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A fluorescent linear optical fiber position sensor

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ABSTRACT

This paper describes a fluorescent long-line optical fiber position sensor to satisfy an industrial need for measuring position over a wide range of distances, varying from centimeters to many meters, where high resolution is not required. As is well-known, the light power transmitted by an optical fiber decreases with distance. By measuring the light power collected at both ends of a fluorescent long-line optical fiber, a position sensor has been developed. The position of the point where a light beam enters the fiber can be determined by comparing the light power collected at its two ends. In addition to their low cost and easiness of handling, plastic optical fibers present the advantages common to all multimode optical fibers such as flexibility, small size, and a good behaviour against electromagnetic interferences. Besides, sensors based on optical fiber eliminate the risk of electrical sparks in explosive environments, and they can be read from remote positions. In this work, several fluorescent optical fibers with different diameters, wavelengths, and light sources have been tested.

1. Introduction

In the last years, a great effort has been made in the research on systems based on the utilization of optical fibers [1]. Great developments have been made on optical fibers and their applications, including fiber-based sensors for environment, automotive, and health monitoring for aircraft structures among others [2]. Recently, a great variety of plastic scintillating fibers have been developed for applications such as particle discrimination, calorimeters, tacking detectors, sensors, etc. The scintillating core of these fibers contains a combination of fluorescent dopants selected to produce the desired scintillation, optical, and radiation characteristics. In this paper, we propose a sensor developed with one of these fibers.

The sensor proposed determines the position of the incident point of a light source that enters the fiber perpendicularly to it. Part of the optical power of the incident light of wavelength λ_1 passes through the fiber without interacting with it. Another part of the energy is absorbed by the fiber and emitted at a wavelength λ_2 larger than the incident one. A fraction of this energy of wavelength λ_2 will travel along the fluorescent fiber from the incident point towards its two ends [3–9]. This light will be attenuated as it advances towards the ends. Measuring the optical energy collected at each end of the fiber, the position of the incident light may be determined [10].

Fluorescence and absorption are the fundamental parameters of this sensor. A fiber with high absorption yields high measurement resolutions but small working range, while low-absorption fibers allow large working ranges at the cost of lower measurement resolutions. The basic equations that determine the position of the incident light are presented below. The logarithm of the ratio between the signal powers P_2 and P_1 collected at the ends of the fiber is found to be in a linear relation with the distance z and independent from the intensity of the light injected. Besides, variations in the distance between the light source and the fluorescent fiber have no effect on the ratio between signals if the light is collimated or if the distribution of power along the fiber is symmetrical for any separation.

A theoretical model and an experimental setup for the position sensor are presented together with the experimental results and the discussion. Finally, some conclusions are drawn.

2. Theoretical model

Considering Fig. 1, we can suppose the powers of the signals delivered by photodetectors A and B as follows:

$$P_1 = k_1 \exp(-\alpha z), \tag{2.1}$$

$$P_2 = k_2 \exp[-\alpha(L - z)], \tag{2.2}$$

where P_1 is the signal power detected by photodetector A, P_2 the signal power detected by photodetector B, α the fiber attenuation coefficient, z the distance of the incident point from the end with photodetector A, L the length of the fiber and k is a constant proportional to the light power captured by the fluorescent fiber. It depends on the source intensity, the ratio of the fluorescent light

