Refractometric sensors based on long period optical fiber gratings

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In this work, results of the design of uniform and non-uniform long-period gratings are presented, with a view to being used as refractometric sensors. We found an optimal combination of the longitudinal variation of the fiber refractive index and the grating period, which increases the sensor linearity in comparison with a uniform grating, without decreasing its average sensitivity within a range of the external refractive index from 1.41 to 1.44.

Keywords: Long-period fiber gratings; refractometry; genetic algorithms.

En este trabajo se presentan los resultados del diseño de rejillas de período largo uniformes y no uniformes, con el fin de ser usadas como sensores refractométricos. Encontramos una combinación óptima de la variación longitudinal del índice de refracción de la fibra y el período de la rejilla, la cual incrementa la linealidad del sensor en comparación con una rejilla uniforme, sin disminuir su sensibilidad promedio dentro de un rango del índice de refracción externo de 1.41 a 1.44.

Descriptores: Rejillas de período largo; refractometría; algoritmos genéticos.

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1. Introduction

Long-period gratings (LPGs) have experienced an increasing presence over the last few years in telecommunications [1–3] and sensing applications [4,5]. One of their important advantages over Bragg gratings is that their fabrication process is simpler and, therefore, has a lower cost. Besides, they present low retro-reflection and high sensitivity in sensing applications [4].

Changes in the center wavelength of uniform LPGs, due to the variation of the index of refraction of the surrounding medium, have been determined both experimentally and theoretically [4,6,7]. It has been found that this characteristic response depends on a combination of the grating parameters, such as the cladding mode order coupled to the fundamental core mode, the difference between the fundamental core mode and the cladding modes effective indexes, and the grating period. Moreover, the sensitivity of this type of refractometric sensors mainly depends on the cladding mode order and the grating period [7]. On the other hand, the characteristic response is non-linear, particularly in the range of the surrounding index, where the device sensitivity is higher [6,7].

This work presents a proper technique to achieve an acceptable degree of linearity in the refractometric sensor response. It is shown that an LPG whose parameters, such as core and cladding refractive indexes and period, vary longitudinally, may provide a reasonably linear characteristic response over a certain interval of the external index of refraction.

2. Analysis of the LPGs response

LPGs, photoinduced in single-mode optical fibers, have the property of coupling the fundamental core mode (LP_{01}) to different order cladding modes (LP_{0i}), yielding a transmission spectrum with several loss bands, corresponding to each cladding mode experiencing coupling. The central wavelengths of the loss bands of a uniform grating are given by [1]:

$$\lambda_i = (n_{co}^{eff} - n_{cl,i}^{eff})\Lambda, \tag{1}$$

where n_{co}^{eff} is the core mode effective index, $n_{cl,i}^{eff}$ is the cladding mode effective index of order i, and Λ is the grating period. In order to determine n_{co}^{eff}, the core index n_1, the cladding index n_2, and the mode wavelength must be considered. Similarly, to determine $n_{cl,i}^{eff}$ the fiber can be modeled as a fiber with no core, so that only the cladding index n_2, the external medium index n_3, and the modes wavelengths need to be considered. In general, these effective indexes depend on the material and waveguide dispersions in the fiber [6]. To obtain the effective indexes of the core and cladding modes, the step-index fiber approximation [8] can be employed. Since $n_{cl,i}^{eff}$ depends on n_3, the variation of the latter causes changes on the center wavelengths λ_i.

For the investigation carried out in this work, a single-mode optical fiber with core and cladding radii of 3.8 and 62.5 μm respectively was considered. The core is composed of 4.03 m% GeO_2, 9.7 m% B_2O_3 and 86.27 m% SiO_2, and the cladding of pure SiO_2. In addition, the Sellmeier equations were used to determine the material dispersion in both core and cladding [9]. Using these parameters, the response was calculated for a uniform LPG with a period (Λ)

of 300 μm, length (L) of 5 cm, coupling coefficient (κ) of 0.35 cm^{-1}, and a dc component of the UV-induced index change of 1.4×10^{-3}. The response was obtained for the 8^{th} order cladding mode, because this combination of mode order and grating period provides high sensitivity to the external index variation. Figure 1 shows the change in the central wavelength as the external index increases from 1.0 to 1.6. It can be observed that the refractometric sensor response is non-linear and decreases pronouncedly as n_3 approaches n_2. When $n_3 \approx n_2$ the loss band almost disappears. Also, for $n_3 > n_2$, this loss band reappears at a much higher wavelength [6]. According to Eq. (1), λ_i can be modified if there is a change in the effective index difference $[\Delta n_{eff} = (n_{co}^{eff} - n_{cl,i}^{eff})]$ or in Λ. These considerations suggest that a certain variation of n_2 and Λ, along the grating, may modify the response for a particular interval of n_3, especially if the grating has regions where n_2 is less than some values of n_3 inside the interval. This is because those regions will not contribute to the grating center wavelength, since they experience a wavelength shift and can be neglected within the grating wavelength working range. Thus, in order to obtain a modified response, it is necessary to design a non-uniform LPG in which the cladding index, or both the cladding and the core indexes, and the grating period vary longitudinally.

