The spectral sensitivity of Long Period Gratings fabricated in elliptical core D-Shaped Optical Fibre

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ABSTRACT

Long period gratings (LPGs) were written into a D-shaped optical fibre, which has an elliptical core with a W-shaped refractive index profile. The LPG's attenuation bands were found to be sensitive to the polarisation of the interrogating light with a spectral separation of about 15nm between the two orthogonal polarisation states. In addition, two spectrally overlapping attenuation bands corresponding to orthogonal polarisation states were observed; modelling successfully reproduced this spectral feature. The spectral sensitivity of both orthogonal states was experimentally measured with respect to temperature, surrounding refractive index, and directional bending. These LPG devices produced blue and red wavelength shifts of the stop-bands due to bending in different directions. The measured spectral sensitivities to curvatures, $d\lambda/dR$, ranged from -3.56nm m to +6.51nm m. The results obtained with these LPGs suggest that this type of fibre may be useful as a shape/bend sensor. It was also demonstrated that the neighbouring bands could be used to discriminate between temperature and bending and that overlapping orthogonal polarisation attenuation bands can be used to minimise error associated with polarisation.

Keywords: Long-period fibre gratings, temperature measurement, curvature measurement, D-shaped optical fibre

1. INTRODUCTION

A fibre long period grating (LPG) is an axially periodic refractive index variation inscribed in an optical fibre, usually by ultra-violet irradiation. Coupling of light from the core to various cladding modes results in a set of attenuation bands in the transmitted light. The study of the LPG attenuation bands has yielded many potential applications in the field of sensing through their sensitivities to strain, temperature, refractive index and bending/shape [1-14]. The LPG sensitivity can manifest itself in two ways; firstly through the spectral shift in the attenuation band, which here we refer to as spectral sensitivity, and secondly through a change in the strength of the attenuation band.

Recently, LPGs have been inscribed into various types of optical fibres with different materials and various geometries with a view to optimising the sensitivity to specific measurands or reducing the cross-sensitivity to other measurands. Examples include the use of air-clad [8] or depressed-cladding [9] fibres to desensitise the structure to changes in the refractive index of the surrounding medium, and the use of three-layered W-fibres either to reduce sensitivity to temperature changes [10] or, alternatively, to maximise the temperature sensitivity [11]. A promising application of LPGs is in bend or shape sensing where several papers have been published [5,6,12]. A few papers have been presented concerning LPGs written in asymmetric optical fibres [7,12], which have shown red/blue wavelength shifts depending on the way the fibre is bent. There can be an additional problem of birefringence when fabricating an LPG sensor in asymmetric optical fibres, leading to polarisation dependence [15-20]. On the other hand, this polarisation dependence of the LPG can be utilised for creating polarisation filters [19,20].

In this paper we present the results of an investigation into the spectral characteristics, sensitivities to various measurands and polarisation dependence of LPGs written into a three layered fibre, which consists of an elliptical core surrounded by a depressed elliptical inner cladding and a D-shaped outer cladding. This study yields firstly a high sensitivity of the attenuation bands (red/blue wavelength shifts) to the orientation of the bend in the fibre; secondly the generation of a polarisation insensitive attenuation band and thirdly the observation that there are spectral sensitivity differences between the two polarisation states of the LPG for temperature and curvature and that, as a result, an LPG written in this fibre type can be used to discriminate between various measurands and reduce errors contributed by the polarisation dependence of the LPG.

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2. FABRCIATION

The D-shaped single mode fibre (supplied by KVH Inc.) has an inner core composed of GeO_2/SiO_2 with a major semi-axis of 5 μm and a minor semi-axis of 3 μm. The inner cladding is doped with fluorine but the dimensions are not given, though modelling described later suggests values of 12 and 8 microns for the semi-axes to obtain a reasonable fit with experimental data. For the modelling we had to assume the outer cladding was composed of pure SiO_2. The effective cladding radius was 62.5 μm and the distance between the core and the flat of the D was 18 μm. The D-fibre is not specifically designed to be photosensitive and so its photosensitivity was increased by hydrogenation at a pressure of 120 Bar for a period of 2 weeks at room temperature. The LPGs were fabricated using a frequency doubled argon ion laser at a wavelength of 244 nm with a point-by-point writing technique and then annealed for 24 hours at a temperature of 80^oC. The orientation of the D shape was determined and tags were attached to the fibre to ensure there was no twist in the fibre during fabrication. Several grating periods were used from 140 μm to 400 μm with a grating length of 5 cm. The characterisation of the attenuation bands was carried out by illuminating the LPGs using a broadband light source (non-polarised) and observing the transmission spectrum with an optical spectrum analyser (OSA; Hewlett Packard model 88142A) with an accuracy of 0.05 nm.

The use of a polariser and a polarisation controller working in conjunction with the broadband light source revealed a 15nm separation between the attenuation bands associated with the two orthogonal polarisation states, see figure 1 for an example. The fine structure (multiple peaks) of the attenuation bands shown in figure 1 is due to UV over-exposure

