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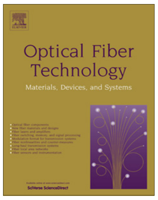

Bragg gratings in surface-core fibers: Refractive index and directional curvature sensing

Jonas H. Osório [a,*], Ricardo Oliveira [a,b], Stenio Aristilde [a], Giancarlo Chesini [a], Marcos A.R. Franco [c], Rogério N. Nogueira [b], Cristiano M.B. Cordeiro [a]

[a] *Instituto de Física "Gleb Watagin", Universidade Estadual de Campinas, UNICAMP, Brazil*
[b] *Instituto de Telecomunicações, Pólo de Aveiro, Aveiro, Portugal*
[c] *Instituto de Estudos Avançados, IEAv, Departamento de Ciência e Tecnologia Aeroespacial, São José dos Campos, Brazil*

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ABSTRACT

In this paper, we report, to our knowledge, the first extended study of the inscription of Bragg gratings in surface-core fibers and their application in refractive index and directional curvature sensing. The research ranges from fiber fabrication and grating inscription in untapered and tapered fibers to the performance of simulations and sensing measurements. Maximum sensitivities of 40 nm/RIU and 202.7 pm/m^{-1} were attained in refractive index and curvature measurements respectively. The obtained results compares well to other fiber Bragg grating based devices. Ease of fabrication, robustness and versatility makes surface-core fibers an interesting platform when exploring fiber sensing devices.

1. Introduction

Optical fibers are a very important platform for building up sensors. Temperature, pressure, strain, refractive index and curvature are examples of parameters which can be monitored by the employment of optical fiber-based systems. The importance of developing fiber sensors has recently grown due to the advantages they can provide over other sorts of sensors, such as high sensitivity, electromagnetic immunity and increased robustness. Moreover, fiber-based devices are usually very compact and lightweight [1,2].

Numerous technologies can be employed for turning the fiber sensitive to the parameter whose variation is desired to be measured. Fiber gratings, for example, can be used to sense many parameters, such as refractive index, strain, curvature and temperature variations [3,4]. Furthermore, tailoring fiber geometry is another possibility for achieving the desirable sensitivity. It is often done when dealing with photonic crystal fibers [5].

Specifically for refractive index monitoring, long-period gratings [6,7], multimode interferometers devices (MMI) [8,9] and birefringent microfibers [10,11] are some of the fiber based devices that are usually employed for obtaining this sort of measurement. For these technologies, sensitivities values can range from hundreds to thousands of nanometers per refractive index unit.

Concerning curvature measurements, again long-period gratings and MMI based setups are often employed [12,13]. Moreover, Bragg gratings inscribed in multicore fibers have also been studied as an alternative for obtaining directional curvature determination [14–16].

In this paper, we report, to our knowledge, the first extended study of Bragg gratings inscribed in surface-core fibers and their application in refractive index and curvature probing. Surface-core fibers have firstly been reported by C. Guan et al. in [17], where theoretical studies of refractive index sensitivity can be found. Besides, an experimental study of refractive index sensing based on interferometry has also been published [18]. Recently, we have reported the fabrication and the possibility of inscribing long and short-period gratings in surface-core fibers [19]. Moreover, we studied the use of surface-core fibers for hydrostatic pressure sensing [20].

The research reported herein comprehends an investigation that ranges from fiber fabrication and simulation to its application in refractive index and directional curvature probing. When studying refractive index variations, a maximum sensitivity of 40 nm/RIU could be measured for refractive index variations around 1.42 RIU. Other fiber Bragg gratings devices reported in literature show sensitivity values ranging between 15 nm/RIU and 30 nm/

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* Corresponding author.
E-mail address: jhosorio@ifi.unicamp.br (J.H. Osório).

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RIU [21–23]. Regarding curvature probing, a directional behavior was demonstrated and a sensitivity of 202.7 pm/m^{-1} could be attained. This value is two times higher than the values found in literature for similar FBG based sensors [14–16]. It's worth emphasizing that is not our intention reporting record high sensitivities values, but present the study of a specialty fiber structure obtained from a very simple fabrication process and its application in sensing measurements.

2. Fiber fabrication

Surface-core fibers are designed so that the core region is placed at fiber external boundary. In order to obtain the fiber, a four-step process is carried on. Firstly, a multimode germanium doped rod is drawn from its initial diameter of 21–0.8 mm (Fig. 1a). In the second step, the rod is inserted in a HF bath for etching. During this process, the diameter is decreased form 0.8 mm to 0.65 mm. By performing this procedure, the silica layer (Fig. 1a) is removed. This step is important for refractive index tests, since it allows a more pronounced interaction between the core mode evanescent field and the external medium.

In the third step, the thinned rod is merged to a silica tube (with inner and outer diameter of 5 mm and 10 mm, respectively) by the employment of a blowtorch in order to obtain the fiber preform (Fig. 1b). Finally, the preform is directly drawn to its final diameter (130 μm). The fiber cross-section is shown in Fig. 1c and a zoom of the core region is presented in Fig. 1d. As the core's refractive index is higher than the surrounding medium's one, light is guided through the surface-core fiber by total internal reflection.

