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The Bending and Temperature characteristics of Long Period Gratings written in Elliptical Core Step-Index fibre

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ABSTRACT

We describe the characterisation of long period gratings written in elliptical core fibre, which yield a discriminatory sensor for curvature and temperature with a resolution ±0.05m^{-1} for curvature and ±0.9 ^{o}C for temperature.

INTRODUCTION

A fibre long period grating (LPG) is an axially periodic refractive index variation inscribed in the core of a photosensitive single-mode optical fibre by ultra-violet irradiation, which couples light from the core of the fibre into the fibre cladding modes at discrete wavelengths. The index modulation change within the core of a single mode optical fibre is approximately 10^{-4} and has a period typically between 100-600 μm. The index modulation produces a set of attenuation bands seen in the transmission spectrum of the optical fibre core. The study of the LPG attenuation bands has yielded many potential applications in the field of sensing through their sensitivities to strain (ε), temperature (T), the refractive index of the surrounding medium (n_s) and bending[1-4]. The LPG's sensitivity to these parameters can manifest itself in two ways. Firstly the central wavelength of the attenuation band can shift in the spectral domain, which will be referred to as spectral sensitivity and secondly a change in the spectral transmission profile of the attenuation band may occur. The spectral shift of the attenuation band arises from the phase matching condition of the LPG[1].

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. A few papers have been presented concerning LPGs written in asymmetric optical fibres[3] for bend sensing; this approach can lead to problems with polarisation dependence[5,6] due to birefringence in the fibre.

This paper presents a study of the spectral characteristics and polarisation dependence of LPGs written into an elliptical core step-index fibre (E-core fibre) to form bend sensors. The evolution of the LPG's attenuation bands under increasing curvature differs from normal step-index fibre. In normal step-index fibre a splitting of attenuation bands is observed due to induced birefringence at 2m^{-1} curvature or over. In the E-core fibre we observed splitting for both polarisation states of the LPGs attenuation bands for curvatures from 0.2m^{-1} to 2m^{-1}. We found that the wavelength separation between adjacent bend-induced attenuation bands and the normal attenuation bands is approximately linear as a function of curvature. Finally, a normal LPG attenuation band and a bend induced attenuation band are used to discriminate between temperature and bending effects, giving a well-conditioned sensitivity matrix that is comparable to other discrimination approaches[7,8].

FABRICATION AND CHARACTERISATION OF LONG PERIOD GRATINGS

This elliptical core step-index fibre 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 with a cladding radius of 62.5 μm, which is assumed to be pure SiO_2. The E-core 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. The LPGs were fabricated using a frequency doubled argon ion laser at a wavelength of 244 nm with a point-by-point writing technique. Several grating periods were used from 200 μm to 450 μm with a grating length of 4 cm. The characterisation of the attenuation bands was carried out by illuminating the LPG using a broadband light source and observing the transmission spectrum with an optical spectrum analyser (OSA) 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 roughly 20nm separation between the attenuation bands associated with the two orthogonal polarisation states.

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Two examples are shown in figure 1 and figure 2, the former corresponding to an LPG with a period of 200μm and the latter an LPG with a period of 400μm.