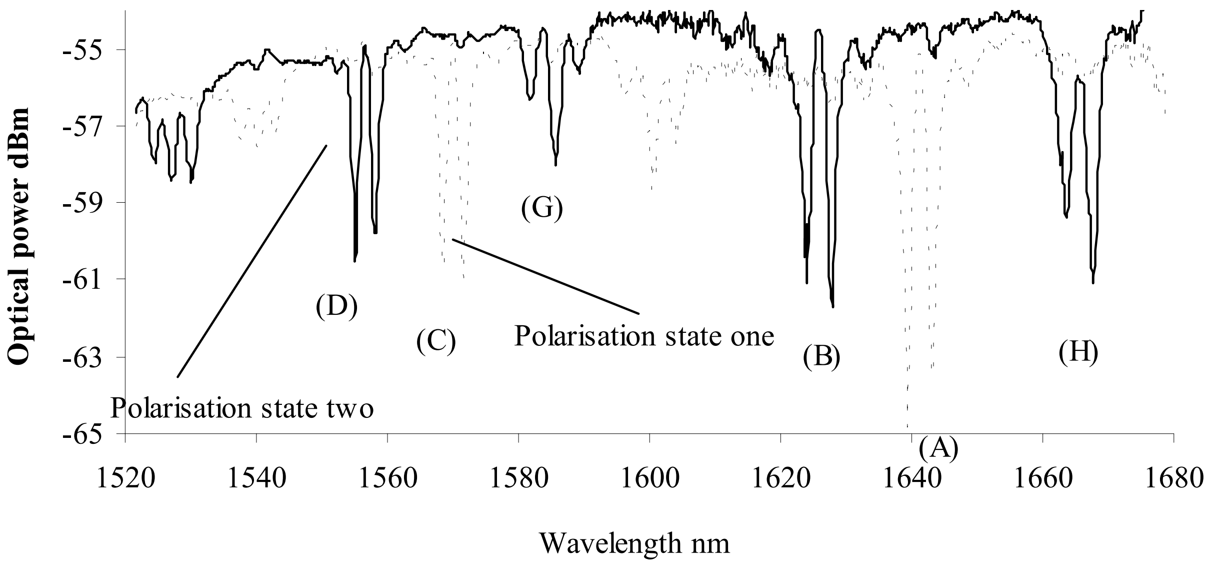

Figure 1. A section of the transmission spectrum of an LPG (length of 5cm, period 250μm) written into the D-shaped fibre showing the two orthogonal polarisation states of the attenuation bands.

The fabrication of an LPG with a period 300μm and a length of 5cm produced overlapping attenuation bands around 1637nm, see figure 2. A second LPG with the same length and period was fabricated under a different set of writing conditions. This second LPG generated orthogonal polarised overlapping attenuation bands at 1659nm, see figure 3. Due to the different writing conditions a difference between these two LPGs is expected. All the LPGs written in the D-shaped fibre produced an absorption feature around 1400nm and the strength of this feature indicates different UV exposures. The first LPG had an absorption feature strength of 12dB while for the second LPG the figure was 9dB.

The authors of [17] (and references contained therein) have demonstrated that in circularly symmetric fibre the UV-induced birefringence caused by the photoinscription anisotropy can have a non-negligible effect on the LPG phase-matching condition. This suggests that the wavelength satisfying the phase-matching condition for the overlapping attenuation bands corresponding to the two orthogonal polarisation states would be different for LPGs recorded with different exposures, as seen here.

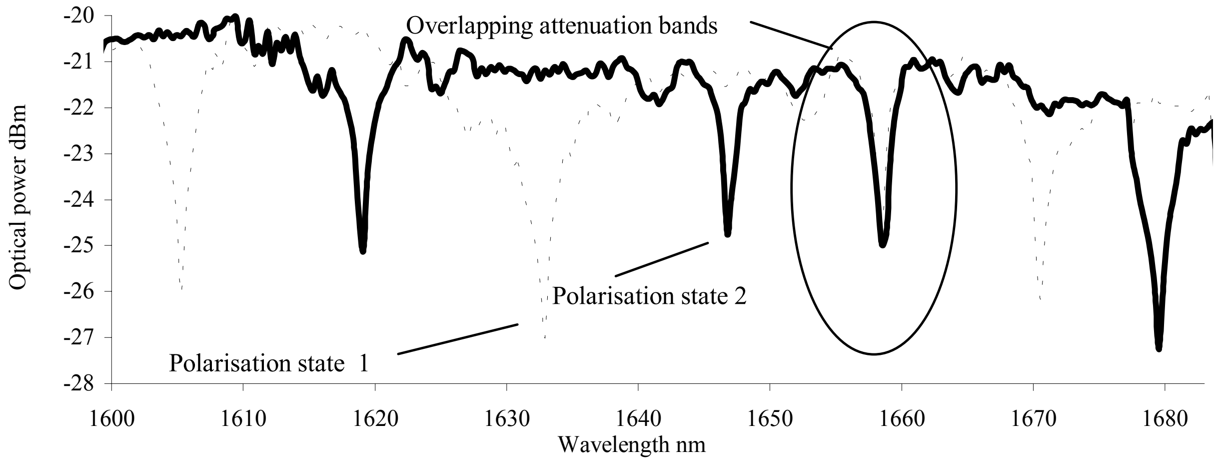

Figure 2. Part of the transmission spectrum of an LPG (period=300μm, length =5cm) written in the D-shaped fibre

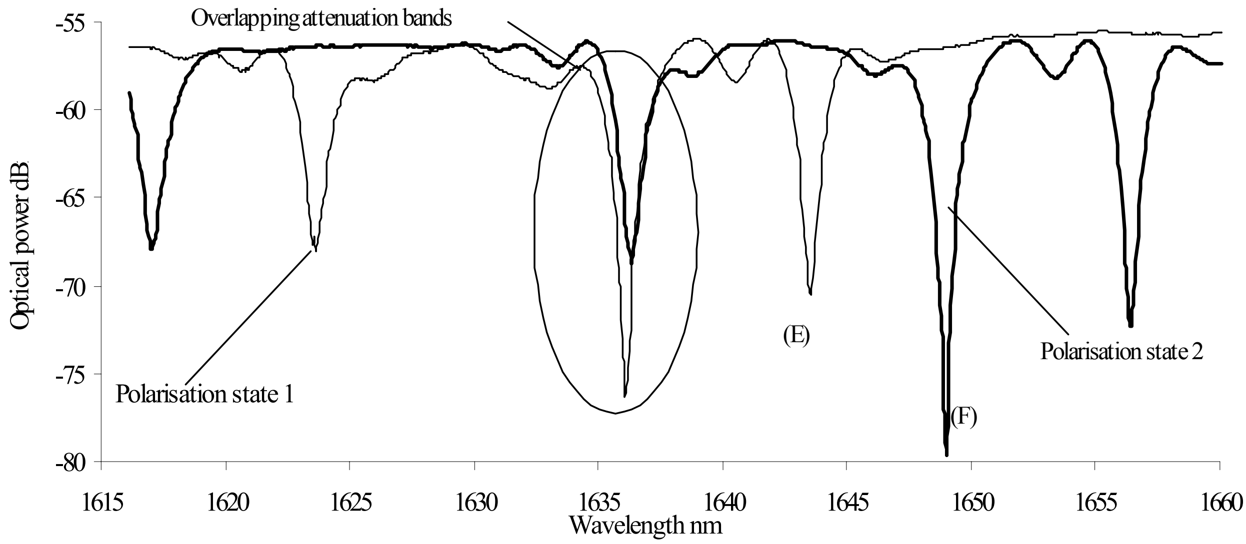

Figure 3. The transmission spectrum of an LPG (period=300μm, length =5cm) written in the D-shaped fibre

A finite element programme (Femlab) was used to obtain the effective refractive indices of the core and cladding modes at various wavelengths and hence determine the wavelength at which phase matching occurs for a given grating period, cladding mode and polarisation state. This information is depicted graphically in figures 4 and 5.