It is worth underlining that all the steps for surface-core fiber fabrication are straightforward, what makes it much simpler than the fabrication of other specialty optical fibers such as photonic-crystal fibers. For obtaining photonic-crystal fibers, for instance, usually stack-and-draw procedure is employed [24]. In this method, numerous silica tubes and rods are drawn and manually assembled in a preform stack. In sequence, jacketing processes allows obtaining the desired proportion between core, cladding and outer fiber sizes. This process is very time consuming and demands much effort from a technical point of view.

3. Bragg gratings imprinting

Fiber Bragg gratings consist of short-period longitudinal modulation of optical fibers core refractive index. It allows coupling between forward and backward propagating core modes. The coupling occurs at a specific wavelength λ_B as shown in Eq. (1), where n_{eff} is the effective refractive index of the fundamental core mode and Λ is the grating period.

$$\lambda_B = 2n_{eff}\Lambda \qquad (1)$$

The grating inscription was performed by employing the phase mask technique. A Quantel Q-Smart 450 UV laser together with a phase mask were used to create an FBG in the infrared region. A cylindrical lens was used for focusing the UV laser beam on the fiber during gratings' inscription process and the resulting FBGs have their lengths in the order of millimeters. For monitoring the FBG spectrum in real-time during grating inscription, a SMF pigtail was butt coupled to the surface core fiber. A small amount of index matching oil was used in the coupling for reducing Fresnel reflections at fiber ends and for lowering the background noise. A CCD camera was placed at the end of the fiber in order to provide an image of the core illumination conditions. By observing the CCD camera image, one could find the core position and optimize the coupling of light to the fiber. The FBGs were inscribed with enough reflectivity to be seen in reflection. Fig. 2a shows the spectrum (collected from a FS2200 Industrial BraggMETER from FiberSensing) of a FBG which was imprinted in a surface-core fiber by using a phase mask with period 1062.65 nm (spectra are normalized for better visualization). The tested fibers were maintained under tension during the gratings spectra acquisition.

4. Refractive index sensing

As in the studied fibers the core region is placed on fiber external surface, the evanescent field associated to the guided mode permeates the surrounding medium. It causes the core effective refractive index to be dependent on external refractive index variations. As the Bragg peak spectral location is determined, besides grating period, by the mode effective refractive index value (Eq. (1)), variations in external refractive index imply on Bragg peak shifting. Therefore, by monitoring the Bragg peak shift, a refractive index sensor can be obtained.

In the refractive index measurements, the surface-core fibers were immersed into solutions of water and glycerin and the reflection Bragg peak was monitored. Results showed, however, a very low sensitivity to external refractive index variations (0.07 nm/RIU). It can be identified by the minimum wavelength shift which was observed in Bragg peak spectral position as the external refractive index, n_{ext}, was varied (Fig. 2a). Thus, in order to enhance fiber sensitivity, tapers from surface-core fibers were produced prior to Bragg grating inscription. The tapers were prepared by using flame-brushing technique [25] and the grating imprinting was done by using the same phase-mask technique. In the flame-brushing technique, the resulting fiber taper presents two transition zones and a uniform region with constant diameter (taper waist). The gratings were imprinted in the uniform waist of the fiber tapers (prepared with 10 mm in length).

The diameter reduction causes the mode effective refractive index to be more sensitive to the surrounding refractive index variations. Tapers 80 μm and 20 μm thick were tested and the resulting spectra are shown in Fig. 2b and c (the spectra were normalized for better visualization). It is worth observing that the grating in the 80 μm taper was imprinted by using a phase mask with pitch 1075.34 nm and the one in the 20 μm with a phase mask with pitch 1071.2 nm, implying in different spectral positions for the Bragg peaks. Moreover, since the core mode in the 20 μm taper has a greater fraction of its evanescent field in the external med-

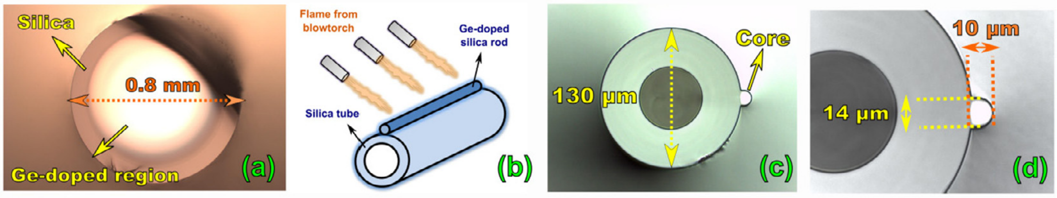

Fig. 1. (a) Germanium-doped silica preform employed for obtaining the fiber core. (b) Diagram for germanium doped silica rod and silica tube merging procedure using blowtorch. (c) Surface-core fiber cross-section. (d) Inset of the core region.