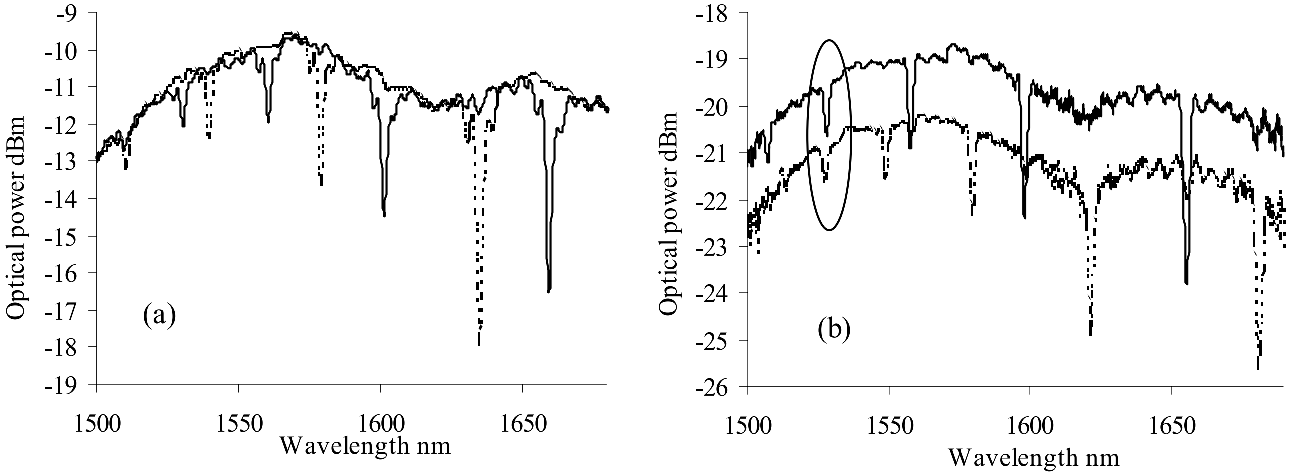

Figure 1 Examples of the transmission spectra of LPGs written in the elliptical core step-index fibre (a) period of 200μm and (b) period of 400μm, both having a length of 4cm (fast axis (——), slow axis (- - -)).

The two spectra shown in figure1 show attenuation bands that are in approximately the same spectral location, though the grating periods differ by a factor of two. Secondly, it was found that for the LPG with a period of 400μm had two spectrally overlapping attenuation bands corresponding to the two orthogonal polarisation states of the LPG, (circled in figure 2), this spectral property may be used to allow polarisation insensitive interrogation.

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. 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 3. 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. The polarisation controller was used to maximise the light in one polarisation state, so one state could be studied at a time.

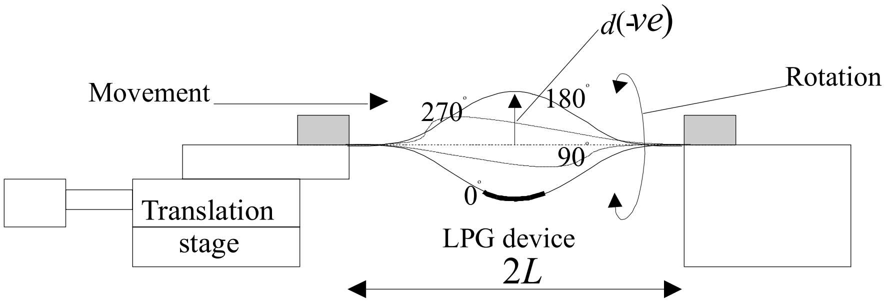

Figure 3. Schematic of the bending/rotational test rig.

The sensor's curvature, *R,* is given by REF4

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

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. The experimental results are shown for an LPG with a period of 250μm; the spectral behaviour of this LPG being typical of all the LPGs written in the E-core fibre. The curvatures imposed on the LPG in the 0° position (in figure 3) are shown, the other positions were also investigated but only small variations were found. Both polarisation states of the LPG were investigated and the results are shown in figures 4 (slow axis only) and 5.

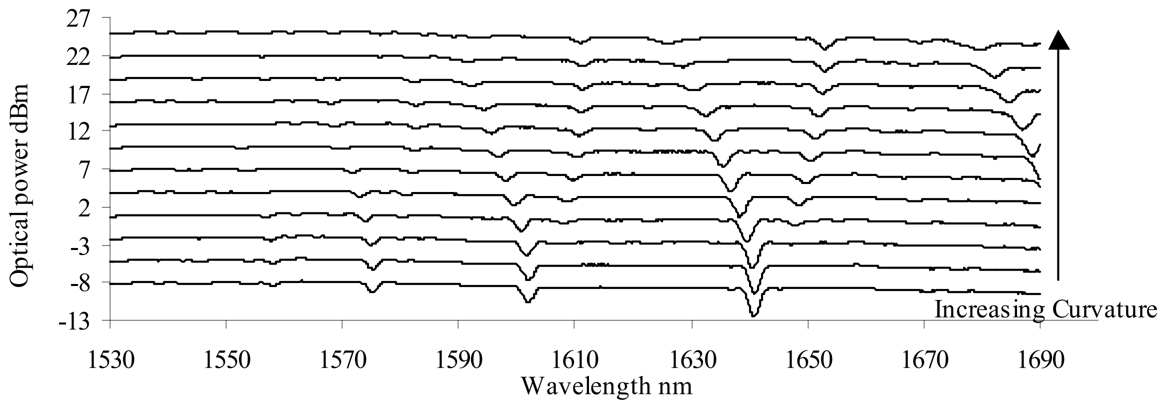

Figure 4. The transmission spectra of an LPG attenuation bands associated with slow axis (period 250μm, length 4cm) with increasing curvature from 0m^{-1} to 2m^{-1}