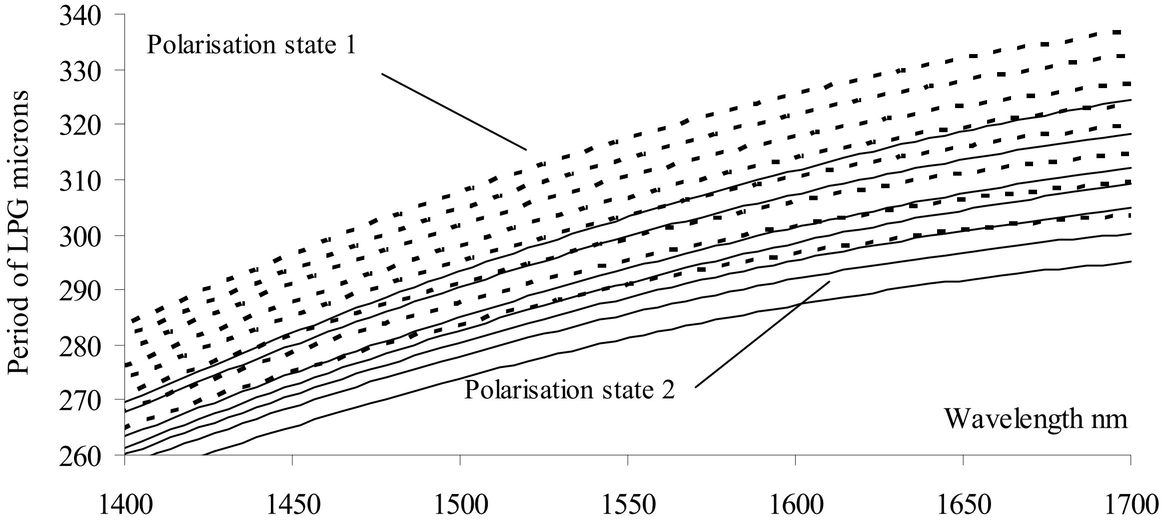

Figure 4. The modelled Long period grating Λ–λ curves for the D-shaped optical fibre showing the phase matching condition for both orthogonal polarisation states of the long period grating.

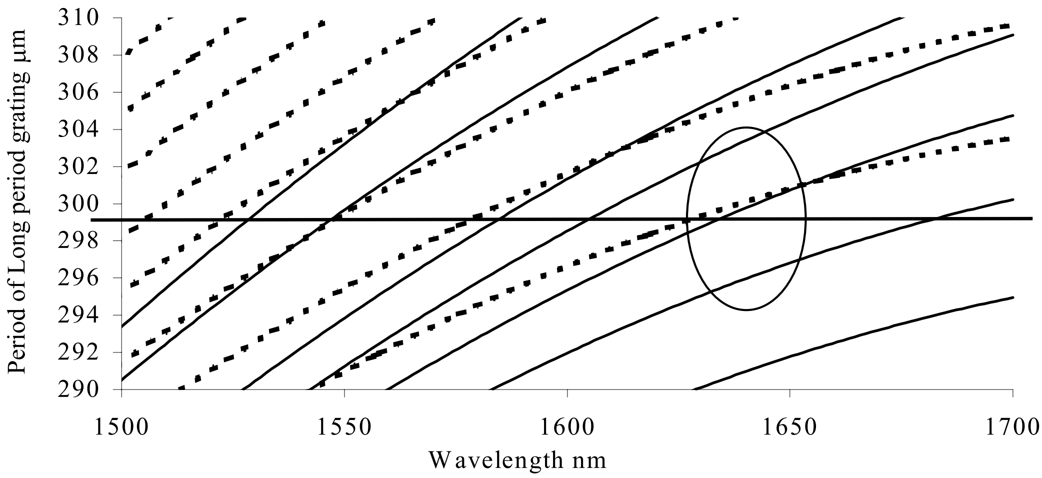

Figure 5. Detail of the Λ–λ curves of LPGs written in the D-shaped optical fibre showing spectrally overlapping orthogonal polarisation states at 1640nm for an LPG with a period of 300µm.

Figures 4 and 5 show the general phase-matching conditions for the attenuation bands; the Λ–λ curves are depicted for a group of cladding modes with the highest coupling coefficients. It can be seen that the overlapping of the curves for the two polarisation states makes for a complicated LPG transmission spectrum. Also the appearance of the transmission spectrum is further complicated due to the fact that the coupling coefficients of the resonances can be very different. This as already been reported in low birefringence D fibre [12], but the effect is increased here due to the presence of the depressed inner cladding. The transmission spectrum over an extended wavelength range of an LPG with a period of 300µm can be seen in figure 6. It must be stated that only the resonances with the highest coupling coefficients are shown in figures 4 and 5, but in reality those with lower coupling coefficients also contribute to the transmission spectrum, producing weaker attenuation bands.

