Fabrication of a tactile sensor array with fiber Bragg gratings using a 3D printed mold

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***Abstract*— This work describes the fabrication of a tactile sensing array instrumented with six optical fiber Bragg gratings. Bragg gratings were housed in silicone elastomer with the aid of a mold manufactured with a 3D printer using filament of acrylonitrile butadiene styrene, 1.75 mm diameter. The sensor array was tested by measuring the FBGs wavelength shifts for different loads applied in the central position of the array. FBGs have shown linear responses with correlation coefficients better than 0.99. Additionally, the six FBGs have coupled responses, allowing the application of the sensor array in *quasi*-distributed tactile sensing.**

Keywords—Optical sensors; Fiber Bragg Gratings; Force Sensing

I. INTRODUCTION

Along the last four decades, optical fibers reached an important role in the development of technologies and equipment for optical communication and optical sensing. In the field of optical sensing, fiber Bragg gratings (FBGs) show outstanding performance thanks to their intrinsic characteristics such as low loss transmission, immunity to electromagnetic interference, flexibility, reduced size and weight as well as resistance to temperature and electrical passivity. Besides, FBGs can be easily encapsulated and integrated in optical links [1]. Such set of characteristics make FBGs transducers interesting for applications in *quasi*-distributed sensing systems.

Recently, researches have pointed to the use of FBG-based transducers in tactile sensing systems. In these systems, an array of FBGs is spread out on the surface of a flat structure. Deployment strategies include gluing the gratings directly on the surface of a metal or polymethyl methacrylate (PMMA) sheet [2-3] or placing polymer-encapsulated FBGs under the structure [4]. Such sensor arrays can be used in force detection, vibration and temperature detection in diverse fields like robotic systems, military procedures involving dangerous or delicate tasks, industrial automation [4], biomedical [5] and medical areas in minimally invasive surgeries [6]. Different approaches such as artificial neural network and compressive sensing have been used to process data provided by sensing systems composed of a set of FBGs [2,7].

The tactile sensor array (TSA) of this work was produced with the aid of a mold manufactured in a 3D printer using and acrylonitrile butadiene styrene (ABS) filament. This process simplifies the production of elements with specific project requirements, making its use ideal for the mold fabrication. The array is comprised by 6 FBGs encapsulated in room temperature vulcanizing (RTV) silicone elastomer. This material was used due to its flexibility, improved tactile response, adequate heat resistance and durability, inertness, fast cure process, wide range of hardness (10 – 80 Shore A) and low fabrication cost [8]. The fabrication steps and a preliminary characterization of the tactile sensor array are described.

II. MATERIAL AND METHODS

A. FBG as strain sensor

The FBG consists in a periodic modulation in the refractive index of the core along a segment of the optical fiber. The Bragg reflection promoted by this structure leads to a band centered at the Bragg wavelength (λ_B), according to (1)

$$\lambda_B = 2n_{eff}\Lambda \qquad (1)$$

where n_{eff} is the effective refractive index of the optical fiber core and Λ is the spatial periodicity of the modulation. Both n_{eff} and Λ, are affected by changes in temperature and strain allowing the sensing of these parameters via wavelength-coded detection [1]. When the temperature is constant, the effect of mechanical deformation on the grating resonance leads to a Bragg wavelength shift $\Delta\lambda$ given by (2)

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e)\varepsilon_z, \qquad (2)$$

where ε_z is the relative deformation (strain) along the fiber axis and p_e is the elasto-optic coefficient. For a germanium doped

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optical fiber, the elasto-optic coefficient is 0.213. For operation close to 1550 nm a typical strain sensitivity of 1.2 pm/με is found [1].

B. FBGs production

The FBGs of the proposed sensor array were fabricated at the Photorefractive Devices Unit of the Federal University of Technology – PR (UTFPR). Gratings were written in standard single mode fiber (DRAKTEL, G-652, SSMF) by the exposition to the laser light diffracted by a phase mask [8]. The writing system uses an excimer ArF laser (Coherent Xantos, 193 nm, 2.5 mJ pulse energy, 250 Hz, exposition time of ~ 1 minute) and six different phase masks (Ibsen Photonics). Spectral characteristics of the FBGs used in the array are shown in TABLE I.

TABLE I. SPECTRAL CHARACTERISTICS OF THE FBGS AT (22.0 ± 0.5) °C.

FBG	λ_B (nm)
1	1520.807
2	1523.550
3	1526.687
4	1530.637
5	1534.128
6	1537.619

All FBGs have full width at half maximum (FWHM) of 0.21 nm, length of ~ 3 mm, reflectance lower than 15 % and temperature and strain sensitivities of 9.8 pm/°C and 1.13 pm/$\mu\varepsilon$, respectively.

Fig. 1 shows a typical reflection spectrum of these FBGs. This spectrum was obtained with an optical spectrum analyzer (Anritsu MS9710B, resolution of 0.07 nm) and a superluminescent LED (Superlum Pilot-4, centered at 1545.9 nm with an FWHM of 57.9 nm) used as light source.

