Experimental test of Polymer Optical Fiber Temperature sensor on different surrounding media

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Abstract: Influence of external media on a fiber-optic temperature sensor based on a macro-bend multimode Polymer Optical Fiber (POF) is analyzed. The sensor has a linear response with a sensitivity of $1.92 \cdot 10^{-3}(^{o}C)^{-1}$ at a fixed bend radius. 2.4 times sensitivity variations for different surrounding media are reported.

Keyword: POF sensor, Temperature, Surroundings media, Refractive Index, Intensity, Bend Loss, Macro-bend.

1. Introduction

The field of temperature sensors covers a high percentage of today's world sensors market due to the large number of application in which it is necessary to measure temperature, for instance: automotive industry, air-conditioning control and medical applications. Nevertheless, the characteristics of traditional temperature sensors such as thermocouple, thermistor and resistance temperature detectors are not well suited to be used whenever specific needs are required. This is the case of temperature measurement in many low cost industrial processes in presence of electromagnetic disturbances. These problems together with the advantage in fabrication of low-low optical fiber and in low-cost components for optical fiber communication prompted the development of innovative temperature sensors based on optical fibers.

To solve these problems, innovative solutions based on amplitude or phase fiber-optic techniques [1] have been developed. Phase modulation sensors are based on changes in the phase on an electromagnetic wave traveling along an optical fiber caused by temperature changes. Examples for these sensors include Mach-Zehnder [2], Fabry-Perot interferometers [3] and Bragg gratings [4]. Amplitude sensors modulate the light carried by the optical fiber. Some of these sensors are based on physical principles such as light attenuation [5], frustration of total internal reflection [6], controlled mode coupling [7], light generation [8] and fluorescence [9].

Most of the phase modulation sensors are characterized by their large sensitivities. But their complexity of implementation and the higher price of the equipment needed, make them unsuitable for the applications described above. On other hand, the amplitude temperature sensors usually are cheaper than the phase modulation sensors but they need to use a reference technique to avoid false readings caused by fluctuation of the light source, optical fiber attenuation coefficient or other undesired losses.

In this paper, the authors characterize under different surrounding media a low-cost intensity macro-bend temperature sensor based on Polymer Optical Fiber (POF). The sensor system used a macro-bend POF probe and a dummy POF probe for measuring the temperature variation of a hot plate. A single optical source feed both branches through an optical coupler. Other techniques to measure the temperature with a macro-bend sensor have been developed using either single mode [10, 11] or multimode [12] silica optical fiber. The main advantages of using POF instead of glass fiber to build the sensor are the large core diameter, making them less fragile and easier to handle; while reducing development and maintenance costs. Although polymer based sensors have a smaller temperature range. The highly multimode nature of POF sensors implies especial features as the possible influence of external surrounding media that have to be considered in the device performance.

In this context, the purpose of this work is to determine the influence of the external surrounding media on the macro-bend POF [6] temperature sensor. Different surrounding media have been used to measure the calibration curve of the POF temperature sensors and they have been compared with the calibration curve when surrounded by air.

2. Sensor principle and design

The optical fiber is a multimode step index optical fiber. The radius of curvature is R and the thickness of the core is $2\rho_{Core}$. The refractive indices of the core and cladding are n $_{ore}$ and n $_{ladding}$, respectively. Optical power is launched at the beginning of the rectilinear region of the fiber.

In the bend optical fiber, the guidance of the core rays can follow two ways [13]. Only the rays entering the bent part of the fiber in the meridional plane remain with the same angle of incidence along a given ray path. On the other hand, the skew rays entering this plane, after the successive reflections within the core, do not follow a simple repeatable pattern because of the asymmetry introduced by bending the fiber.