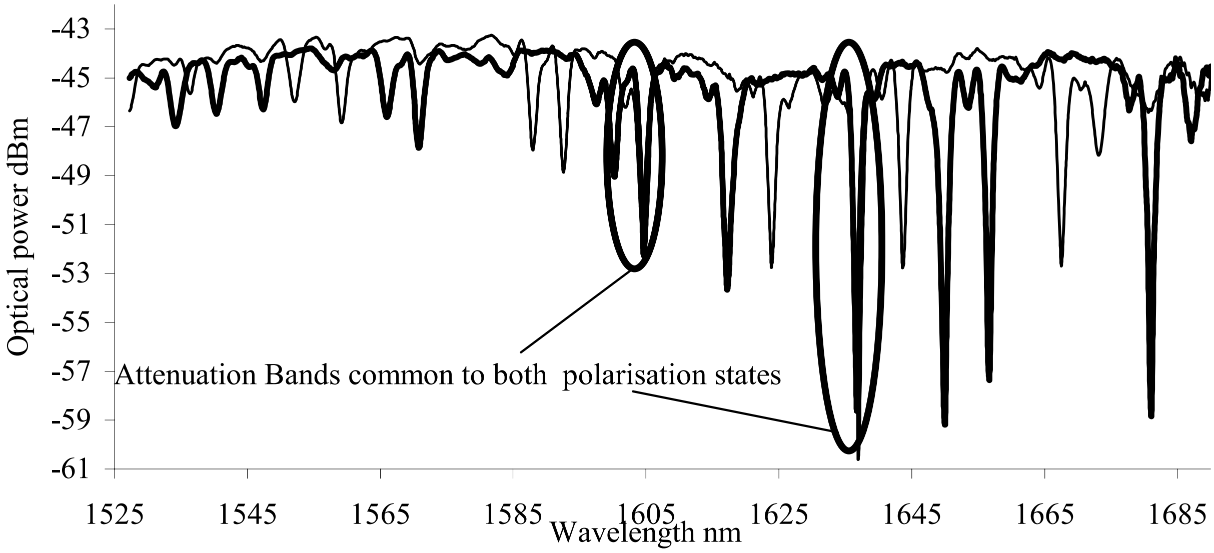

Figure 6. The transmission spectrum of an LPG (period=300μm, length =5cm) written in the D-shaped fibre.

2. SPECTRAL BENDING CHARACTERISTICS

The LPGs were clamped mid-way between two towers, one of which was mounted on a translation stage that was moved inwards to induced a bend in the optical fibre. The tags used during fabrication and markers on the fibre were used to ensure there was no unwanted twist in the fibre during the experiment. Additionally, rotation of the LPG sensor was performed on this rig by subjecting the sensor to a known curvature then rotating the sensor around its clamped axis with the flat side always pointing upwards, defining as a 0° reference the original orientation (fibre hanging downward, flat-side up), see figure 7. The broadband light source was connected to a polariser, which in turn was connected to a polarisation controller; the light from this arrangement illuminated the LPG and observations were made using an OSA.

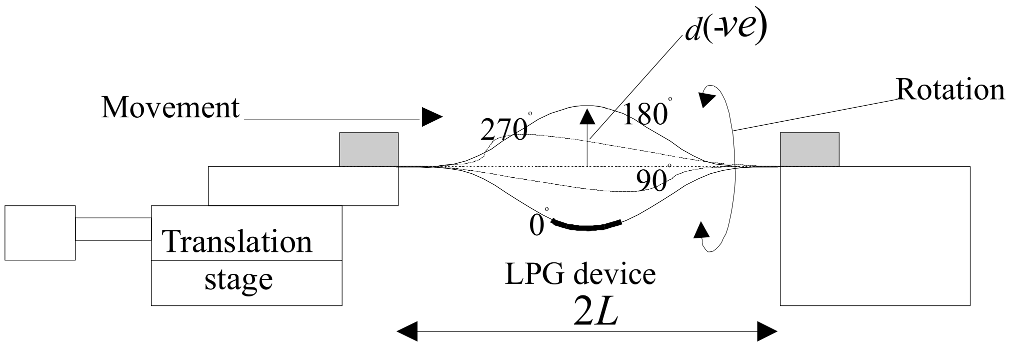

Figure 7. Schematic of the bending/rotational test rig.

The sensor's curvature, R, is given by [6]

$$R = \frac{2 \cdot d}{\left(d^2 + L^2\right)} \tag{1}$$

where L is the half distance between the edges of the two towers and d is the bending displacement at the centre of the LPG.

Several LPGs written in the D-shaped fibre were tested and some of experimental results are shown in figures 8 and 9. Both polarisation states of the LPGs were investigated for several attenuation bands, the labelling of the attenuation bands being as in figure 1.

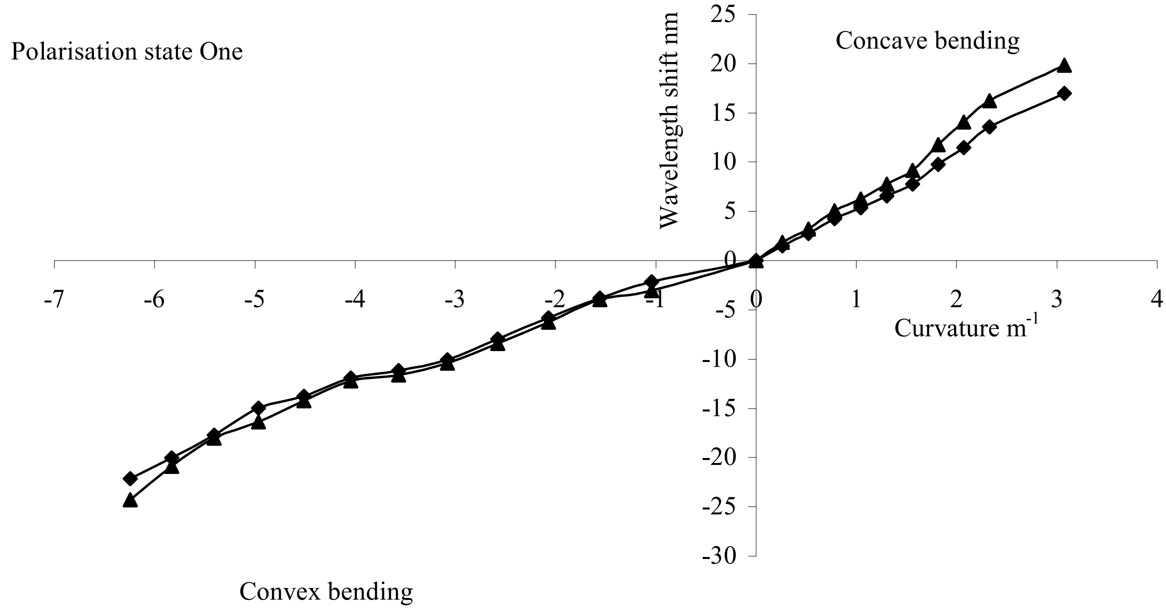

Figure 8. Examples of the spectral sensitivity of the attenuation bands associated with a LPG with period of 250µm and a length of 5cm in one polarisation state with central wavelengths at Band (A) 1643nm (▲) and Band (C) (◆) 1571nm

