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Reflected power-based 2D bending sensor using femtosecond laser FBG inscription in multicore fiber

P. Roldán-Varona[a†], D. Pallarés-Aldeiturriaga[a,b], L. Rodríguez-Cobo[b] and J.M. López-Higuera[a,b,c]

[a]Photonics Engineering Group, University of Cantabria, 39005 Santander, Spain;
[b]CIBER-bbn, Instituto de Salud Carlos III, 28029 Madrid, Spain;
[c]Instituto de Investigación Sanitaria Valdecilla (IDIVAL), 39005 Cantabria, Spain.

ABSTRACT

In this paper, we present research on the use of femtosecond lasers to develop a two-dimensional bending sensor by inscribing a 4 mm fiber Bragg grating (FBG) in each of the four cores of a multicore fiber (MCF) `Fibercore SM-4C1500`. The sensor located at the end of the fiber is spliced to a 50/125 multimode fiber (MMF). Due to the geometry of the MCF, part of its cores do not directly attach to the core of the multimode fiber, so that different curvatures cause variations in the reflected power. In this way, a reflection configuration and a commercial spectrometer are used to study its power response, simplifying the sensing, since it is not necessary to have WDM elements for the handling of wavelengths that vary tenths of nm in this type of sensors. Likewise, by carefully controlling the laser parameters and the motor stage position we are able to inscribe the FBGs by means of the point-by-point (PbP) method.

Keywords: Bending, sensor, femtosecond laser, fiber Bragg grating, multicore fiber.

1. INTRODUCTION

The inscription of FBGs in optical fiber has traditionally been done for the sensing of different parameters, as a consequence of their high sensitivity and manufacturing simplicity. Traditionally, the point-by-point (PbP) method has been used to inscribe them using femtosecond lasers. Although this method requires great precision in the alignment of the laser beam into the core, the simplicity that this technique presents compared to the plane-by-plane (Pl-b-Pl) method, in which an adequate optics is required, makes it suitable for applications that require a simple implementation [1].

Likewise, the writing speed and, therefore, the time of inscription of the structure is markedly reduced compared to the line-by-line (LbL) method. In addition, by means of the PbP method, it is possible to operate with the second order in the third telecommunications window, since it is possible to carry out structures of period $\sim 1\ \mu$m[‡] thanks to the use of adaptative optics [3].

On the other hand, the use of multi-core optical fibers allows to solve the cross-sensitivity issues derived from the sensing of multiple parameters with standard fibers (one core). In the case presented in this paper, it is not a question of distinguishing different parameters, but of sensing the curvature in two axes. Multicore fibers are presented as a good solution to obtain the exposed purpose since there are four parallel cores with collocated FBGs.

Moreover, bend sensing is improved from a fiber with multiple cores that incorporate FBGs, since bend causes stretching in one core and compression in the opposite [4]. In this way, with four cores it is possible to discern bending in a two-dimensional plane. The main disadvantage of these fibers is the difficulty of coupling light in each particular core [2], but the great novelty presented here is the fact that it is not intended to optimally couple light in each core, since the variation of the coupled power (and subsequently reflected) is measured to determine the bending.

† pablo.roldan@unican.es, (+34) 942 200 877, (+34) 942 200 877, http://gif.teisa.unican.es

‡The pulse energy used in this paper induces a smooth positive isotropic Refractive Index Change (RIC), classified as Type I within the RIC induced by the femtosecond laser [2].

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2. MANUFACTURING

All inscriptions were performed using a femtosecond commercial Fiber Laser Chirp Pulse Amplifier (FLCPA) from CALMAR lasers, operating at 1030 nm, with a 370 fs pulse duration and a variable Pulse Repetition Rate (PRR) from 1 Hz to 120 kHz. Laser pulses were focused through to NA= 0.5 objective lens from `Mitutoyo`, converging on the stretched fiber, which is located on a slide and covered with a coverslip. Between them an index-matching oil has been deposited in order to eliminate the spherical aberration of the fiber itself, favoring the focusing of the laser pulses [3]. The slide, where the fiber is located, is placed in a platform fixed to a nanoresolution XYZ motor stage from Aerotech. Using a CCD camera and a white light source that illuminates the platform, it is possible to accurately visualize and determine the position of the fiber. Figure 1a shows the schematic setup for the in-fiber inscription.