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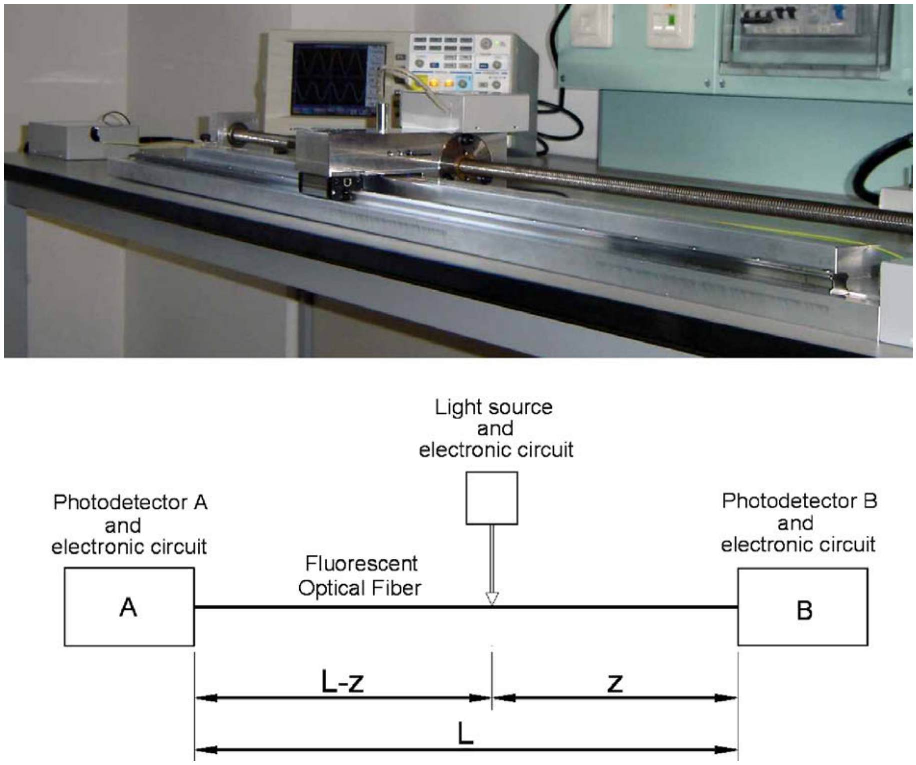

Fig. 1. Photograph and scheme of the test bench used in the laboratory.

energy to the excitation light energy, the fraction of the total fluorescent energy emitted in the fiber and guided toward A and B, the coupling losses between the fiber and the photodetector, and the photodetector responsivity.

The coefficient α is considered constant whatever the value of z, and the fluorescent fiber is considered perfectly homogeneous [11].

From (2.1) and (2.2) the ratio P_2/P_1 is calculated as:

$$\left(\frac{P_2}{P_1}\right) = \frac{k_2}{k_1}\exp(-\alpha L)\exp(-2\alpha Z). \tag{2.3}$$

Equation (2.3) may be solved to calculate z:

$$z = k + \frac{L}{2} + \frac{1}{2\alpha}\ln\left(\frac{P2}{P1}\right) = \frac{L}{2} + \frac{1}{2\alpha}\ln\left(\frac{V2}{V1}\right); \quad k = \frac{1}{2\alpha}\ln\frac{k_1}{k_2}, \tag{2.4}$$

where the last equation is a consequence of the use of quadratic detectors. V_1 and V_2 are the voltages measured at photodetectors A and B, respectively. By measuring the ratio V_2/V_1, the position z can be easily inferred.

3. Experimental set-up

To carry out laboratory experiments, a test bench was constructed as shown in Fig. 1. Different light sources were used: a blue LED emitting in the neighborhood of 470 nm, a green LED emitting around 520 nm, and a green laser at 532 nm. The fluorescent fibers were purchased from Industrial Fiber Optics [12]. We used two different doped polystyrene optical fibers: an amber fiber with the emission peak centered at 540 nm, and a red one with emission at 635 nm. The POF diameter was 1 mm in all cases. The emission spectra of the sources and the POFs are shown in Fig. 2. The LED sources were modulated at 4 kHz to avoid the influence of ambient light. In other experiments the light source was not modulated but the fiber was shielded from ambient light. An IF-D91 photodiode was used at each end of the fluorescent fiber [12]. The IF-D91 is a high-speed photodiode detector housed in a "connectorless-style" plastic fiber optic package. The optical response of the IF-D91 extends from 400 to 1100 nm, thus being compatible with a wide range of visible and near-infrared LED and laser diode sources. This includes the 650 nm visible red LEDs usually employed for optimum transmission in PMMA plastic optical fibers. The detector package includes an internal micro-lens and a precision-molded PBT housing to ensure efficient optical coupling with standard 1000 μm core plastic fiber cable.