Inspecting figure 4, as the LPG is subjected to increasing curvature "the normal" attenuation bands experience a blue wavelength shift but there is also the generation of "bend-induced" attenuation bands which have a red wavelength shift. Comparing these results to standard step-index (SI) fibre, two differences were observed. Firstly for the SI fibre significant induced birefringence occurs at a curvature of about 2m^{-1}, beyond which splitting of the attenuation bands are observed; in the case of the LPGs written in the E-core fibre the bend-induced attenuation band started to be evident at a curvature of only about 0.1m^{-1}. This is likely due to the intrinsic birefringence of the E-core fibre, which doesn't exist in the SI fibre. Secondly, the evolution with respect to curvature differs from SI fibre, here the bend-induced attenuation band appears spectrally separated from the normal attenuation bands and not from the splitting of the normal attenuation bands. The spectral sensitivities of the LPG attenuation band at 1601nm (figure 4) in both polarisation states as a function of curvature are shown in figure 5.

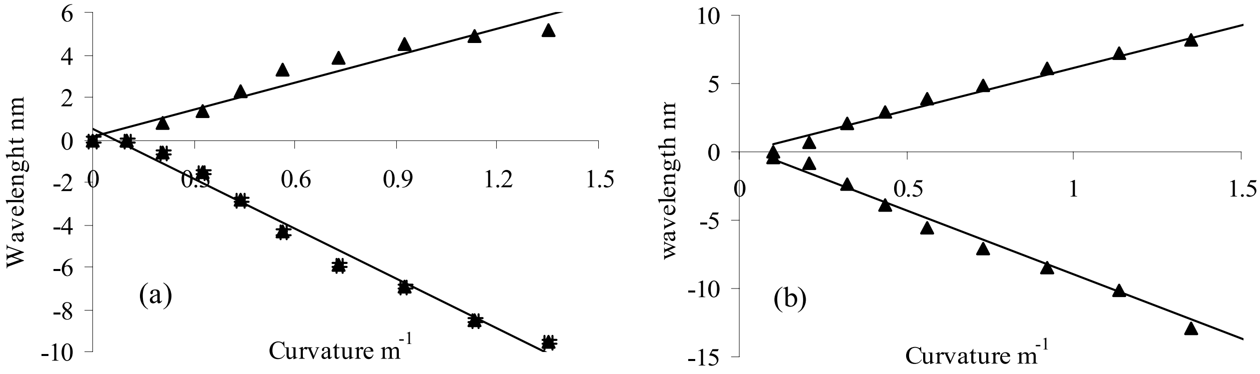

Figure 5. The spectral curvature sensitivity of both polarisation states of the LPG (period 250μm, length 4cm) written in elliptical core step-index fibre. (a) the slow axis and (b) the fast axis.

The spectral sensitivity for fast axis with respect to curvature is $d\lambda/dR$=+6.2 ± 0.7 nm m for the bend-induced attenuation band and $d\lambda/dR$=-9.4 ± 0.5 nm m for the normal attenuation band. The spectral sensitivity for slow axis with respect to curvature is $d\lambda/dR$=+4.2 ± 0.8 nm m for the bend-induced attenuation band and $d\lambda/dR$=-8.2 ± 0.6 nm m for the normal attenuation band. Using the assumption of linearity between wavelength shift and curvature, the resolution of slow axis was ± 0.06 m^{-1} and fast axis was ± 0.05 m^{-1} (residual analysis). The spectral sensitivities are expected to be different due to the fact that the attenuation bands are associated fast axis possesses an electric field that extends further into the cladding than the slow axis and thus has a higher sensitivity.

