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2004 Meas. Sci. Technol. 15 1647

(http://iopscience.iop.org/0957-0233/15/8/037)

INSTITUTE OF PHYSICS PUBLISHING MEASUREMENT SCIENCE AND TECHNOLOGY
Meas. Sci. Technol. **15** (2004) 1647–1650 PII: S0957-0233(04)73735-2

Implementation of vectorial bend sensors using long-period gratings UV-inscribed in special shape fibres

Donghui Zhao[1], Kaiming Zhou[1], Xianfeng Chen[1], Lin Zhang[1], Ian Bennion[1], Gordon Flockhart[2], William N MacPherson[2], James S Barton[2] and Julian D C Jones[2]

[1] Photonics Research Group, Electronic Engineering, Aston University, Birmingham B4 7ET, UK
[2] School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh EH14 4AS, UK

E-mail: d.zhao@aston.ac.uk

Received 22 December 2003, in final form 23 February 2004
Published 19 July 2004
Online at stacks.iop.org/MST/15/1647
doi:10.1088/0957-0233/15/8/037

Abstract
We report the implementation of vector bending sensors using long-period gratings (LPGs) UV-inscribed in flat-clad, four-core and D-shaped fibres. Our experiments reveal a strong fibre-orientation dependence of the spectral response when such LPGs are subjected to dynamic bending, which provided an opportunity to realize curvature measurement with direction recognition.

Keywords: bend sensor, long-period grating, special shape fibre

1. Introduction

In-fibre grating-based sensors have many advantages over conventional electric and alternative fibre optic sensor configurations [1, 2]. They are relatively straightforward and inexpensive to produce, immune to electromagnetic interference and interruption, lightweight and small in size and self-referencing with a linear response. Moreover, their wavelength-encoded multiplexing capability allows for arrays of gratings to be embedded in structural materials for smart structure applications. Strain measurements within such structures are often used to determine structural deformation, where bending is inferred from the measured strain [3]. In such applications, the bending induced strain is direction-dependent. Thus, it is important to implement optical bend sensors capable of curvature measurement with direction recognition. To date, most demonstrated fibre grating-based (including Bragg and long-period structures) optical bend sensors are limited to the measurement of curvature amplitude and few have provided the necessary directional information [4–7].

In this paper, we report the implementation of vector bending sensors using UV-inscribed long-period grating (LPG) structures. We have studied the bending sensitivity characteristics of the LPGs in three special fibre types: flat-clad fibre (FCF), four-core fibre (4CF) and D-shaped fibre (DF). The LPGs in these fibres show strong spectral dependence not only on the degree of curvature but also on the direction of the applied bending. The non-circular cross-section of the FCF allows measurement using a single centrally situated grating to distinguish between bending in orthogonal planes. Gratings in the 4CF and DF structures placed off the axis of symmetry show a response as a function of angle with respect to the bending plane.

2. Fibre structures and LPG spectra

Figures 1(*a*) and (*b*) show the image and dimensions of the cross section of FCF, respectively. This fibre was provided by the Prim Optical Fiber Corporation. The cladding of the fibre has a near-rectangular shape with two flat and two curved sides. The dimensions of the cladding cross-section are 145 μm × 96 μm and the core is located at the centre of the fibre with a diameter of 10.2 μm.

The FCF was photosensitized by H_2 loading before the UV-inscription. The LPG structure, with a period of 296 μm,

