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A micro opto-mechanical displacement sensor based on micro-diffraction gratings: design and characterization

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***Abstract*— A micro opto-mechanical displacement sensor is here presented. It is constituted by a sensing element based on two overlapped micro-diffraction gratings (MDGs). They present a platinum layer (45 nm of thick) on a glass substrate, a period of 525 µm constituted by a width of 150 µm of platinum separated (71.4% duty cycle). The working principle is based on the modulation of light intensity induced by the relative displacement between the MDGs: when a laser light perpendicularly hits the MDGs, the intensity of the transmitted light is a periodic function of the relative displacement between the two MDGs. A fiber optic is used to transport the transmitted light to a photodetector in order to avoid concerns related to the alignment between the optical components.**

The sensor's output is the ratio between the light intensity measured by the photodetector during the displacement of the MDGs and largest light intensity values measured in the whole range of measurement, therefore, it is lower than 1. The proposed sensor allows to discriminate displacement lower than 10 µm, using a cost effective micro-fabrication process implemented by the technique of Lift-Off. It shows a good linear behaviour in two ranges covering about one half of the MDGs period. Within the linear ranges it shows high sensitivity (about 0.5%/µm) and good accuracy (lower than 4 % in the whole range of calibration); furthermore, the results show that a design with a duty cycle of 50 % overcomes the marked decrease of sensitivity in a range of measurement corresponding to a grating period.

I. Introduction

Three dimensional techniques of micro-fabrication are rapidly expanding and have increasing roles in medicine and biology. They are used as tools for molecular biology and biochemistry [1] and they are expanding in both diagnostic and therapeutic areas [2]. The small size, good metrological characteristics and cost-effectiveness make the potential of micro-fabricated sensors enormous in medicine: they are mainly used for monitoring physical parameters, such as, pressure [3], displacement, and flow [4, 5] among others. During last decades, also fiber optic sensors (FOS) have shown a significant development in medical areas; the immunity from electromagnetic interferences, small size and large bandwidth make attractive FOS to be used in medicine for monitoring of flow [6,7,8], force, displacement and pressure [9]. The advantages of micro-fabricated sensors and FOS encourage in developing hybrid solutions based on these two technologies for sensors design.

In a previous study [10] we presented a FOS for strain measurements based on a micromachined diffraction grating; these microgratings are used to estimate several physical parameters (e.g., pressure, force and displacement among others [11]).

In this work we present a FOS constituted by two MDGs which were micro-fabricated by implementing the technique of Lift-Off. The working principle of the proposed sensor is based on the modulation of the light by the relative displacement between the two MDGs interposed to a laser source and a fiber optic tip: the laser light, modulated by the abovementioned displacement, is monitored by a photodetector, which is connected to the distal extremity of the optical fiber. Therefore, the intensity can be considered an indirect measurement of the displacement. The sensor can be considered an extrinsic intensity modulated FOS, because the optical fiber is used simply to guide light from an optical source to an optical sensor head and from the sensor head to a photodetector.

The aim of this work is twofold: 1) the experimental characterization of the micro opto-mechanical displacement FOS; 2) to estimate the influence of the grating geometry on the sensor sensitivity and measurement range.

The sensor shows some peculiarities: its principle of work can be used to indirectly measure mechanical parameters which cause a displacement, such as force [12], pressure and flow-rate; moreover, the use of fiber optic makes the sensor immune to electromagnetic interferences, overcomes typical concerns related to the alignment of the optical components, and allows to deploy the light source and the photodetector away from the sensing element.

II. Operation Principle

The sensing element of the transducer consists of two identical uniform-period MDGs. The light emitted by a laser hits the surface of the two MDGs perpendicularly, which are vertically aligned when a null relative displacement is applied. The MDGs are interposed to the laser source and a tip of an optical fiber which transports the transmitted light to a photodetector. When a relative displacement (Δx) is applied between the two MDGs, the diffraction efficiency of the phase grating changes, and it modulates the transmitted laser light.

Since the first diffraction mode intensity, I_1, according to the diffraction theory of Fraunhofer, is a periodic function of Δx,

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the relative position of the two MDGs can be estimated by I_1; therefore I_1 can be considered an indirect measurement of the abovementioned relative displacement.
Considering that only one gratings' period is hit by the light ($N=1$), $I_1(\Delta x)$ can be expressed as follows [11]:

$$I_1(\Delta x) = I_0 \left[\left(T/2 - \Delta x \right) \cdot \operatorname{sinc} \frac{\left(T/2 - \Delta x \right)}{2 \cdot T} \right]^2 \cdot \sin^2 \phi_0 \cdot G(\Delta x) \quad (1)$$

$$G(\Delta x) = \begin{cases} \sin^2 \dfrac{\pi \left(T/2 + \Delta x \right)}{2 \cdot T} & 0 < \Delta x < T/2 \\ \sin^2 \dfrac{\pi \left(3 \cdot T/2 - \Delta x \right)}{2 \cdot T} & T/2 < \Delta x < T \end{cases} \quad (2)$$