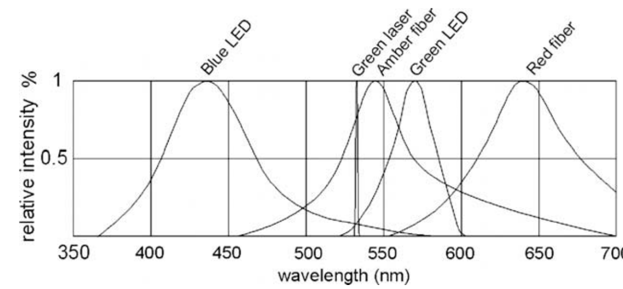

Fig. 2. Emission spectra of the light sources and the POFs.

Both photodiodes were followed by a selective amplifier tuned on the LED modulation frequency and an active rectifier. An automatic system based on CNC (numerical control- Fagor 8055) was used to position the light source along the fluorescent fiber.

4. Results and discussion

The results obtained in the different tests are presented in the following plots. Figs. 3 and 4 correspond to experiments with the amber fiber of 1 mm, a blue LED and carried out with and without light modulation. In particular, Fig. 3 shows two sets of signals expressed in mV obtained at the ends of the fiber in relation to the

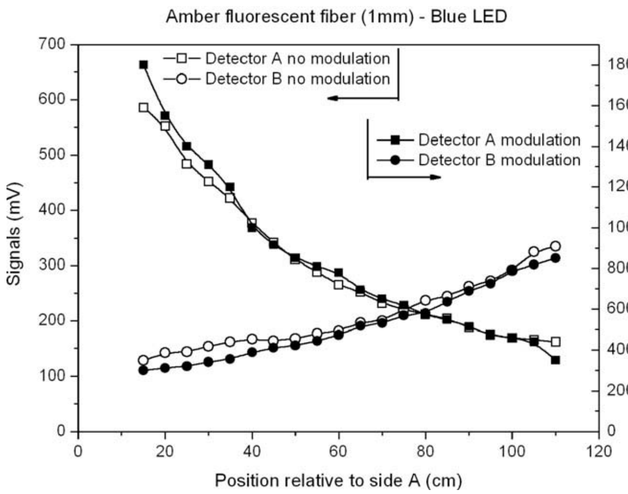

Fig. 3. Experimental results for amber fluorescent fiber and blue LED with modulation and without signal modulation.

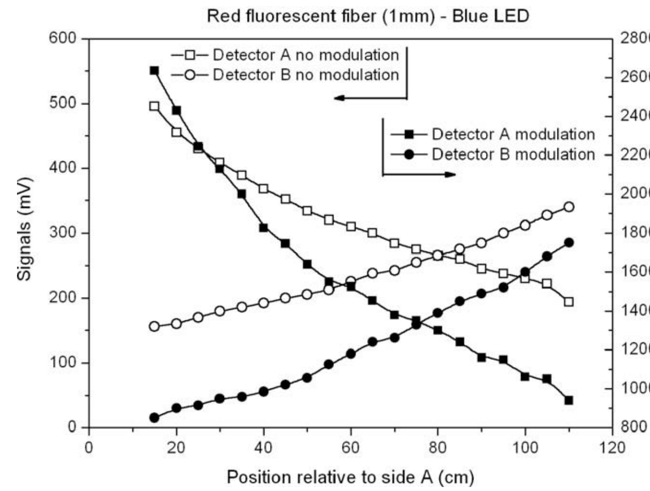

Fig. 5. Experimental results for red fluorescent fiber and blue LED with modulation and without signal modulation.

