POLYMER OPTICAL FIBER CURVATURE SENSOR: A REVIEW AND HYSTERESIS ANALYSIS

ARNALDO G. LEAL JUNIOR, ANSELMO FRIZERA, MARIA JOSÉ PONTES

Laboratório de Telecomunicações, Programa de Pós-Graduação em Engenharia Elétrica, Universidade Federal do Espírito Santo
Avenida Fernando Ferrari, 514, Goiabeiras, 29075-910, Vitória, ES, Brazil.
E-mails: arnaldo.leal@aluno.ufes.br, frizera@ieee.org, mjpontes@ele.ufes.br

Abstract— Over the past few years, polymer optical fibers began to draw attention and research efforts for sensor applications due to its higher elastic strain limits, fracture toughness, flexibility in bend and relative low cost when compared with glass optical fibers. These advantages enable the polymer optical fiber application for measurement of strain, temperature, level, pressure, angle, among other parameters. However, optical fiber sensors present some drawbacks, such as the refractive index variation and signal attenuation with different temperature and humidity. There is also a variation on the output signal due to light source power deviation. Although the first two drawbacks can be solved through a dummy sensor technique or dual-wavelength compensation, there is a lack of alternatives for the compensation of viscoelastic effects of polymer optical fibers. This paper presents a review of polymeric optical fiber properties and sensor applications proposed throughout the years. Moreover, a quasi-static test is performed and shows a high hysteresis for sensor application. For this reason, a dynamic bending analysis is proposed for evaluation of the viscoelastic effects in frequencies higher than the fiber relaxation time. The presented experimental setup provides a compensation method for the viscoelasticity of the polymeric fiber.

Keywords— Fiber optic sensor, Polymer optical fiber, Curvature sensor, Quasi-static analysis, Viscoelasticity

1 Introduction

Optical fibers are compact and lightweight, allow multiplexing systems, are chemically stable and are not influenced by electromagnetic fields. These characteristics make the optical fibers suitable for sensors applications (Bilro, 2011). There are two major types of optical fibers: glass optical fibers (GOF) and polymer optical fibers (POF). Although POFs present higher signal attenuation which limits their application in communication systems to short distances, it possesses some advantages over GOFs such as low cost, high elastic strain limits, high fracture toughness, high flexibility in bend and negative thermo-optic coefficients. These mechanical advantages make POFs very sensible to strain which is desirable for sensors of this nature. Polymer based optical fibers typically have diameters between 0.25 mm and 1 mm which is larger than the typical diameters found in GOFs. Therefore, it is possible to use low precision plastic connectors which generally results in a lower cost system (Zubia e Arrue, 2001). Moreover, polymers have great biocompatibility which makes it a promising alternative for biomedical applications (Peters, 2011).

The light propagates in an optical fiber confined into the nucleus and the curvature of the fiber affects its propagation characteristics. Furthermore, only the light coupled to the optical fiber with angles lower than the acceptance angle are propagated inside the fiber. The acceptance angle is function of the core refractive index, external refraction index and the critical angle. Additionally, the acceptance angle is important to determine the optical fiber numerical aperture (NA) which is the sine of the acceptance angle and it represents the maximum amount of light that an optic system can receive (Ziemann, 2008). POFs have higher NA than GOF, therefore POFs have higher signal attenuation and higher modal dispersion which leads to smaller bandwidth since there is a time difference between the light propagation with angles close to 0º and propagation with angles close to the critical angle (Bilro, 2011).

The aforementioned characteristics have to be taken into account when utilizing POFs in sensors applications. Researchers have studied optical sensors characteristics and properties and came out with several sensing applications for optical fibers (Bilro, 2011). In this paper, a review of POF for sensor application is presented. Besides the optical properties presented in this section, mechanical and thermal properties are discussed as well. The knowledge obtained in this review and the quasi-static tests performed allows the proposal of an experimental setup to estimate the light power attenuation of a POF under a cyclic bending in different frequencies. Since the bending cycle may present periods smaller than the relaxation period of the polymer tested, this experimental approach helps to evaluate the viscoelasticity influence on the POF. If the viscoelasticity influence on the output signal is evaluated, it is possible to estimate a dynamic compensation equation in the data processing.

