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Self-referenced Temperature Sensor Based on a Polymer Optical Fiber Macro-Bend

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ABSTRACT

The design and development of a plastic optical fiber (POF) macrobend temperature sensor is presented. The sensor has a linear response versus temperature at a fixed bend radius, with a sensitivity of $8.2 \cdot 10^{-4} (ºC)^{-1}$ and a 8% non-linearity full scale error. The sensor system uses the power variation between two discrete wavelengths for auto reference purposes. An analysis for selecting operation wavelengths has been carried out in order to optimize the response of the sensor. The proposed sensor can be used in harsh environment and has a low-cost.

Keywords: POF Sensor, temperature, intensity, bend loss, loop, self-referenced.

1. INTRODUCTION

The use of temperature sensors in today's society is continually growing. There are a large number of applications in which it is necessary to measure temperature, for instance: automotive industry, air-conditioning control, medical applications, among others. Some decades ago, world sensor market was made up of traditional temperature sensors such as thermocouples, thermistors and resistance temperature detectors. These sensors are not well suited to be used in the presence of electromagnetic disturbances or inflammable atmospheres. These problems together with the advantage in fabrication of optical fiber and in low-cost components for optical fiber communications promoted the development of innovative temperature sensors based on optical fibers.

Many optical fiber sensors have been developed based on amplitude or phase techniques [1]. Different interferometric configurations have been proposed as temperature sensors such as Mach-Zehnder [2] and Fabry-Perot [3]. These 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. Temperature amplitude modulation sensors are based on optical power variations. Some proposed sensors are based on frustration of total internal reflection [4], light generation [5] and Fiber Bragg Grating wavelengths shifts [6]. 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 fluctuations of the light source or other undesired losses [7].

In this paper, the authors propose a low-cost intensity macro-bend temperature sensor based on polymer optical fiber (POF). Other techniques to measure the temperature with a macro-bend sensor have been developed using silica optical fiber [8]. The main advantage of using POF fiber instead glass fiber is the large diameter of the fiber, making them less fragile and easier to handle, reducing development and maintenance cost. Although polymer based sensors have a smaller temperature range. The novelty of this work is to develop and implement a self-reference technique based on a single macro-bend loop. The sensor system used a relation between two different wavelengths to avoid possible errors related to optical power fluctuations of the light. Previous POF macrobend temperature sensor as the one reported in [4] used a dummy fiber-optic sensor, making them less reproducible.

2. PRINCIPLE OF OPERATION

A curved step index optical fiber schematic is shown in Figure 1.

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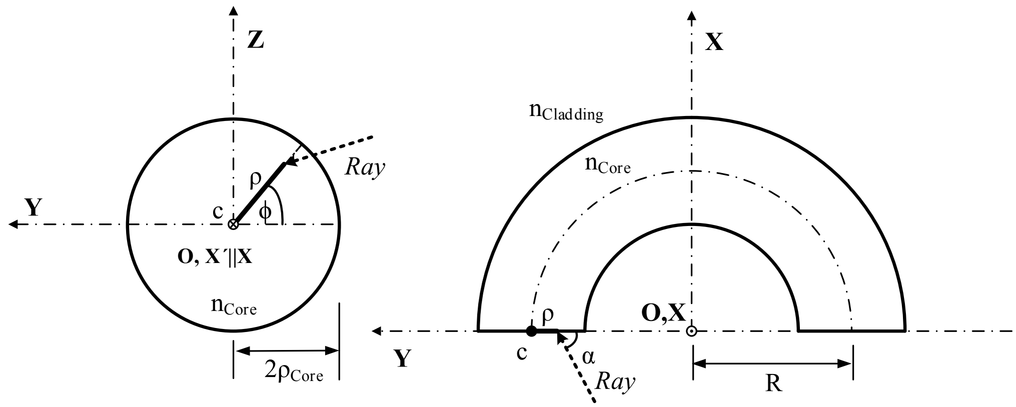

Figure 1. Schematic of the frontal and top view of a bend section.

