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Development and analysis of a model based on chirped fiber Bragg gratings employed for cracks characterization in materials

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ABSTRACT

In this work a model was developed that allows to understand the behavior of a chirped fiber Bragg grating for the detection and characterization of cracks in materials. In addition to the amplitude response, we show that the group delay of the grating provides useful information for the characterization of the crack. The position of the crack can be determined thanks to the linear chirp of the grating that fixes a correlation between the spatial position and both, the wavelength and the group delay. However, our analysis shows that this simple approach has a source of error, which can be overcome if a controllable external strain can be applied to the embedded grating, additional to the strain generated by the embedding process. Thus, the width of the crack can be also estimated. The effect of the appearance of a crack on the grating generates simple o multiple transmission peaks that are analyzed considering the behavior of a Fabry–Perot fiber cavity. This simple model was experimentally tested and preliminary results were in good agreement with the simulations.

1. Introduction

The interest of the aerospace industries in structural health and monitoring systems is continuously increasing. Among the techniques available in literature those based on Fiber Bragg Grating (FBG) sensors are much promising thanks to their peculiarities [1,2] In comparison with the traditional mechanical and electrical sensors, the optical fiber sensors possess some unique advantages such as small size, light weight, immunity to electromagnetic interference (EMI) and corrosion, embedding capability, and therefore they have been employed in monitoring of engineering structures worldwide [3]. Bettini et al. [1] started from a numerical model capable of simulating the spectral response of a grating subjected to a generic strain profile. While a standard uniform FBG can transduce only the average strain on its total length, a chirped one is able to provide direct information about the strain distribution profile along the grating itself. In fact, having a variable grating period, this kind of sensors has in principle a one-to-one correspondence between reflection spectrum wavelength and position on the perturbation [1]. Linear chirped Bragg gratings (linear CFBG) have a period that increases monotonously, the Bragg wavelength changes linearly with the position. Because of this, the reflectivity spectrum becomes broad. Under convenient conditions, the spectrum wavelengths can be related with the position along the grating. Thus, embedded CFBG have been proposed for the identification of crack location in composites [4,5] and disbonding in composite joints [6]. More recently, an experimental study of fatigue damage development in composite patch repairs using CFBG has been reported [7]. These works based on CFBG extract the information from the measurement of the reflection spectra assuming the one-to-one correspondence between reflection spectrum wavelength and position on the perturbation.

In addition, some advances on chirped Bragg gratings in polymer fibers have been reported. Chirped fiber Bragg gratings were photo-inscribed in undoped PMMA polymer optical fiber using an UV KrF excimer laser operating at 248 nm. The evolution of the reflection spectrum was investigated as a function of the applied strain, temperature, and pressure, and one of the proposed applications was sensing transverse cracks in structural health monitoring [8,9].

Nevertheless, an exhaustive study of the system has not yet been carried out. The contribution of the work presented here lies in the development of a rigorous model that allows a deep understanding of how a CFBG behaves when it is altered by the appearance of a crack in a

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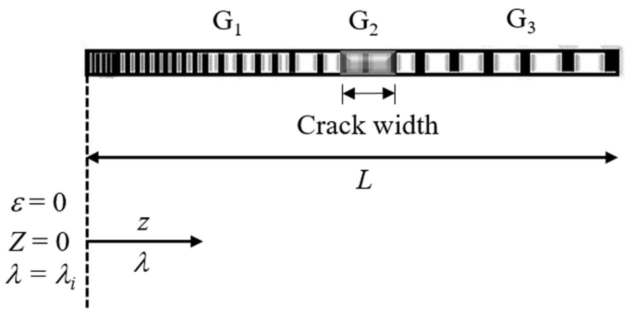

Fig. 1. Scheme of CFBG with a crack, as it is assumed in the simulations.

material. This allows to determine not only the location of the crack but also its size. It is shown that, in addition to the conventional analysis of the amplitude response of the grating, it is possible to perform the aforementioned characterization using only the phase response i.e., the group delay spectrum of the grating. The CFBG is modeled by using the T-matrix method [10,11]. In order to model the development of a crack, we assume that a differential strain will appear between the uniformly embedded part of the grating and the part of the grating that overlaps the crack. In addition, we show that if an external and controllable strain is applied to the embedded CFBG, then more detailed information can be obtained. After our rigorous analysis, we are able to provide a simple model in terms of an effective Fabry–Perot that accounts for most of the results obtained with the numerical simulations. This model takes into account the penetration of light in a reflecting FBG, which defines the effective length of a FBG [12]. Finally, some preliminary experimental results are also provided.