2 Polymer optical fibers properties

Several authors have studied the mechanical and thermal properties, and attenuation properties of a POF under flexion, torsion, and elongation. Since the POFs are made of plastic materials and GOFs are made of silica, it is expected that the Young modulus of the POFs be lower than GOF's. However, there is not an exact value for the Young modulus on polymers, these values lie in the range between 1.6 GPa and 5 GPa for PMMA (Polymethyl Methacrylate) POF (Peters, 2011). The differences in the results are caused by the polymer anisotropy, internal stresses generated in the manufacture process and differences between the experimental approaches which includes different strain rates for the Young modulus estimation and testing conditions (Peters, 2011).

In order to evaluate the Young modulus deviation with the strain rate and strain range, Kiesel et al. (2007) measured a static Young modulus for three different strain rates (0.01, 0.3, 0.6 mm $^{-1}$) with the strain range between 1% and 5.5%. The static Young modulus lies between 3.83 GPa and 5.04 GPa. The static Young modulus is applied for small strains (lower than 1%), in strains larger than 1% the nonlinear effects due to polymer viscoelasticity became relevant and must be considered in Young modulus estimations. Therefore, the deviation between the Young modulus values in strain ranges above 1% could be caused by the nonlinear effects of the polymeric material which was not considered on most estimations.

The polymers viscoelasticity is taken into account by Stefani et al. (2012), for this reason a dynamic mechanical analysis (DMA) is performed. A current driven shaker is employed to perform the DMA, the shaker can provide a peak to peak displacement of 6 mm in a frequency range of 0 to 18 kHz and it is comprised of a shaker within a climatic chamber. The fiber is fixed at one end of the shaker which have an accelerometer beneath it. There is a force gauge on the other side of the testing machine. The shake is driven by a waveform generator which generates a sine wave on a fixed frequency. The data acquisition card monitors the accelerometer, force gauge and wave input. Results show the typical phase lag of the viscoelastic materials. Moreover, the phase lag increases when the frequency is increased. Almost all parameters which defines the dynamic Young modulus depends on the phase lag, as it is shown in Eq. 1.

$$E = E_0 \cos(\delta) + iE_0 \sin(\delta) \qquad (1)$$

Where E is the dynamic Young modulus, E_0 is the static Young modulus and δ is the phase lag. There is no phase lag in elastic materials, therefore the dynamic Young modulus is the static Young modulus which can be obtained from the stress-strain curve inclination calculation in the elastic region.

Results obtained in the DMA analysis points to the possibility to analytically model a POF through the Maxwell viscoelastic model. This model and several other models are based on the assumption that an elastic material behaves like a spring and a viscous material behaves like a dashpot. Since a viscoelastic material lies between the two types of materials presented, the Maxwell model is a spring in a linear configuration with a dashpot (Roylance, 2001). There are several other models with the same principle such as Standard Linear Model, Wiechert Model, Voigt Kelvin Model, among others. The parameters of the model are obtained from the DMA, the instantaneous strain are obtained from direct measure with the hypothesis that the shaker response is a lot faster than the polymer dynamic. Furthermore, the polymer viscosity is estimated in a product between the dynamic Young modulus and the material time constant.

The temperature has to be controlled on a DMA because it causes deviations in transmission results. It is important to account the losses due to temperature changes. However, the temperature change in polymers are limited due to glass transition. The glass transition temperature for PMMA is about 100ºC (Peters, 2011).

