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A novel fibre Bragg grating sensor packaging design for ultra-high temperature sensing in harsh environments

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Abstract

The aim of this article is to introduce a novel packaging of conventional Corning SMF-28 single-mode fibre Bragg grating sensors for ultra-high temperature sensing. The package is in a cylindrical shape made of yttria-stabilized zirconia tubes. The fibre optic sensor is epoxied to one end inside the tube to be protected from high external temperatures and also harsh environments. Highly-oriented pyrolytic graphite tube with an exceptional anisotropic thermal conductivity with higher conductivity in transverse than radial direction is positioned around the fibre to protect it from high temperatures. Air cooling system is also provided from the other end to dissipate the transferred heat from inside the tube. The shift in the Bragg wavelength is influenced by the thermal expansion of the package and internal temperature variations, which translates into thermal expansion of the fibre. The modelling and experimental results revealed that the Bragg wavelength shift increases to 1.4 pm °C⁻¹ at higher temperatures with linear behaviour at temperatures above 600 °C. The finite element modelling and the experimental results are also in good proximity indicating the similar trend for the shift in the Bragg wavelength.

Keywords: fibre Bragg grating sensor, high temperature sensor, packaging

1. Introduction

Apart from telecommunication, fibre optics are widely used as reliable sensors in a range of sensing applications such as structural health monitoring [1–4], biosensing [5, 6], concentration and hydrogen sensing [7–10], pressure sensing [11, 12], vibration and acoustic sensing [13, 14], temperature monitoring [15, 16] and dual parameter sensing [17, 18]. Lightweight, immunity to electromagnetic interference, small size, and high sensitivity make fibre optic sensor superior to conventional electrical based sensors. Nevertheless, there are some limitations for sensing different parameters in certain applications. For instance, high temperature sensing in rigorous environments is of high interest. The body of the space shuttles, turbine blades used in jet engines or power plants, as well as high temperature vessels are some of the examples where accurate temperature monitoring is critical. Unpackaged optical fibres are currently used commercially for temperature sensing of up to about 300 °C [19].

So far, there have been many studies to increase the thermal resistivity of the fibre Bragg gratings (FBGs) for high temperatures. Long UV-laser writing process [20], fabrication of chemical composition gratings (CCGs) [22–28], and the development of sapphire-based fibres with femtosecond written gratings [29–31] are some of the recent studies to make optical fibres applicable for high temperature sensing. In spite of certain advantages, all approaches suffer from significant drawbacks such as low and inaccurate sensitivity, extreme complexity and high cost of fabrication. In most of these methods, a complex post-processing procedure is needed to modify the fibre and its effective refractive index to increase the resistivity of the FBGs. CCGs, for instance,

Figure 1. 3D CAD of the package design: (a) isometric view, (b) cross sectional view, and (c) HOPG rolled stacked layers.

decay detrimentally when exposed to high temperatures. They are also highly dependent on the temperature and the diffusion of the dopant [23]. On the other hand, femtosecond lasers are significantly expensive compared to conventional inscription methods of gratings. It is also noteworthy that the fused silica fibre starts decaying at temperatures above 1000 °C. Synthesis of sapphire-based optical fibres and the inscription of the gratings thereon are also complex and costly. Moreover, the reflectivity and sensitivity of sapphire-based sensors are mostly weak and unreliable. In addition, due to the inherent property of the regular FBGs, they cannot stand at temperature higher than 300 °C as their gratings degrade [19].

Hence, there is a need for the development of a simple high temperature optical-based sensor using conventional FBGs. The aim of this study is to introduce a new packaging design to protect and employ conventional FBGs when exposed to harsh environments at ultra-high temperatures of up to 1000 °C and above.

To achieve high temperature sensing in harsh environment, the package must have high corrosion resistance along with proper strain sensitivity for high temperature sensing and heat isolation properties. In this article, a novel packaging design will be disclosed in which a FBG is encapsulated inside a structure with anisotropic heat conductivity. The modelling and experimental results are presented and benefits of the proposed design are highlighted.

2. Package design and materials

The three-dimensional (3D) CAD model of the design is shown in figure 1(a). Very low heat conductivity, high corrosion resistance at high temperatures and accurate translation of the external temperature to a reflected peak shift are the main design objectives of the package. The package design should also be able to dissipate the transferred heat from the external environment properly. As discussed later, a particular allotrope of carbon with anisotropic thermal conductivity is used to facilitate the heat dissipation. A forced air convection cooling system is also designed to achieve this goal.

