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Sensitive zone parameters and curvature radius evaluation for polymer optical fiber curvature sensors

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ABSTRACT

Polymer optical fibers (POFs) are suitable for applications such as curvature sensors, strain, temperature, liquid level, among others. However, for enhancing sensitivity, many polymer optical fiber curvature sensors based on intensity variation require a lateral section. Lateral section length, depth, and surface roughness have great influence on the sensor sensitivity, hysteresis, and linearity. Moreover, the sensor curvature radius increase the stress on the fiber, which leads on variation of the sensor behavior. This paper presents the analysis relating the curvature radius and lateral section length, depth and surface roughness with the sensor sensitivity, hysteresis and linearity for a POF curvature sensor. Results show a strong correlation between the decision parameters behavior and the performance for sensor applications based on intensity variation. Furthermore, there is a trade-off among the sensitive zone length, depth, surface roughness, and curvature radius with the sensor desired performance parameters, which are minimum hysteresis, maximum sensitivity, and maximum linearity. The optimization of these parameters is applied to obtain a sensor with sensitivity of 20.9 mV/°, linearity of 0.9992 and hysteresis below 1%, which represent a better performance of the sensor when compared with the sensor without the optimization.

1. Introduction

Human kinematics assessment has become a need in clinical evaluations, rehabilitation exercises, pathologies diagnosis, and surgical interventions [1]. Among many techniques for joint angle assessment, the video-based technique provides the most reliable results and is the gold standard [2]. However, it is a costly and time-consuming technique, which is limited to laboratory environment [3]. In order to achieve a portable and wearable technique for angle measurement, electrogoniometers and potentiometers have been used in single axis measurements. Nevertheless, they are bulky and may limit natural pattern of human movement [4]. Inertial measurement units (IMU) overcome the disadvantages associated with previously mentioned techniques, but they are sensitive to electromagnetic interferences and demand frequent calibration [5]. Furthermore, IMUs can present high errors on the angle measurement [6].

Advances in polymer process and manufacturing technologies enable the growth of polymer optical fiber (POF) sensors. In general, optical fiber systems for sensing applications are compact, lightweight, allow multiplexing systems, and present immunity to electromagnetic interference [7]. Furthermore, POFs have intrinsic advantages over silica optical fiber for sensors applications, such as large core diameter, which allows the application of low precision connectors. POFs also present more resistance to impact and vibrations, and higher strain limits that make them more flexible and easy to handle [8].

POF sensors can be applied in structural health monitoring [9], biomedical applications [10], rehabilitation purposes [11], among others. The methods and principle of operation for POF sensors include specklegram analysis to obtain a strain sensor [12]. The principle of light coupling between two or more fibers can also be applied as accelerometers [13] and liquid level measurement [14]. Moreover, the variation of the light reflection is a sensing principle applied as a displacement sensor [15].

Although there are many other operation principles under development for POF sensors, intensity variation is one of the most commonly used principle, due to its ease of implementation, good price-quality ratio, and simplicity in signal processing [7].

A very common approach for intensity modulation sensor is to measure the signal attenuation on a fiber under bending. Moraleda et al. [16] developed a macrobending based temperature sensor. The working principle is based on variations of the optical fiber

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numerical aperture due to bending radius and temperature changes. If the bending radius is constant, the changes on the numerical aperture are caused by the temperature. The sensor works between 27.2 °C and 50.2 °C with a sensitivity for a 2 mm bend radius of 1.29×10^{-3} °C^{-1}. Dunne et al. [17] developed a wearable garment-integrated curvature sensor for monitoring the seated spinal posture and a two-leaved decision tree model for posture classification evaluates the subject posture. Bilro et al. [18] develops a POF goniometer capable of measuring angles up to 90°.

Aiming at enhancing the sensor sensitivity as a function of curvature, several authors propose a lateral section on the fiber to create a region on the fiber known as the sensitive zone [19]. This process can make the optical sensor up to three orders of magnitude more sensitive to curvature changes [20]. The sensitive zone can be created through a continuous section on the fiber [21] or grooved region applying precision drilling [22].

In order to evaluate each parameter influence in the sensor performance as well as the trade-off among them, this paper presents a thorough study of the lateral section parameters of a POF sensor with continuous sensitive zone and the sensor curvature radius.

The investigation is based on experimental results for POF curvature sensor with different section length, depth, surface roughness, and curvature radii. The sensor is bent dynamically in angles between 0 and 90°. The sensor performance is evaluated with respect to the sensitivity, hysteresis, and linearity. The objective is to introduce guidelines for the choice of lateral section parameters and curvature radius. Furthermore, it presents a sensor response prediction in a POF based curvature sensor with sensitive zone.

This paper is organized as follows. Section 2 exposes the POF curvature sensor principle of operation and theoretical background. Section 3 presents the materials and methods employed for the sensor parameters experiments and analysis. The results are presented and the discussion are made in Section 4. Final remarks and future works are discussed in Section 5.