Aware of the temperature limitation, Kovacevic and Djordjevich (2009) analyzed some optical parameters variations with temperature and POF length. Although the temperature range was quite large (–60 ºC to 100 ºC), the parameters show little variation. The refractive index maximum variation was 0.03 RIU. Bandwidth and mode dispersion have appreciable variation with temperature only after 10 m length. The mode dispersion decreased with the temperature and bandwidth slightly increased when the temperature rises. Silva-Lopez et al. (2005) investigated the strain and temperature sensitivity for POFs, the results show a strain and temperature sensitivity greater in magnitude than that of the GOFs. Moreover, the thermo-optic is negative which presents the possibility for temperature compensation in strain sensors (Peters, 2011).

Bilro (2011) evaluate the power loss due to temperature variation from 25ºC to 70ºC in a POF, however, there was not an appreciable power loss in this temperature range since it was used a compensation method in the characterization. Additionally, it was evaluated the power loss with the relative humidity variation in a range of 50% to 90% in a fixed temperature of 30ºC. There was not a considerable variation with relative humidity. However, all experiments presented were made on static conditions, thus the viscoelastic effects were suppressed. Since the viscoelastic material is affected by temperature, it is possible that a dynamic mechanical analysis with temperature variation achieves a considerable variation in the response curve. PMMA is a thermorheologically simple material (Lakes, 2009), in this type of polymer the effect of lowering or raising the temperature simply shifts the viscoelastic response horizontally without change the curve shape. This horizontal shift is the time-temperature shift factor that depends on the polymer relaxation time, reference temperature and actual temperature (Roylance, 2001).

Equation 2 shows the time-temperature shift factor (aT) calculation. Referring to Eq.2, C_1 and C_2

are material constants which depends on the reference temperature (T_{ref}) chosen. Universal values for C_1 and C_2 are 17.4 and 51.6 respectively. The reference temperature for these values is the glass transition temperature (Roylance, 2001).

$$\log(aT) = \frac{-C_1(T - T_{ref})}{C_2 + (T - T_{ref})} \quad (2)$$

3 POF based sensors

Although POF based sensors can be employed to evaluate the beam dispersion and phase deviation for measurement as in a turbidity sensor (Bilro, 2011), several POF sensors take advantage of the polymer flexibility to measure the transmission losses on a bending fiber. Both macrobending and microbending power loss are applied for sensing applications.

Fegadolli et al. (2008) takes advantage of microbending power loss to develop force detection platform. The rectangular platform is comprised of a lower fixed plate and an upper movable plate, both fixed and moving plates have cylindrical rods placed throughout its length. The optical fiber lies between the two parts, when force is applied on the movable part, the POF is squeezed and the signal attenuation is detected and processed. Applying the same work principle, Chen et al. (2012) proposed a breathing sensor. The sensor is embedded on seat cushion or bed and detects the body vibration during breathing. The sensor proven to be capable of detecting body vibration with maximum error of the frequency measurement less than 0.2 Hz and the frequency measurement range can be up to 2000 Hz.

Among the many applications of macrobending POF based sensors, the biomedical and rehabilitation applications draw more attention of the researchers. POFs are preferred in rehabilitation purposes due to its biocompatibility and are more rugged and safer than the glass optical fibers (Chen et al., 2012). Lee et al. (2006) proposed an optical fiber angular sensor to measure the human joint angle based on macrobending power loss. It was investigated the phototransistor voltage and angle correlation with different fiber tip angles (0°, 20° and 35°). Results shows an asymmetric dependence of voltage and angle for 20º and 35º tip angles.

Dunne et al. (2008) developed a wearable garment-integrated curvature sensor for monitoring the seated spinal posture and the subject posture is evaluated by a two-leaved decision tree model for posture classification. The posture classification made by a decision tree algorithm is compared with the classification from a visual analysis of professionals. However, the lack of agreement between the eight experts presents a problem for system evaluation and for long-term monitoring of seated posture.