Where I_0 is the light intensity hitting the MDGs, and $\phi_0 = \left(2\pi/\lambda \right) \cdot (n_1 - n_0) \cdot t$ is the phase delay over the thickness of one grating finger, t is the thickness of the radiopaque materials and n_1 its refractive index; $n_0=1$ is the refractive index of the air. Considering $N=1$, the sensitivity and measurement range of the transducer can be tuned by changing the grating period (T): the sensitivity decreases with T; on the other hand the measurement range increases with T [11].

III. Sensor Design and Fabrication

The two MDGs have been developed by patterning a thin film of platinum (Pt) on glass substrates. Each grating has been micro-fabricated using standard processes of photolithography and lift-off.

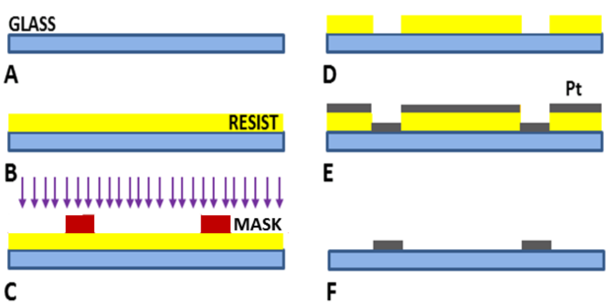

Figure 1. Schematic of the micro-fabrication steps. A: Glass substrate; B: Resist deposition; C: UV Exposure; D: Patterned resist; E: Platinum deposition; F: Patterned platinum.

The main steps of the fabrication process can be summarized as follows (Fig. 1):

- Spin coating: deposition of 7.5 µm of a negative resist (ma-N 490, by Micro Resist) on a glass substrate, previously cleaned.
- Soft bake: baking at 60 °C for 2 minutes, on a hotplate.
- UV exposure for 100 s (using the mask aligner MJB 3 HP/200W, by SUSS MicroTech). A schematic of the photomask is reported in Fig. 2A, where the negative desired pattern has been reproduced.
- Development: 8 minutes in a bath of ma-D 332/S, by Micro Resist.
- Sputtering: deposition of 45 nm of Platinum, using the Sputter Coater SCD 500, by Bal-Tec.
- Resist stripping: 10 minutes in a bath of mr-Rem 660 (by Micro Resist).

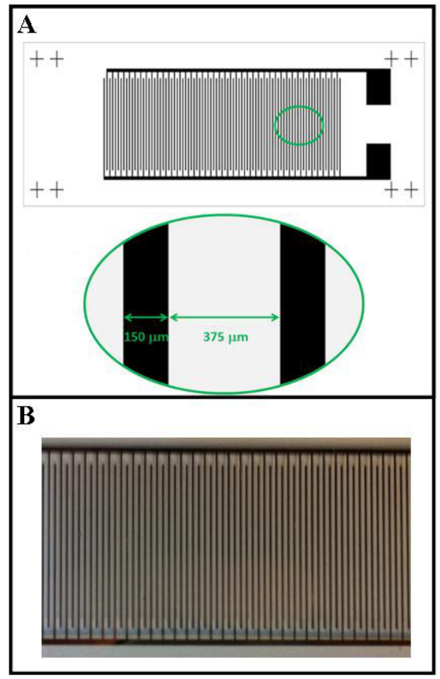

Figure 2. A) Schematic of the photomask; B) Photo of the obtained diffraction grating.

The obtained structure is platinum pattern of lines 45nm thick on a substrate of pyrex glass, a period of 525 µm constituted by a width of 150 µm of platinum spaced apart 375 µm (71.4% duty cycle).

IV. Experimental Setup and Results

The experimental setup was mounted on an optical table with the aim of minimizing vibrations and of overcoming the typical concerns related to the alignment of the optical components. The experimental setup has been used for evaluating the response of the transducer and for assessing the influence of MDGs geometry on this response. As schematically reported in Fig. 3, the experimental setup consists of: the sensing element (i.e., the two MDGs); a micropositioning kit, a single-axis translational stage (PT1, Thorlabs), which allows to apply relative displacements between the two MDGs perpendicularly to the grating direction; a laser source (HeNe, wavelength of 632.8 nm, Thorlabs HLNS008L) emits the light that is modulated by the MDGs, than it is analyzed by a photodetector InGaAs (AQ2200-211, Yokogawa). The digital output of the photodetector is processed in Matlab environment; lastly, a fiber optic is placed downward the MDGs; it picks up the radiation modulated by the phenomenon of diffraction, and it conveys the radiation, whose intensity changes when the displacement is applied, to the photodetector.

