Revista Mexicana de Física **41**, *No. 6 (1995) 890–896*

Micro-bending fiber optic sensor for micro-displacement measurements

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Recibido el 14 de junio de 1995; aceptado el 14 de agosto de 1995

ABSTRACT. The construction and characterization of a fiber sensor for the measurement of micro-displacement is reported. A theoretical model is used to relate the light modulated as a function of the displacement. Using this model and the experimental results obtained we give the sensitivity, dynamic range and time constant of the transducer.

RESUMEN. Se reporta el desarrollo experimental y la caracterización de un sensor de amplitud de fibra óptica para medir micro-desplazamientos. La relación entre la luz modulada a la salida del sensor con los desplazamientos provocados se efectúa a través del modelo teórico, el cual, junto con los resultados experimentales obtenidos, nos da la sensitividad, el intervalo dinámico y el tiempo de respuesta de transductor.

PACS: 48.81.Pa; 42.81.Wg; 42.81.Dp

1. INTRODUCTION

Fiber optic sensors are basically divided into two groups: interferometric or phase modulated sensors and amplitude modulated sensors. Interferometric sensors are optically and electronically more complex, since they require monomodal fiber and coherent sources. On the other hand amplitude modulation sensors are easier to construct, as multimodal fiber and non-coherent sources may be used. They are also less expensive but have less sensitivity than interferometric ones. Depending of the type of sensors there are different configurations [1] but on both configurations the sensitivity is higher than with conventional sensors. In addition, fiber optic sensors are immune to electromagnetic interference and it is possible to use them in many more geometrically practical situations. Therefore, for many practical applications fiber optic sensors are a very attractive option.

Among fiber optic amplitude sensors there are several types depending on the specific applications. For example, Faraday effect sensors are used to measure magnetic field [2],

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vanishing field [3], gratings [4], total internal reflection [5], fiber movement [6] and micro-bending. Most of them have been applied to the detection of acoustic signals.

Micro-bending sensors have been extensively studied due to their importance in acoustic applications [7–9], and for the measurement of flow level [10] and micro-displacement [11]. In this last case one observes the modes propagating on the cladding of the fiber (black field technique [11]), while in the previous cases one observes the guided modes propagating on the core of the fiber (bright field technique).

In this work we present the implementation and characterization of a micro-bending fiber optic sensor for the measurement of micro-displacements using the bright field technique, we measured the sensitivity, the dynamic range and the time constant of the sensor.

Section 2 gives a brief theoretical review explaining the physical principles of the sensor. Section 3 provides a description of the sensor. Section 4 describes the characterization of the sensor. Finally, in Sect. 5, we present our conclusions.

2. THEORETICAL MODEL OF THE SENSOR

The operation of this sensor is based on the light intensity losses taking place in a fiber, subject to microbendings. If a periodic deformation is induced on the fiber the propagation modes are coupled to the radiation modes, *i.e.*, the core modes are transferred to the cladding modes. The sensitivity of the sensor depends on the optimization of the bending-deformation losses and the mechanical configuration of the device [9].

If an optical fiber is placed between two plates with a periodic surface modulation and I_0 is the irradiance coupled to the fiber and T the transmission coefficient, then the irradiance of the transmitted light is given as

$$I = I_0 T. \tag{1}$$

If a field variation, a change on the parameter of interest, Δp is applied to the plates, then the plates will have a displacement Δx, which will cause variation in the transmission coefficient ΔT. Therefore the fiber will undergo a change in the irradiance given by

$$\Delta I = I_0 \frac{\Delta T}{\Delta x} \frac{\Delta x}{\Delta P} \Delta P, \tag{2}$$

where the factor $\Delta T/\Delta x$ is known as the sensitivity coefficient. This coefficient is an optical parameter which depends on the fiber characteristics. It has been theoretically [8] and experimentally [9] shown that the highest sensitivity is obtained when the mechanical deformation wavelength λ_m is

$$\lambda_{mp} = \frac{2\pi a n_c}{NA}, \tag{3}$$

for a parabolic refractive index, where a is the radius of the core, n_c its refractive index and NA is the numerical aperture of the fiber. On the other hand, for a constant refractive index fiber profile λ_m is given as

$$\lambda_{me} = \frac{\pi a n_c \sqrt{2}}{NA}. \tag{4}$$

Furthermore, the factor $\Delta x/\Delta p$ only depends on the mechanical characteristics of the system. If the fiber is fixed at both ends [9], then

$$\frac{\Delta x}{\Delta p} = \frac{1}{3\pi n} \frac{A\lambda_m^3}{Ed^4}, \tag{5}$$

where n stands for the number of deformation, E for the Young modules of the fiber, d for its diameter and A for the diaphragm area in which the field is acting. In this way the equation relating the intensity as a function of the field variation is given as

$$\Delta I = I_0 \frac{1}{3\pi n} \frac{A\lambda_m^3}{Ed^4} \frac{\Delta T}{\Delta x} \Delta p. \tag{6}$$