Williams et al. (2010) also investigate the spinal curvature. Such research is limited to lumbar curvature. Results of the lumbar monitoring are compared to a video-based method and good precision was proven. Donno et al. (2008) develops a POF goniometer capable of measure higher angles (up to 90º). Dynamical tests are conducted in three frequencies: 0.1 Hz, 1.25 Hz, and 5 Hz with good accuracy between and low hysteresis of the POF sensor and the reference potentiometer. The proposed goniometer can be applied for knee joint angle measurement by athletes to test and train their exercises and to physiotherapy rehabilitation. Bilro (2011) presents a similar approach to knee angle monitoring. However, the sensor is characterized in quasi-static tests and the sensor is evaluated with a video based system which accounts only the movements on the sagittal plane. It was also presented the wireless prototype of the POF sensor. Moreover, a characterization of the same POF sensor principle was made to apply the POF goniometer to elbow angle measurement.

One drawback of macrobending sensor is the nonlinearity between sensor attenuation and bend radius. To overcome this problem, one of the proposed solutions is to polish the side of the sensor bending portion. The linearity between attenuation and bend radius can be obtained if the fiber losses its cladding and part of its core. Bilro (2011) compared three methods for lateral cutting: cleavage, cleavage with polishing and manually hot-knife cut.

Microscopic images of the fiber sections of each of the methods shows that the cleavage with polishing provides a more regular section. Besides the appropriate cutting technique, the length of the polished area as well as the polishing depth affects the attenuation and refractive index of a POF (Bilro, 2011).

Jing et al. (2015) provides an investigation of the variations on the refractive index of a side polished POF. The effects of the curvature radius, polished position and polished depth are measured. The highest sensitivity (154 dB/RIU) was achieved in a polishing position of 5mm, 500µm of polishing depth and polishing angle of 60°. An analytical formulation is proposed in Lomer et al. (2007) to define the polishing depth as a function of the bend radius, fiber core radius and the semi-axis on y direction.

Experimental results showed good agreement with the analytical model. A more sophisticated side polish technique is presented in Stupar et al. (2012). In this polishing method, the sensitive zone created by several teeth which were obtained through precision drilling. The fiber sensitivity on the bending section can be controlled by adjusting the depth, number of teeth, width of the linear range and distance between teeth. Bilro (2011) reported a sensitivity enhancement on the polished region after applying lacquer coating.

The main drawback of the signal intensity modulation optical fiber sensors is its larger sensitivity to external perturbations e.g. temperature, microbending, source power deviations, among others. It results on indistinguishable variation on the received signal from that produced by actual modification of the measurand (Vallan et al., 2012).

Bilro (2011) and Moraleda et al. (2013) employed a dummy sensor for a self-referencing system which lowers the temperature, humidity and source power deviations to acceptable values.

Vallan et al. (2012) investigated another compensation technique, based on two signals at different wavelengths inserted to the system. The signals are coupled and, at the end of the first fiber, a wavelength-selective element filters the two signals which are fed to the second fiber with two different distances.

Therefore, one signal is responsible for the displacement measurement and the other corrects the sensor readings for disturbances. The results obtained for this dual-wavelength compensation technique showed the wavelength dependence of the attenuation drift in POF sensors which makes this method feasible to compensate environmental effects on the sensor.

Yuan (1998) developed a compensation technique using a five fiber structure on the sensing probe. Although this system can sense two dimensional physical parameters and automatically compensate the light source deviations, the sensor has not a compact design which is desired for some rehabilitation purposes (Bilro, 2011).

Zawawi et al. (2013) compensated the light power deviations from the light source with an aluminum foil placed in a defined distance of the source fiber tip. The reference signal was collected at the end tip of the reference fiber due to reflection of the aluminum foil surface. The signal is compared with the one of the source fiber and a compensated response of the output voltage is achieved.