2. POF curvature sensor theoretical background

A POF curvature sensor takes advantage of the optical fiber radiation loss due the macrobend. Considering that the fiber is fixed on a rotating joint, as the angle of the joint with the normal increase, the output power decreases for positive bend. If the bend occurs on the opposite direction, the output power increases. Therefore, a POF based curvature sensor is capable of measure a single plane curvature on both directions (flexion and extension). One drawback of macrobending sensor is the nonlinearity and low sensitivity between the sensor attenuation and the bend radius. In order to increase the sensor sensitivity and linearity, a side-polish on the curvature region of the sensor was proposed [23]. The sensitivity between attenuation and bend radius can be increased if the fiber losses its cladding and part of its core.

The polished region is the sensitive zone, if only meridional rays are considered, the sensitive zone is located on the bending side of the fiber, which has an angle θi with the incident angle. As the bending occurs, the angle θi increases and creates a variation on the transmission mode [24]. In other words, higher guided modes are coupled to lower guided modes, which increase the surface scattering loss that cause the decrease of the output power. Therefore, the increase of fiber losses due to the sensitive zone makes the POF curvature sensor more sensitive to curvature. For the sensitive zone on the convex side (as presented in Fig. 1), a flexion of the fiber will lead to an increase of reflections on the convex side and a reduction on the concave side. Since the sensitive zone is on the convex side, the flexion movement results in more rays escaping when compared with the fiber at the straight position,

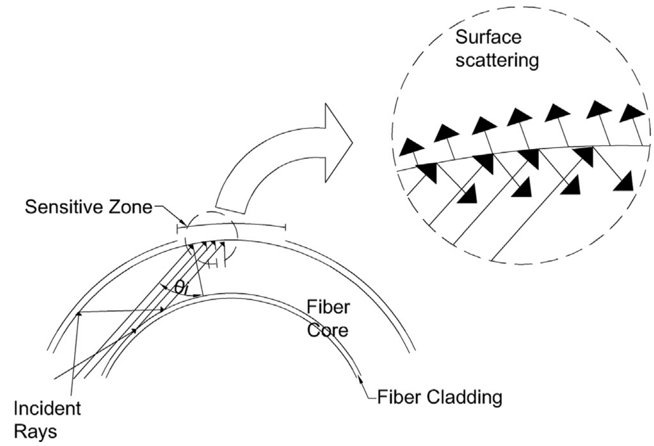

Fig. 1. Incident light and sensitive zone angle.

which leads to a reduction of optical power when compared with the fiber at the straight position. Whereas, on the extension movement, the opposite occurs, there are more reflections on the concave side, which leads to an increase of the optical power.

Fig. 1 shows the relation between the incident angle, the sensitive zone, and the surface scattering loss. The length of the polished area as well as the polishing depth affects the attenuation and refractive index of a POF and has direct influence on the sensor sensitivity [23]. Furthermore, the surface roughness affect the scattering losses, which also affects the sensor sensitivity, linearity, and hysteresis. Moreover, if the curvature radius is too small, more stress is supported by the fiber, this high stress has influence on the viscoelastic response, which may cause a variation of the sensor hysteresis, linearity and sensitivity due to the increase of the strain on the sensitive zone.

The lateral section parameters influence the sensor performance. Different section length, depth, and surface roughness provide different sensitivity, hysteresis, and linearity on polymer optical fiber sensors. Bilro et al. [23] presented an analytical model for a sensor with continuous section sensitive zone. Kovacevic et al. [25] presented an analytical model for a grooved sensitive zone. Both models presented in [23,25] are validated only on static conditions. Leal Junior et al. [26] presented an analytical model that accounts the viscoelastic response of the POF and is validated in dynamic conditions. The influence of the surface roughness on the side polish fiber surface Plasmon resonance sensor is presented in [27] and a model for the surface roughness influence on this type of sensor is proposed in [28]. However, this analysis is made for a single mode silica fiber and the sensor operation principle is different from the one presented for POF curvature sensor based on intensity variation.

Furthermore, if the fiber is under stress, there is also the stress-optical effect, which causes a variation of the POF refractive index and leads to higher signal attenuation [29]. Since the POF is a viscoelastic material, it does not have a constant response with stress or strain [30]. For this reason, the sensor curvature radius also have influence on the sensor sensitivity, hysteresis and linearity.

The sensitivity is defined as the difference between the initial sensor response, when the fiber is at 0°, and the sensor response after the bending, when the fiber is at 90°, divided by the bending limits, which is 90° in this case (Eq. (1)). Both initial and final sensor response are acquired in Volts (V) and the bending angle in degrees (°) [31].

$$Sensitivity\ (V/^{\circ}) = \frac{Po(\theta_i) - Po(\theta_f)}{\theta_f} \quad (1)$$