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A micromachined intensity-modulated fiber optic sensor for strain measurements: working principle and static calibration

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Abstract— **This paper describes an intensity-modulated fiber optic sensor for strain measurements. The sensing element is a polydimetilsiloxane (PDMS) micro-diffraction grating, 15 mm long, 2 mm thick, with channels 150 µm wide, spaced apart 200 µm. The working principle of the sensor can be summarized as follows: when the sensing element is strained perpendicularly to the grating plane, light passing through the grating undergoes a modulation caused by the phenomenon of diffraction. Since the grating is interposed between a laser source and a fiber optic, the coupled radiation intensity between these two optical elements can be considered as an indirect measure of strain.**

A static calibration of the measuring system has been performed, showing that the device, with measuring range of about 0.04, is capable to discriminate strain of 0.005 and it presents a sensitivity increase with strain in the whole range of measurements.

I. Introduction

Optical fibers were firstly used in medicine, in the early sixties, in order to visualize internal anatomical sites by illuminating endoscopes [1] and to develop minimally invasive tools essential for medical diagnosis and surgery [2]. During last decade, optical fibers have been employed in sensors design to sense physiological parameters. The increased use of fiber optic sensors (FOSs) is due to several features, such as: the cost reduction of key optical components allowing to realize even disposable or mono-patient FOSs; the increase of components quality; the development of miniaturization [3]. A growing interest also regards miniaturization procedures, thanks to the advantages related to microfabricated devices with respect to large-scale ones, such as: better dynamic characteristics, low power consumption, reduced mass, small size, and cost-effectiveness.

The implementation of novel and low-cost solutions are of huge interest in the field of advanced endoscopy as well as minimally invasive surgery. In this framework, hybrid solutions, based on optical fiber and on microdevices could represent an alternative to existing solutions, for developing sensing elements, such as strain/force sensors.

This paper reports a preliminary study about the development of an intensity-modulated FOSs with a working principle based on a micromachined sensing element. The latter has been developed implementing soft-lithography techniques, and it consists on a micro-diffraction grating of polydimetilsiloxane (PDMS). Its detection strategy is based on the following principle: when a strain is applied in the direction perpendicular to the micro-grating by means of traction, the optical path of a light passing through it changes. Therefore the traction modulates the intensity of diffraction orders instead of compression as shown in a previous study [4]. During the years, sensors based on micro-diffraction grating have been developed in order to monitor several physical parameters (e.g., pressure [5] and strain [6]), but they have been applied mainly in fields different from the biomedical one. Moreover, the proposed approach presents some peculiarities: the sensor is capable of detecting strain due to traction force; the sensing element is made of PDMS, that is elastic and it can be easily manipulated; moreover, the presence of fiber optic, allows to not align individual optical components and make the sensor immune to electromagnetic interferences. Finally, differently from what occurs in case of fiber Bragg grating-based force sensor, the working principle of the proposed sensor does not require expensive devices (e.g., optical spectrum analyzer) to measure the transducer output [7].

The paper is organized as follows: Section II is focused on the sensor description, including details related to its working principle and microfabrication process. The model of the sensor detection strategy and the experimental set-up are described in Section III and Section IV, respectively. Results are discussed in Section V, while conclusions are reported in Section VI.

II. Sensor Description

A. *Working Principle*

The working principle of the sensor is based on the intensity variation of the light coupled between a laser and a fiber optic. The radiation emitted by the laser source is modulated by a micro-diffraction grating interposed between the laser and the fiber tip: when the grating is strained, the period and the depth change, causing a modulation of the transmitted light which is conveyed within the fiber optic. The light intensity, modulated by the micro-diffraction grating, is monitored by a photodetector, which is connected to the distal extremity of the fiber by means of a custom-made connector.

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B. Microfabrication Process

The sensing element of the transducer (i.d., micro-diffraction grating) consists in a patterned layer of a biocompatible soft polymer, the polydimetilsiloxane (PDMS). This biomaterial is widely used in micro-patterning, being easily manipulated and elastic.