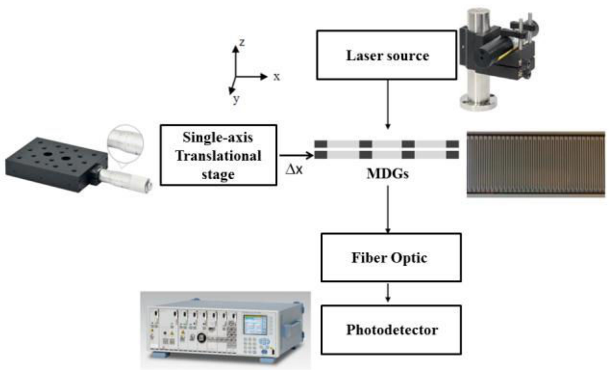

Figure 3. Schematic representation of the experimental setup.

In order to assess the static response of the transducer, five sets of measurements were carried out. The light emitted by the laser source perpendicularly hits the two overlapped MDGs; the first is fixed to the optical table, the second one undergoes displacements by the differential micrometer drives perpendicularly to the gratings direction from 0 mm to 2.5 mm, in steps of 10 µm. The light modulation induced by the two MDGs is monitored by the photodetector.

Fig. 4 shows the transducer response in a range of four gratings' periods ($4{\cdot}T$=2100 µm). All experimental data are reported as mean ± the expanded uncertainty which was calculated by considering a Student reference distribution with 4 degrees of freedom and a level of confidence of 95 %.

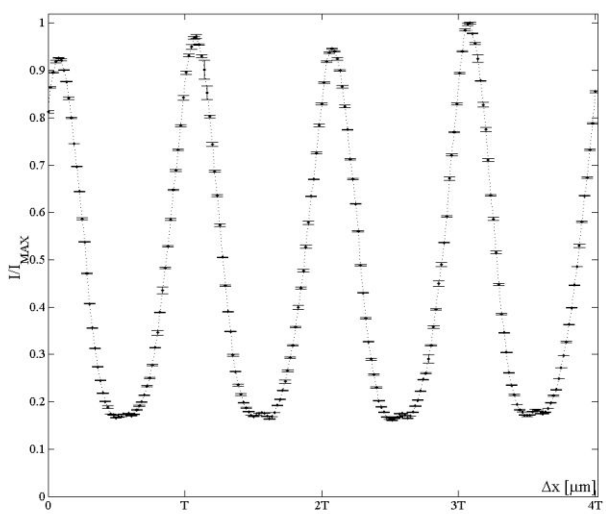

Figure 4. Experimental data: normalized power *vs* displacement in a range of $4{\cdot}T$.

Fig. 4 shows that the normalized power I/I_{MAX} (the ratio between the light power measured by the photodetector in the whole range of measurement, I, and the maximum one, I_{MAX}) in a range of measurement covering 4 gratings' period presents a periodic trend as predicted by the diffraction theory of Fraunhofer and expressed in (1) and (2).

V. Discussion

As shown in Fig. 4, the proposed sensor allows to discriminate displacement lower than 10 µm, using a cost effective micro-fabrication process (i.e., photolithography and lift-off). The good linear behaviour of the sensor can be highlighted by focusing the attention on a range of Δx covering one gratings' period (Fig. 5).

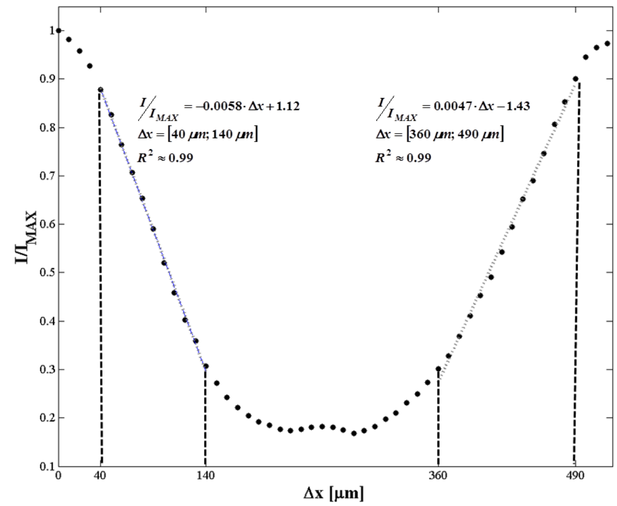

Figure 5. Sensor response considering a range of Δx covering one gratings' period; the two ranges of linearity are also reported.

