Non-uniform shape sensor based on FBGs inscribed in multicore optical fibers

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Abstract: A multi-point curvature sensor composed by an array of fifteen wavelength multiplexed FBGs has been inscribed in a multicore optical fiber and is demonstrated in order to measure non-uniform curvatures with a resolution of $0.5\cdot10^{-3}$ m^{-1}.

OCIS codes: (060.3735) Fiber Bragg gratings, (060.2370) Fiber optics sensors, (060.4230) Multiplexing.

1. Introduction

Optical fibre curvature sensors are very versatile devices. They can be employed to implement multitude of optical sensors such as shape sensors, accelerometers and displacement sensors. The description of a curvature requires the determination of the curvature radius and the direction of curvature. Multicore optical fibers are ideal candidates to perform this multidimensional measurement.

Here, we propose to exploit the space diversity provided by multicore fibers in combination with the wavelength division multiplexing properties of FBGs to implement a multi-point curvature sensor. In particular, we report a multi-dimensional non-uniform curvature optical fiber sensor based on the inscription of an array of high-reflectivity FBGs along a commercial homogeneous four-core optical fiber.

2. Sensor implementation and measurement principle

The multi-point curvature sensor has been implemented using a commercial homogeneous multicore optical fiber provided by Fibercore that is composed by four identical single-mode cores arranged in the corners of a 36 µm side square. In this application it is desirable for all the inscribed FBG sensors to be similar in terms of spectral characteristics: reflectivity, Full-Width at Half Maximum (FWHM) and apodization. However, the simultaneous inscription of FBGs in all the cores is a challenging process as it is hampered by several limitations, such as the inhomogeneity of the laser fluence along the multiple cores and the lens effect of the optical fiber [1]. Prior to the FBG inscription, the optical fiber was hydrogen-loaded at 20-bar pressure for two weeks at room temperature to increase its photosensitivity. To maximize the similitude between the FBGs, they are simultaneously inscribed in all the cores using a defocused beam from an Argon-ion frequency-doubled laser. The inscription technique was based on the use of a uniform phase mask combined with a precise relative movement stage between the phase mask and the optical fiber.

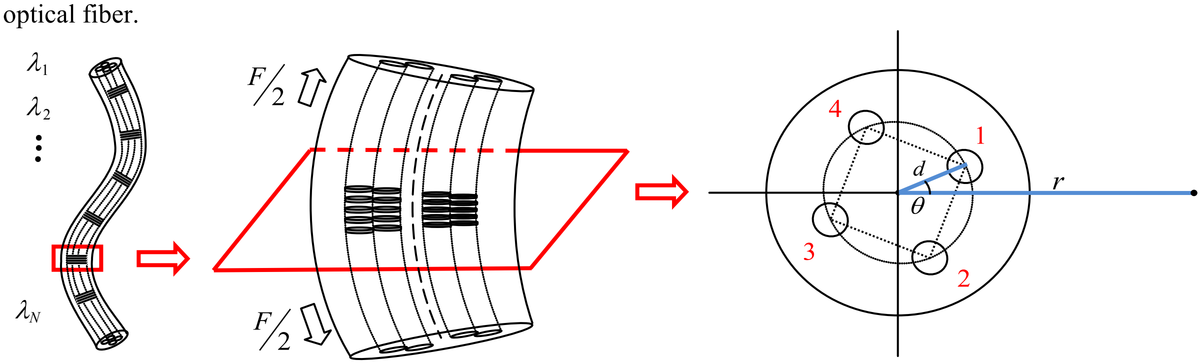

Fig. 1. Schematic view of the curvature sensor. In the left side, a general view of the multi-point curvature sensor is presented. In the center, a small section of the curved optical fibre with one of the FBGs in the center is represented. The external force, F , is defined in the middle figure. In the right side, a transversal section of the optical fiber is displayed where the radius r, the distance from the neutral axis to the center of the cores d and the direction of curvature θ, are represented.

