Non-contact torsion transducer based on the measurement of Moiré patterns using plastic optical fibers

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ABSTRACT

An angular and displacement sensor that uses a polymer optical fiber and Moiré patterns is demonstrated. Moiré fringes are generated using two transparent superimposed planar gratings placed in front of an optical mirror. Moiré patterns with periods ranging from 0.4 to 2 mm have been obtained in this way with 1mm-diameter plastic optical fibers for torsion angles ranging from 10º to 20º have been compared with theoretical calculations and a good agreement has been confirmed. Measuring the period length and the number of periods, both the relative angle between the gratings and the displacement of the fiber with respect to the mirror are obtained. With this technique very low angles can be measured with a very high resolution. The sensor principle has been successfully checked in the laboratory. Finally, the effect of employing different plastic fibers is also discussed. Besides, other possible applications of this measurement technique are presented and discussed.
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Keywords: Torsion sensor, Moiré patterns, plastic optical fiber.

1. INTRODUCTION

The simultaneous measurement of displacement and angle are topics of interest in a wide range of industrial applications. Interferometric (Mach-Zehnder, Michelson or Fabry-Perot) [1-4], intensity [5], spectrum [6, 7], or encoded patterns [8], among others modulation techniques are intensively used to measure displacement with different dynamic and resolution ranges. Several approaches have already been presented to measure angles [9, 11]. However, in some cases the technical complexity of the sensing principles or the demodulation technique used, or the complex technology required, or the high costs for specific applications, suggest the necessity of alternative, simple and low costs solutions for the extensive use of the optical sensing technology in real applications.

Sensors using plastic optical fibers (POFs) are presented as a low cost alternative due to their inherent advantages: easy manipulation and simple optical connections, cheap optical sources, excellent flexibility, and low cost among others. These fibers will potentially provide very good technical performance/cost ratio for optical communications and sensing solutions. Recently, Moiré patterns formed by the overlapping of two identical transparent gratings were experimentally checked using POFs [10].

In this paper an angular and displacement sensor using polymer optical fiber and Moiré patterns is demonstrated. The sensor principle and the transducer head architecture are presented. Experimental results are also shown and discussed.

2. SENSING PRINCIPLE

The sensing principle is based on the measurement of the period length and number of periods of a Moiré pattern. If two transparent film uniform gratings are overlapped with a relative angle between them, so a Moiré pattern is generated. This effect is illustrated in Fig. 1.

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The Moiré fringes shown in Fig.1b were created in the *xy* plane by means of the overlapping of two similar uniform gratings of period P, like those shown in Fig.1a. The direction of the Moiré fringes is perpendicular to the bisector of the angle created by the superimposed grating fringes.

We use a mathematical formalism to characterize the Moiré pattern formed by the overlapping of two gratings F_1 and F_2 (Fig. 1b). For example, the equation for a grating of period P along the x axis is: y=LP (L= 0, ±1, ±2, …). The fringes of the grating F_1 form an angle $\alpha/2$ with the y axis, and the grating F_2 is symmetrically inclined at $-\alpha/2$. The gratings F_1 and F_2 are respectively described by the two following sets of equations [12],

$$y \cos\alpha/2 = x \sin\alpha/2 + nP, \qquad n = 0, \pm1, \pm2, \ldots \tag{1}$$

$$y \cos\alpha/2 = - x \sin\alpha/2 + mP, \qquad m = 0, \pm1, \pm2, \ldots \tag{2}$$

The geometrical loci of all points of intersection of the two gratings form an array of dark fringes whose index is given by: L=$m - n$ (L= 0, ±1, ±2, ±3, …). Substituting for m and n yields:

$$L = \frac{2 \text{ x} \sin(\alpha/2)}{P} \tag{3}$$

By rearranging Eq. (3) we obtain the equations describing the fringe pattern:

$$x = \frac{L\,P}{2 \sin(\alpha/2)} \tag{4}$$

For small values of α (sinα≈α, in radians) we obtain: x≅LP/α.