The bending radius is R and the core radius is ρ_{Core}. The refractive indices of the core and cladding are n_{Core} and $n_{Cladding}$, respectively. Optical power is launched at the beginning of the rectilinear section of the fiber. The guidance of the rays in the core is achieved by ensuring that the propagation angle, α, satisfies the condition: $0 \leq \alpha \leq \alpha_c$, where the critical angle (α_c) is given by $\alpha_c = \sin^{-1}(n_{cladding}/n_{core})$. The expression of the numerical aperture (NA) for the rectilinear section is given by:

$$NA = n_{Core} \cdot \sin\alpha \leq \left(n_{Core}^2 - n_{Cladding}^2\right)^{1/2} \tag{1}$$

However, in the bend section, the guidance of the rays in the core can follow two ways. 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. So the local numerical aperture changes at a given location of the bent optical fiber; this dependence is given by [4]:

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

where ϕ is the ray angle at the beginning of the bend, which varies from 0º to 180º and ρ is the radial position in the core satisfying the relation $0 \leq \rho \leq \rho_{Core}$.

In this intensity sensor, the losses induced by the bending effect depend on changes in the numerical aperture. Numerical aperture changes on the fiber are related to variations of the refractive index of the cladding and core with temperature. The numerical aperture in the bent section of the fiber versus temperature can be expresses as:

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

3. EXPERIMENTAL RESULTS AND CALIBRATION CURVES

In this section, the sensor manufacturing process, the experimental set-up and the measurement of the sensor calibration curve are reported. A commercial step index POF fiber with a good tensile strength and flexing is used. These characteristics provide good mechanical properties at the time of manufacturing the sensor. From the middle section of the fiber length, the buffer coating is stripped. The length of this stripped section is about 30mm. The fiber sensor is formed by creating a single 180º loop (½ turn) with a bend radius of 2mm. The buffer coating in the junction of the two branches is fixed by cyanoacrylate adhesive. With this simple method, a stable macro-bend fiber temperature sensor can be manufactured.

The schematic of the experimental set-up is shown in Figure 2. The light source is a 360 to 2500nm tungsten halogen bulb (Avantes® AvaLigth-Hal). The fiber-optic sensor is fixed close to the rectangular highly conductive metal base plate of a heating unit (Linkam® LTS350). The temperature of the hot plate is controlled with a controller unit (Linkam® TP94). Temperature measurements are taken at a 1mm distance from the hot plate surface. Setting a distance between the sensor and the hot plate prevents possible changes in the refractive index of the cladding due to the contact with other materials as it is discussed in a previous work [4]. For measuring the real temperature of the optical fiber sensor at 1mm distance, an independent electronic temperature sensor (Texas Instruments® LM35) is used in the measurements.

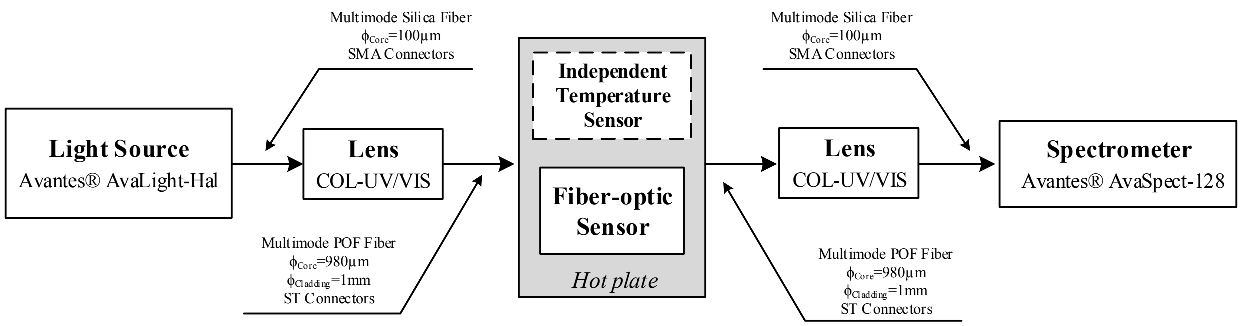

Figure 2. Schematic of the experimental set-up for characterizing the POF temperature sensor.

In order to avoid false readings caused by fluctuations of the light source or other undesired losses, a relation between transmittances at two different wavelengths (λ_1, λ_2) is measured to implement a self-referenced technique. The transmittances at two wavelengths $(\tau_{\lambda_1}, \tau_{\lambda_2})$ can be expressed as:

$$\tau_{\lambda_1} = \frac{P_{\lambda_1}(T)}{P_{R\,\lambda_1}(T_0)} = \beta_{\lambda_1} \cdot F_{\lambda_1}(T) \tag{4}$$

$$\tau_{\lambda_2} = \frac{P_{\lambda_2}(T)}{P_{R\,\lambda_2}(T_0)} = \beta_{\lambda_2} \cdot F_{\lambda_2}(T) \tag{5}$$

where P_{λ_1} and P_{λ_2} are the output optical powers for two wavelengths at a given temperature (T). $P_{R\,\lambda_1}$ and $P_{R\,\lambda_2}$ are the output power for both wavelengths at a reference temperature $(T_0 = 23ºC)$, which are considered as the 100% transmission. β_{λ_1} and β_{λ_2} are factors including the attenuation of the fiber leads, collimation losses and connector losses at each wavelength. Finally, F_{λ_1} and F_{λ_2} are the optical power modulation function versus temperature at each wavelength.