The optical fiber sensor proposed in this paper is based on a macro-bend POF. In this intensity sensor, the losses induced by the bending effect depend on the numerical aperture changes with temperature. The refractive index of the core and cladding POF depend on temperature. The POF used in the experiments is a Mitsubishi Rayon® Eska® SH-4001, with core and cladding manufactured using polymethyl methacrylate (PMMA) and fluorinated polymer, respectively. The temperature dependence of the core and cladding refractive index can be expressed as:

$$n_{Core}(T) = n_{Core}(T_0) + K_1 \cdot (T - T_0) \tag{1}$$

$$n_{Cladding}(T) = n_{Cladding}(T_0) + K_2 \cdot (T - T_0) \tag{2}$$

where $_1$ -1.1 ·10$^-$ ( )$^{-1}$ [14] and $_2$ - . ·10$^-$ ( )$^{-1}$ [15] are the thermo-optic (TO) coefficient of the core and cladding, respectively. n $_{ore}$(T$_0$) and n $_{ladding}$(T$_0$) are the refractive index of the core and cladding at the reference temperature (T$_0$ 2), respectively. The expression of the numerical aperture (NA) for the bend region [13] is given by:

$$NA(T,R,\rho,\phi) = n_{Core}(T)\left[1 - \frac{n^2_{Cladding}(T)}{n^2_{Core}(T)}\left(\frac{R+\rho_{Core}}{R-\rho\cdot\cos\phi}\right)^2\right]^{1/2} \tag{3}$$

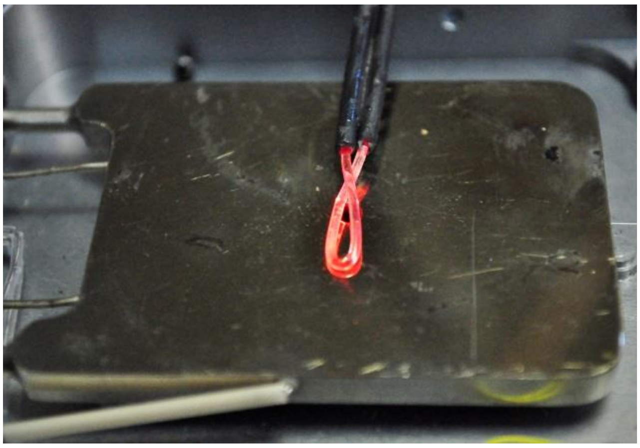
where is the ray angle at the beginning of the bend, which varies from 0 to 1 0 , ρ $_{ore}$ is the fiber core radius and ρ is the radial position in the core satisfying the relation 0 ρ ρ $_{ore}$ and n $_{ladding}$, n $_{ore}$ are those described on Equation (1) and Equation (2).

Analyzing Equation (3), it can be seen that the local numerical aperture increases when the applied temperature increases. This increment happens because an optical ray that is unguided at the reference temperature becomes guided at temperatures greater than the reference temperature.

3. Manufactured sensor and measurements.

The fiber used in the experiment was a multimode step index POF with a good tensile strength and flexing. These characteristics provide good mechanical properties at the time of manufacturing the sensor. From the middle section of a length of the fiber, the buffer coating is stripped. The length of this section is about 3 cm. The fiber sensor is formed by creating a single 180º loop (1/2 turn) with a bend radius of 2 mm, as shown in Figure 1). To fix the radius of the loop, the buffer coating in the junction of the two ramifications is fixed by cyanoacrylate adhesive. With this method, a stable macro-bend fiber temperature sensor is manufactured.

(**a**)



(**b**)

Figure 1. (a) Photograph of the macro-bend POF Sensor. (b) Fiber temperature sensor under the influence of a copper plate

The input wavelength to the system was 660nm. The fiber loop was fixed on the rectangular highly conductive metal base plate, the temperature of which is controlled using a heating (Linkam LTS350) and a controller (Linkam TP94) unit. Using an external electronic temperature sensor, the real temperature of the optical fiber has been measured. An additional macrobend fiber loop, identical to the proposed fiber optic sensor placed on the hot plate, is used for reference purposes. This fiber-optic reference or dummy sensor, placed outside of the heating unit, monitors the optical power fluctuations not related to the sensing magnitude. The output voltage at the reference and sensing branch has been measured from +29 to 70ºC at 2ºC intervals. The minimum temperature has been limited by the cooling capabilities of the heating unit and the maximum range was limited by the capabilities of the POF. Between each temperature increment, a time interval of two minutes has been set to ensure the stabilization of the voltage values. The sample rate and the number of samples of the output power ratio at each temperature have been fixed at 5Hz and 10 samples, respectively. A total of six sets of measurements at full temperature range have been carried out to perform a complete statistical analysis of the sensor parameters. In order to express the results in terms of optical power, the output voltage at the reference and sensing branch has been expressed in optical power units. The sensor calibration curve has been calculated by the arithmetic mean of the output optical power ratios for each temperature in all sets of experiments. The output optical power at the reference ($P_{Reference)}$ and sensing (P_{Sensor}) branch can be expressed as:

$$\gamma_{SR} = \frac{P_{Sensor}}{P_{\mathrm{Re}ference}} = \frac{\beta_{Sensor}}{\beta_{\mathrm{Re}ference} \cdot F'(T_0)} \cdot F(T) \quad (4)$$

where β_{Sensor} and $\beta_{Reference}$ are factors including the attenuation of the fiber leads, coupler insertion losses and connectors losses, of the sensing and reference branch respectively. F(T) is the optical power modulation function versus temperature at the fiber-optic sensor and $F'(T_0)$ is the insertion loss at reference temperature (T_0) of the dummy sensor.

To acquire the voltage from the receivers, to calculate the optical power of each branch and to post-process the data, computer software based on National Instrument Labview® code has been development.

4. Temperature sensor characterization on different surrounding media.

The step index POF fiber is highly multimode, so part of the light propagates through the cladding, but the cladding is only around 20μm thin, so external media with a specific refractive index can influence the propagation through the fiber. Practical implementation of the sensor implies different manufacturing procedures and testing, and different surrounding media related to them.

One possible disturbance of the refractive index is the use of adhesives on the probe to fix the temperature sensor on the sensing point. These adhesives typically are manufactured with polymeric materials and have a different refractive index and thermal expansion to the one of the fiber cladding. In these experiments, the adhesive used to fix the probe was a polypropylene tape whose refractive index [16] is higher than the refractive index of the cladding.

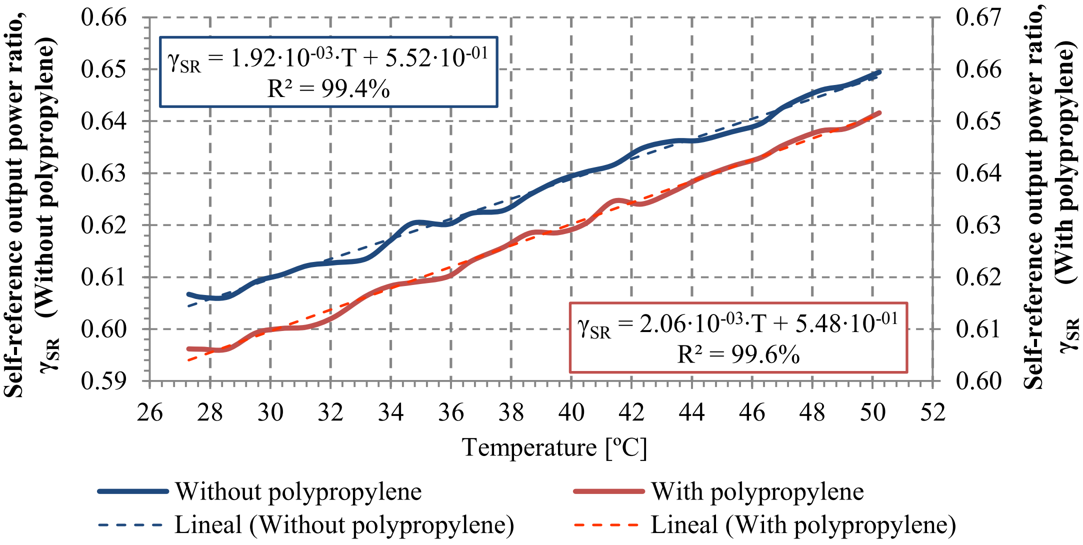


Figure 2. Calibration curves for a sensor with and without tape coating.