The main structure is based on the two hollow yttria-stabilized zirconia (YSZ) tubes as shown in figure 1(b). YSZ is well-known for its low thermal conductivity (1.2–1.8 W m⁻¹ K⁻¹) and it is most widely used as a thermal barrier coating on turbine blades. The doped yttria inhibits the detrimental phase transformation of zirconia and lowers the thermal conductivity of zirconia [32].

The fundamental concept of the package is based on the thermal expansion of YSZ which is ultimately translated to axial strain on the fibre. Corning SMF-28TM single-mode fibre optic sensor is epoxied (Ceramabond ARMC-835, Graphite Store) to the bottom end of the YSZ tube as shown in figure 1(b).

Although YSZ is known to have one of the lowest thermal conductivities among the conventional materials, heat transfer is a time dependent phenomenon. Hence, heat dissipation inside the tube is crucial to protect the fibre from high temperatures.

A cylindrical stopper is designed to hold the top end of the fibre optic sensor as a fixed constraint relative to the thermal expansion of the zirconia tubes. To effectively transfer the heat flux from the internal package, four air vent holes are designed to allow the flow of the forced air convection.

The optical fibre sensor is passed through the centre hole of the stopper and it is fixed using a polymeric epoxy (EPO-TEK 353ND). Invar is selected as the stopper material as it is an iron–nickel alloy with a very low thermal expansion coefficient (1.2 × 10⁻⁶ K⁻¹) [33]. It is designed to minimize the effect of the mechanical loading on the fibre due to the stopper’s thermal expansion.

In addition to YSZ, a highly-oriented pyrolytic graphite (HOPG) with excellent anisotropic properties, particularly in thermal conductivity, is designed to protect the fibre by minimizing the amount of radial heat transfer, see figure 1(b). Graphite is a lamellar material with stacks of identical planes (called graphene), where carbon atoms are bonded in a
honeycomb structure. Natural graphite is full of defects and inclusions leading to an imperfect structure. HOPG is a perfect graphite structure with negligible amount of imperfections and a high degree of c-axis alignment. As indicated in figure 1(c), the HOPG tube (provided by Optigraph GmbH) is made of rolled HOPG layers stacked concentrically. The in plane and c-axis thermal conductivity of the HOPG in the package is set to be 8 and 1000 W m$^{-1}$ K$^{-1}$ at room temperature, respectively. Nonetheless, the thermal conductivity decreases by raising the temperature due to lattice phonon scattering. Therefore, the in plane and c-axis thermal conductivity of the HOPG in the modelling [34–36]. The properties of the materials used in the package are given in table 1.

### 3. Finite element modelling

#### 3.1. Governing physics

Thermal-structural multiphysics theory was employed to study the physical and thermal response of the 3D model to external temperature variations. COMSOL 4.3a was used as the simulation platform for the FEA model.

The following partial differential equations are employed to incorporate heat conduction equation (1) under the convective boundary condition expressed by equation (2) into the model

\[ \rho C_p \frac{\partial T}{\partial t} - \nabla \cdot (k \Delta T) = Q \]  
\[ n_e(\nabla T) = q_0 - h(T - T_{\infty}) \text{ at surfaces} \]  
where $C_p$ (K kg$^{-1}$), $\rho$ (kg m$^{-3}$), and $k$ (W m$^{-1}$ K$^{-1}$) are the substrate specific heat capacity, density and thermal conductivity, respectively, $h$ the heat transfer coefficient and $n$ the normal vector to the boundaries.

In order to fulfil the mathematical computations, equation (3) is used to define the total strain $\varepsilon$:

\[ \varepsilon_{mn} = \varepsilon_{mn}^M + \varepsilon_{mn}^T \]  
\[ \sigma_{ij} = D_{ijmn} \varepsilon_{mn} \]  
where $\varepsilon_{mn}^M$ and $\varepsilon_{mn}^T$ represent the strains imposed due to mechanical and thermal stresses, respectively. Also, $\sigma_{ij}$ (Pa) is the elastic stress, and $D_{ijmn}$ (Pa) is the tensor of elastic coefficients when there is a linear relationship between stress and strain.