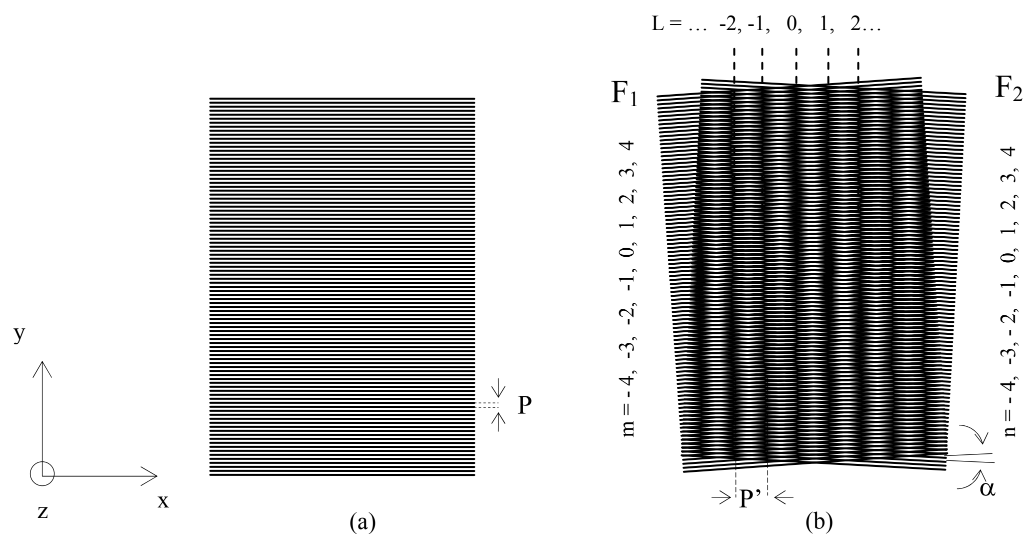

Fig. 1. Moiré fringes pattern generated by two superimposing gratings (opaque and transparent fringes): a) a grating of period P and b) Moiré pattern of period P′ created by the superimposing of two identical uniform (F_1 and F_2) gratings with an angle α.

Equation (4) represents a set of straight lines perpendicular to the y axis whose spacing is approximately α^{-1} times the period of the original gratings. The periodicity of the Moiré fringes formed by two identical gratings as a function of the angle α is given by:

$$P' = \frac{P}{2\sin(\alpha/2)} \tag{5}$$

In this paper we only analyze those Moiré patterns generated by gratings of straight and similar fringes

Taking into account the above mentioned, the proposed sensing principle can be described as follows: first the period of the Moiré fringes P' is measured; then, from this value, and knowing the period P of the grating, the angle α can be calculated using Eq. (5). If the POF fiber is displaced in the x direction, then this displacement can be measured by counting the number of Moiré fringes seen along that movement. The latter allows determining displacements with a resolution of half a Moiré period.

The length of the Moiré fringe's period depends on the period of the superimposed gratings. Thus, millimetre-length Moiré periods can be obtained by superimposing millimetre-length gratings.

In Fig. 2 the Moiré period versus the angle α is shown for six different grating periods. It can be observed that the Moiré period P' decreases when the angle α increases. However, this decreasing is not linear, but three distinct regions can be observed instead. The first region is between 0 to 5 degrees: the values of P' are relatively large and they diminish quickly as α increases. This is, therefore, a very sensitive region. In the second region, that ranging from 5 to 20 degrees, the variations in P' are moderate (smaller than a dozen mm). For example, when the period of the arrays is P=0.4 mm, the period of the Moiré fringes goes from 4 mm (at α=5º) to 1.6 mm (at α=20º). These magnitudes of the periods are compatible with the POF when these are used. In the third region, from 20 to 40 degrees, the variations of P' are small, approaching to a constant asymptotic value. This is the least sensitive region.