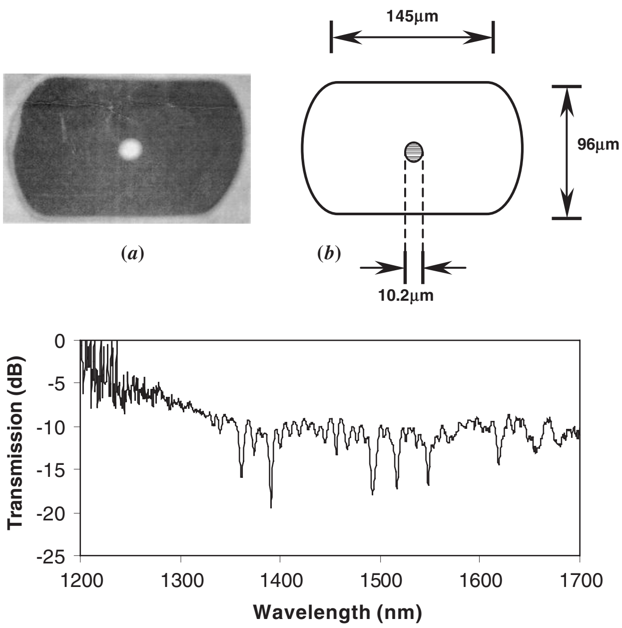

Figure 1. (*a*) Image and (*b*) dimensions of the cross section of FCF, and (*c*) FCF-LPG transmission spectrum.

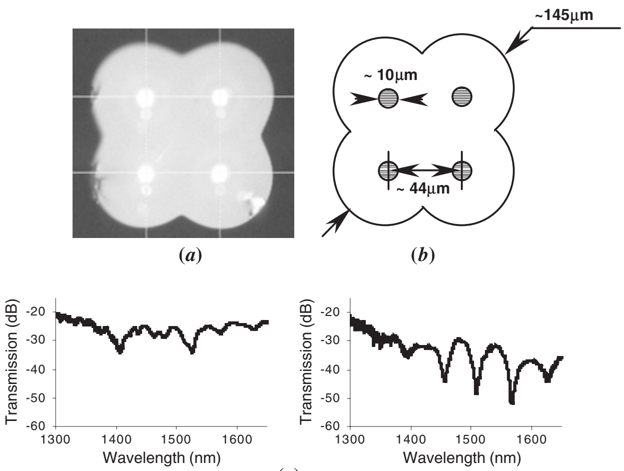

Figure 2. (*a*) Image and (*b*) dimensions of the cross section of 4CF, and (*c*) LPG transmission spectra for two cores.

was written into the FCF using a 244 nm UV laser and point-by-point exposure. Figure 1(*c*) gives a typical transmission spectrum of the LPG in FCF, showing several resonant loss peaks originating from coupling between the core and cladding modes. The irregular distribution in the spectral spacing of the loss peaks is due to the non-circular shape of the cladding. Coupling strengths of 5–12 dB were achieved for the loss peaks generated in the wavelength range shown in figure 1(*c*).

The 4CF, manufactured by France Telecom, was originally developed for applications in telecommunications. As shown in figure 2, the fibre consists of four cores arranged in a square with an adjacent core separation of 44 μm. The diameter of each core is $\sim$10 μm and the outer diameter of the fibre is $\sim$145 μm. All four cores were single-mode at 1550 nm [8].

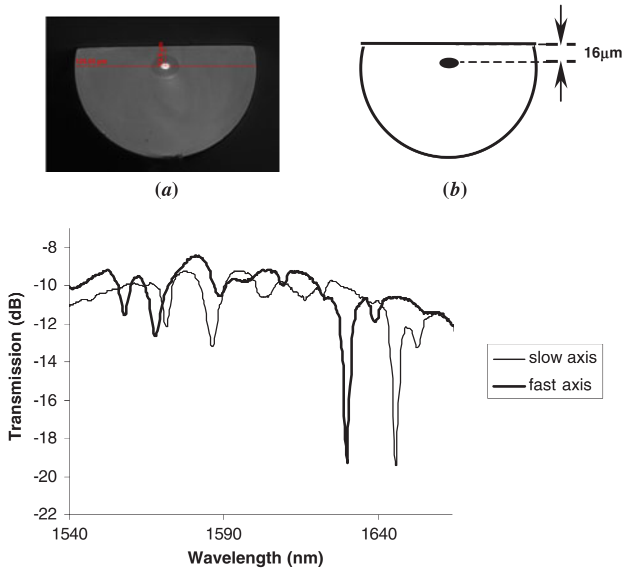

Figure 3. (*a*) Image and (*b*) dimensions of the cross section of DF, and (*c*) DF-LPG transmission spectrum, two series of peaks corresponding to the two polarization states.