The mechanical and thermal strains are also defined as:

\[ \varepsilon_{11} = \varepsilon_x, \varepsilon_{22} = \varepsilon_y, \varepsilon_{33} = \varepsilon_z; \varepsilon_{12} = \varepsilon_{21} = \frac{\gamma_{xy}}{2}; \varepsilon_{13} = \varepsilon_{31} = \frac{\gamma_{xz}}{2}; \varepsilon_{23} = \varepsilon_{32} = \frac{\gamma_{yz}}{2} \]  
\[ \varepsilon_{mn}^T = \alpha (T - T_0) \delta_{mn} \]  
where $\gamma_{mn}$, $\alpha$, and $T_0$ are shear strain, coefficient of thermal expansion, and initial temperature, respectively. $\delta_{mn}$ is the Kronecker delta which is 1 for $m = n$ and 0 for $m \neq n$.

Consequently, the stress on the domain is represented by

\[ \sigma_{ij} = \left( \frac{E}{1 + \nu} \right) \left( (1 - \nu)(1 - 2\nu) \varepsilon_{ij} - \nu \varepsilon_{kk} \right) + (1 - \nu) \alpha \Delta T \delta_{ij} \]  
where $\nu$ is the Poisson’s ratio.

The strain derived from the above modelling paradigm must be translated to an optical spectrum where the wavelength peak shifts accordingly. To this end, an opto-mechanical model should be developed as explained below.

The Bragg wavelength ($\lambda_B$) which is reflected based on the Bragg condition (equation (8)) is directly proportional to the spacing (pitch length, $\Lambda_B$) between the periodic modulation of the refractive index inside the core of the fibre and the effective refractive index ($n_{eff}$) influencing the propagating light [17–19]

\[ \lambda_B = 2n_{eff}\Lambda_B \]  

In particular, the shift in the Bragg wavelength due to the change in imposed strain and temperature can be written as,

\[ \Delta \lambda_B = 2 \left( \frac{\partial n_{eff}}{\partial T} + n_{eff} \frac{\partial \Lambda_B}{\partial T} \right) \Delta T \]  
\[ + \frac{1}{2} \left( \frac{\partial n_{eff}}{\partial \varepsilon} + n_{eff} \frac{\partial \Lambda_B}{\partial \varepsilon} \right) \Delta \varepsilon \]  

The first term in equation (9) representing the effect of the strain on the grating spacing and relevant change in the refractive index can be rewritten as

\[ \Delta \lambda_B = \lambda_B (1 - p_\varepsilon) \varepsilon \]  
\[ p_\varepsilon = \frac{n_{eff}^2}{2} [p_{12} - v(p_{12} + p_{11})] \]  

where $p_{12}$ and $p_{11}$ are the components of the strain-optic tensor.

The second term in equation (9) indicates how the temperature affects the Bragg wavelength shift in the optical fibre. The temperature variations would change the refractive index as well as the grating spacing due to thermal expansion of the fibre. This term can be defined as

\[ \Delta \lambda_B = \lambda_B (\alpha_A + \alpha_{n_{eff}}) \Delta T \]  

where $\alpha_A$ and $\alpha_{n_{eff}}$ are the thermal expansion coefficient and thermo-optic coefficient of the fibre, respectively.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity (W m$^{-1}$ K$^{-1}$)</th>
<th>Density (kg m$^{-3}$)</th>
<th>Heat capacity (J kg$^{-1}$ K$^{-1}$)</th>
<th>Young’s modulus (GPa)</th>
<th>Coefficient of thermal expansion (K$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>YSZ</td>
<td>2</td>
<td>5920</td>
<td>500</td>
<td>210</td>
<td>$11 \times 10^{-6}$</td>
</tr>
<tr>
<td>Invar</td>
<td>10</td>
<td>8054</td>
<td>515</td>
<td>145</td>
<td>$7 \times 10^{-6}$</td>
</tr>
<tr>
<td>Fused silica (fibre)</td>
<td>1.38</td>
<td>2203</td>
<td>703</td>
<td>73</td>
<td>$0.55 \times 10^{-6}$</td>
</tr>
<tr>
<td>HOPG</td>
<td>In plane $\varepsilon$-axis</td>
<td>2200</td>
<td>In plane $\varepsilon$-axis</td>
<td>1000</td>
<td>$-1 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1000</td>
<td>$c$-axis</td>
<td></td>
<td>$25 \times 10^{-6}$</td>
</tr>
</tbody>
</table>
Figure 2. (a) One-eighth section of the design used for the modelling, (b) simplified conductive air block, (c) meshing schematic of the design, (d) detailed mesh view. Dimensions are in mm.