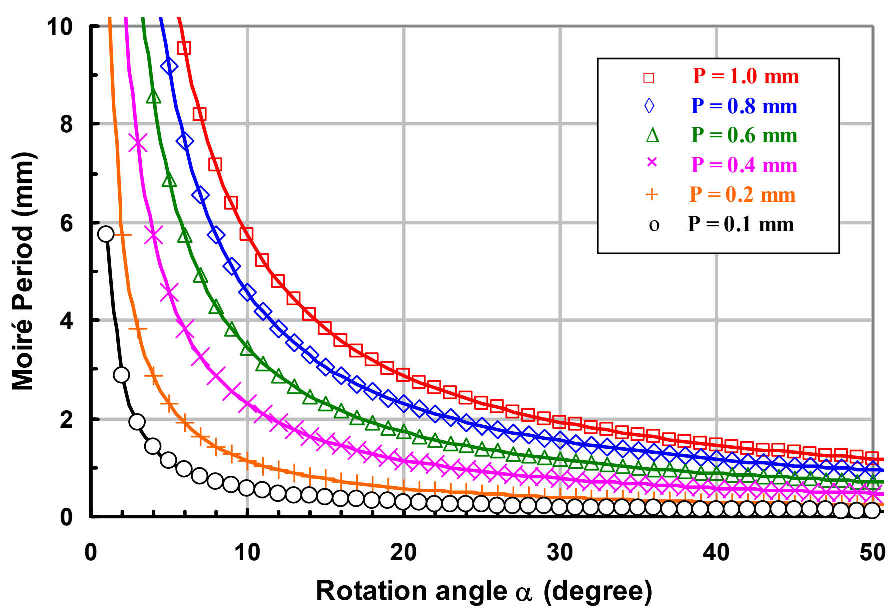

Fig. 2. Moiré pattern period P´ versus the relative angle α of two superimposing gratings of periods P=1, 0.8; 0.6; 0.4; 0.2 and 0.1 mm.

3. MEASUREMENT OF MOIRÉ PATTERNS WITH PLASTIC OPTICAL FIBERS

The Moiré fringes generated by superimposing two arrays of transparent and opaque fringes can be illuminated and collected by optical fibers. In fact, Moiré patterns are simply obtained by geometric interference with scarce dependence on the characteristics of the light. Therefore, it can be enough to use a multimode optical fiber to illuminate the Moiré fringes.

The numerical aperture (NA), that represents the capacity of an optical fiber to collect light, is defined by Eq. (6), where n_1 and n_2 are the refractive index of core and cladding respectively:

$$NA = \sqrt{n_1^2 - n_2^2} \tag{6}$$

The POFs present generally high NA. For example, a step-index PMMA-POF (1mm core diameter) with core index 1.492 and 1.402 cladding index presents a NA of 0.5. This high value offers a significant advantage both for connecting fibers and for illumination. If the fiber is 3.5mm away from a surface, it can illuminate a 15 mm^2 spot with 4.5mm diameter.

The spatial resolution, which determines the capacity of the optical fiber to distinguish two consecutive opaque fringes, is directly related to the diameter of the fiber and the period of the fringes. We have developed a computer program that selects the most suitable optical fiber for different Moiré periods. Fig.3 shows the coupling efficiency in a receiving fiber when the incident light goes through an array of straight and identical fringes. The calculus has been carried out for a 0.98mm core diameter fiber. It can be seen that when the fringe width shrinks, the intensity of the injected light also diminishes. However, a maximum of 5 fringes/mm can be easily measured. For smaller fringe periods there are other more suitable commercially available optical fibers.