The 4CF was also photosensitized by a standard H_2-loading process before the LPG inscription. In order to write gratings selectively on the cores, we mounted the fibre on a rotation stage to accommodate the setting of the fibre orientation. Both single- and double-exposure methods were employed to write grating structures in one or more cores. The latter involves a second UV exposure to the fibre after it was rotated by 180° following the first exposure. Several 4CF samples were fabricated with LPG structures in one, two and three cores, respectively, or in all four cores. A fan-out coupling device connecting 4CF to a single-mode fibre was specially fabricated and used to interrogate all the 4CF-LPG devices. Figure 2(*c*) shows LPG responses in two cores generated from two grating structures with periods of 450 μm and 400 μm. Again, we note that the loss peaks are not regularly distributed, but the resonances have exhibited strengths up to $\sim$15 dB.

The D-shaped fibre used in the investigation was purchased from KVH. It is a kind of polarization maintaining (PM) fibre with D-shape cladding and normalized birefringence 1.5×10^{-4} due to its elliptical core. The flat surface of the cladding is parallel to the major axis of the elliptical core, as shown in figures 3(*a*) and (*b*). The cladding radius is 125 μm and the centre of the core to the flat surface is 16 μm.

After the H_2-loading process, the LPG structure with a period of 381 μm was written into the D-shaped fibre. The transmission spectrum of the DF-LPG was measured using a system incorporating a broadband light source, a polarization controller and an optical spectrum analyser, and the result is illustrated in figure 3(*c*). In general, two sets of peaks in the transmission spectrum were observed, corresponding to the two polarization states. By adjusting the polarization controller, one set of peaks could be selected and the other eliminated. As shown in figure 3(*c*), the 8.48 dB transmission peak at 1629.66 nm can be switched to the peak at 1645.43 nm

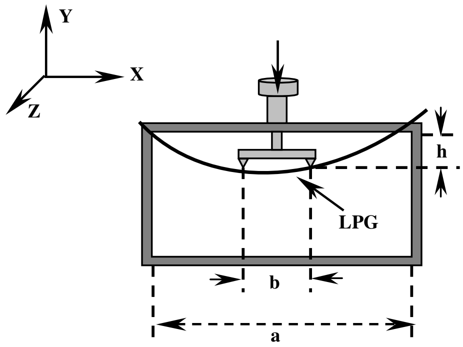

Figure 4. The geometric configuration of the four-point bending system used in the investigation ($a = 120$ mm, $b = 20$ mm and bending depth $h = 0$–14 mm).

with an extinction ratio of 8.34 dB when the polarizer is rotated by 90°. This verifies the correspondence of the two sets of coupled cladding modes to the input lights with two orthogonal polarization states.

3. Bending experiment

A four-point bend system was produced for carrying out curvature measurements: figure 4 illustrates the geometric configuration of this system. The LPG-containing fibre was attached with no twist to a 0.5 mm thick, 20 mm wide and 150 mm long metal plate. In order to eliminate the axial strain, only the two ends of a 10 cm central section of the fibre were fixed loosely on to the metal plate. The fibre was bent by depressing the centre of the metal plate with a micrometre drive. Experimental characterization has indicated that the curvature varies linearly with the bending depth, h, using this arrangement [5].

Bend measurement experiments were conducted to examine the spectral responses of FCF-, 4CF- and DF-LPGs to variations of the curvature at different fibre orientations. For 4CF, the sample with LPG structure in only one of the four cores was used. The grating transmission spectrum during bending was monitored using a broadband light source and an optical spectrum analyser. For FCF-LPGs, the spectral response under dynamic bending was measured for the bending directions along the flat and curved sides, respectively. In the cases of 4CF-LPGs and DF-LPGs, the fibres were rotated through a series of angles and the bending-induced loss peak shifts were measured at each angular position.