SPECTRAL TEMPERATURE CHARACTERISTICS

The sensitivity to temperature was investigated by placing the sensor on the top of an insulated Peltier cooler. 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. The experiment was conducted with the fibre in the cooler in two configurations (i) straight and (ii) subject to a curvature of 0.2m^{-1}. The spectral sensitivity of both orthogonal polarisation states are shown in figure 6.

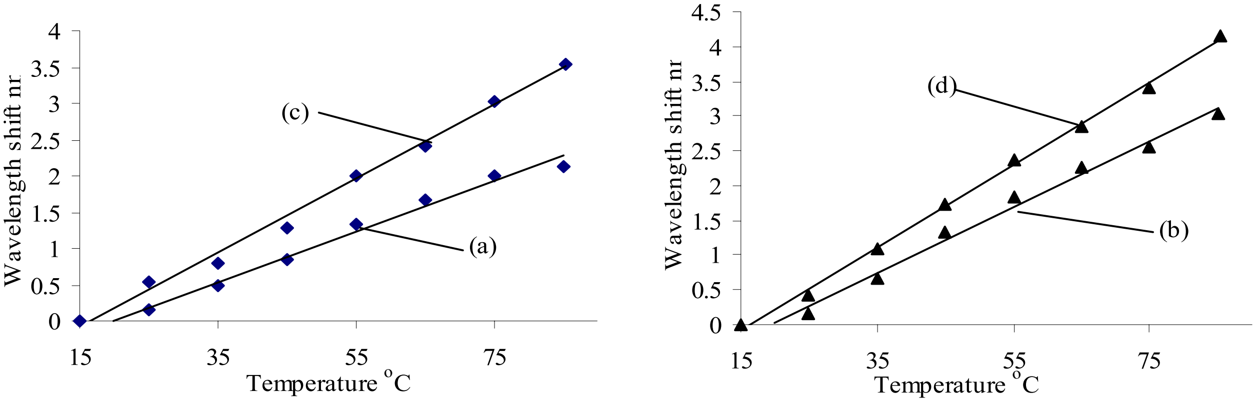

Figure 6. The spectral temperature sensitivity, in both polarisation states, of the LPG (period 250μm, length 4cm) in elliptical core step-index. (a) the slow axis (at a wavelength of 1601nm) along with (c) the bend-induced attenuation band. (b) the fast axis (at a wavelength of 1620nm) along with (d) the bend-induced attenuation band.

All the observed attenuation bands had red wavelength shifts with respect to temperature. The spectral sensitivity for fast axis is $d\lambda/dT = +0.048 \pm 0.008$ nm $^{o}C^{-1}$ for the bend-induced attenuation band and $d\lambda/dT = +0.059 \pm 0.005$ nm $^{o}C^{-1}$ for the normal attenuation band. The spectral sensitivity for slow axis is $d\lambda/dT = +0.035 \pm 0.008$ nm $^{o}C^{-1}$ for the bend-induced attenuation band and $d\lambda/dT = +0.051 \pm 0.008$ nm $^{o}C^{-1}$ for the normal attenuation band. Leading the resolution of slow axis was ± 1.8 °C and fast axis was ± 0.9 °C (residual analysis). Using this LPG to discriminate between curvature and temperature, for fast axis obtain a sensitivity matrix with a condition number of 174, while slow axis yields a condition number of 200; these figures are comparable to those obtained with other discriminatory sensors.

CONCLUSION

The attenuation bands of an LPG written into elliptical core step-index fibre were found to be sensitive to the polarisation of the interrogating light with a spectral separation of around 20nm between the two orthogonal polarisation states. The spectral sensitivity of both orthogonal polarisation states was measured with respect to curvature and temperature.

The bending of the LPG devices produced attenuation bands, which had blue wavelength shifts with sensitivities up to –9.4 nm m and red wavelength shifts with sensitivities up to +6.2nm m. With light in the fast axis, the use of neighbouring normal and bend-induced attenuation bands were used to demonstrate a discriminatory sensor for temperature and curvature, giving an overall curvature resolution of $\pm 0.05\text{m}^{-1}$ over the range of 0m^{-1} to 2.0m^{-1} and an overall temperature resolution of ±1.4 °C from 20 °C to 90 °C for this sensor.

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