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Nanofabrication of phase-shifted Bragg gratings on the end facet of multimode fiber towards development of optical filters and sensors

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ABSTRACT

This work describes the process of nanofabrication of phase-shifted Bragg gratings on the end facet of a multimode optical fiber with a pulsed DC sputtering system based on a single target. Several structures have been explored as a function of parameters such as the number of layers or the phase-shift. The experimental results, corroborated with simulations based on plane-wave propagation in a stack of homogeneous layers, indicate that the phase-shift can be controlled with a high degree of accuracy. The device could be used both in communications, as a filter, or in the sensors domain. As an example of application, a humidity sensor with wavelength shifts of 12 nm in the range of 30 to 90% relative humidity (200 pm/% relative humidity) is presented.

1. Introduction

The deposition of a stack of high and low refractive index materials on different substrates, such as silicon wafers, quartz, BK7 glass, or optical fiber, has been explored in several publications with the aim of developing optical filters and sensors [1–10].

In this work the substrate will be the end facet of an optical fiber, which allows obtaining a device that includes many interesting properties. On the one hand, optical fiber is immune against electromagnetic interferences, presents small diameter and high bandwidth, and is capable of multiplexing several signals. On the other hand, though some authors consider the deposition of high and low refractive index layers as a multilayer stack [1,3–4,6–8] or a micrograting [2], others use more subtle terms such as Bragg stacks [5], or simply Bragg gratings [10]. This last term is more adequate in the work presented here because focus is centered on the monitorization of bands generated in the reflected spectrum according to the Bragg-Snell equation for normal incidence [5]:

$$m\lambda = 2(n_H h_H + n_L h_L) \quad (1)$$

where m is the diffraction order and n_H, n_L, h_H, and h_L are the refractive indices and thicknesses of the high-(H) and low-(L) refractive index materials respectively. All these variables increase the potential of optical fiber and allow controlling the shape of the optical spectrum, as it will be shown later, which can be used both for the design of optical filters and sensors. Indeed, the direct contact of the Bragg grating with the outer medium, combined with the small size of the micrograting makes this type of structure a good candidate for a small-size sensing probe.

Regarding the techniques used for nanodeposition of each layer in the Bragg grating, there are some works focused on layer-by-layer (LbL) self-assembly [2,11]. However, even though much progress has been done in the last years in terms of increasing the deposition speed [12], sputtering is the most adequate technique for this type of structures due to the fine control in the nanocoating thickness it offers, by applying a specific combination of parameters such as power, current, vacuum pressure or gas flow rate [13,14]. This makes sputtering a useful tool for deposition of nanocoatings on optical fibers [15–17].

In a recent work it has been proved that it is possible to develop a Bragg grating on the end facet of an optical fiber by DC sputtering technique with a single target, which increases the simplicity of the nanodeposition process [10]. In this work, the possibility of including a variation of the thickness in one of the layers of the grating is explored. This type of structure is considered in the literature as a one-dimensional photonic band gap structure (PBG) with a defect [11]. However, it is more usual to use the term phase-shifted grating [18–21]. Consequently, this notation will be

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used henceforward. As an example of application of this type of device, a humidity sensor will be shown, which opens the possibility to develop other sensing applications where the defect layer is even composed of another material that is sensitive to other parameters.

In Section 2 the experimental setup and the methods used for fabricating and simulating the Bragg gratings will be explained. In Section 3 the experimental results are detailed. Finally, some conclusions are included in Section 4.

2. Methods and materials

This section describes the process of generation of a grating and the possibility to generate a phase-shift in the middle of the grating, as well as the numerical analysis used to simulate the structure.

2.1. Generation of gratings with pulsed DC sputtering

Fig. 1 shows the experimental setup used in the construction process of the gratings. In this set-up, a white light source ANDO and a HR4000 spectrometer were used to monitor, in a reflection configuration, the deposition process on the fiber end facet with SpectraSuite software. A pulsed DC sputtering equipment (Nadetech Innovations, Ltd.) with a single target of SnO_2 was used for the deposition. In order to control the generation of high and low refractive index layers, the gas injection into the vacuum chamber was automated with a LabView controlled gas panel, which allowed modifying the properties of the material deposited at any moment.

Fig. 2 shows a schematic representation of a 7 period grating deposited on the end facet of a multi-mode optical fiber (core and cladding diameter 62.5/125 μm) from Telnet Redes Inteligentes Inc. (Zaragoza, Spain).