4. Experimental results and discussion

We have observed strong directional bending sensitivity characteristics in all of the FCF-, 4CF- and DF-LPG structures using the arrangements described above. Figure 5 plots the bending sensitivities of the measured FCF-LPG when it was bent along its flat and curved sides, respectively. It can be seen clearly from this figure that the respective bending sensitivity characteristics exhibit opposite slopes, indicating that the LPG resonance shifts towards longer wavelengths when it is bent along the flat side whereas the resonance moves towards shorter wavelengths when it is bent along the curved side. The figure also shows that the bending sensitivity is significantly larger for the flat side (~1.5 nm m^{-1}) than for the curved side bending direction (~0.5 nm m^{-1}). These distinct bending responses, clearly related to the geometric shape of the fibre, suggest that the FCF-LPG device can be usefully employed in smart structures for monitoring deformation.

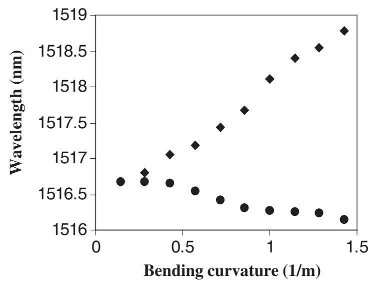

Figure 5. Wavelength shift of the FCF-LPG against curvature. ● Bending applied to the curved side of the fibre. ♦ Bending applied to the flat side of the fibre.

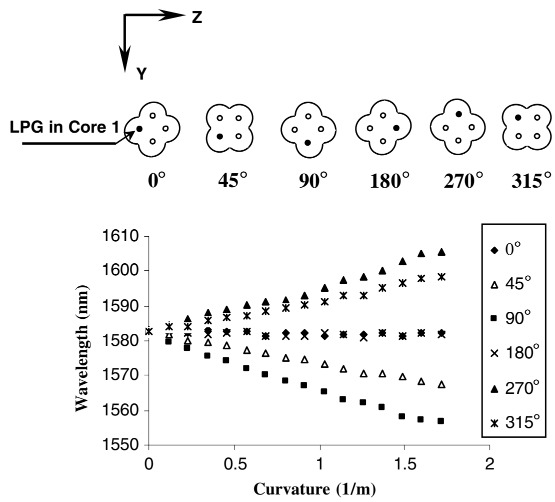

Figure 6. (*a*) Six fibre orientations used in the bending sensitivity investigation using the 4CF-LPG device. (*b*) Bending-induced wavelength shifts of the 4CF-LPG against curvature for the six fibre orientations.

With the 4CF-LPG device, we have carried out initial investigations with the LPG structure written in just one of the four cores. Since the core containing the LPG is not located on the fibre axis, we made the bending measurements at six different fibre orientations to characterize the relationship between this orientation and the bending sensitivity. Figure 6(*a*) shows the six fibre positions corresponding to the rotation angles used in the experiment. For each angle, the LPG response was examined for a series of curvatures from 0 to 1.71 m^{-1}.

We have found that the bending responses of the 4CF-LPG were strongly dependent on the fibre orientation. The LPG loss peak (1) remained insensitive to bending and its attenuation decreased slightly only when the fibre was set at 0° and 180° and (2) shifted in wavelength in opposite directions when the fibre was rotated from 0° to 90° and from 180° to 270°, respectively.