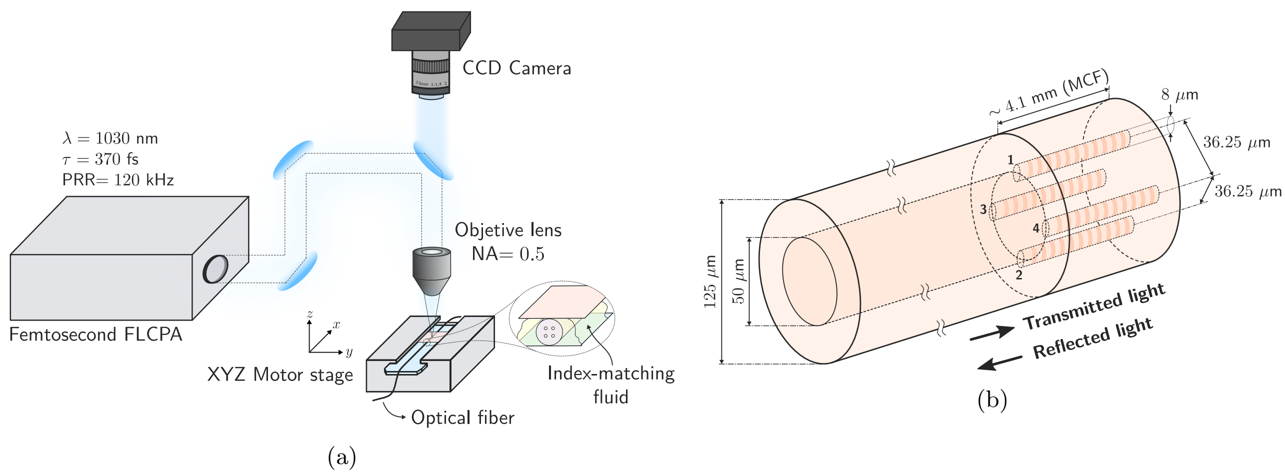

Figure 1. Manufacturing stage. Schematic setup for the in-fiber inscription (a), and schematic and dimensions of the sensor section (b).

It is necessary to indicate that the FBGs have been inscribed in the four cores of the MCF `Fibercore SM-4C1500`, each with a diameter of 8 um, and a separation between consecutive cores of 36.25 μm. The processed fiber, with a length of $\sim$ 4.1 mm, has been previously fused to a commercial MMF with core and cladding diameters of 50 μm and 125 μm, respectively. The schematic of the sensor is depicted in Figure 1b.

The FBGs have been inscribed in each of the four cores of the MCF, after having been merged with the MMF. For this, the point-by-point (PbP) FBG inscription process has been used, which allows to have a complete control of the position of each index modification that comprises the grating. The four FBGs, each with a length of 4 mm, have been inscribed with a pulse energy of 0.47 μJ and a PRR of 20 Hz. In order to discern the cores, each FBG has been inscribed with a different period, all of them in the 3rd telecommunications window[§]. The period and Bragg wavelength (2nd order) of each core[¶], as well as the writing speed, are shown in Table 1. The result is depicted in Figure 2.

3. EXPERIMENTAL RESULTS

3.1 Characterization

The characterization of the structure of FBGs has been carried out during the inscription. A broadband optical circulator (1460-1620 nm) has been used: port 1 connects a broadband light source (`HP 83437A`), port 2 the fiber processed, and port 3 an Optical Spectrum Analyzer (OSA) (`Anritsu MS9740A`). In this way, the spectra were collected every mm of inscription of the FBGs. The result is shown in Figure 3.

[§]Second order has been used: $\lambda_b = \frac{2}{m} \cdot n_e \cdot \Lambda, \quad$ with $m = 2$.