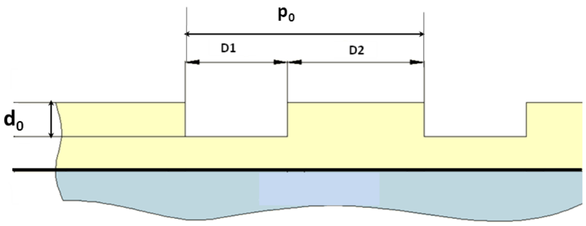

Figure 1. Schematic of the micro-diffration grating (not in scale); D_1=150 µm; D_2=200 µm; $D_2+D_1=p_0$: the period of the unstrained grating; d_0=50 µm: the depth of the unstrained grating.

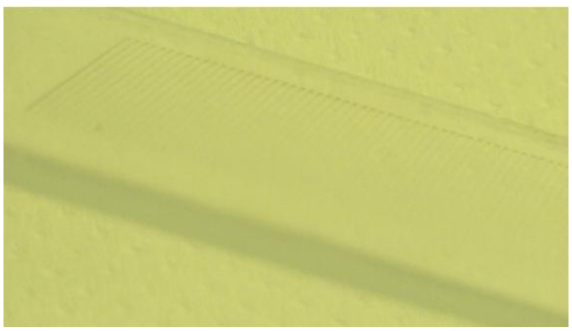

Figure 2. Snapshot of the PDMS microdevice.

The polymeric layer has been microfabricated, implementing soft-lithography techniques (Fig. 1). The main steps of the microfabrication process can be outlined as follows:

- SU-8 photolithography: 50 µm thick negative photoresist, SU-8 (2000) 50 MicroChem, has been used for developing the master mould. It has been spin-coated on a glass substrate. Using a proper lithography mask, the photoresist has been exposed at UV radiation for 32 s (by means of a SUSS MJB 3 Mask aligner, equipped with an exposition lamp supplying 60 W) in order to transfer the desired pattern.
- PDMS deposition on master mould: the polymer obtained by mixing PDMS with a curing agent in a 10:1 volume ratio, has been deposited and uniformly distributed on the master mould, that is housed in a customized support.
- PDMS polymerization: PDMS has been cured at 100 °C for 45 min and then it has been cooled by placing it in a freezer for 1 min.
- PDMS peel-off from the SU-8 master mould.

Although the microdevice in PDMS obtained is 2 mm thick and it has channels 150 µm wide, spaced apart 200 µm and 15 mm long, the abovementioned microfabrication process easily allows to miniaturize the sensing element.

A snapshot of the device is reported in Fig. 2.

III. Theoretical Model

When passing through the grating, light undergoes the phenomenon of diffraction that depends on manifold factors: refractive index of the air (n_{air}=1); refractive index of the PDMS (n_{PDMS}=1.43); geometrical characteristics of the grating. In particular, assuming that the grating remains binary and the optical field is plane before it passes through the grating, the intensity of the zeroth and first diffraction orders can be expressed as follows [8]:

$$\begin{cases} I_0(\phi) = \dfrac{1+\cos(\phi)}{2} \\ I_1(\phi) = 2 \cdot \dfrac{1-\cos(\phi)}{\pi^2} \end{cases} \tag{1}$$

where I_0 and I_1 are the intensity of zeroth and first orders and ϕ is the depth of phase modulation. Since the magnitude of ϕ depends on the depth of the grating (d), the intensities reported in (1) change when the grating is subject to traction (Fig. 3).

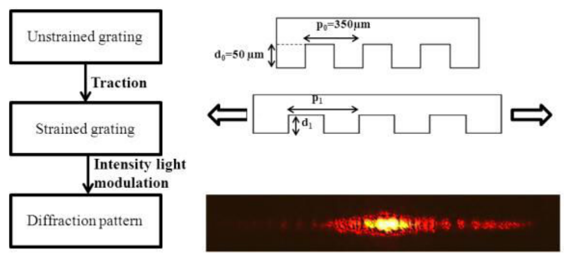

Figure 3. Changes in size of micro-diffraction grating subject to traction and diffraction pattern of the light passing through the grating.