Figure 2 shows the calibration curves for a sensor with and without the tape. In these measurements, the distance between the optical sensor and the hot plate was fixed at 1mm to avoid any possible contact with the copper plate. The sensitivity obtained with and without tape was $2.06 \cdot 10^{-3}$(ºC)$^{-1}$ and $1.92 \cdot 10^{-3}$(ºC)$^{-1}$, respectively. In both cases, the linear regression coefficient is greater than 99%

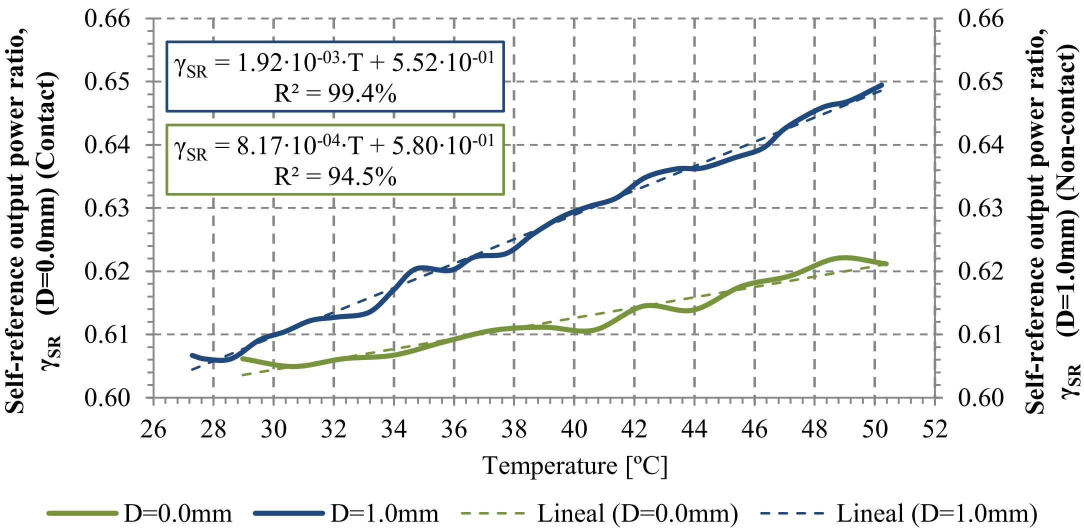


Figure 3. Calibration curves for a sensor with no contact and in contact with the metallic surface of the hot plate.

Another important parameter to consider is the possible influence of the hot plate metal surface. Placing the sensor very close to the surface can cause changes of the refractive index surrounding the cladding. In our experiments, the heater for measuring the calibration curves is a hot plate made of copper. The refractive index of the copper (n_{Copper} = 0.23) [17] is much lower than the refractive index of the cladding. To analyze its influence, it has been measured the output voltage ratio in two scenarios: non-contact and in contact with the hot plate. The distance to ensure non-contact between the sensor and the hot plate has been fixed at 1.0mm. On other hand, for this experiment, no tape has been used in order to isolate the phenomenon to be analyzed. The bend radius of the optical sensor is 2.0mm.

Measurements are shown on Figure 3, it can be seen that the sensitivity at both scenarios was $1.92 \cdot 10^{-3}$(ºC)$^{-1}$ and .17$\cdot 10^{-4}$(ºC)$^{-1}$, for in contact and 1mm distance respectively. The sensitivity is reduced by a factor of around 2.4 when the POF is in contact with copper, with an imaginary refractive index one order of magnitude lower than the polypropylene refractive index, and with a much higher absorption coefficient. The linear regression coefficients for the two measured distances are 99. and 9 . , respectively.

4. Conclusion

Macrobending loss caused by the different thermo-optic coefficients of the cladding and core of a step-index Polymer Optical Fibers (POFs) has shown to be a usable technique for temperature sensing. The sensor has been tested in the range from +27.2 to +52.2ºC. The sensor sensitivity for a bend radius of 2mm is $1.29 \cdot 10^{-3} (ºC)^{-1}$. The proposed sensor requires only a few and relative low-cost components. The influence of external media in contact with the sensor has been analyzed obtained substantial change in the sensor sensitivity when in contact with a copper plate. The sensor can be used in a large range of applications, for instance: instrumentation process, automotive industry, air-conditioning control, chemical industry, biomedical and detection of metal particles in contaminated fluids.

Acknowledgements

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