A total of 15 FBGs with different central wavelengths have been written to implement the multi-point curvature sensor. Each FBG is 2 mm long while the distance between the centers of the FBGs has been set to 4 mm. A Gaussian apodization has been used in order to reduce the reflectivity of the side lobes of the optical reflectivity spectrum. The multicore optical fiber sensor has been connectorized to four standard singlemode single-core optical fibers in order to interrogate all the cores at the same time using a four-channel multicore fiber fan-out device from

Optoscribe and a commercial FBG interrogator form Micron Optics. The combination of the use of a commercially available multicore telecommunications fiber to implement the curvature sensor and the interrogation setup used can reduce the cost of the sensing system and increase the interrogation speed compared with previous reported solutions [2-5]. The high reflectivity of the FBGs inscribed to implement the curvature sensor lead to a higher signal to noise ratio compared with other schemes that are using low reflectivity FBGs.

It is known that, when a multicore optical fiber is curved, the cores will suffer a different level of strain depending on the relative position between the neutral deformation axis and the center of each core. This can be used to determine the curvature radius and the curvature direction. Fig. 1 shows a schematic view of the multicore optical fiber when it is curved.

The strain in each core is theoretically obtained assuming that the neutral deformation axis is in the geometrical axis of the optical fiber and the curvature is uniform where the FBG is placed. For a more generic approximation, we also consider an external force, F, that leads to the existence of a strain, ε_F, in all the cores even in the absence of a curvature. This force is defined to be uniform along the FBG, tangent to the curvature and it appears when the fiber is constricted. The direction of curvature, θ, the radius, r, and curvature $R_c = 1/r$ can be obtained as:

$$\theta = \arctan\left[\frac{(\varepsilon_4+1)^2-(\varepsilon_2+1)^2}{(\varepsilon_3+1)^2-(\varepsilon_1+1)^2}\right] \tag{1}$$

$$r = d\left(\frac{(\varepsilon_1+1)^2+(\varepsilon_3+1)^2}{(\varepsilon_3+1)^2-(\varepsilon_1+1)^2}\cos\theta \pm \sqrt{\left[\frac{(\varepsilon_1+1)^2+(\varepsilon_3+1)^2}{(\varepsilon_3+1)^2-(\varepsilon_1+1)^2}\right]^2\cos^2\theta-1}\right) \tag{2}$$

$$\varepsilon_F = \sqrt{\frac{(\varepsilon_3+1)^2-(\varepsilon_1+1)^2}{4\frac{d}{r}\cos\theta}}-1 \tag{3}$$

where ε_i are the measured strain in each of the four cores ($i = 1, .. 4$) and d is the distance from the neutral axis to the center of the cores.

3. Experimental results

We have employed a curvature sensor that has a total length of 6 cm and has been monitored using a commercial FBG interrogator. The implemented multi-point curvature sensor has been tested using different polymer molds with constant curvatures R_c from 2.9 to 26.17 m^{-1}. If these polymer molds are placed in series, we are able to set and monitor controlled non-uniform curvatures, too. Fig. 2 shows the results obtained from two non-uniform curvatures formed by the succession of two different polymer molds. The first one has a radius r of 0.0894 m and the second one a radius of 0.1718 m. Since the molds have opposite concavity, when the optical fiber is curved into two opposite directions, a null curvature (infinite radius) can be brought at some point along.

Fig. 2a to Fig. 2c represent the results when the 6th and 7th FBGs have been placed in the transition between the two molds, while Fig. 2d to Fig. 2f show the results when the 3rd FBG in in the proximities of the molds transition. Fig. 2a and Fig. 2d represent the evolution of the radius along the optical fibre. For the sake of clarity, we have also represented in these figures the two constant radii of the molds. The maximum measured radius (theoretically infinite) is limited due to the physical dimensions of the FBG and the measurement precision.