[¶]It must be taken into account that the cores 1 and 2, like the 3 and 4, are the ones facing each other (separated by 51.2 μm), as it can be seen in Figure 1a.

Table 1. Period, writing speed and reflection wavelength (2nd order) corresponding to each FBG

#core	Λ	Writing speed	λ_b (2nd order)
1	1.063 μm	21.26 μm/s	1531.7 nm
2	1.076 μm	21.52 μm/s	1550.5 nm
3	1.069 μm	21.38 μm/s	1540.8 nm
4	1.083 μm	21.66 μm/s	1560.5 nm

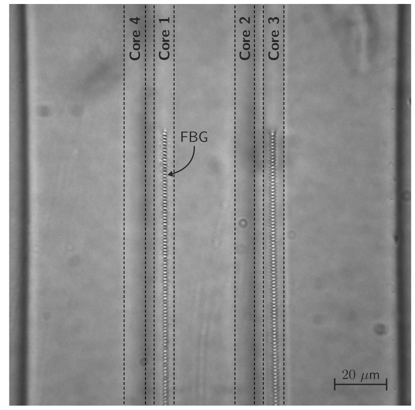

Figure 2. Result of laser inscription in the MCF. The position of each core is shown, and the FBG corresponding to core 1 is focused.

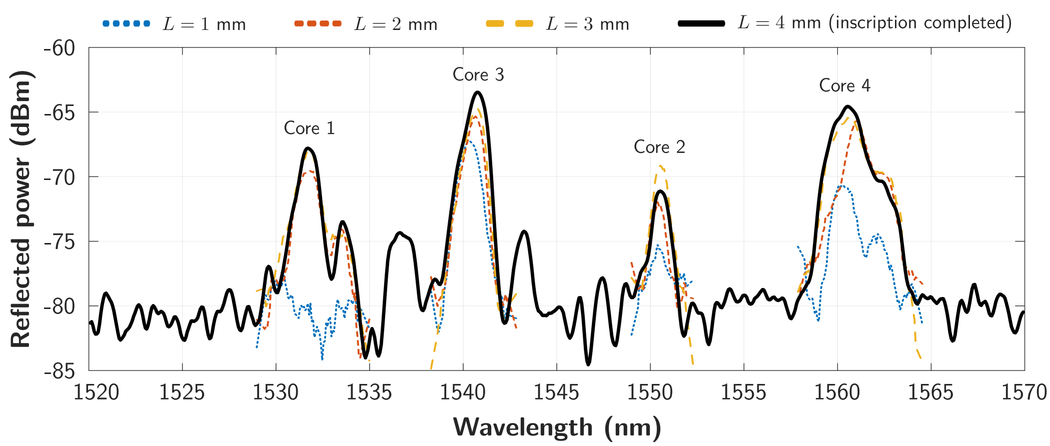

Figure 3. Reflection spectra with the wavelengths indicated in Table 1. The sensor segment response for FBG lengths (L) 1, 2, 3 and 4 mm is depicted.

Typically, in order to model fiber bending, a coordinate transformation called conformal mapping is used, through which the action of the bending is transformed into a tilt refractive index [2]. It can be used to treat losses in curved fibers. In this way, unlike what is done in a traditional way, which consists of measuring displacements in the reflected wavelength to characterize the curvature of the fiber, in this paper we propose to use the reflected power for that purpose, specifically the increase or decrease of the power loss of each MCF core, as a consequence of the incomplete coupling of the MCF cores to the MMF core.

The experimental setup consists of two XYZ platforms separated an initial distance d. A fiber rotator is located on each platform [4]. As shown in Figure 4a, one platform is fixed, while the other moves on the X axis. By placing the MCF sensor section at the intermediate point between the platforms[‖], fiber bending is achieved by moving the movable platform. Bending in any direction is achieved through the synchronized rotation of the fiber in both platforms. An estimate of the curvature is achieved through the following expression:

$$d - x = d \cdot \text{sinc}\left(\frac{d \cdot \kappa}{2}\right), \tag{1}$$

where x refers to the displacement of the movable platform on the X axis, and $\kappa = \frac{1}{R}$ is the curvature, the inverse of bending radius R towards bending axis.