It has been shown that the following equation can also be employed to model the shift in the Bragg wavelength by strain and temperature variations:

\[
\frac{\Delta \lambda_B}{\lambda_B} = \beta \varepsilon + \gamma \Delta T
\]

(13)

where \(\beta\) and \(\gamma\) are opto-mechanical and opto-thermal coefficients, respectively. Experimentally, for silica-based fibres, \(\beta\) and \(\gamma\) are calculated to be \(0.78 \times 10^{-6}\) and \(6.68 \times 10^{-6}\), respectively [19, 20].

The change in the Bragg wavelength is correlated to the variations of strain, temperature or any other parameter that would result in strain changes in the fibre.

3.2. Geometrical domain and boundary conditions

The geometric arrangement of the four air holes on the top stopper allows for a one-eighth symmetry model to be analysed. Figure 2(a) shows the one-eighth slice of the package. At the two symmetry surfaces (where the 3D model is sliced), the boundary conditions of zero flux transfer and displacement in the out of plane direction are applied. External temperature of up to 1000 °C is applied to the bottom surface of the package where the interface to ultra-high temperature is expected to occur. A fixed constraint is applied at the top end of the package while the rest of the package is allowed to expand under thermal loading. As the fluid dynamics of the input air is not the main interest of this study, a simplified model based on the thermal conduction instead of convection is used to provide a modelling estimation for the air cooling of the internal package. The empty space occupied by the air in the package is modelled as a single solid body with a constant value of thermal conductivity. The value of the thermal conductivity is expected to be a function of the applied air flow and is to be determined experimentally.

Due to the complex shape and mixed internal boundaries in the one-eighth model, tetrahedral mesh element is selected as the mesh type. Different solid domains in the model are assigned different element density to maximize the modelling accuracy while optimizing the computational time. Since a high temperature gradient, which translates into a large displacement due to thermal expansion, is expected at the bottom of the package, high mesh density is selected for the bottom zirconia tube as shown in figure 2(b). Similarly high mesh density is applied to the fibre as we are interested in the strain gradient imposed on the fibre. The simulation result of the internal temperature and fibre strain is determined to converge to within <1% at 241 255 or more mesh elements which is deemed acceptable for the simulation. All subsequent simulation results presented in this paper has at least 242 000 mesh elements to meet minimum modelling accuracy.

4. Experimental procedure

A heat dissipation scheme based on forced air convection is designed to alleviate the temperature, inside the package structure, below 300 °C. The holes designed on the stopper are expected to guide the forced air in and out of the YSZ tubes. Two different air flow rates of 1.5, and 2.0 scfm (standard
Figure 3. System diagram and cross sectional view of the furnace setup.

Figure 4. The experimental setup: (a) inside the tube furnace, (b) the package inside the alumina plate which is exposed to high temperatures inside the furnace, (c) the other end of the package outside the furnace where fibre optic and the thermocouple exit the package, and (d) the air pipe on top of the alumina plate to guide forced air convection into the package.

cubic feet per minute) were used to investigate the effect of flow rate on internal temperature variations. Figure 3 shows the system setup used for the experiments. A thermocouple type T was inserted into the package via one of the air holes of the stopper to measure the package’s internal temperature during the experiment as indicated in figures 3 and 4(c).

The experiments were carried out using MTI tube furnace (GSL 1500X) as shown in figure 4. The alumina plate is placed on top of the furnace as an insulation layer. A small hole, with diameter equal to the outer diameter of the sensor package, is punctured through the alumina plate. The sensor package is then placed through the hole in the alumina plate. The bottom surface of the package is made aligned with the bottom surface of the alumina plate, so only the end surface of the tube is directly exposed to high temperature (figure 3).

Figures 4(c)–(d) also shows how the fibre optic sensor is pulled out of the tube and connected to the interrogator. The air pipe (as a part of the cooling system) is also placed on the alumina plate and the package to render air convection for the system (figure 4(d)).

The heating regime of the furnace is illustrated in figure 5. The heating rate was 8 °C min⁻¹ with 15 min holding time at 300, 600, and 1000 °C, respectively. Sm-125 interrogator (Micron Optics, USA) was also used to measure the reflective wavelength spectrum. A custom designed MATLAB script is used to analyse the shift of the Bragg wavelength.
5. Results and discussion

5.1. Modelling results

To avoid complex computations of fluid dynamics and air turbulence, an equivalent conductive solid block was used to model the air surrounding the fibre optic inside the tube (figure 2(a)). As discussed earlier (figure 4(c)), a thermocouple is used to monitor the package’s internal temperature for validation of modelling. The thermocouple is inserted into the tube through one of the air vent holes of the stopper. Since the blocking of one air hole is expected to reduce the overall convective heat flux out of the package, the thermal conductivity of the modelled solid block is determined empirically by matching experimental measurements.