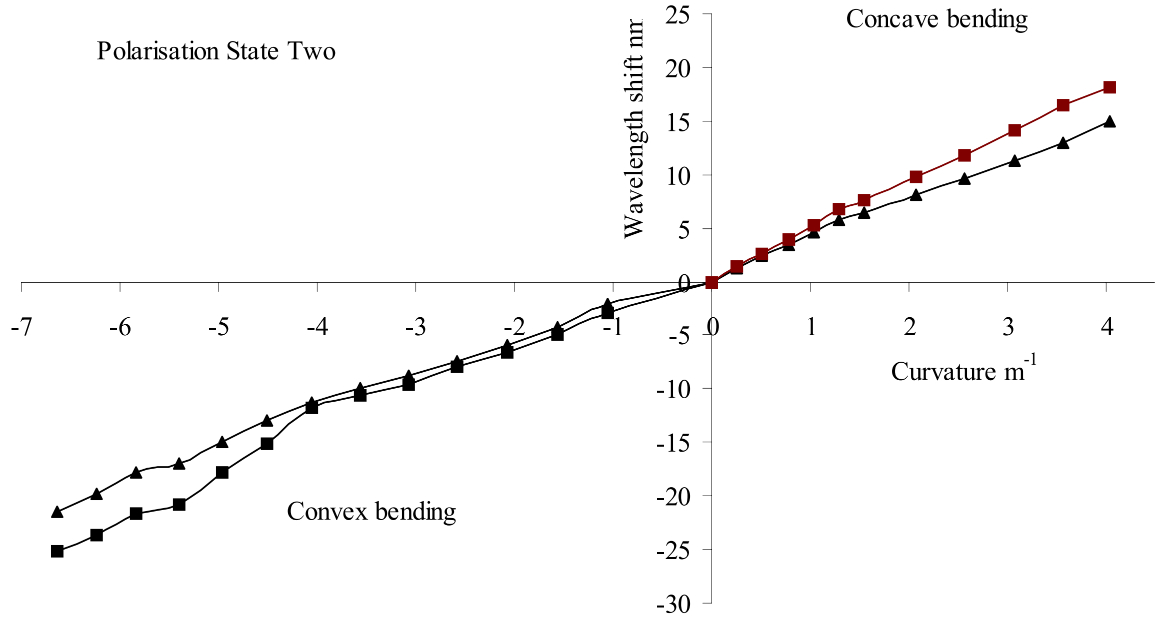

Figure 9. Examples of the spectral sensitivity of the attenuation bands associated with a LPG with period of 250µm and a length of 5cm in the other polarisation state with central wavelengths at Band (B) 1623nm (▲) and Band (D) (■) 1554nm.

Inspecting figures 8 and 9 it can be seen that both blue and red spectral shifts were observed with all monitored attenuation bands. It was found that the bending of the LPGs with a concave bend (flat of D facing up) produces the higher sensitivity for both orthogonal states. In polarisation state two the spectral sensitivities were 3.92nm m and 3.56 nm m for concave and convex bending respectively which gives approximately a 10% difference between the two. In polarisation state one the spectral sensitivities were 6.51nm m and 3.41nm m for concave and convex bending, respectively, which gives almost a factor of two difference between the two types of bend. The spectral sensitivity to concave bending is significantly different between the two orthogonal states. The difference in bending sensitivities can be explained by the fact that the polarisation states are orthogonal to each other and parallel and perpendicular to the fibre central axis. Also the fibre's asymmetry affects the cross-sectional strain/stress profile, which also contributes to the different sensitivities for the two polarisation states.

For the LPG with a period of 300μm, the overlapping orthogonal polarisation attenuation bands at 1636nm and the neighbouring attenuation bands were investigated as a function of curvature. Firstly, non-polarised light was used to illuminate the LPG, which was subjected to various curvatures. Over the range of curvatures used ($0.0m^{-1}$ to $2.1m^{-1}$), we did not observe any splitting of the overlapped band using an OSA resolution of 0.2nm, indicating that the bend sensitivity of the two polarisation states was broadly similar. This LPG operating with non-polarised light produced a spectral bending sensitivity of 2.2nm m ± 0.2nm m.

The overlapping orthogonal polarisation attenuation band was then investigated using polarised light along with the neighbouring single-polarisation state attenuation bands at 1643nm and 1649nm (stop-Band E and stop-Band F in figure 2, respectively). The overlapping attenuation bands were found to possess slightly different spectral sensitivities for the two polarisation states: 2.2nm m ± 0.1nm m and 2.0nm nm ± 0.1nm m. The neighbouring single-polarisation state attenuation bands had sensitivities of 0.9nm m ± 0.1nm m for Band (E) at 1643nm and 2.5nm m ± 0.1nm m for Band (F) at 1649nm, see figures 10 and 11. The spectral separation sensitivity between the common polarisation stop-band and stop-band (E) as a function of curvature is 1.3nm m ± 0.1nm m for polarisation state 1. The spectral separation sensitivity for polarisation state 2 (between the common polarisation stop-band and stop-band (F)) is 0.5nm m ± 0.1nm m. The spectral sensitivity of the stop-bands was determined over a curvature range from 0 to $4m^{-1}$.