4 Quasi-static test and dynamic bending analysis proposal

A quasi-static test is made by fixing a multimode HFBR-EUS100Z POF (Broadcom Limited, Singapore) with step index on a plastic goniometer through 3D printed supports. The supports are placed in different positions to provide different curvature radii on the tests. The test comprises of bending the fiber on sequential 10° steps for flexion and extension in 0-90° range. The fiber remains on the desired angle for 10 seconds. As the bending occurs, the light attenuation increases due the fiber curvature. The light variation is acquired by the photodiode (PD) IF-D91 (Industrial Fiber Optics, USA). The light source is a low cost 3 mW 650 nm laser (Phywe, Germany). The signal acquisition is made by an Arduino Micro and the sample rate is 10 Hz. Furthermore, a reference fiber is applied to compensate the possible fluctuations in the light source, temperature and humidity variations. The laser provides light for both fibers and these fibers are further split into the reference and sensor fibers through the light coupler (LC) IF-562 (Industrial Fiber Optics, USA). Figure 1 shows block diagram of the experimental setup. In order to enhance the sensor sensibility, lateral sections with controlled length and depth were made on the fiber through a Computer Numeric Control (CNC) milling machine.

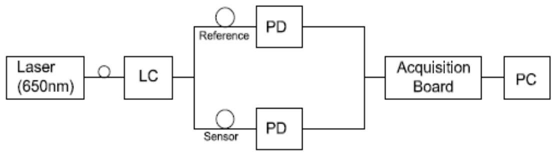

Fig. 1. Experimental setup for quasi-static test of the optical fiber sensor.

Tests hysteresis (Eq. 3) is analyzed on the experimental setup presented with different curvature radii. Three consecutive tests were made in each radius. The curvature radii tested were 40, 45, 50, 55, 60, 65, 70, 75, and 80 mm. These radii were chosen due the goniometer maximum length (80 mm) and the minimum curvature radius recommended by the POF manufacturer (40 mm). Test results are summarized in Table 1.

Referring to Eq.3, hysteresis is the ratio between the vertical differences of flexion and extension linear approximations curves. Where $(Y_{mn} - Y_{mp})$ is the difference between the flexion and extension curve on a predefined point and $(Y_{Max} - Y_{Min})$ is the maximum and minimum points of the hysteretic curve.

$$Hysteresis(\%) = \left| \frac{(Y_{mn} - Y_{mp})}{(Y_{Max} - Y_{Min})} \right| \times 100\% \quad (3)$$

Table 1. Quasi-static tests results.

Curvature Radius (mm)	Hysteresis (%)
40	9.8
45	6.7
50	5.5
55	5.1
60	4.3
65	2.5
70	2.4
75	2.3
80	1.8

Although there is a negative correlation between the curvature radius and the hysteresis, it is still higher for the maximum curvature radius tested. Therefore, a compensation technique for the hysteresis needs to be developed in order to achieve a reliable curvature sensor.

The review presented on previous sections and observations made on the quasi-static analysis enables the proposal of a novel experimental setup to investigate the dynamic mechanic behavior of a bending POF under different frequencies. One reason of the hysteretic behavior is the polymer viscoelasticity. The dynamic bending analysis proposed in this section estimates the POF viscoelastic effects and come out with a compensation technique for the viscoelasticity.

As aforementioned, the POF sensitivity do not relates linearly with the bend radius. The linearity is achieved by means of lateral polishing in the fiber. The cleavage with polishing method is employed to the lateral polish since it is simpler and cheaper than the precision drilling technique.

Although a lacquer coating can enhance the polished optical fiber sensitivity, it can lead to deviation on measured values through time due to the coating chemical stability. Even though these are minor deviations (standard deviation of 1.8%), the effects of the coating stability are mixed with the effects of the material viscoelasticity (Bilro, 2011). Therefore, the viscoelasticity compensation technique would present some inaccuracies due to the impossibility to filter the coating chemical stability effects. For this reason, the polished region of the POF must not be coated for the dynamic test.