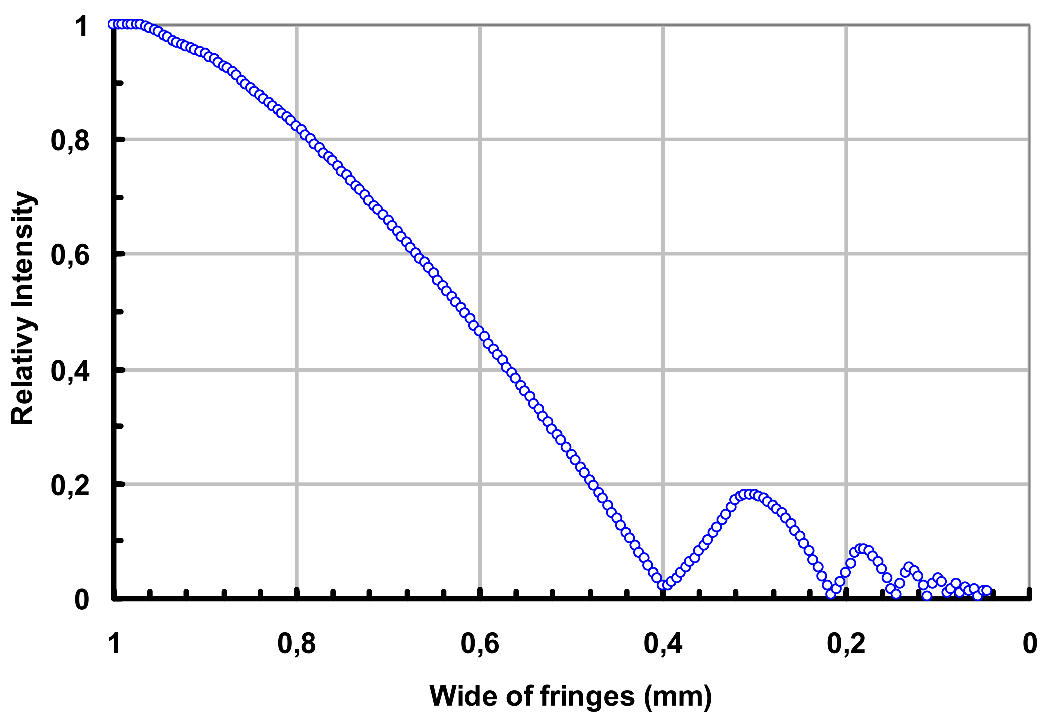

Fig. 3. Coupling efficiency of a multimode fiber when the light goes through a film grating. The graph has been obtained for a fiber core of 0.98mm diameter.

In order to experimentally check the periodicities of Moiré patterns, we have measured, using POFs, different patterns generated by gratings of different periods. The method for measuring was based on an emission and reception system with POFs. The POFs were fixed at a distance *d* from a reflective surface. This distance provided the maximum coupling efficiency in the receiving fiber. Between the fibers and the reflective surface there were two gratings (one that can rotate and the other one fixed). Varying the mobile grating angularly, different periods of the Moiré pattern were obtained. The system (fibers and reflective surface) was optimized with the objective of carrying out the characterization of Moiré patterns without additional optical devices and looking for the minimization of the effect of diffraction.

The characterization setup is shown in Fig. 4. It consisted in two fibers that were identical and parallel. One of them was the emitting fiber and the other was the receiving fiber. The tips of both fibers were cleaved normal to the fiber axis. The reflective surface was flat and metallic with a good reflection coefficient. This surface was perpendicular to the axis of the fibers**.** In front of the reflecting surface there were two films with transparent and opaque fringes. These films were the superimposing gratings. One of these gratings was free to rotate, thus allowing the generation of Moiré patterns of different periods. The end of the receiving fiber was coupled to a power meter HP81520A. PMMA POFs step-index multimode fibers of 1 mm diameter and two-meters length were used. The core diameter was 0.98 mm and its index was n_1=1.49; the cladding index was n_2=1.41 and the numerical aperture was 0.47. A He-Ne laser (λ=543nm) was employed in the experiments.

The coupling efficiency in the receiving fiber depends on the distance between the fiber and the reflective surface, on opto-geometric parameters of the fiber and on the type of reflective surface. In previous works we have calculated the coupling efficiency of the fiber probe for different displacement sensors [13]. For the POFs used in the sensor described in this paper, the maximum coupling efficiency was obtained for a distance of about 1.8 mm.