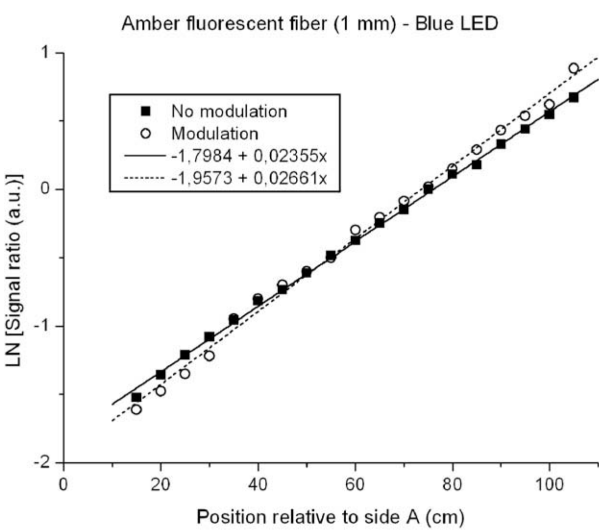

Fig. 4. Logarithm of the ratio of signals obtained at the ends of the amber fluorescent fiber in arbitrary units. They correspond to a blue LED source with modulation and without signal modulation.

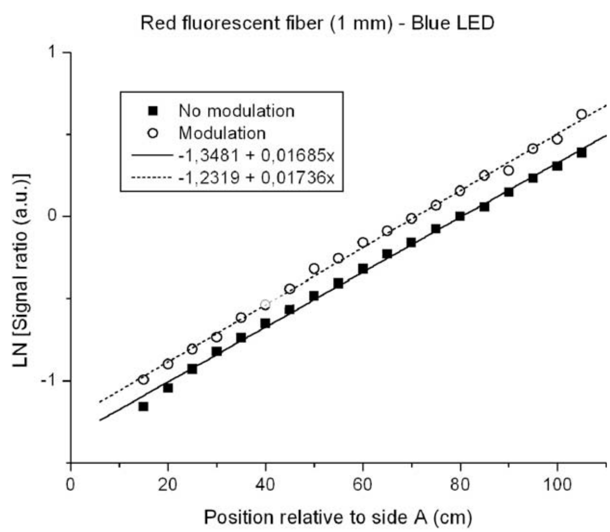

Fig. 6. Logarithm of the ratio of signals obtained at the ends of the red fluorescent fiber in arbitrary units. They correspond to a blue LED source with modulation and without signal modulation.

position of the incident light relative to side A and Fig. 4 shows the logarithm of the ratio between both sets of signals. Figs. 5 and 6 correspond to the same type of experiments, but, in this case, a red fiber of 1 mm and a blue LED were used.

It can be seen from Figs. 3 and 5, that the response of the photodetectors A and B is not the same. In such a case, the curves should cross at halfway between points A and B. Moreover, it is also noteworthy in those figures that the individual signals from the amber and red fluorescent fibers present random fluctuations.

According to Eq. (2.4), the position z depends on the logarithm of the ratio between both sets of signals. This ratio also serves to minimize the effect of the asymmetry of the photodiodes and electronics response at A and B, and to reduce data dispersion as can be easily seen from Figs. 4 and 6. These figures are nearly linear, which confirms the validity of the simple model presented in Section 2.

On the other hand, Fig. 4 shows that the experiment with light modulation yields a greater sensibility than without modulation. This situation is not repeated for the red fiber. It can be observed in Fig. 6 that the slope is practically independent of the type of light modulation.

Furthermore, the experiments with red fiber yield curves with smaller slope than with amber fiber.

Experiments were also carried out for different light sources. The results are shown in Fig. 7 for the green laser working with amber and red fibers of 1 mm in diameter. The behaviour of the amber fiber is better than that of the red fiber, although the sensitivity is again worse than for the blue LED. Therefore, amber fibers and a blue light source can be considered to be the most appropriate combination to carry out this type of position sensors. The straights lines in Figs. 4, 6 and 7 represent a least-square fit.

