deviation (SD) of the response of the curve, which can be considered as the ‘resolution of the detector unit’ [27]. LoD indicates the lowest change in input that could be measured with a 3-sigma (3σ) marginal error. It is calculated as

\[
\text{LoD} = \frac{3 \times \text{Resolution of the Detector Unit}}{\text{Sensor's Sensitivity}} = \frac{3 \times 0.01 \text{ pm}}{20.30 \text{ pm/°C}} = 0.00148 \text{°C (for temperature)}
\]

\[
= \frac{3 \times 0.01 \text{ pm}}{2.89 \text{ pm/με}} = 0.0873 \text{ με (for strain)}
\]

5.1.2 Resolution

In order to assess the resolution of the proposed sensor for measuring the temperature and strain simultaneously, the following experiment was performed as shown in Fig. 5. For this, at first, the temperature and strain of 40 °C and 206 με, respectively were applied to the sensor head and the respective wavelength change due to the applied temperature and strain were measured. After that, the temperature was increased to
45 °C at a 206 με and the strain was changed to 406 με and the shift in the wavelength was measured in each case. Finally, incorporating the values into transfer matrix eq. (2), the wavelength shifts due to their respective temperature and strain were calculated arbitrarily. In this way, by randomly changing the input temperature and strain, simultaneous measurement of both the parameters along with the rms deviations of strain and temperature were evaluated. From these deviations, resolution of ±0.5 °C and ±10 με were determined for temperature and strain, respectively. This performance is globally acceptable and the achieved values are limited by the resolution of the OSA, control accuracies of the oven and the cantilever set-up.

5.1.3 Figure of Merit (FOM)

The figure of merit (FOM) is an important indicator to objectively evaluate the performances of sensors. FOM determines the performance of the sensor system in terms of detection accuracy. According to the theory of measurement, the FOM of a sensor is defined as:

\[
\text{FOM} = \frac{\text{Sensitivity of the sensor unit}}{\text{FWHM of the reflected spectrum from a sensor}}
\]

\[
= \frac{20.30 \text{ pm}}{0.20 \text{ nm}} = 0.1015 \text{°C}^{-1} \quad \text{(for temperature measurement)}; = \frac{2.89 \text{ pm/με}}{0.20 \text{ nm}} = 0.0144 \text{με}^{-1} \quad \text{(for strain measurement)};
\]

6 Repeatability and Reproducibility Analysis of the Proposed Sensor

To ensure the repeatability of the sensor, experiments are conducted periodically for the same inputs. Three sets of data (Set I, Set II and Set III) are obtained and the corresponding scatters plot is depicted in Fig. 6 by taking the temperature (Fig. 6(a)) and strain (Fig. 6(b)) along the x-axis versus wavelength shift along the y-axis. From Fig. 6(a), it is inferred that, the maximum deviation in measuring temperature sensitivity of 0.11 nm between Set I (1535.52 nm) and Set III (1535.63 nm) at 110 °C. For strain sensitivity, the maximum deviation 0.18 nm between Set I (1537.54 nm) and Set III (1537.72 nm) at 1538 με. Set II data almost coincides with that of sets I and III. The average deviation among the three sets for temperature sensitivity is 0.06 nm and for strain, sensitivity is 0.10 nm over the range of 25–225 °C and 50–2050 με, respectively.

Similarly, to assess the reproducibility of the proposed sensor, FBGs with different central wavelength (in the same slope region of the SMS) were employed in the circuitry. Furthermore, the experiment was performed at a different time
throughout a month. No significant changes in the achieved data were observed. Hence, our proposed sensor is highly reproducible.

We have repeated the experiments a few times with the same sensing probe i.e., FBG. No significant degradation in the performance of the proposed sensor was observed during the repetition. Hence, our sensing probe is reusable.

To emphasize the performance of our proposed sensor, a comprehensive comparison with different schemes has been made for measuring the temperature and strain simultaneously with respects to the different sensing parameters (Table 1). It’s worth noting that the efficiency in terms of the sensing parameters of the designed sensor head is better than other similar techniques reported so far.

### 7 Conclusions

In conclusion, an experimental study of an etched silica FBG sensor for measuring strain and temperature simultaneously has been proposed. An effective interrogation technique between the FBG and SMS has been employed in the circuitry for this purpose. Using this proposed sensor structure, an enhanced intrinsic sensitivity with higher accuracy covering a larger measurement range was demonstrated thoroughly. The temperature and strain sensitivity was measured to be 20.30 pm/°C and 2.89 pm/µε, which is double the typical values. Also, the proposed sensor has the higher accuracy of ±10 µε and ±0.5 °C for measuring the strain and temperature, respectively. The experimental results provide a shred of strong evidence about the sensing performance of our proposed sensor with enhanced sensitivity compared to the other reported methods. The grating could be thinned further below the core diameter to achieve higher strain and temperature sensitivity. For this purpose, special packaging technologies such as providing the nano-layer could be employed on the etched part to sustain additional mechanical strength without decreasing the sensitivity of etched FBG. The proposed sensor has good characteristics in the applications for biochemical, biomedical due to its miniaturized size and high intrinsic sensitivity. The main drawback of the proposed sensor structure is directly related to the weakening of the sensor probe due to the smaller diameter of the fiber. This aspect can be easily addressed by adopting a proper packaging design. Further improvement of the sensor performance will be the research focus, so it can work over a wider measurement range and with enhanced higher sensitivity.

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### Availability of Data and Material

Not applicable.

### Authors’ Contributions

Koustav Dey has performed the experiments, collected the raw data, did the primary analysis and prepared the manuscript. B. Ramesh has finalized the contents of the manuscript. Sourabh Roy has analysed the results, drawn the conclusions and finalized the contents of the manuscript.

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### Declarations

Not applicable.

### Consent to Participate

Not applicable.

### Consent for Publication

Not applicable.

### Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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**Table 1** Comparing the different sensing parameters with other reported methods

| Temp. Sensitivity (pm/°C) | Temp. Range (°C) | Strain Sensitivity (pm/µε) | Strain Range (µε) | Resolution | Ref. |
|--------------------------|------------------|-----------------------------|------------------|------------|-----|
| 10.39                    | 0–80             | 0.89                        | 0–2000           | ±12 µε, ±0.4°C | [6] |
| 8.40                     | (−)70–20         | 1.40                        | 0–500            | –          | [7] |
| 11.00                    | 40–90            | 1.22                        | 0–1500           | 6 µε, ±0.5°C | [8] |
| 11.70                    | 40–300           | 1.20                        | 0–500            | –          | [9] |
| 47.00                    | 20–60            | 2.20                        | 0–900            | –          | [10]|
| 13.00                    | 100–800          | 3.25                        | 0–1000           | –          | [12]|
| 9.70                     | 10–60            | –                           | 0–1667           | ±4.30 µε, ±1°C | [14]|
| 12.60                    | 22–90            | 1.14                        | 0–800            | ±9.21 µε, ±0.26°C | [15]|
| 33.00                    | 0–50             | 0.74                        | 0–708            | ±10.07 µε, ±0.31°C | [18]|
| 20.00                    | (−)100–300       | 2.85                        | 0–1000           | –          | [19]|
| **20.30**                | **25–225**       | **2.89**                    | **50–2050**      | ±10 µε, ±0.5°C | This Work |
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