From this expression and the experimental measurements it is possible to obtain the sensitivity of the detector. However, if the field variation is a displacement, as in our case, $\Delta x/\Delta p$ takes the value of one and Eq. (6) becomes

$$\Delta I = I_0 \frac{\Delta T}{\Delta x} \Delta x. \tag{7}$$

In order to obtain the time constant of the sensor a step signal was introduced in the linear response region. The sensor behaves as a first order low pass filter with Laplace transfer function

$$H(s) = \frac{1}{s + 1/\tau}. \tag{8}$$

Then, if a unit step function $x(s) = 1/s$ is introduced as a displacement step, the optical irradiance variation $I(t)$ is given as

$$I(t) = 1 - \exp(-t/\tau), \tag{9}$$

which can be experimentally observed and used to find the time constant of the detector τ.

3. Experiment

One meter of multimodal optical fiber with parabolic refractive index was used. Its Young modules was 7×10^{-10} N/m^2 and its numerical aperture 0.275. The core of the fiber was

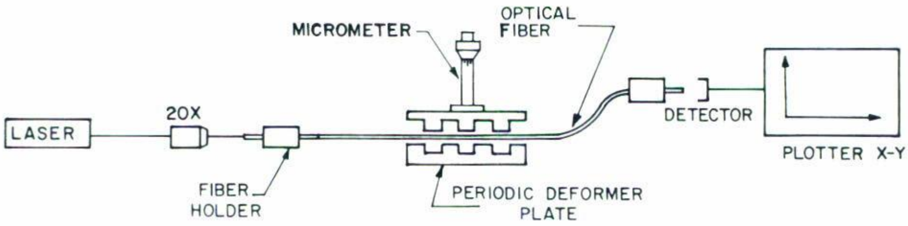

FIGURE 1. Schematic diagram of the experiment.

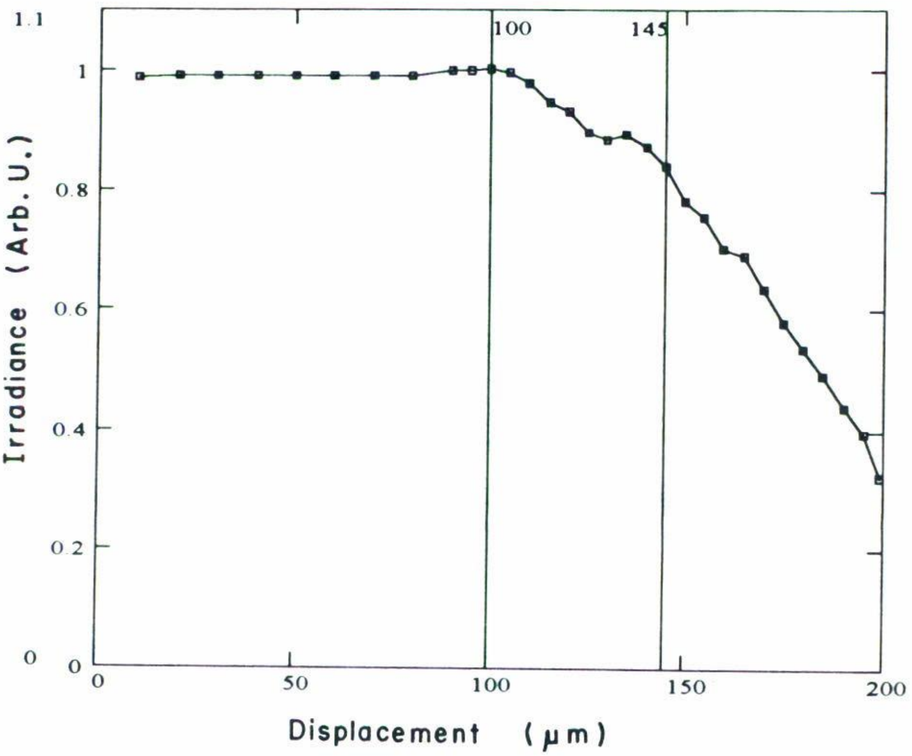

FIGURE 2. Irradiance as a function of the displacement. Notice the linear drop in the two marked regions. As shown, the dynamic range of the device is 100 μm.

