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Analytical model for a polymer optical fiber under dynamic bending

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ABSTRACT

Advantages such as sensibility in bending, high fracture toughness, and high sensibility in strain enable the application of polymer optical fibers as sensors for strain, temperature, level, and for angle measurements. In order to enhance the sensor design, this paper presents an analytical model for a side polished polymer optical fiber under dynamic bending. Differently from analytical models that use only the geometrical optics approach with no correction for the stress-optical effects, here the refractive index is corrected at every bending angle to consider the stress-optical effects observed polymer optical fibers. Furthermore, the viscoelastic response of the polymer is also considered. The model is validated in quasi-static and dynamic tests for a polymer optical fiber curvature sensor. Results show good agreement between the model and the experiments.

1. Introduction

Over the years a new trend for optical fibers application has been observed. Silica fibers, which still are more employed for communications purposes, began to be applied in sensors due to several advantages over traditional measurement technologies for strain, temperature, angle, level, among others. The advantages include lightweight, magnetic fields immunity and multiplexing capabilities [1]. An alternative to the silica fibers is the polymer optical fiber (POF) that, in general, presents lower cost. Although, POF systems have higher transmission losses, which limit its application to short distance communications [2], it has some advantages over silica fibers for sensor applications, such as high sensitivity in bending, high fracture toughness, and high sensitivity in strain [2]. Among the applications for POFs are angle [3], liquid level [4], temperature sensors [5], and accelerometers [6].

An important step before the analytical modelling of the curvature sensor is its characterization. Vallan et al. [7] proposed a static characterization of the POF strain. The characterization was made on a rectangular and a trapezoidal cantilever to apply the POF as a deflection sensor for these structures. Similar characterization is made on Lomer et al. [8] to obtain a liquid level sensor based on the attenuation of the signal due to the fiber bending. Moraleda et al. [5] characterize the fiber response on a certain geometry to obtain a temperature sensor based on the fiber bending. Donno et al. [3] presented a curvature sensor based on POF for knee angle measurements.

In order to quantify and simulate the effects on a bending fiber, some effort has been made to obtain analytical models for an optical fiber under this condition. Most of these methods are derived from [9], where the author calculates the electrical and magnetic fields for a curved waveguide and achieves a curvature loss formula for optical fibers. Marcuse [10] improves the curvature loss formula for the case of a multimode fiber. However, it requires knowledge of the propagation constant variation with the optical fiber bending. Although these models achieved good results for static analysis, the attenuation also has variation on the geometry of the bending. In other words, the attenuation of the fiber bend in a circular geometry is different from a fiber bend in an ellipsoidal shape [11].

Therefore, it is necessary to consider the fiber geometry in bending. The following models have the experimental validation made in an optical fiber bending setup with circular shape. Some models are applicable only to POFs. The difference in these models is that only the geometrical optics are applied, which is a good approximation for POFs considering that, generally, they are employed for sensing in short distances and present higher numerical aperture than silica fibers [1].

The model for a POF sensor with a sensitive zone depends upon the length and depth of such zone. Moreover, it also depends on the geometry of the lateral section. The lateral section can be made by a continuous section or can also be a toothed region with specific characteristics for the teeth shape (angle, length and depth). Fu et al. [12] described the POF curvature sensor principle of operation and proposed a model for static measurements. Kovacevic

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et al. [13] provided an analytical model for the parameters optimization of a POF with toothed sensitive zone. Although it is a feasible technique to predict the lateral section parameters and the signal attenuation in bending on static conditions, the fabrication process itself is a major limitation. If it is desired an optimized sensor, the dimensions of the fiber and the sensitive zone require a precision drilling [13]. Bilro et al. [14] presents a very similar model. However, in this case, it is a model for a continuous section on the sensitive zone.

None of the models discussed above considered the influence of the fiber bending load characteristics on the signal output. A POF under a pure bending load condition presents changes on its refractive index, which depends on the stress tensor applied on the fiber and on its structure, geometry, and physical properties [15]. Furthermore, the polymer is a viscoelastic material and its characteristics have to be included on the stress-optical analysis.

This paper presents an analytical model for dynamic bending of a POF, which is based on the geometrical optics approach combined with the stress-optical analysis and viscoelastic models. The validation is performed with two different experimental setups: one using a goniometer for quasi-static tests and another using a servomotor for dynamic measurements. Moreover, the POF curvature sensors analyzed have different lateral section parameters and are analyzed under different angular velocities. The analysis of different POF sensors in different experimental setups and different dynamic conditions prove the robustness of the model.

This paper is divided as follows. Section 2 presents the model derived from geometrical optics. In Section 3, the geometrical optics model is integrated with the viscoelastic and stress-optical effect on the fiber refractive index. Section 4 presents the validation of the model proposed. Section 5 presents the final remarks of the paper and future works suggestion.