Finally in Fig. 8 we have compared the results of the experiments made with amber fibers of two different diameters 1 and 0.75 mm, and for different light sources. It is shown that experiments with 0.75 mm fibers do not follow Eq. (2.4). Its behaviour is quite anomalous and typical for all measured 0.75 mm fibers. Thinner fibers are more brittle and they have a lot of cracks along

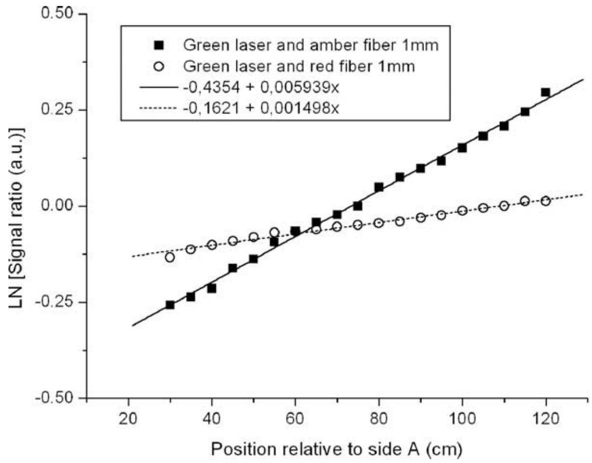

Fig. 7. Logarithm of the ratio of signals obtained at the ends of the red and amber fluorescent fiber in arbitrary units. The light source used was a green laser.

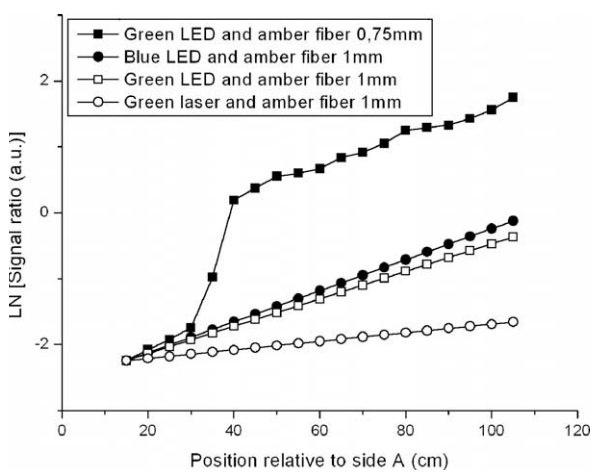

Fig. 8. Experimental results with amber fibers of diameters 1 mm and 0.75 mm for three different light sources; blue LED, green LED and a green laser.

them, as can be observed by direct inspection. That is the reason why the transmission of this fiber is not a linear function of the distance.

These measurements have also shown to be independent of both the intensity of the light source and variations of the distance between the light source and the fluorescent fiber, as long as the light is collimated or if the distribution of power along the fiber is symmetrical for any separation.

Differences in detector gain, small inaccuracies in the mechanical positioning, possible imperfections in the fiber, coupling losses at the ends of the fiber, and the electronic circuitry in the modulated and non-modulated signals could explain the small differences existing between the values obtained in the laboratory and the theoretical ones.

Supposing that the errors on α and L are negligible, the expression for the resolution can be obtained as:

$$\Delta z \approx \frac{1}{2\alpha}\sqrt{\left(\frac{\Delta V_1}{V_1}\right)^2 + \left(\frac{\Delta V_2}{V_2}\right)^2}, \tag{4.1}$$

where ΔV_i represents the error on the measurement of V_i.

In practice, resolution values depend on the performance of the electronics associated to the detectors. In the experiments carried out with the amber fiber of 1 mm of diameter and $\alpha = 0.355$ dB/m, the resolution of the system has been found to be 1.1 mm.

5. Conclusions

To verify the correct performance of the proposed fluorescent optical fiber linear position sensor, different laboratory experiments have been carried out. The sensor is suitable for measurements of position in a range varying from a few centimeters up to several meters, when a great precision is not necessary ($\sim$1 mm). It presents the well-known advantages of all other sensors based on optical fibers. The response of the sensor has a linear behaviour as can be expected from the simple model. We have also shown that the modulation does not have much influence on the sensitivity of the sensor. The best result was found for a blue excited amber POF of 1 mm of diameter. For smaller diameters, the bad quality of the fibers made them useless for implementing such a sensor.

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