The Moiré patterns that have been employed in the experiments were obtained with gratings having opaque and transparent fringes of similar width. As been previously mentioned, one of the gratings was fixed to the reflective surface whilst the other one could rotate with respect to their central axis. Since the Moiré fringes that are formed by this way are perpendicular to the bisector of the angle between the superimposing gratings, the receiving fiber had to move according to this direction (x direction in Fig. 1b). In all the cases, the measurements of optical power were carried out each 0.1 mm step of displacement of the fiber.

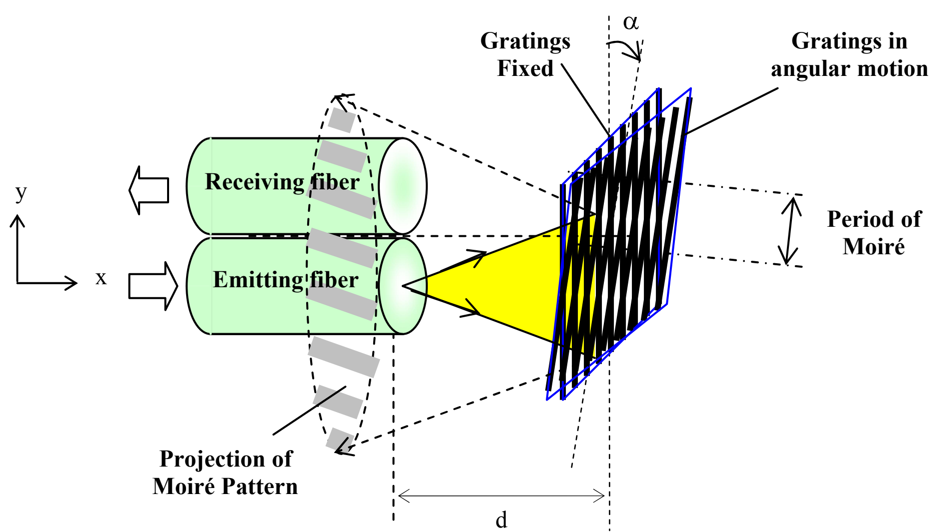

Fig. 4. Structure and principle of operation of the optical fiber sensor with transducer head structure work in reflection.

In Fig. 5 the results obtained for fringes of period 2, 1 and 0.4 mm are shown. For achieving this range of Moiré periods, the mobile grating was rotated from 0 to 20 degrees. It should be said that the Moiré periods obtained for small rotation angles are relatively big and, therefore, difficult to be accurately measured with a small optical fiber. From these experiments it is readily verified that the bigger the angle α the smaller the Moiré period.