62.5 μm in diameter which together with a protective clad totalled 125 μm. This fiber had an acrylic coating.

The experiment arrangement is shown in Fig. 1. One of the ends of the fiber was fixed to the focal point of a coupling 20X microscope able to couple 30% of a 5 mW He–Ne laser beam. The other end was coupled to a PIN detector whose exit was connected to a x–y plotter in order to detect any modulation of the beam. The system to produce deformation consisted of two metallic plates each with 20 square teeth and 1.02 mm. The fiber was placed perpendicular to the surface modulation of the plates and a micrometer which was used to produce the mechanical displacements was placed directly on the upper plate. This displacements would cause the desired optical modulation. Finally the contact area between the micrometer and the upper plate was 19.63×10^{-6}.

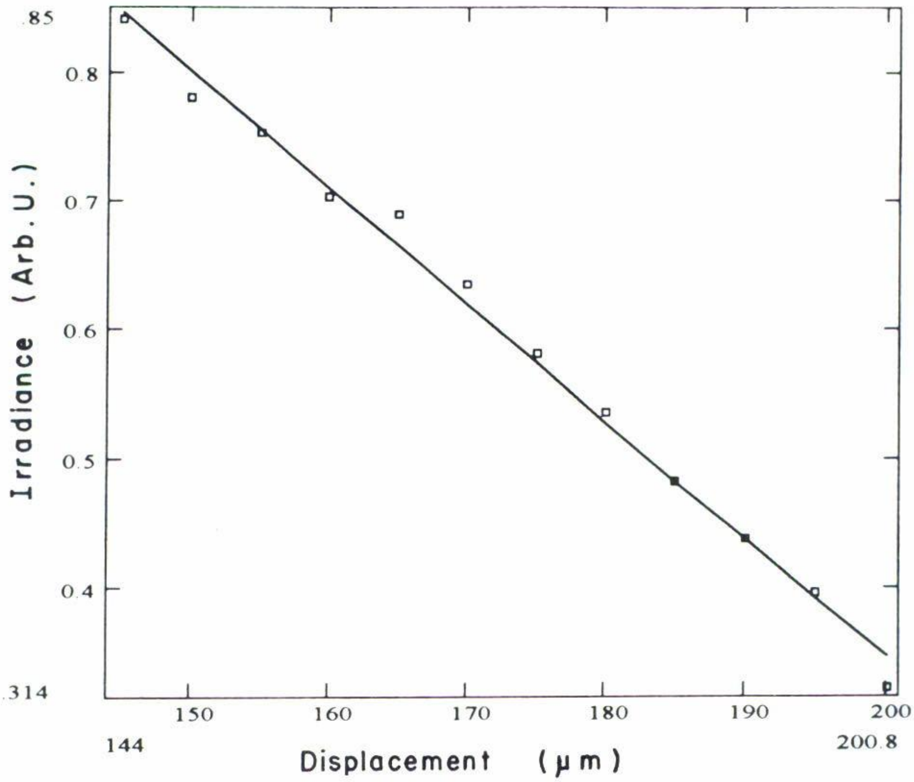

FIGURE 3. Decrease in the observed signal within the 100–145 μm range. Dots show the experimental points and the solid line shows the adjusted model. The sensitivity measured in this region is 0.4%/μm.

In order to observe only the light which was guided through the core (bright field technique) and not the optical modes from the clad, 15 cm of the fiber before the sensor and the detector were painted black.

4. Characterization

Figure 2 shows the experimental measurements when a mechanical displacement from 0 up to 200 μm was applied to the upper plate of the sensor shown in Fig. 1. It can be observed that from 0 to 80 μm the transmitted light intensity remains constant while a slight variation is observed from 80 to 100 μm. This variation is due to a fitting process between the plates and may, as a result give, a small increase or decrease in the signal intensity. On the same figure a decrease in the signal can be seen for a variation from 100 μm to 200 μm which corresponds to the dynamic range of the device. After this point a continuous decrease in the signal is observed and its is not possible to consider any measurement. A careful observation of the dynamic range region shows that there are in fact two linear regions, one from 100 to 145 μm and one from 145 to 200 μm.