2. Device model

A CFBG can be used to detect the appearance of cracks in materials (e.g., polymers, compounds, cement, etc.), which can be part of structures such as bridges, buildings, roads, aerospace vehicles, automobiles, among others. These cracks can be generated during the manufacturing process or hardening (setting) of the material, by the action of loads applied to it, by aging of the structure or by accidental damage. To perform this detection, the grating can be embedded or superficially fixed on the material. The model proposed here allows the detection of cracks transverse to the grating, and in a first approximation it is considered that the fissure is generated in a certain instant and its size remains invariant. Specifically, this paper attempts to establish a technique for unambiguously determining the position and width of cracks that may appear in the material. The basic idea is to assume that, once the CFBG is embedded in a given material as for example a composite, it is subjected to a differential strain between the sections correctly embedded and the section that overlaps a crack. We assume that some strain (ε) is generated in the material during its setting, and that cracks can appear in this process. Initially, the embedded CFBG will be subjected to an unknown strain, which will be different in the small portion of the grating overlapping the crack. Afterwards, we will consider also that an additional and calibrated strain can be applied to the CFBG, modulating the differential strain between the overall CFBG and the section overlapping the crack. Fig. 1 shows the gratings scheme considered in the analysis with a crack in $z = L/2$, where L is the total length of the CFBG.

In order to simulate the differential strain in a simple way, we assume in our model that the grating portion overlapping the crack (G2) is strain free and its spectral properties remain unchanged, while the portions G1 and G3 will be affected by a uniform strain. Given the linear chirp of the CFBG, there is a bi-univocal relationship between the z-position and the corresponding wavelength variation, i.e. each spectral position of the grating corresponds to a spatial position z.

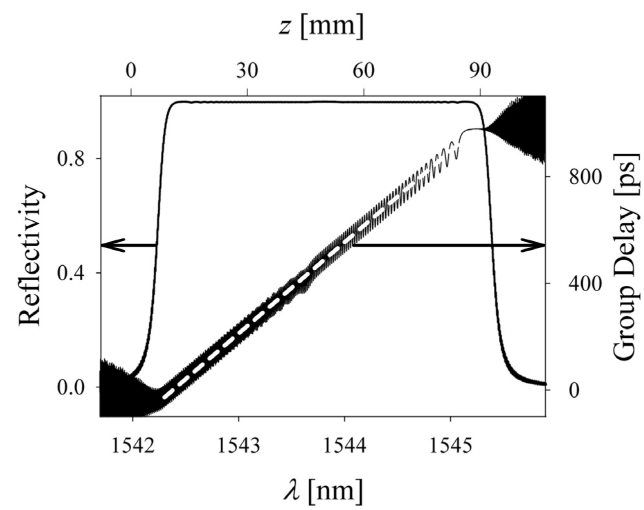

Fig. 2. Computed reflectivity and group delay for the initial CFBG. The white dashed line is the average chromatic dispersion that fits the numerical values.

3. Numerical simulation

For our numerical simulations, we consider a grating linearly chirped (Fig. 2). A defect (simulating a crack) is assumed in a given spatial position, for example in the middle of the grating, with different widths from 1 to 6 mm. The original grating (without strain) has the following parameters: length L = 10 cm, refractive index amplitude modulation $\delta n = 2.3 \times 10^{-4}$, initial period $\Lambda_i = 514$ nm, final period $\Lambda_f = 515.1$ nm, effective refraction index of the mode n_{eff} equal to 1.5. The CFBG reflection band has the initial and final wavelengths λ_i and λ_f equal to 1542.31 nm and 1545.31 nm, respectively, which determine a linear chirp $C = (\lambda_f - \lambda_i)/L = 30$ pm/mm. Assuming a negligible fiber dispersion, the group velocity $v_g = c/n_{eff}$ determines the nominal group delay in reflection, per unit length $[\tau(\lambda_f) - \tau(\lambda_i)]/L = 2(v_g)^{-1} = 10$ ps/mm. Finally, the nominal chromatic dispersion of the grating when it is operated in reflection will be $[\tau(\lambda_f) - \tau(\lambda_i)]/(\lambda_f - \lambda_i) = 2(Cv_g)^{-1} = 333$ ps/nm.

Fig. 2 gives the computed reflectivity and group delay spectra for the CFBG, using the Transfer Matrix Method [10]. In it, we have included the average chromatic dispersion (white dashed line) that is obtained by fitting the central part of the plot. The slope of the average chromatic dispersion is 342 ps/nm and the origin $\tau = 0$ is at $\lambda = 1542.39$ nm.

As it will be shown later, when some strain is applied to the CFBG (over G1 and G3, because G2 is not affected) changes are observed on the reflection spectrum and the group delay of this system. We assume a standard dependence of the silica refractive index (n_{Silica}) with the strain (ε): $\delta n_{Silica}/n_{Silica} = -p_e\,\varepsilon$, being $p_e = 0.21$ [13].

3.1. Spectral characteristics

Next, we will analyze the changes generated in the system due to the application of a strain. To understand how the deformation affects the behavior of the CFBG, in Fig. 3 the different spectral sections of the total grating are shown schematically versus wavelength. It is observed that, under a certain strain, two portions (G1 and G3, see Fig. 1) move in the same direction towards longer wavelengths. However, since the strain over G2 is zero, it does not shift with strain, but it overlaps with G1. While G1 and G3 are spectrally displaced by applying an external stress on the CFBG, G2 remains unchanged at its original spectral position. In addition, a spectral window appears between G1 and G3, from the absence of the contribution of G2 in the total spectrum of the grating (see Fig. 4). From a spectral point of view, a positive longitudinal deformation generated on gratings G1 and G3 (G2 is fixed), causes