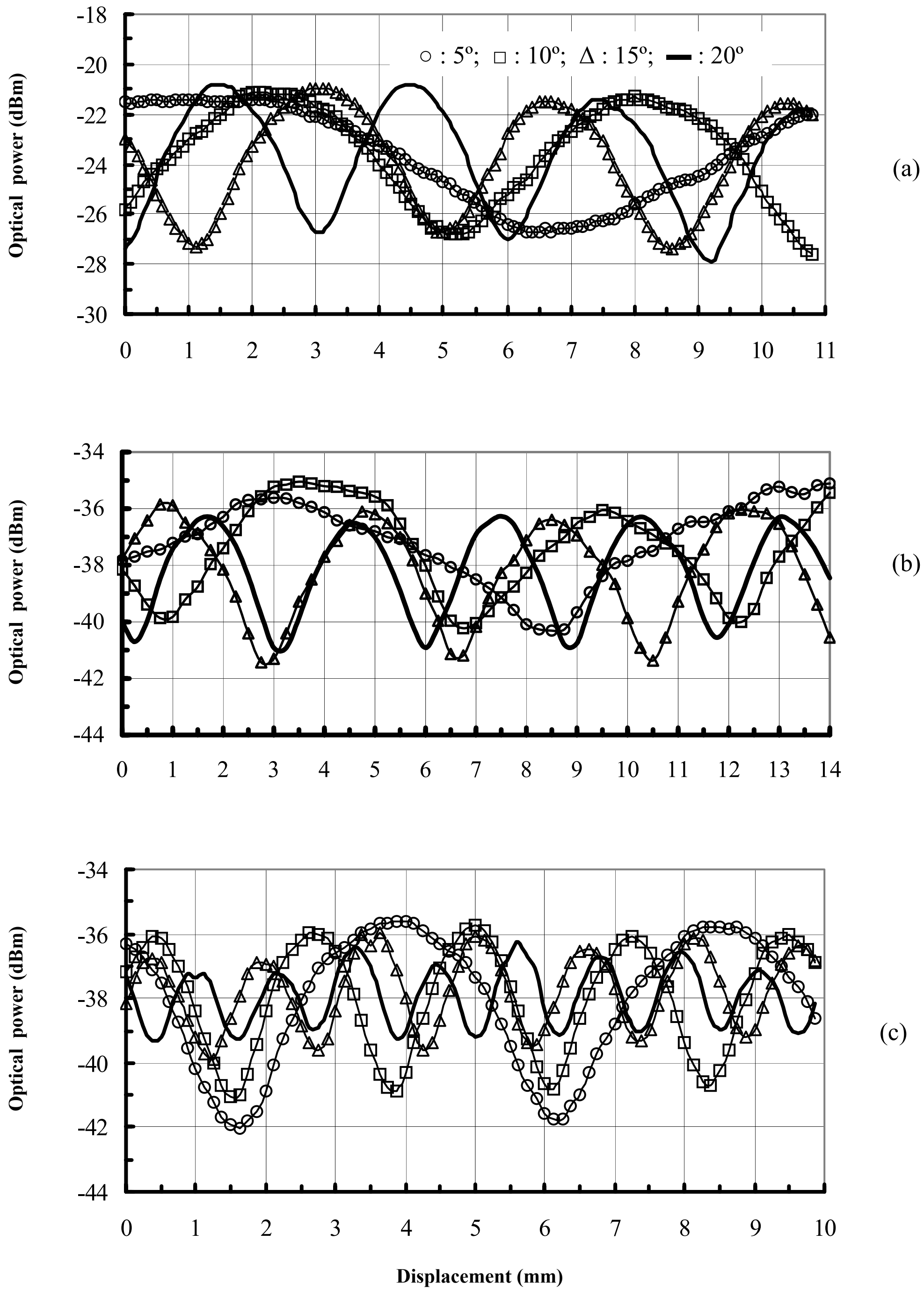

Fig. 5. Moiré patterns generated with two film gratings. Measurement of the optical power coupled in the receiving fiber as a function of the lateral displacement for relative angles between the gratings of 5º, 10º, 15º and 20º for grating periods of a) P=2.0 mm, b) P=1.0 mm, and c) P=0.4 mm.

In all measurements of Fig. 5 the optical power coupled in the receiving fiber presented sinusoidal fluctuations with the displacement. Besides it can be observed that the contrast of the signal diminishes with smaller Moiré periods. In the case of Fig. 5a (grating period of 2 mm) the Moiré period was smaller than the predicted by Eq. (5). On the contrary, when the period of the gratings was equal or smaller than 1mm, the Moiré periods fully agree with the theory. These small deviations from the theoretical predictions can be attributed to diffraction effects. These problems can be overcome by using a collimating lens in the illumination and projection of the fringes.

4. TRANSDUCER STRUCTURE

The Fig. 4(a) illustrates the structure of the sensing head. It comprised to two main parts or subsystems: the emitting and receiving part and the Moiré pattern generation part. The latter is formed by two uniform film gratings placed in front of an optical mirror. One of these grating was directly created on the mirror. The other one was superimposed to the first grating. Even though the emitting and receiving part could be simplified by using a single fiber for both tasks, in this paper two fibers were used. One fiber was used to illuminate the gratings and the other one collected the reflected light. Therefore the collected optical power would depend on whether there is a maximum or a minimum of the Moiré pattern at the collection point. Therefore, displacements in the y direction were detected as a fringe pattern. With very simple calculations on this detected signal, both the relative angle between the gratings and the displacement of the fiber can be obtained. In order to get an optimum optical power coupling between the emitting and the received fibers and to maximize the insensibility to displacements on the x axis, the coupling curves were obtained (see Fig.6). The optimum working distance *d* between the fibers and the mirror is the peak of that graph.

