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Global overview of the sensitivity of long period gratings to strain

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ABSTRACT

This paper presents the results of a statistical study of the influence of radial and axial strain on the cladding modes of long period gratings (LPG). Ten thousand gratings were randomly chosen in a parameter space and their sensitivities to strain in the range $[-1000\ \mu\epsilon;\ +1000\ \mu\epsilon]$ were calculated. Cross-sensitivity to axial and radial strain was found to be generally very weak and can be neglected. However, a linear correlation between the sensitivities to axial and radial strain was found. The greatest sensitivities to axial strain were found in the range -0.55 pm/$\mu\epsilon$ to -2 pm/$\mu\epsilon$ and to radial strain between -0.3 pm/$\mu\epsilon$ and 0.5 pm/$\mu\epsilon$. The absolute values of the sensitivities to axial and radial strain were found to decrease with the cladding radius and the grating period. The coupling coefficient is slightly affected by the strain. The LPGs with the smallest claddings and smallest periods exhibited the highest coupling coefficient and the highest sensitivities to strain.

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1. Introduction

In 1978, Hill et al. [1] demonstrated that it was possible to induce a periodic modulation of the refractive index of the core of an optical fiber with light. This gave rise to intense research on optical fiber gratings, from which two principal structures emerged. The most commonly known is the fiber Bragg grating (FBG) [2]. The second is the long period grating (LPG) [3–5]. The period of modulation of FBGs is of the order of a few hundred nanometers, while the period of LPGs is of the order of a hundred microns.

This difference in modulation period leads to significant differences in their behavior. An FBG inscribed in a single mode fiber couples the incident core mode to the contra-propagative core mode. This means that the light is transferred by the grating from the mode propagating in the forward direction to the mode propagating in the backward direction. The degree of coupling depends on the wavelength. It is maximal for the resonant wavelength, called the "Bragg wavelength". In consequence, the reflection spectrum of the grating exhibits a peak centered on the Bragg wavelength, while its transmission spectrum exhibits a hole around this wavelength.

An LPG couples the core mode to several co-propagative cladding modes. Again, each coupling is maximum for a resonant wavelength, which differs from one mode to another. Because of the coupling, light is injected in the cladding and finally flows out of the fiber due to inhomogeneities. The transmission spectrum then exhibits holes around all resonant wavelengths.

This property of an LPG makes it useful in sensors: any external influence which modifies the period of modulation or the refractive index of the fiber shifts the resonant wavelengths. The measurement of these shifts allows the strength of the influence to be retrieved. The influence of temperature, strain and the refractive index of the surrounding medium on the LPG has been widely studied (see for example [6–8]). However, the sensitivity of LPGs to strain remains an open question for two reasons. Firstly, LPGs are complex systems which contain several independent parameters. Most published studies consider a basic configuration and then vary each parameter individually. Results obtained in this way are valid for the original configuration but lack generality. Secondly, in all the studies the radial strain is assumed to be linked to the axial strain via Poisson's ratio. This is true if the fiber is fixed at two points on a monitored structure and free to deform in the transverse plane. But it can be completely wrong if the fiber is embedded in a host material [9,10], where it is necessary to study the sensitivity of LPGs to axial and radial strain simultaneously. The aim of this paper is to remedy this gap, and produce results useful for the design of real-world strain sensors based on LPGs.

Using a statistical approach, we explored a parameter space using ten thousand random samples. Our methodology is explained in Section 2. Section 3 is devoted to the study of the cross-sensitivities, and presents new findings on the relationship between axial strain sensitivity and radial strain sensitivity. The influence of the various parameters is presented in Section 4. Section 5 presents the influence of the parameters on the coupling coefficient. We conclude with a presentation of some rules to optimize the sensitivity of LPGs to strain.

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2. Methodology

2.1. Parameter space

Each LPG has a characteristic periodic modulation of the effective index of the mode propagating in the core. This modulation can be obtained either by modifying the geometry of the fiber or by inducing a variation of the refractive index of the core with UV illumination. In the following, we will consider the latter case.

The fiber is made of two concentric cylinders: the core and the cladding (see Fig. 1). The radius of the core is a_1 and the radius of the cladding is a_2. The refractive index of the core is n_1, of the cladding n_2, and the surrounding medium n_3. The extension of the surrounding medium is assumed to be infinite since it is several orders of magnitude greater than the wavelength.

A uniform LPG is characterized by 4 parameters: the period of the index modulation Λ_{LPG}, the amplitude of modulation Δn_{LPG}^{dc}, the mean effective index Δn_{LPG}^{dc} and the length of the grating L. We assume that the gratings have a uniform azimuthal refractive index profile in the cross-section of a fiber, but it should be noticed that some gratings fabricated by CO_2 laser or UV illumination might have a non-uniform azimuthal refractive index profile [11,12]. This non-uniformity may induce a shift in the resonant wavelength of the order of a few percent.

The LPG couples the mode propagating inside the core to cladding modes. The sensitivity of the LPG to an external constraint varies from one cladding mode to another, depending on the order of the mode m.