Discrete temperatures set points of 300, 600 and 1000 °C were used as external temperature in the steady state FEA analysis. Figure 6 shows the experimental and simulation results of internal temperature variations at two different flow rates. The experimental measurement reveals the correlation of internal temperature to external temperature to be nonlinear while that of simulation results follows a linear pattern. As stated above, in the modelling, a conductive solid block with a constant thermal conductivity was used to simplify the simulation of the complex fluid dynamics inside the package. Therefore, a linear response of internal temperature to external temperature is shown in figure 6. Meanwhile, the heat dissipation, in practice, is mainly conducted through the forced air convection. It is observed that there exists a nonlinear response of internal temperature with respect to external temperature. However, the discrepancy between the experimental and simulated results is less than 5 °C which is deemed to fall in an acceptable range for the proof of concept study.

For a flow rate of 2.0 scfm, a thermal conductivity value of 1400 W m⁻¹ K⁻¹ for the air block in finite element modelling yields the closest match with the experimental result. Similarly, for a flow rate of 1.5 scfm, the thermal conductivity is selected to be 950 W m⁻¹ K⁻¹. Additional experimental details of the internal temperature response at different flow rates will be discussed in section 5.2.
As defined earlier in equation (9), the shift in the Bragg wavelength is mainly dependent on two main environmental variables imposed on the fibre: temperature and structural strain.

The internal temperature is correlated to the flow rate of forced air convection entering the package. As seen from the experimental results in figure 6, the maximum internal temperature is increased from 63 to 77 °C when the flow rate is decreased from 2.0 to 1.5 scfm.

As the FBG sensor is fixed at both ends, the strain is correlated to both the thermal expansion of the YSZ tube, exposed to high temperature, and the thermal expansion of the fibre itself, exposed to the increased internal temperature. Both the expansion of the YSZ tube and the fibre is expected to be in the same direction as the package is fixed at the top end. Hence, the expansion of the fibre is expected to reduce the overall axial strain. Using the developed FEA model, the accumulated strain on the fibre at two different flow rates is shown in figure 7. The reduction of the flow rate raises the amount of strain on the fibre due to higher internal temperature and higher thermal expansion of the fibre.

The predicted Bragg wavelength shift by external temperature variations, according to equation (13), is shown in figure 8. The amount of peak shift at the flow rate of 1.5 scfm is slightly higher than that of 2.0 scfm at high temperatures. The maximum difference in the Bragg wavelength shift happens at the external temperature of 1000 °C where it drops from 1.2 nm to 1.0 nm. In addition, it can be seen that the sensitivity of the fibre alters slightly at different flow rates. As discussed earlier, the change in the flow rate results in a varying internal temperature and consequently, a different peak shift and sensitivity. The difference between internal temperature variations at the flow rates of 1.5 and 2.0 scfm correlates with the Bragg wavelength shifts as seen in figure 8.

### 5.2. Experimental results

Figure 9 shows the internal temperature response to external temperature variations at flow rates of 1.5 and 2.0 scfm. The maximum temperature inside the tube reaches about 77 °C at the flow rate of 1.5 scfm compared to about 63 °C at the flow rate of 2.0 scfm. Therefore, it is expected to detect different peak shifts at alternating flow rates. According to figure 10,
Figure 10. The internal temperature (measured by the thermocouple inside the tube) response to the external temperature (measured by the furnace thermocouple).

The internal temperature correlates nonlinearly to external temperature. The measurements show a hysteresis when ramping up and down the external temperature. Maintaining the temperature at 1000 °C for 15 min causes the internal temperature to increase by about 2 °C and 1 °C at the flow rates of 1.5 and 2.0 scfm, respectively. Such a delay in dynamic response leads to the formation of hysteresis in the Bragg wavelength shift. It could be concluded that the dynamic response of the internal temperature will improve by increasing the flow rate due to the additional dissipation of heat.

Figure 11 depicts the Bragg wavelength shift in response to external temperature. The trend is very similar to internal temperature. The total peak shift is 0.91 nm at 2.0 scfm and 1.14 nm at 1.5 scfm from 25 °C to 1000 °C.