3. Simulation and results

To show the characteristic response linearity of a non-uniform LPG, a grating photoinduced in the fiber described above and illustrated in Fig. 2a is proposed. Such a grating has total length $L = 5$ cm, $\kappa = 0.35$ cm^{-1}, and a longitudinal linear variation of n_1 and n_2, as shown in Fig. 2b, maintaining the index difference $(n_1 - n_2)$ constant. It also has a particular period chirp, which is also shown in Fig. 2b.

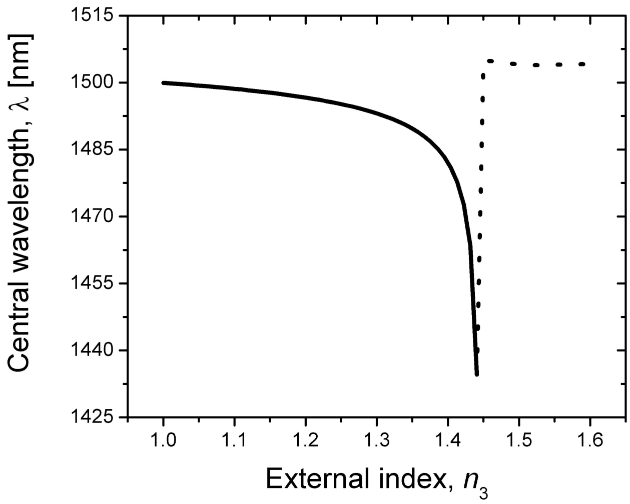

FIGURE 1. Central wavelength calculated for the loss band corresponding to the 8^{th} order cladding mode, for an LPG with $\Lambda = 300$ μm, $L = 5$ cm, and $\kappa = 0.35$ cm^{-1} as a function of n_3.

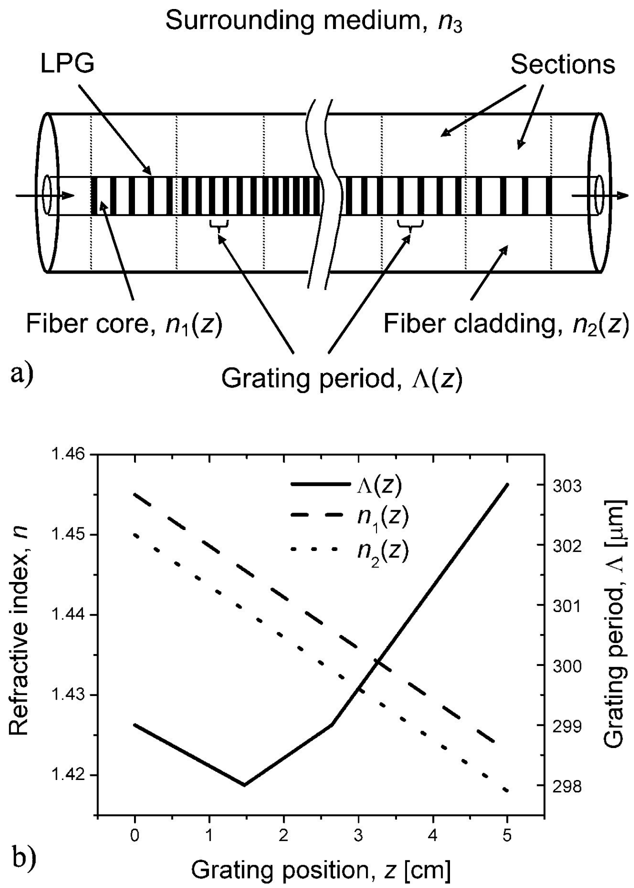

FIGURE 2. Non-uniform LPG proposed to obtain a linear characteristic response as a function of n_3, (a) schematic diagram of the LPG, grating sections are indicated by dotted lines and (b) longitudinal linear variation of n_1 (dashed line) and n_2 (dotted line), preserving $(n_1 - n_2)$ constant along the grating, and period chirp (solid line).

Since the LPG spectral response was calculated using the fundamental matrix approach [10], the grating was divided into $M = 17$ sections, each having a length of L/M.

Figure 3 illustrates the change in the central wavelength of three different gratings. Firstly, a uniform LPG (a) with $n_1 = 1.450$, $n_2 = 1.445$, $\Lambda = 300.4$ μm, $L = 5$ cm, and $\kappa = 0.35$ cm^{-1}. Then, a non-uniform LPG (b), with the same characteristics as the proposed grating above, except that it has a constant period of 300 μm. Finally, the proposed grating (c). Note that for external index values from 1.41 to 1.44, the two non-uniform gratings response presents ripples, due to the grating segmentation; in other words, a ripple appears when the external index nearly matches the cladding index of one section, so that the effect of this section is neglected, producing a slight wavelength shift to a greater value. However, if the LPGs are modeled by a greater number of sections or by a continuous method, these ripples will disappear. Also note that grating c has a response with a higher degree of linearity than gratings a and b in the external index range from 1.41 to 1.44.