In fact, ϕ can be expressed as follows:

$$\phi = \frac{2 \cdot \pi \cdot (n_{pdms} - n_a) \cdot d}{\lambda} \tag{2}$$

For small deformations, the change in optical phase as a function of strain can be expressed with the following relation [4]:

$$\Delta\phi \propto \frac{2 \cdot \pi \cdot \Delta n \cdot d_0 \cdot \varepsilon}{\lambda} \tag{3}$$

being d_0=50 µm the depth of the unstrained grating and the strain can be expressed as $\varepsilon = \Delta p / p_0$, where p_0 is the period of the unstrained grating (350 µm) and $\Delta p = p_1 - p_0$ is the change in the PDMS period on traction (Fig. 3).

Equations (1-3) express the ideal optical response of the grating undergone strain and give the relation between the light intensity transmitted by grating and its strain.

IV. Experimental Setup

The experimental setup shown in Fig. 4 is adopted in order to calibrate the sensor and to verify the theoretical model expressed in (1-3). The whole components are assembled on an optical table in order to minimize vibrations and to facilitate the alignment between laser, micro-diffraction grating and fiber optic.

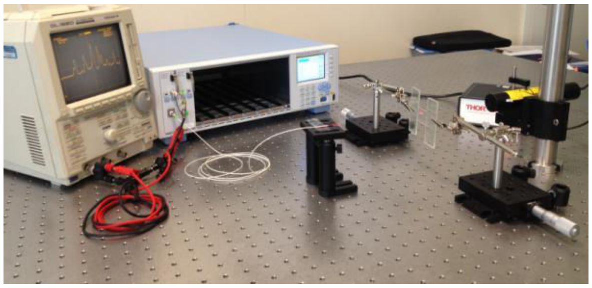

Figure 4. Experimental setup for static calibration.

The micro-diffraction grating is placed between two glass plates, fixed by two clips on post-holders. Each post-holder is held on to the base panel of a single-axis flexure stage (PT1/M, Thorlabs) supplied with differential micrometer drives (150-811 ST, Thorlabs, 25 mm travel translation stages, 1 μm resolution), that strain the sensing element perpendicularly to the gratings direction. The radiation emitted by laser source (HeNe, wavelength of 632.8 nm, Thorlabs HLNS008L) is modulated by the micro-diffraction grating, which is placed between the laser source and the optical fiber tip. Laser and optical fiber have been mounted on a system (a clamping arm and a Kinematic V-Clamp Mount for laser, a holder for fiber) fixed to the optical table, in order to be both aligned with the micro-diffraction grating. The optical fiber (BFH48-400, Thorlabs, 400 μm core diameter, 1 m length, NA 0.48) transports the laser radiation transmitted by the grating to the photodetector. The photodetector InGaAs (AQ2200-211, Yokogawa, mounted in the Frame Controller AQ2212) acquires the transmitted light intensity and converts it in an output voltage signal (V_{out}) monitored by a digital oscilloscope (Yokogawa DL 1520).

V. RESULTS

Experimental trials, carried out in order to evaluate static characteristics of the transducer and verify the mathematical model, are performed by applying assigned strains to the micro-diffraction grating. Strains up to 8% in step of 0.5% are applied to the micro-diffraction grating through traction performed by means of the two translational stages. During the trials, the photodetector V_{out} is monitored by the digital oscilloscope. Five sets of measurements were performed for static calibration. All results are reported as mean ± the expanded uncertainty, which is evaluated by multiplying the standard uncertainty by a coverage factor of 2.8. The coverage factor was obtained by considering a Student's reference distribution with four degrees of freedom and a confidence of 95% [9]. The static characterization is reported in Fig. 5.