While ramping up (figure 11(a)), two small retreats of the Bragg wavelength are seen at 300 and 600 °C due to the slight decrease in the internal temperature during the holding times which is about 0.5 °C. However, a smooth return of the Bragg wavelength at both flow rates is observed while ramping down the external temperature (figure 11(b)). Also, the response of the Bragg wavelength shows a hysteresis at both flow rates (figure 11(c)) because of the delayed dynamic response of the internal temperature during the holding times, particularly at 1000 °C. All the results illustrated in figures 9 and 11 show a linear correlation between the Bragg wavelength and the internal temperature exists.

The response of the Bragg wavelength to internal temperature is plotted in figure 12. As seen, the Bragg wavelength response is in agreement with the internal temperature variations. The trend is linear and the hysteresis, as discussed, is due to the slight internal cooling which occurs at the holding times. The sensitivity of the package to internal temperature variations at the flow rate 1.5 and...
Figure 12. The shift in the Bragg wavelength by internal temperature. Despite a hysteresis, the Bragg wavelength is directly proportional to internal temperature.

Figure 13. Sensitivity of the fibre to external temperature variations with flow rate of 2 scfm. Sensitivity improves at higher temperatures.

2 scfm is 21.5 and 22.9 pm °C⁻¹, respectively. This value of sensitivity is comparable to the reported values of FBG sensors to temperature which is around 10–12 pm °C⁻¹ [19, 38–40].

The sensor package sensitivity to environmental (external) temperature is displayed in figure 13. The sensitivity of the sensor is shown in three different regions based on the heating protocol employed in the experiments (see figures 5 and 9). As indicated, the sensitivity is ~0.3 pm °C⁻¹ until 300 °C while it increases to 0.8 and 1.4 pm °C⁻¹ by elevating the temperature to 600 and 1000 °C, respectively. It is seen that the sensitivity of the sensor increases considerably at higher temperatures; however, it stays linear from ~600 to 1000 °C.

The reflected spectrum at room temperature, 300, 600 and 1000 °C is exhibited in figure 14 indicating the increased rate of the Bragg wavelength shift at higher temperatures. As shown in figure 9(b), the rate of increase in the internal temperature is expedited at higher external temperatures. Hence, the rate of the shift in the Bragg wavelength could be attributed to the change of the internal temperature and also the additional elongation of the tube at higher temperatures.

Figure 15 compares the numerical model and the experimental results of the packaged FBG sensor. Both experimental results show excellent agreement with the result obtained using the numerical model. A constant offset in the wavelength shift of nearly 0.2 nm is seen between the numerical model and experimental measurements. The offset may be attributed to the slight uncertainties in selected material properties of the simulated model. Nevertheless, the numerical model and the experimental results show a very similar trend by external temperature variations.

It is also noteworthy that due to the Bragg wavelength shift of about 1 nm at 1000 °C, there is a high potential to employ parallel wavelength division multiplexing using current packaged sensor for multiple point sensing.

The authors also believe that the current package is capable of measuring temperatures even higher than 1300 °C, if an appropriate flow rate is selected to provide internal cooling.

For the future work, it is intended to expand the experiments and modelling to prepare the package for practical sensing applications in harsh environments such as jet engines. We also aim to employ a dual parameter (temperature and strain) fibre optic sensor [17] to compensate the effect of temperature on the Bragg wavelength shift. The dual parameter sensor is based on periodic coating of the gratings to obtain two single peaks representing strain and temperature changes, respectively. The sensor, developed in our research group [17, 18], can be employed in the current package to isolate...
the effect of flow rate from the package strain on the Bragg wavelength.

6. Conclusion

A fibre optic sensor packaging for ultra-high temperature sensing is introduced. In contrary to recently proposed solutions for high temperature measurement by optical sensors, the package design described herein employs a conventional single-mode FBG sensor in a simple packaging design. The package was made of YSZ with high corrosion resistance and high working temperature. HOPG tube was located inside the tube encircling the fibre to facilitate heat dissipation. In addition, two air flow rates of 1.5 and 2.0 scfm were employed to cool the internal package in the experiment. A finite element modelling was also performed to validate the experimental results. There is good agreement between the modelling and experimental results. A total of 0.9 nm of Bragg wavelength shift is obtained at 1000 °C with a flow rate of 2.0 scfm.

Acknowledgment

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Figure 14. The reflected spectrum of the sensor indicating the Bragg wavelength shift at the soaking temperatures 300, 600, and 1000 °C at the flow rate of 2.0 scfm.

Figure 15. Predicted and experimental Bragg wavelength shift by external temperature at flow rates (a) 1.5 scfm and (b) 2.0 scfm.
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