Fig. 2b and Fig. 2e show the 180-degrees change in the curvature direction during the transition from one mold to the other. Since the curvature direction is contained in the same plane, the small rotation of the optical fiber can also be observed in these figures as a slight slope. Fig. 2c and Fig. 2f represent the reconstruction of the shape of the optical fiber for these two particular cases. The curvature resolution can be obtained from the last section of the curvature sensor, where the fiber is kept at the constant curvature of the polymer molds, (see Fig. 2a and 2d). The curvature resolution has obtained a significant value of $0.5\cdot10^{-3}$ m^{-1}.

The external strain has been calculated as well. However, since the optical fiber is not affected by any external force, the results have shown strains along the optical fiber below 10 με.

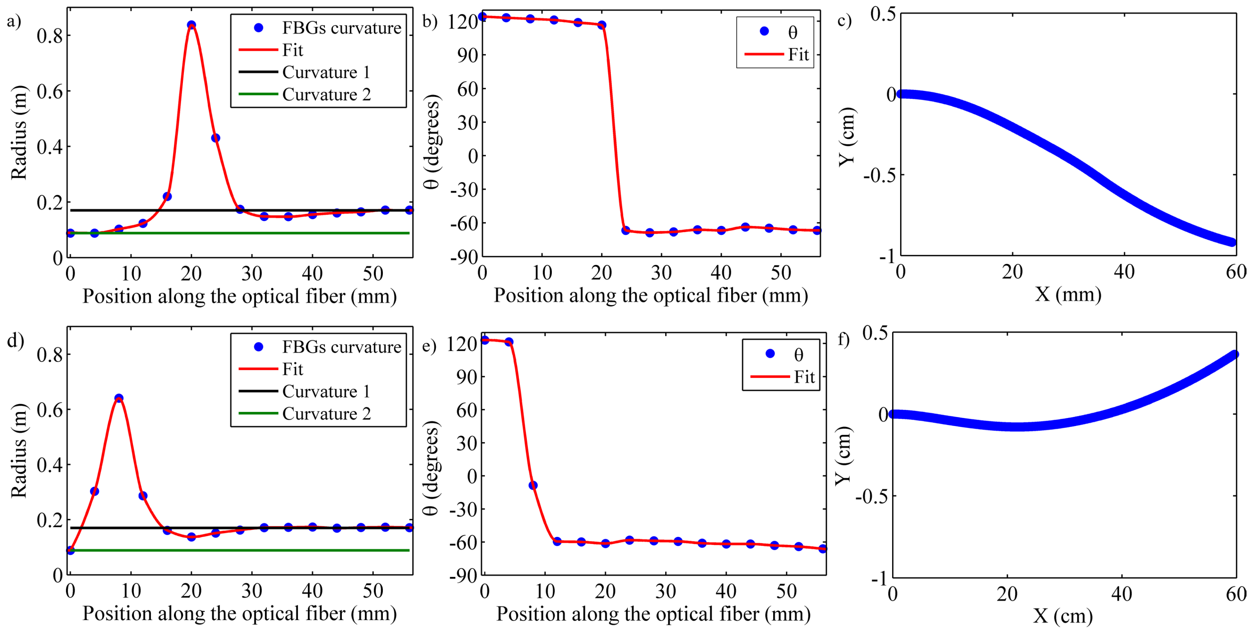

Fig. 3. Non-uniform curvature measurement. From left to right, is represented the radius *r*, the curvature direction *θ* and the reconstruction of the shape of the optical fiber. a) to c) display the results when the transition between the two molds was between the 6th and 7th FBG. d) to f) display the results when this transition was in the proximities of the 3rd FBG.

4. Conclusions

In conclusion, we have demonstrated a multi-point multidimensional curvature sensor that is based on the inscription of in-line apodized high reflectivity FBG arrays inscribed in a commercial homogeneous multicore optical fiber. Each array is composed of a set of fifteen FBGs centered at different wavelengths. The analysis of the strain relations in each core has shown that it is feasible to obtain both curvature magnitude and direction independently of any strain produced by external forces. The characterization of the multi-point curvature sensor shows a good performance obtaining a resolution of $0.5\cdot10^{-3}$ m^{-1} for constant curvature measurements.

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