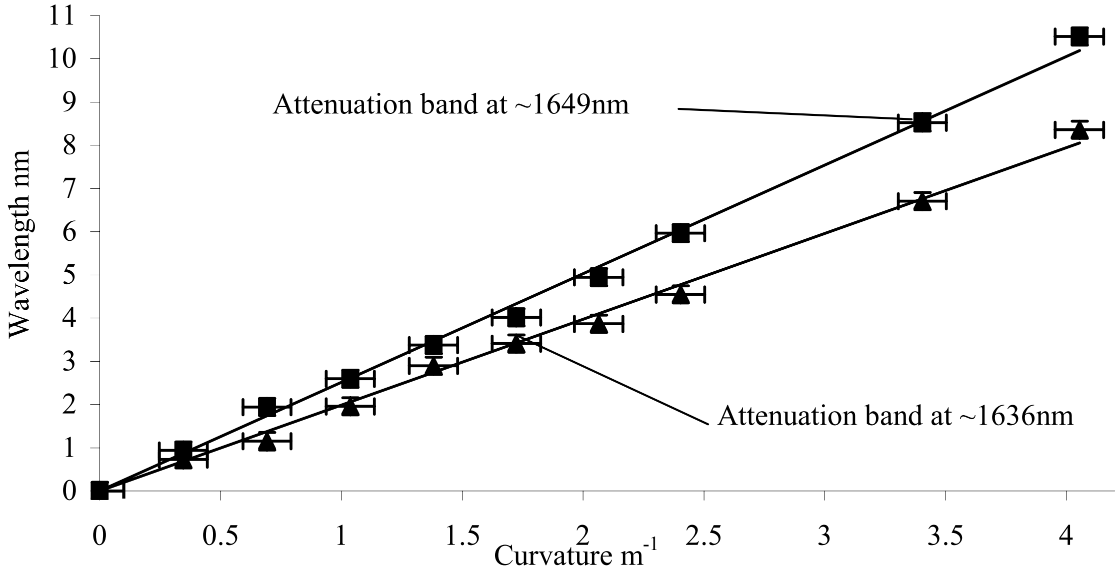

Figure 10. The spectral variation of the overlapped attenuation band and the neighbouring single polarisation attenuation band as a function of curvature for polarisation state 1.

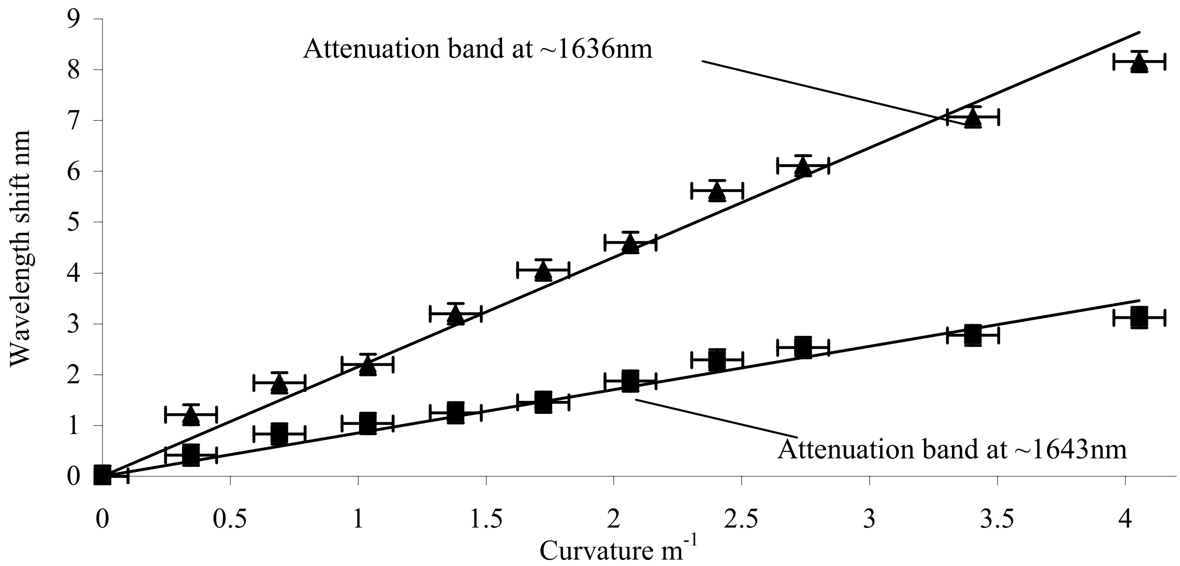

Figure 11. The spectral variation of the overlapped attenuation bands and the neighbouring single polarisation attenuation band as a function of curvature for polarisation state 2.

The effect of bending on the waveguide was modelled by the use of the conformal mapping technique [21,22], which replaces the curved optical fibre waveguide by an equivalent straight waveguide with the following index profile as a function of curvature R and longitudinal strain ε

$$n(R) \rightarrow \left(n(0,\lambda) + \frac{dn}{d\varepsilon} \cdot \varepsilon \right) \cdot \exp\left(\frac{d}{R} \right) \qquad (2)$$

Where $n(0)$ is the initial refractive index of the core/cladding at a wavelength of λ, R is the curvature experienced by the fibre and d is the distance from the centre of the fibre. After completing the above transforms, a finite element package (Femlab) was used to obtain the effective refractive indices of the core and the cladding modes at various curvatures (concave and convex bending) at a given wavelength.

The package was used to obtain the effective refractive indices of the core and cladding modes and their group indices at rotational angles of 0° (a concave bend) and 180°(a convex bend). The modelling of the fibre in both cases shows that the core mode varies as a function of polarisation state due to compression and strain of the cross the fibers' core which is dependent upon bending orientation. This strain variation is due to the asymmetric shape of the fiber, which explains the blue and red wavelength shifts observed. Also there is a small strain variation cross the fibers core for a given curvature that affect the sensitivity of the two polarisation states, which is observed experimentally and shown in figures 8 and 9.

3. SPECTRAL TEMPERATURE CHARACTERISTICS

The sensitivity to temperature was investigated by placing the sensor on the top of an insulated Peltier cooler, see figure 12. The temperature was varied and, after allowing time for thermal stabilisation, the spectral locations of the central wavelengths of the attenuation bands for each orthogonal polarisation state were monitored using an OSA, see figure 13.