2. Geometrical optics model

A typical POF sensor for curvature measurements employs a POF with a lateral section, which creates a sensitive zone to increase the sensor sensitivity and linearity of the signal attenuation when the fiber is bending. A POF without any modification has a circular cross-section with three layers: core, cladding and jacket. The core section conducts most part of the optical signal due to its higher refractive index than the cladding and the jacket provides only mechanical and chemical protection. Light losses happen due to absorption and frustrated total internal reflection when in contact with the surface [1]. As the bending occurs, the incident angle increases and creates a variation on the transmission mode. When the sensitive zone of the fiber is bending, there are more losses due to the absence of the cladding in that region, increasing the radiation losses. Another source of loss is the surface scattering caused by the coupling between higher and lower guided modes [16].

Fig. 1 shows the fiber geometry considered in the POF sensor modelling. This figure is out of scale, since the diameter of fiber core is not much smaller than the cladding part as observed in practical perspective. The sensitive zone along the curvature region is represented by the section length given by c. p denotes the depth of removed material on the fiber core. The optical fiber length in Fig. 1 is given by L, meanwhile the optical fiber diameter is d, and the curvature radius is R. This will compose the sensitive zone for sensing the curvature.

The optical power coupled to the POF sensor is modeled under geometrical optics concepts, as considered by [13], and written as,

$$dP = 2\pi L_0 \cos(\theta)\sin(\theta) d\theta dS. \tag{1}$$

where (dP) is an element power radiated into a solid angle $d\Omega$ subtended by a section (dS) at an angle ($d\theta$). L_0 is the light source radiance.

The integration of (1) over the cross sectional area gives the input power of the model to be coupled to the fiber sensor, where a is the optical fiber core radius, and θ_c is the critical angle.

$$P_{in} = \pi^2 L_0 a \sin^2(\theta_c). \tag{2}$$

Assuming an uniform mode distribution, where the light source has constant radiance, it can be defined [13] from the parameters of Fig. 1, the difference of the fiber core cross sectional area (S_C) and the maximum area of removed material (S_o) as,

$$S_C - S_o = \frac{\pi a^2}{2} + a^2 \arcsin\left(\frac{a-p}{a}\right) + (a-p)\sqrt{a^2-(a-p)^2}. \tag{3}$$

Eq. (3) defines the cross section of the sensitive zone, which is critical for the evaluation of the P_S, the optical fiber sensitive zone power. P_S can also be defined as the remaining power when it enters the sensitive zone, i.e.,

$$P_S = \pi L_0 (S_C - S_o)\sin^2(\theta_c). \tag{4}$$

Furthermore, a loss of power due to partial transmission can occur when the light meets the side-polished interface [13]. Since this is a dielectric media, the losses are calculated through the Fresnel's equations and the reflection coefficient (r_T) for an unpolarized light is,

$$r_T = \frac{(r_{PP}^2 + r_{PL}^2)}{2}, \tag{5}$$

where r_{PP} is the reflection of the perpendicular rays and r_{PL} is the reflection of parallel rays, defined as,

$$r_{PP} = \frac{\sin(\theta_p) - \sqrt{\frac{1}{n_C^2} - \cos^2(\theta_p)}}{\sin(\theta_p) + \sqrt{\frac{1}{n_C^2} - \cos^2(\theta_p)}}, \tag{6}$$

$$r_{PL} = \frac{\frac{1}{n_C^2}\sin(\theta_p) - \sqrt{\frac{1}{n_C^2} - \cos^2(\theta_p)}}{\frac{1}{n_C^2}\sin(\theta_p) + \sqrt{\frac{1}{n_C^2} - \cos^2(\theta_p)}}, \tag{7}$$

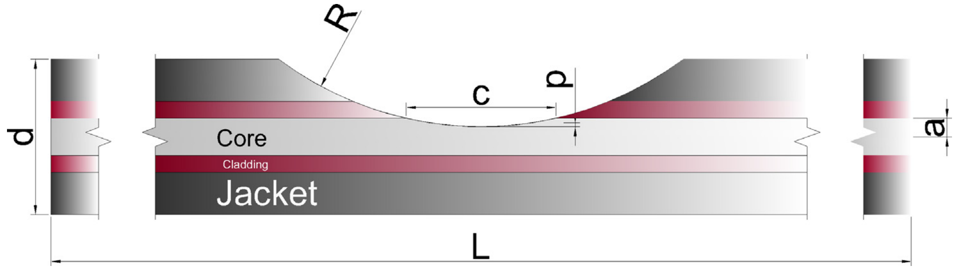

Fig. 1. Section view of the POF sensor analyzed.