Another issues that must be taken into account are light source power deviations and environmental deviations such as changes on the humidity and temperature. Among some compensation methods presented in previous section, the dummy sensor method provides an acceptable compensation for environmental and source power deviations (Vallan et al., 2012). Furthermore, this method does not compensate variations on the attenuation due to mechanical stress which is desirable for this application since the mechanical stress behavior has to be filtered to achieve a compensation technique for viscoelastic effects.

In order to obtain the desired flexion/extension movement with different frequencies, an active orthosis is employed. The referred orthosis has two degrees of freedom: one passive on the hip and the other is an active on the knee. The motor unit of the orthosis is comprised of a DC motor and a harmonic drive which provides a range of movement of 0 to 90º. A precision potentiometer is connected to the harmonic drive output through a toothed belt and is responsible for the knee joint position measurement. The main components for the dynamic bending analysis are the same as presented on the quasi-static test.

These outlined components are assembled to the active orthosis presented. Since it is not required for the dynamic test, the orthosis passive hip joint is removed. The POF and the board with the photodiode and amplifier are fixed on the orthosis through connectors. The test is performed by means of orthosis knee joint movement from 0º to 90º under different frequencies. Furthermore, in order to evaluate the viscoelastic effects, the test must be performed on frequencies higher than the POF relaxation time. The fiber sensor response is compared with the potentiometer response to evaluate the viscoelastic effects of the POF sensor. Figure 2 shows the 3D model of the orthosis with the POF sensor system mounted. The board with the photodiode and amplifier is not represented in Figure 2.

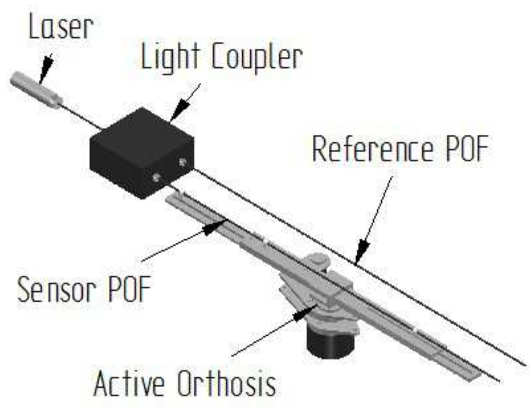

Figure 2. Dynamic bending analysis 3D model

5 Conclusion

This paper presents a review of POF properties and characteristics as well as describes its sensor applications. The properties and applications described are applied to develop a dynamic bending analysis for a POF which evaluates the viscoelastic effects on the signal attenuation due to curvature loss. These effects were first observed in the quasi-static tests performed.

If the viscoelastic effects are estimated, a compensation method can be proposed to correct the measure deviation caused by this undesirable effect on a dynamic movement. Some viscoelastic models are briefly discussed and an analytical model of the fiber dynamic response can be obtained as well. The main drawbacks of the POF based sensors, namely nonlinearity between fiber sensitivity and curvature radius and deviations on output signal due changes in light power source and environmental changes, are discussed and the dummy sensor method for environmental and power source deviations is a good option for the compensation technique.

Moreover, the linear behavior of POF's sensitivity is obtained through the lateral cleavage and polishing method. The POF and optical source with electronic components are fixed on an active orthosis which has an angular range of 0º to 90º with different frequencies of movement. The voltage corresponding to the POF optical output is compared with the orthosis precision potentiometer response in order to account for the variation between the two sensors which is mainly caused by the viscoelastic effects of the polymer optical fiber.

It is important to employ the orthosis as the driving mechanism for the fiber because the final goal of this project is to obtain a POF sensor with viscoelastic effects compensation for dynamic joint angle measurement. The advantages of this application is the sensor ease of installation, noise immunity, electromagnetic fields immunity, among others. In order to enhance this POF sensor precision, another future work is to apply the dynamic bending analysis under different temperatures to evaluate the temperature effects on the polymer viscoelastic behavior.

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