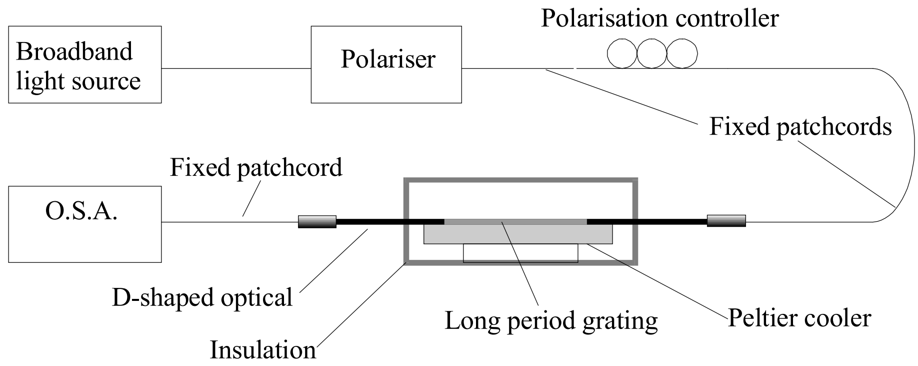

Figure 12. Experimental arrangement used to investigate temperature sensitivity.

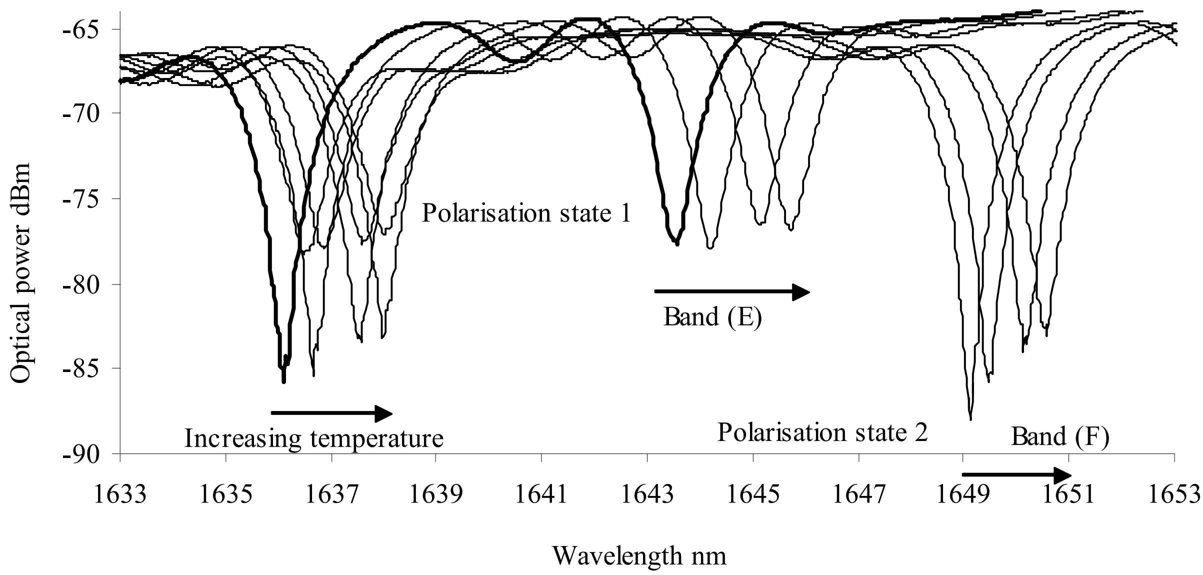

Figure 13. The temperature induced variation of the overlapping orthogonal polarisation attenuation band at 1636nm and the neighbouring attenuation bands of an LPG with a period of 300μm.

There is a reduction in the separation of the overlapping attenuation bands associated with the two orthogonal polarisation states as they possess different temperature spectral sensitivities: $3.7\times10^{-2} \pm1\times10^{-3}$ nmC^{-1} and $4.1\times10^{-2} \pm 1\times10^{-3}$ nm C^{-1}, see figure 14.

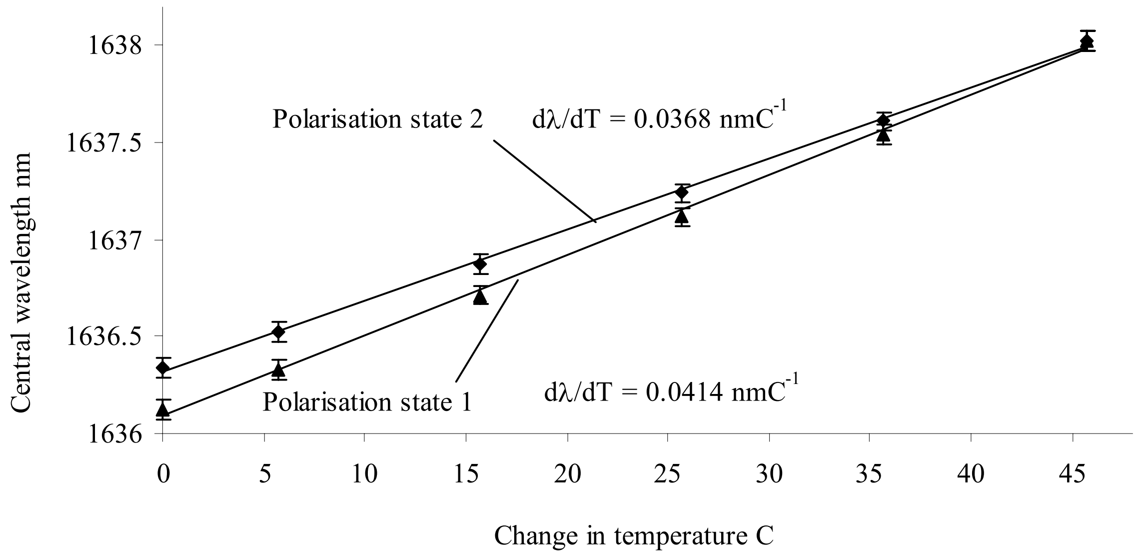

Figure 14. The spectral variation of the overlapping orthogonal polarisation attenuation bands (at wavelength ~1636.5nm) as a function of temperature.

The neighbouring single polarisation state attenuation bands were also investigated and it was found that the spectral separation between Band-(E) and Band-(F) decreased as a function of temperature, see figure 15.