From Equation (4) and (5), the self-referenced output transmittance ratio (γ_{SR}) is defined as:

$$\gamma_{SR} = \frac{\tau_{\lambda_1}}{\tau_{\lambda_2}} = \frac{\beta_{\lambda_1} \cdot F_{\lambda_1}(T)}{\beta_{\lambda_2} \cdot F_{\lambda_2}(T)} = \frac{\beta_{\lambda_1}}{\beta_{\lambda_2}} \cdot F(T) \tag{6}$$

Therefore the ratio of the output transmittances depends on the power sensor variations with temperature and on a constant ratio between the insertion losses at the different wavelengths.

In order to find the output transmittance ratio that offer the highest linearity and sensitivity, the transmittance at different wavelengths has been measured from 360 to 886nm with 4nm resolution using a spectrometer (Avant® AvaSpect-128), in a temperature range from 29 to 70ºC at 2ºC intervals. A searching algorithm based on Mathworks® Matlab® code has been developed to evaluate the ratio of transmittances for all possible pairs of wavelengths. As a result it is obtained that λ_1=529nm and λ_2=835nm are the best option.

Figure 3 shows the measured calibration curves at the two selected wavelengths. At a 1mm distance, the temperature of the independent electronic temperature sensor varies from 27.2 to 50.2ºC.

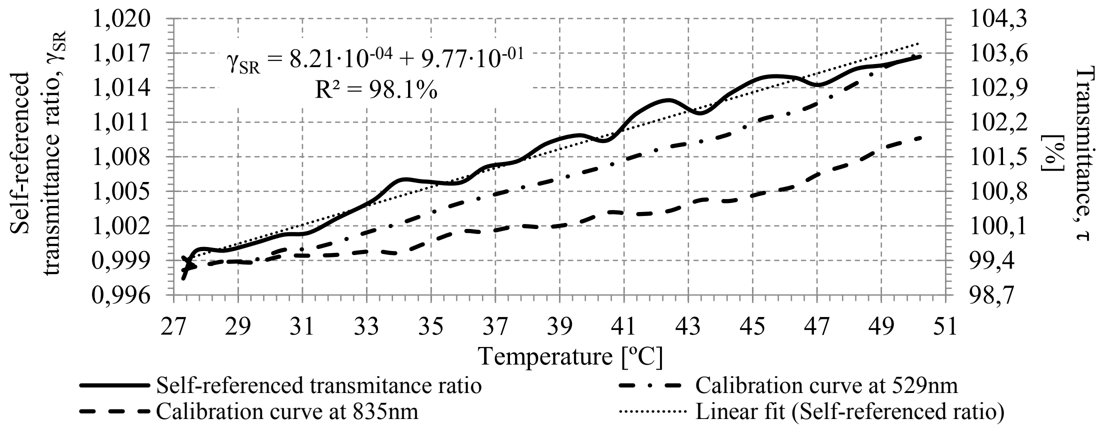

Figure 3. Self-referenced transmittance ratio versus temperature from measured calibration curves at 529 and 835nm.

The measurements show a good linear regression coefficient and sensitivity for the proposed wavelengths. The linear regression coefficient and sensitivity are 98% and $8.21 \cdot 10^{-4}\ (ºC)^{-1}$. A statistical analysis of the calibration curve shows that the sensor has a linear response with a non-linearity full scale error of 8.7%. The designed system allows resolutions of 2ºC.

CONCLUSION

In 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 an usable technique for temperature sensing. The sensor is able to measure a temperature range from +27.2 to +50.2ºC. The sensor sensitivity for a bend radius of 2mm is $8.21 \cdot 10^{-4}\ (ºC)^{-1}$. A self-referenced technique using a single macro-bend loop in order to reduce the repeatability error associated with the manufacturing process is developed. Self-referenced sensor system shows a resolution below 2ºC and 8.7% non-linearity full scale error. The sensors can be used in a large number of applications, for instance: instrumentation process, automotive industry, air-conditioning control, among others.

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