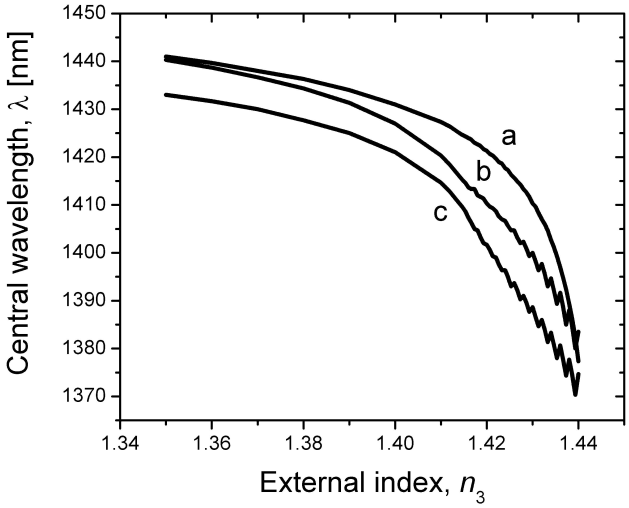

FIGURE 3. Central wavelength calculated for three LPGs with $L = 5$ cm and $\kappa = 0.35$ cm^{-1}, as function of n_3: a) a uniform LPG with n_1 = 1.450, n_2 = 1.445, and $\Lambda = 300.4$ μm; b) a non-uniform LPG with a longitudinal linear variation of n_1 and n_2 as shown in Fig. 2b, and Λ = 300 μm; c) the proposed non-uniform LPG with a longitudinal linear variation of n_1 and n_2, and a period chirp as shown in Fig. 2b.

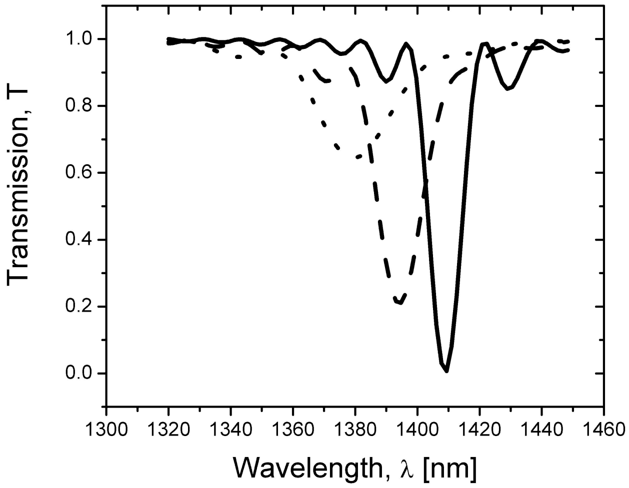

FIGURE 4. Calculated transmission loss bands of LPG c, for $n_3 = 1.415$ (solid line), $n_3 = 1.425$ (dashed line), and $n_3 = 1.435$ (dotted line).

The calculated transmission loss band of LPG (c), for three distinct values of the index of refraction of the surrounding medium, within the device linear range, is shown in Fig. 4. The change in the grating central wavelength can be appreciated, as well as the attenuation magnitude for these three examples, which is considered to have a proper value to be detected by an optical spectrum analyzer.

4. Discussion

The values of the parameters for grating c were chosen according to the results obtained in the simulation of several different LPGs. Once the range of such parameters has been found, an optimization method can be applied in order to find the values that best fit a linear characteristic response. A universal optimization approach is the use of a Genetic Algorithm (GA) [11]. Such a technique will find optimal parameters for each section, intended to best fit the grating response to a linear shape.

Optical fibers with a longitudinal variation of the core and cladding refractive indexes can be manufactured using a modification of the vapor-phase axial deposition technique [12]. A preform, with a longitudinal variation of the refractive index, may be fabricated; then the fiber can be drawn, so that it has a continuous index change of about 2% of the core or cladding indexes within a length of tens of centimeters. The technique of ion implantation may also be employed for this purpose [13,14]; it can be carried out in a wafer, cut from a silica preform. Once the implantation and annealing processes have been performed, the wafer must be joined to the original preform, in order to draw the fiber. A section of fiber a few centimeters long, with an index change up to 30% in the longitudinal index profile, can be obtained.

The fabrication of the designed gratings may be carried out by the point-by-point writing technique with a carbon dioxide laser, in silica single-mode fibers manufactured with one of the above technologies. For example, the method described in [15] is appropriate for this purpose.

5. Conclusions

The characteristic response of a refractometric sensor, based on a uniform LPG, is non-linear. It has been shown that such a response becomes linear for a specific external index range, if a non-uniform LPG is properly designed, in which the core and cladding refractive indexes and the local period vary with a certain pattern. Furthermore, some regions or sections of the grating must have a cladding index less than the index of the surrounding medium, within an interval close to the upper limit of the working refractive index range of the device, because in this interval those sections experiment a shift to a somewhat higher wavelength value and do not contribute to the measured loss band. In addition, a genetic algorithm can be used in order to optimize the refractometric response, in other words, to find the index and period values of the LPG sections that yield the most linear change in the central wavelength.

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