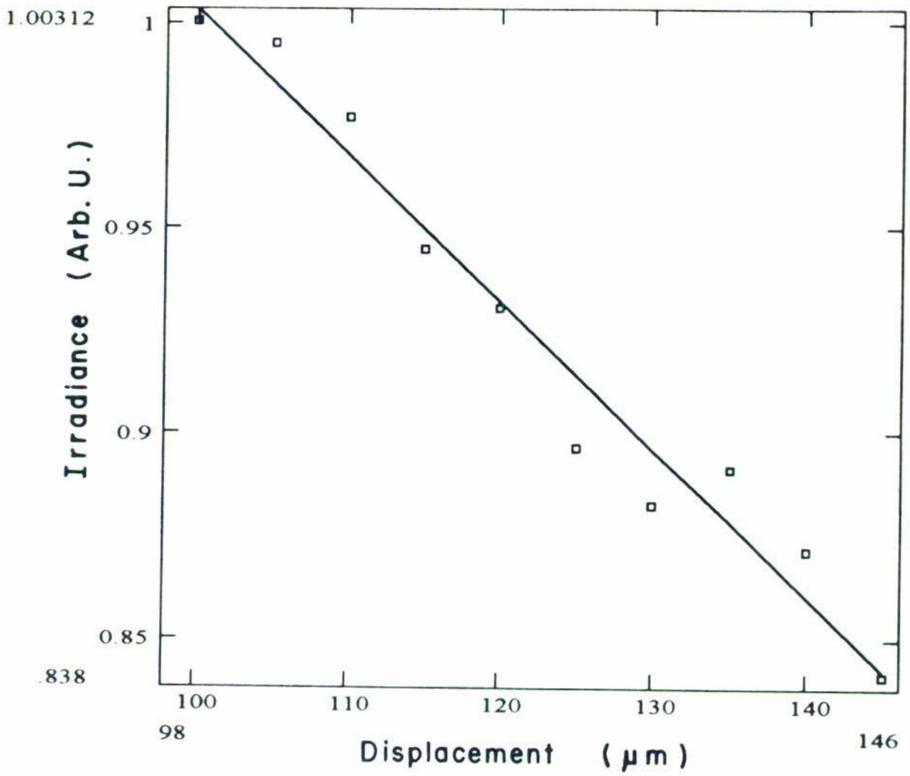

FIGURE 4. Decrease in the observed signal in the 145–200 μm region. Dots show the experimental points and the solid line shows the adjusted model. The sensitivity in this region is 0.9%/μm.

Figure 3 shows the result in the 100 to 145 μm region. The solid line is a line adjustment with a slope of −0.004. The correlation with the experimental data is 0.981, therefore the predicted readings are within a 1.9% error range which we believe is very good. By comparing our measured result with Eq. (7) we obtain a sensor sensitivity of 0.004, which means that we have a 0.4% decrease of light irradiance by each μm of displacement.

Figure 4 shows the result in the 145 to 200 μm region. In this case, we can observe a more uniform decrease. The line adjustment's slope is −0.009 with a correlation of 0.996; therefore, the predicted readings are within a 0.4% error range. The sensitivity is 0.009, which means that we have a 0.9% decrease of light irradiance per μm of displacement.

The time constant of the system depends in general on the mechanical structure. In our case it depends mainly on the elastic properties of the fiber. Therefore the polymer properties used to cover the core and cladding are very important. By introducing a step displacement variation, the experimental results show that in the 100–145 μm region the time constant of the device is 0.6 sec. On the other hand, in the 145–200 μm region the measured time constant was 1.65 sec. As we can see from the mentioned results the device is slower operated in the second region.

5. Conclusions

The details of construction and the characterization of a fiber optic sensor for the measurements of micro-displacements were reported. The dynamic range of the device was 100 μm. This region is divided into two linear operation regions, from 100 to 145 μm and from 145 to 200 μm. The measured time constant of the sensor was 0.6 sec in the fist and 1.65 sec in the second operation region. This difference was attributed to the mechanical deformation of the polymer envelope of the fiber. In fact we found that before the 100 μm region the response of the device was constant, possibly due to a mechanical fitting of the fiber used, whereas after 200 μm it is not possible to measure because the fiber may be permanently damaged and the time constant becomes very long. On the other hand, the observed sensitivity was 0.004 for the 100–145 μm region and 0.009 for the 145–200 μm region.

In conclusion, the studied fiber optic sensor has two linear operating regions; the first where the sensor is fast but less sensitive and the second where the sensor is slow but more sensitive. Additional work is being done in two directions: the use of non-coherent light sources in order to diminish noise problems and the optimization of the mechanical structure of the sensor.

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