Successive deposition of the same material, SnO_2, in two different conditions permitted to obtain high refractive index and low refractive index layers. The conditions for both materials are listed in Table 1. The parameter that leads to the refractive index change is the gas combination (i.e. oxygen-argon for a high refractive index and only argon for a low refractive index layer). In this way, a refractive index contrast between layers created in oxygen-argon atmosphere and layers created only in argon atmosphere is obtained.

The first layer of the period in the deposition process for all cases was an n_H layer (high refractive index), and the second one was an n_L layer (low refractive index).

Henceforward, we will refer to the set of two consecutive high and low index depositions, as a period.

As an average value, the thickness of each layer was approximately of 80 nm with the current deposition time per layer (Table 1). This thickness depends on the distance between the fiber tip and the cathode.

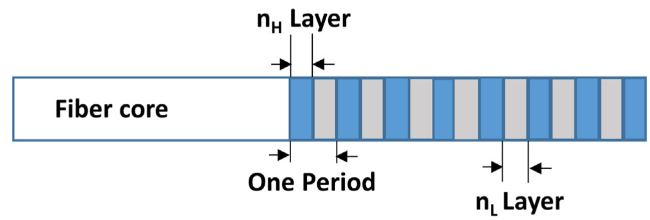

Fig. 2. Simple Bragg grating on the end facet of an optical fiber.

Table 1
Conditions for dc sputtering deposition process.

Condition	Value/description
Deposited material	SnO_2
Deposition time per layer	30 s
Gas combination to achieve refractive index variation per layer	Oxygen-Argon (n_L) or only Argon (n_H)
Pressure in vacuum chamber	2×10^{-2} to 3×10^{-2} mbar
Current intensity	0.21 A
Distance from the fiber end facet tip to the cathode	18–24 mm

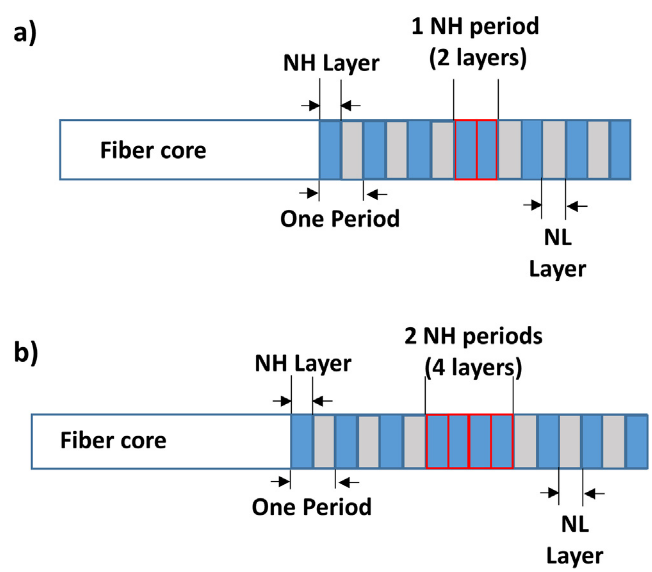

Fig. 3. 6 period Bragg gratings: (a) with π-phase-shift, (b) with 3π-phase-shift.

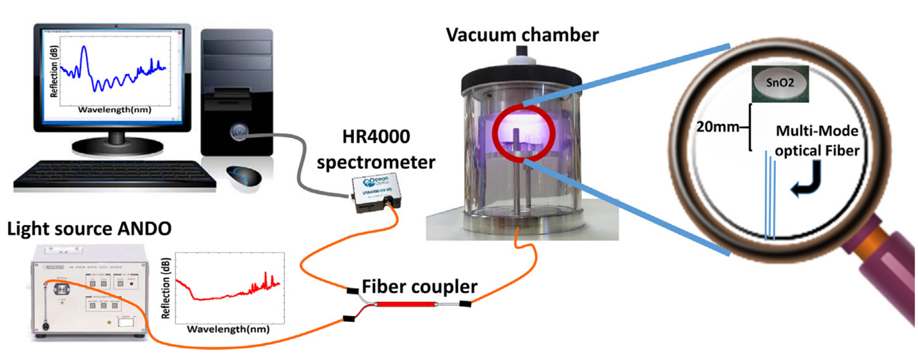

Fig. 1. Experimental setup used to monitor the pulsed DC sputtering process.