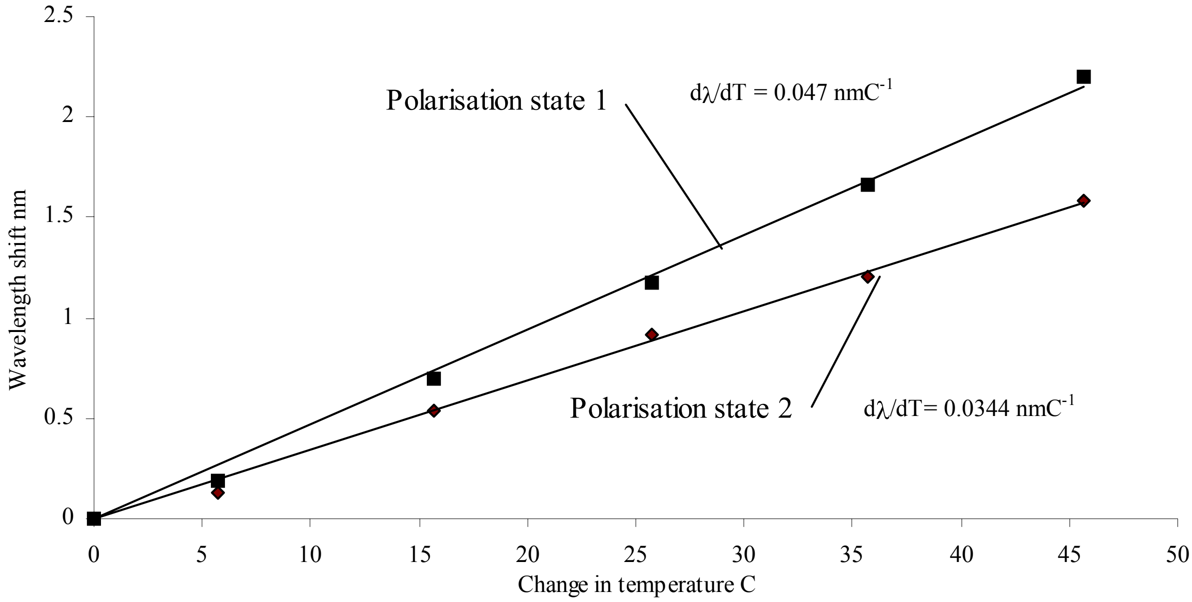

Figure 15. The spectral variation of the neighbouring orthogonal polarisation attenuation band as a function of temperature.

This LPG with a period 300μm and a length of 5 cm can be used to discriminate between temperature and bending effects using the overlapped orthogonal polarisation attenuation bands at 1636 nm and the neighbouring single polarisation bands. An example is shown below for non-polarised illuminating light and using the central wavelengths of the attenuation bands at 1636nm and Band-(E):

$$\begin{pmatrix} \Delta\lambda_{1^{st}} \\ \Delta\lambda_{2^{nd}} \end{pmatrix} = \begin{pmatrix} 2.2 \pm 0.1 & 0.04 \pm 1\times10^{-3} \\ 0.85 \pm 0.03 & 0.047 \pm 1\times10^{-3} \end{pmatrix} \cdot \begin{pmatrix} \Delta R \\ \Delta T \end{pmatrix} \quad (3)$$

This sensitivity matrix yields a condition number of 98, which is comparable to those from other approaches to discrimination [13, 14].

The intrinsic polarisation error in curvature and temperature is calculated by measuring the temperature and curvature sensitivities of the overlapping orthogonal polarisation attenuation band for both orthogonal polarisation states of the illuminating light. This leads to a maximum wavelength variation of the attenuation band due to polarisation of $\pm2.3\times10^{-3}$ nm^{o}C^{-1} for temperature and r R =±0.16 nm m for bending under the assumption that the true polarisation state is not known. Using these error figures in conjunction with a mean spectral sensitivity for curvature and temperature taken from the response under both orthogonal polarisation states, this procedure yields a maximum polarisation dependence curvature error of $\pm8\times10^{-2}$ m^{-1} and a temperature error of $\pm5\times10^{-2}$ ^{o}C. These errors associated with the polarisation dependence generate a maximum error in curvature of 4% and in temperature of 0.5% of the measurement range studied in each case. Using this LPG device as a discriminatory sensor and combining these errors with the second attenuation band (Band-(E)) yields an overall curvature error of ±0.14 m^{-1} and a temperature error of ±0.3 ^{o}C. Also the cross-talk between the parameters was calculated and was found to be negligible compared to the polarisation dependence and the intrinsic error in the spectral sensitivity measurements.

4.CONCLUSION

Long period gratings were written into a D-shaped optical fibre, which has an elliptical core with a W-shaped refractive index profile. The LPG's attenuation bands were found to be sensitive to the polarisation of the interrogating light with a spectral separation of around 15 nm between the two orthogonal polarisation states.

LPGs were fabricated with overlapping orthogonal polarisation state attenuation bands more than once. The use of such bands can considerably simplify the interrogation of the sensor. The modelling of the D-shaped fibre was done using a finite element method, which showed reasonable agreement with experimental data. The spectral sensitivity of both orthogonal polarisation states was measured with respect to temperature and directional bending. The temperature spectral sensitivity was low compared to standard Step-Index fibre.

The bending of the LPG devices produced attenuation bands that had blue wavelength shifts for convex bending with sensitivities up to –3.56nm m and red wavelength shifts for concave bending with sensitivities up to +6.51nm m. The use of neighbouring bands to the overlapping orthogonal polarisation state attenuation bands as a discriminatory device for temperature and bending was also demonstrated which yielded a maximum polarisation dependence curvature error of $\pm8\times10^{-2}$ m^{-1} and a temperature error of $\pm5\times10^{-2}$ ^{o}C. This lead to an overall curvature error of ±0.14m^{-1} over the range of 0m^{-1} to 4.5m^{-1} and an overall temperature error of ±0.3 ^{o}C from 20 ^{o}C to 90 ^{o}C. The spectral characteristics with respect to bending suggest that this type of fibre may be useful as a shape sensor and that polarisation dependence can be reduced by using the overlapping orthogonal polarisation state attenuation bands

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