5. EXPERIMENTAL RESULTS

The experimental coupling curve obtained in Fig. 6 was measured without gratings, just the two fibers in front of the mirror. The POFs used had a core diameter of 0.98 mm. This curve presents two slopes of different sensitivity and a maximum peak of 3.8 μW that corresponds to a distance of 3.5mm between the optical fibers and the mirror. The first slope had a sensitivity of 2.1 μW/mm, while the second was of -0.9 μW/mm.

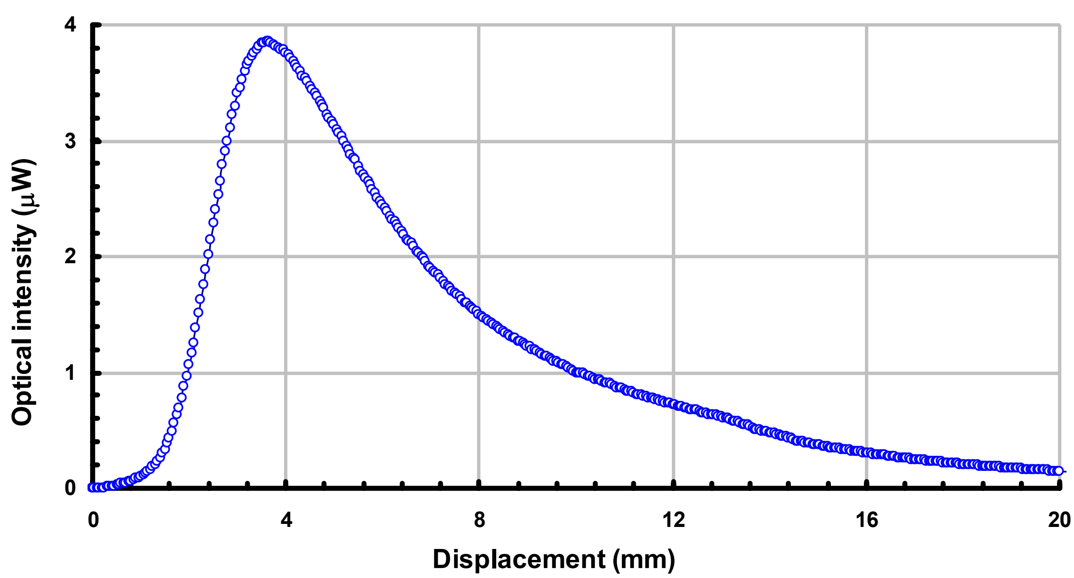

Fig. 6. Experimental optical power coupling curve of the transducer head.

With these results the transducer head was built using an optimum working distance of 3.5mm. The light source employed was a laser of λ=0.6328 µm. The experiments were carried out by applying calibrated displacements along the y axis and recording the Moiré fringes seen by the collecting fiber. Thus graphs like the one shown in Fig. 7 were obtained.

In this demonstration of the transducer, the Moiré patterns were generated using two gratings of 0.4 mm period. In these cases, the measured Moiré periods ranged from 2.2 mm to 1.1 mm for angles going from α=10º to 20º respectively. To corroborate the angle measurement capacity of the proposed sensor, a wide set of experiments were successfully carried out. The results from one of these experiments are summarized in Fig. 8. It represents the variation of the Moiré period with the relative angle between the gratings. As can be seen, the measured results are in very good agreement with the theoretical predictions given by the expression (5) and suggest a very high angle resolution for very low angles. Through the proper processing of the detected signal, the relative angle between the gratings can be obtained from the Moiré grating period. On the other hand, provided the relative angle between the gratings were known, the lateral displacement can also be easily determined from the number of fringes detected during the displacement. Since the displacement resolution is of half the Moiré period, it can be improved using smaller grating periods and reducing accordingly the diameter of the collecting fiber in the transducer head. Thus, custom designs and low cost sensor systems can be obtained using this technology.