Figure 6(*b*) shows the wavelength shift against curvature for the six fibre orientations used. It is clear that all of the responses are near-linear. The maximum bending sensitivities

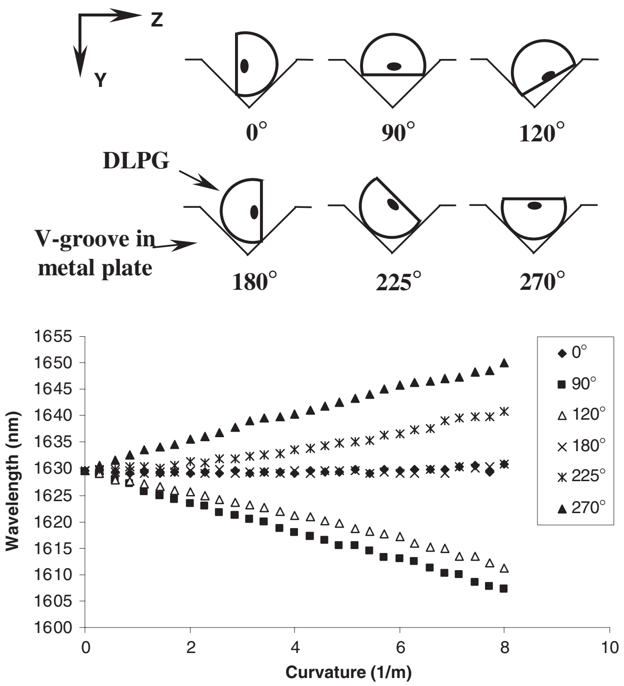

Figure 7. (*a*) Six fibre orientations used in the bending sensitivity investigation using the DF-LPG device. (*b*) Bending-induced wavelength shifts of the DF-LPG against curvature for the six fibre orientations.

occurred at 270° for the increasing wavelength response and at 90° for the decreasing wavelength response. Shifts of up to 23 nm and 26 nm in wavelength were observed with an applied curvature of 1.71 m^{-1} for the 270° and 90° fibre orientations, corresponding to bend sensitivities of 13.2 nm m^{-1} and -14.9 nm m^{-1}, respectively.

The above results were obtained in the 4CF with the LPG written in just one core. Experiments investigating devices with LPGs inscribed in two/three cores, and with FBG and LPG inscribed in different cores, are in progress. It is anticipated that devices using gratings in multiple cores will lead to practical vector sensor devices with temperature sensitivity decoupling functions.

As for the DF-LPG, we examined its bending response for a series of curvatures from 0 to 8 m^{-1} at different fibre orientations. As shown in figure 7, similar results to 4CF-LPG have been obtained. The bend sensitivity changes with the fibre orientation, from positive to negative. The maximum bending sensitivities occurred at 90° and 270° for the negative and positive wavelength response with sensitivities of -2.5 nm m^{-1} and 2.85 nm m^{-1}, respectively. Moreover, there are two bend-insensitive orientations associated with DF-LPG structures. This unique property could be exploited for developing complex vectorial shape sensors for smart structure sensing systems.

Since the D-shaped fibre used here is a PM fibre, it is important to check if the applied bending results in changes of the fibre birefringence. As mentioned above, for DF-LPG, the two sets of peaks are induced by the fibre birefringence. Thus, the spectral separation between the two polarization modes can be a measure of the birefringence. During the bending experiment, the wavelength spacing between the two adjacent peaks was monitored. The result for all six of the fibre orientations shows that the change in the wavelength spacing was within ±1 nm. As the resolution of the optical spectrum analyser used in the experiment was set at 1 nm to monitor the broad resonances of the LPGs, this amount of variation indicates that the bending induced birefringence change is not significant to the intrinsic birefringence of the DF. The possible reason for the polarization independent bending sensitivity of the DF-LPGs is that the birefringence is induced by the geometric effect of the elliptical core which is not significantly affected by the bending.

5. Conclusion

We have studied the bending sensitivity characteristics of LPGs UV-written in three special fibre types: FCF, 4CF and DF. The experimental results clearly indicate that the spectral responses of the LPGs depend strongly not only on the curvature amplitude but also on the fibre orientation. The bending sensitivity with directional recognition suggests that the devices have applications as vector bend sensors for many smart structure applications.

Acknowledgments

This work was supported by the UK Engineering and Physical Sciences Research Council and UK Defence Science and Technology Laboratory. The authors would also like to thank France Telecom for their generosity in supplying the 4CF.

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