It shows a good linear behaviour in the two ranges [40 µm, 140 µm] and [360 µm, 490 µm] as confirmed by the high value of the correlation coefficient ($R^2 \approx 0.99$). In these ranges the transducer presents other valuable characteristics, such as good accuracy (lower than 4% in the whole linear range), and, thanks to the high sensitivity (its absolute value is about 0.5%/µm), small discrimination threshold (<10 µm).

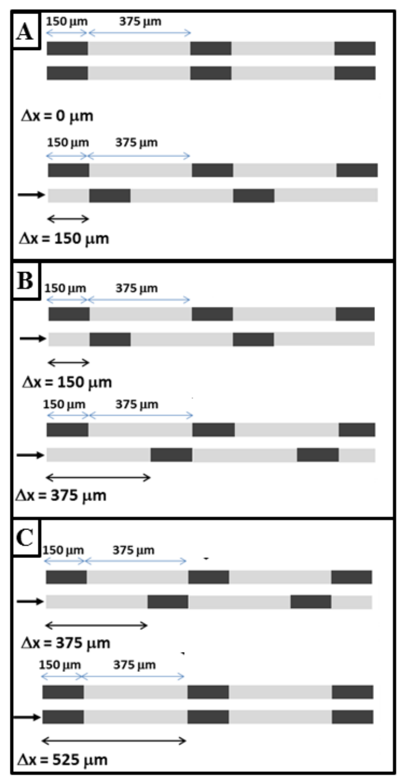

Figure 6. Ranges of Δx where the sensor response can be expressed by (1) and (2): A) range between 0 µm and 150 µm; C) range between 375 µm and 525 µm; B) also the range between 150 µm and 375 µm is shown.

The theoretical model (1) and (2) predicts the sensor response where the platinum of the two MDGs is partially overlapped, as shown in Fig. 6A and 6C (i.e., in the ranges from 0 µm to 150 µm and from 375 µm to 525 µm). These ranges correspond to Δx= [-150 µm to 150 µm] of Fig. 7; the experimental trend agrees with the predicted one, as also confirmed by the low value of RMSE (i.e., 0.075).

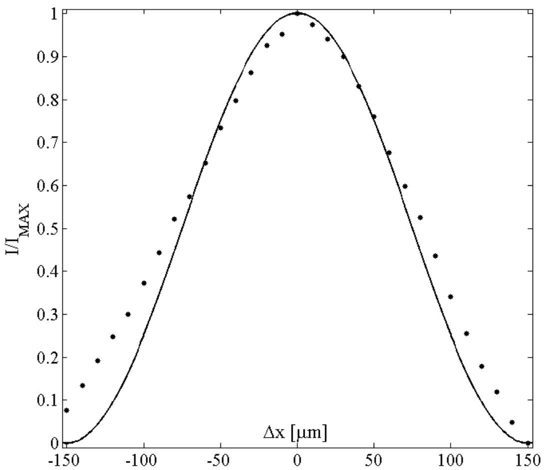

Figure 7. Range of Δx (-150 µm to 150 µm) where the sensor response can be expressed by the model (1) and (2).

In the range between 150 µm and 375 µm, the platinum layers of the MDGs are not partially overlapped (Fig. 6B) because of the high duty cycle (i.e., 71.4%). In this range the sensitivity shows a marked decrease, as experimentally assessed (Fig. 5).

The above described results provide useful information to drive in the design of the grating geometry; in particular: - in order to avoid a marked decrease of the sensitivity, it is necessary to fabricate gratings with duty cycle of 50%; - the lower is the size of *T* the higher is the sensitivity; on the other hand the range of measurement decreases with *T*. Furthermore the experiments show that an optical fiber can be used to pick up the radiation modulated by the MDGs and to transport it to a photodetector. This technical solution allows to overcome typical issues of alignment between the optical components and makes the sensor immune to electromagnetic interferences.

VI. Conclusion

In conclusion, the design, the process of fabrication and the static characterization of an extrinsic FOS with sensing element based on two MDGs is presented. The use of fiber optics can result crucial to overcome concerns related to the alignment between the optical components and to make the sensor immune to electromagnetic interferences. The static calibration and a simple mathematical model are also shown. The transducer shows a wide linearity range, where it is able to discriminate displacement lower than 10 µm and presents good accuracy (< 4%). The results also provide useful information to drive in the design of the grating geometry in order to avoid a marked decrease of the sensitivity and to adjust the sensitivity and the range of measurement.

As a step towards the development of fMRI haptic technologies, future work will include the embedding of the sensor in compliant series elastic actuators [13,14]

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