[‖]Only in order to facilitate the measurement process, a fiber section has been coupled to the sensor located in MCF.

3.2 Bending sensor

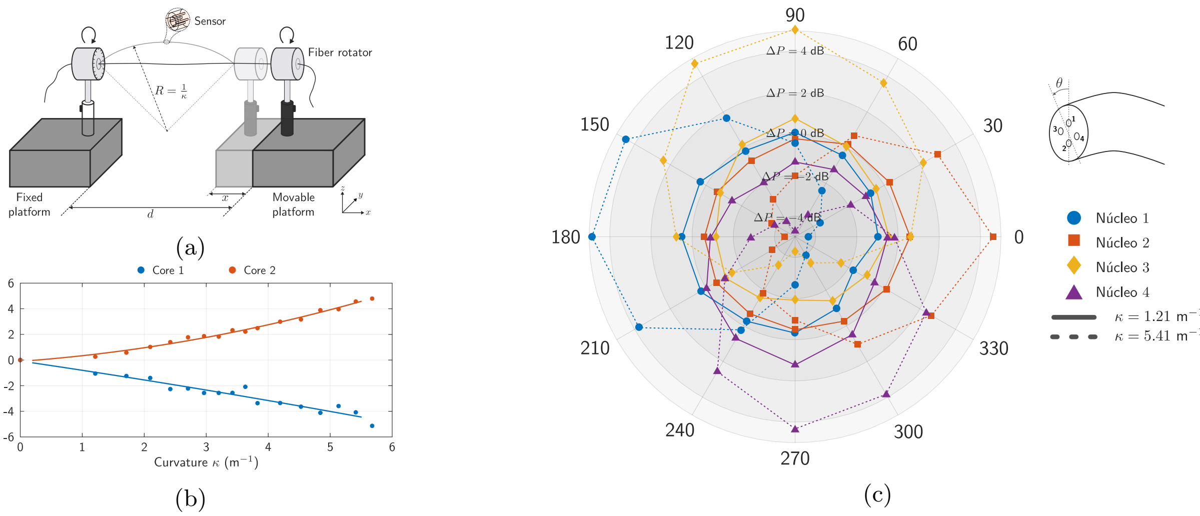

Figure 4. Bending measurement process. Schematic corresponding to the experimental setup (a). Variation of the power reflected by the FBGs of cores 1 and 2 as a function of the curvature κ taking $\theta = 0^o$ (b). Evolution of the power reflected by each core as a function of angular rotation θ and curvature κ (c).

Regarding the results obtained, it can be observed in Figure 4b that the variation of the reflected power ΔP (taking as reference $\kappa = 0$ m^{-1} and $\theta = 0^o$) as a function of the curvature has a high linearity, with slopes of different sign when it is about facing cores (separated 180°). The graph shows the evolution of the power reflected by the FBGs corresponding to cores 1 and 2 taking $\theta = 0^o$. On the other hand, Figure 4c emphasizes the concept that this paper intends to show. In the absence of curvature, angular rotation does not cause variation in power ($\Delta P = 0$ dB). However, when increasing the curvature, so do the losses in the power reflected by each core for the angular position in which it is located (taking into account the sensor arrangement shown in the figure itself), and the corresponding increase in power for the angular rotation located in the opposite direction.

4. CONCLUSIONS

Based on a commercial multimode fiber and a tiny ~ 4.1 mm sensor located inside a four-core fiber, it is possible to determine any two-dimensional bending of the fiber by inscribing four fiber Bragg gratings using the *PbP* inscription method. Taking advantage of the geometric properties of both fibers, it is possible to perform the sensing based on power variations in a high range of ± 6 dB, and not the traditional wavelength shift, which would require precise equipment to distinguish variations of tenths of nm.

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