This means there are 10 independent parameters in the system: a_1, a_2, n_1, n_2, n_3, Λ_{LPG}, Δn_{LPG}^{ac}, Δn_{LPG}^{dc}, L and m. It is possible to reduce this complexity. Firstly, L is not a relevant parameter: the resonant wavelength does not depend on it and the coupling strength evolves periodically with L. It is always possible to choose a length which maximizes the degree of coupling. In the rest of this paper, we will consider that this choice has been made. This implies that the values of L are not independent, but dependent on the other parameters. Secondly, the coupling coefficient [3,13,14] directly depends on Δn_{LPG}^{ac} and Δn_{LPG}^{dc}. In this paper, we will consider a normalized coupling coefficient. Moreover, the resonant wavelength does not depend on Δn_{LPG}^{ac}, so it is unnecessary to include it as a study parameter. We will assume that Bhatia's result for Δn_{LPG}^{dc} ([7], p179) can be generalized, causing a constant shift of resonant wavelength. We will focus on the standard SMF28 telecommunication fiber, since it is widely used. The core radius of an SMF28 fiber is: $a_1 = 4.2\ \mu m$. Its refractive index is determined by a mixed Sellmeier law [15] :

$$n^2(\lambda) = 1 + \sum_{i=0}^{3} \frac{\left[A_i^{SiO_2} + x\left(A_i^{SiO_2} - A_i^{Ge_2O}\right)\right]\lambda^2}{\lambda^2 - \left[\lambda_i^{SiO_2} + x\left(\lambda_i^{Ge_2O} - \lambda_i^{SiO_2}\right)\right]^2} \quad (1)$$

where $A_i^{SiO_2}$, $A_i^{Ge_2O}$, $\lambda_i^{SiO_2}$ and $\lambda_i^{Ge_2O}$ are the Sellmeier coefficients for SiO_2 and Ge_2O given in Table 1, and x is the molar concentration of Ge_2O. The cladding is made of quenched SiO_2. Its refractive index is given by the classical Sellmeier law [6]:

$$n^2(\lambda) = 1 + \sum_{i=0}^{3} \frac{A_i^{SiO_2}\lambda^2}{\lambda^2 - {\lambda_i^{SiO_2}}^2} \quad (2)$$

The coefficients in Eqs. (1) and (2) are given in Table 1. The molar concentration x is chosen so that $n_1 = 1.0036\, n_2$ for $\lambda = 1550$ nm corresponds to the value obtained in an SMF28 fiber.

We have thus reduced the number of free parameters to four, namely: a_2, n_3, Λ_{LPG} and m. We then used a statistical approach to explore this parameter space. First we defined a configuration $\{a_2, n_3, \Lambda_{LPG}, m\}$ by randomly choosing parameters in the following ranges:

- $a_2 \in [15\ \mu m;\ 70\ \mu m]$: the lower limit ensures that the core mode is not influenced by the surrounding medium. The upper limit is of the order of the size of the cladding in a standard SMF28 fiber.
- $n_3 \in [1;\ n_2[$: the refractive index of the surrounding medium must be strictly inferior to the refractive index of the cladding for the cladding modes to be guided.
- $\Lambda_{LPG} \in [200\ \mu m;\ 600\ \mu m]$: these are common values (see for example [6,8,16–18]).
- $m \in [1, 20]$: the upper limit is sufficient for the results to be significant, since it is known that high order modes have a negligible coupling coefficient [14].

The density of probability is uniform for each parameter. However, the configurations do not have the same probability of appearing since we also restrict the resonant wavelength to the range [1350 nm; 1700 nm], whatever the strain. This range contains the bands E, S, C and L defined by the International Telecommunication Union, which are most commonly used.

2.2. Determination of the sensitivity to strain

When a particular configuration $\{a_2, n_3, \Lambda_{LPG}, m\}$ was chosen, we first determined its resonant wavelength λ_{LPG}^m at rest. It is given by the condition of resonance for LPG [14] :

$$\lambda_{LPG}^m = \left[n_{eff}^{core}\left(a_i, n_i, \lambda_{LPG}^m\right) - n_{eff,m}^{clad}\left(a_i, n_i, \lambda_{LPG}^m\right)\right]\Lambda_{LPG} \quad (3)$$

where $n_{eff,m}^{clad}$, the effective index of the mth mode is given by the dispersion equation of the cladding modes [14] :

$$F_g\left(a_1, a_2, n_1, n_2, n_3, n_{eff}^{clad}, \lambda\right) = 0 \quad (4)$$

and n_{eff}^{core}, the effective index of the core mode, is given by the dispersion equation of the core mode [14] :

$$F_c\left(a_1, n_1, n_2, n_{eff}^{core}, \lambda\right) = 0 \quad (5)$$

These three coupled equations are solved with a bisection method.

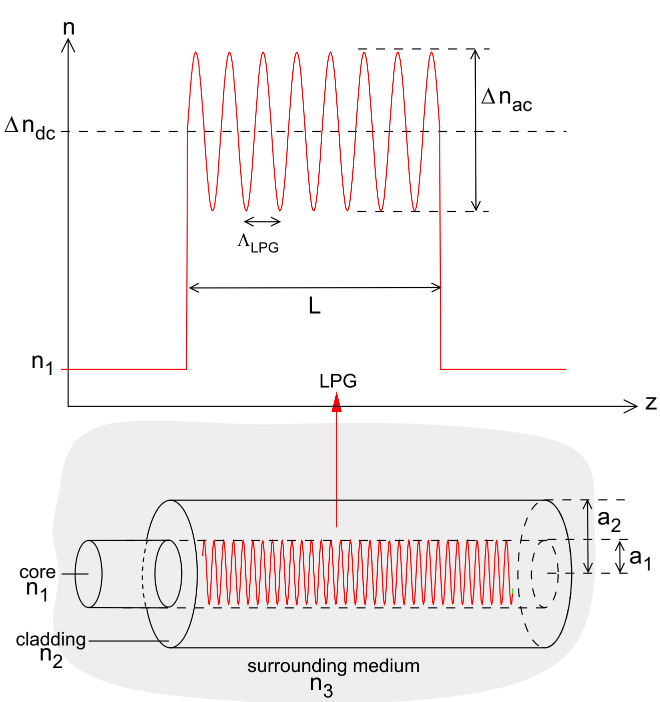

Fig. 1. Long Period Grating.

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