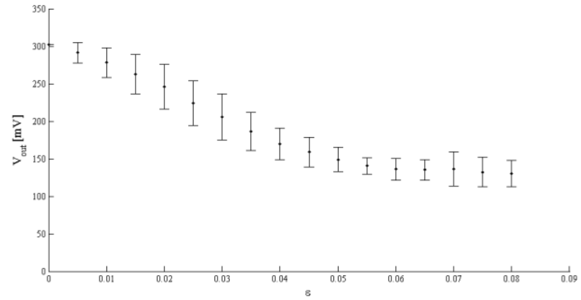

Figure 5. Static characterization of the sensor response: V_{out} vs ε.

Some simplifying hypotheses have been considered: 1) light intensity transmitted by the grating is proportional to light intensity coupled to the fiber; 2) the light intensity that invests the photodetector is equal to the light intensity conveyed into the fiber and 3) is proportional to its output voltage. Thus we can obtain the normalized light intensity transmitted by the grating as follows:

$$I_n(\varepsilon_x) = \frac{I(\varepsilon)}{I_M} = \frac{\alpha \cdot V_{out}(\varepsilon)}{\alpha \cdot V_{M,out}} = \frac{V_{out}(\varepsilon)}{V_{M,out}} \tag{4}$$

where I_n is the normalized light intensity, $V_{M,out}$ is the maximum value of V_{out} measured during calibration, and I_M is the maximum value of light intensity. The constant α converts V_{out} in I, taking into account the conversion factor from light intensity which invests the photodetector and its voltage output, and that only a fraction of transmitted radiation is conveyed into the fiber.

Fig. 6 shows the predicted normalized light intensity (I_n), obtained by the ratio between I calculated from (1-3) and its maximum value, and the experimental ones, obtained by (4) as a function of gratings train.

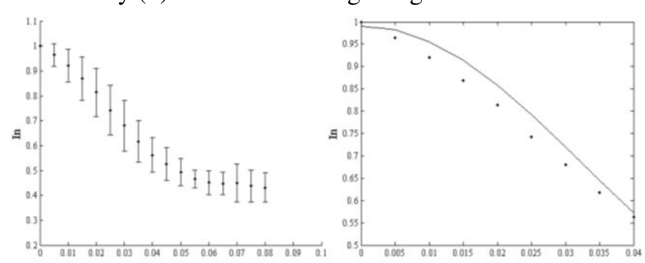

Figure 6. Sensor response. Left side: experimental I_n vs ε; right side: experimental I_n and I_n predicted by model vs ε.

Experimental data show good agreement with theoretical ones up to strain of about 4%. The transducer is able to discriminate ε lower than 1% with a measuring range up to ε%=4%; its sensitivity increases with strain in the whole range of measurement (e.g., the sensitivity is about 28 mV/% for ε ranging from 0 to 2%, and 38 mV/% for ε ranging from 2% to 4%). The increasing trend of the gap between experimental data and theoretical ones for strain up to 4% should be explained by considering that the model (1-3) is valid under the hypothesis of small strain.

VI. CONCLUSION

An intensity-modulated fiber optic sensor for strain measurements has been developed. The device includes: 1) a microfabricated sensing elements, made of PDMS and developed using standard soft-lithography techniques; and 2) fiber optic elements.

The working principle of the sensor as well as its static calibration have been reported. Results show that the sensor:

- has a measuring range of about 0.04;
- is capable of discriminating strain of 0.005;
- presents a sensitivity increase with strain in the whole range of measurements.

Thanks to these appreciable features, the microfabricated grating could be employed in biomedical field, for example, used as force sensor in an *ad hoc* tool for tissue investigation during microsurgery [10], or in monitoring electrode-tissue contact force during radiofrequency ablation, that strongly influence the amount of ablated tissue volume [11].

Future work will be focused on miniaturizing all components of the sensor and on performing other characterization tests.

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