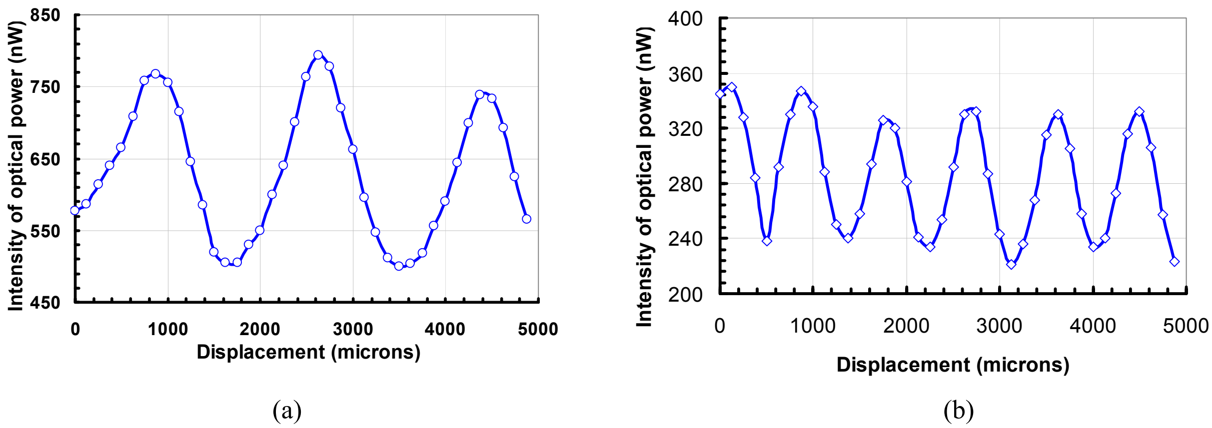

Fig. 7. Moiré fringes experimentally measured when two identical gratings are overlapping with an angle of a) 10º and b) 20º respectively.

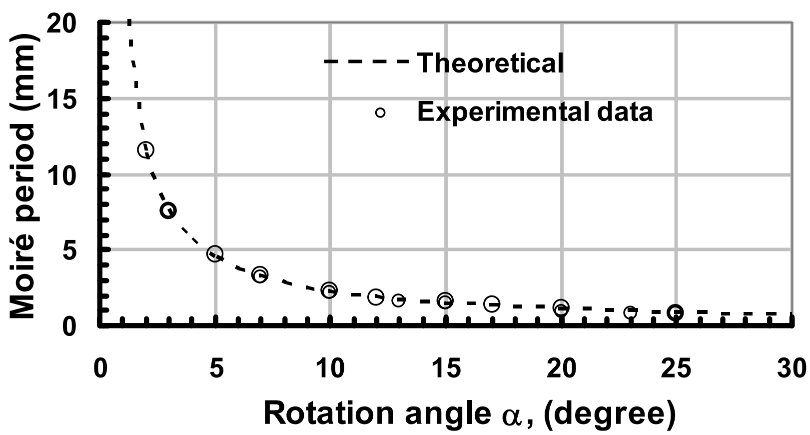

Fig. 8. Moiré period P' versus the relative angle α between the two superimposing gratings. The grating periods were P=0.4mm.

6. CONCLUSIONS

A non-contact torsion transducer for the measurement of linear and angular displacement has been made using plastic optical fibers and Moiré patterns. This sensor has been presented and experimentally demonstrated. Moiré fringes are generated using two superimposed film gratings placed in front of a mirror. Measuring the period of the Moiré pattern the relative angle between the gratings can be obtained. On the other hand, by determining the number of periods of the detected signal the lateral displacement of the sensing head with respect to the mirror can be obtained. The displacement resolution can be improved using smaller grating periods and reducing the fiber diameter accordingly. With this technique, successfully checked in the laboratory, very low rotation angles with very high resolution can be measured. Custom designs and low cost sensor systems can be constructed using this proposed technology. The excellent flexibility of the POFs can allow to make tests or measures without contact in inaccessible or aggressive places.

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