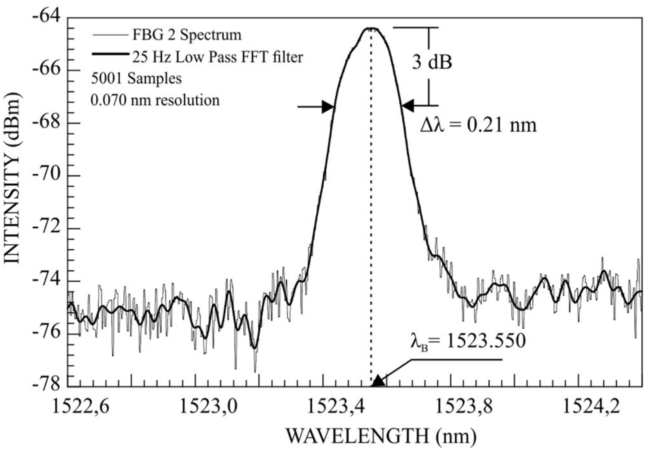

Fig. 1. Reflection spectrum of one of the written FBGs.

C. Fabrication of the sensor array

The sensor array was produced using a mold drawn with a computer-aided design (CAD) software and manufactured with a 3D printer using ABS filament, 1.75 mm diameter. The mold is a rectangular box with bottom dimensions of 75 x 105 mm and walls 5 mm high. These measurements correspond to the internal dimensions. Two parallel walls have narrow slits (2.5 mm depth) used for the adequate placement of the fiber segments containing the FBGs in the mold.

Fig. 2 (a) shows in a diagram the top view of the mold with the optical fibers passing through two opposite slits and also a detail of the slit in the wall.

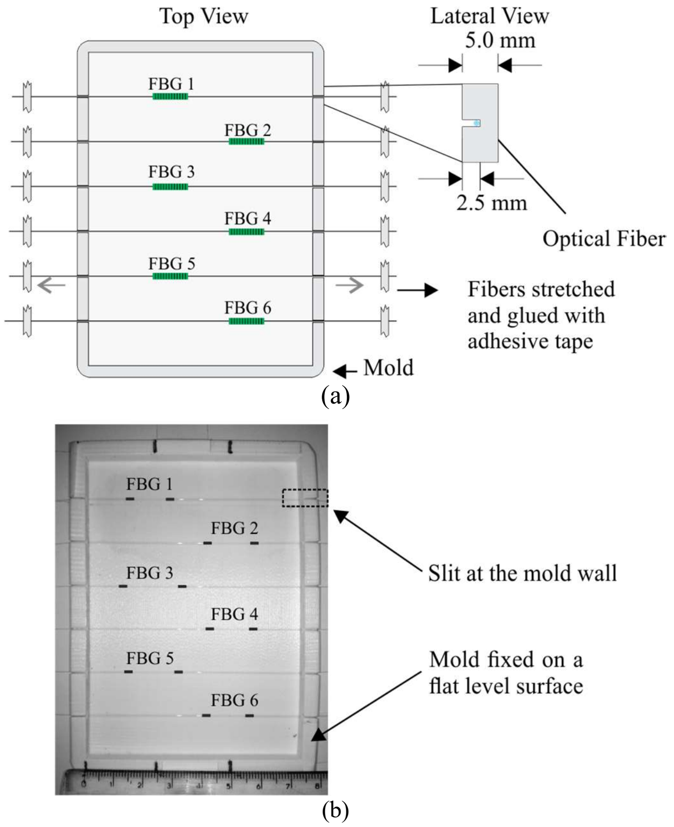

Fig. 2. (a) Diagram showing the FBGs placed at the 3D printed mold and a detail of the slit at the mold wall; (b) Picture of the mold with the installed FBGs.

First, each section of the optical fiber containing one FBG was placed in the mold between two slits in opposite walls. Then, the fiber was stretched and glued with adhesive tape (see Fig. 2 (a)). A picture of the mold with the installed FBGs is shown in Fig. 2 (b). The approximate position of each FBG is indicated by the two black lines drawn on the fibers of the picture. Finally, the mold is filled out with silicone elastomer forming a flexible and resistant sheet embedded with six FBGs.

The RTV silicone elastomer (Dow Corning, BX3-8001) is prepared according to the instructions provided by the manufacturer and carefully spread out in the mold forming a homogeneous layer. A 1:1 proportion of silicone and quartz powder was used in the mixture to increase the rubber hardness. As there is no adhesion between the silicone elastomer and the ABS, the resultant sheet is easily removed from the mold after 24 hours. The surface of the sheet kept in contact with the mold is free from irregularities and therefore used as sensing surface.

In the final configuration of the sensor array, fibers are 15 mm apart from each other. This separation corresponds to the distance between the slits in the mold walls. The horizontal distance between the FBGs is approximately 25 mm, as shown in Fig. 3 (a).

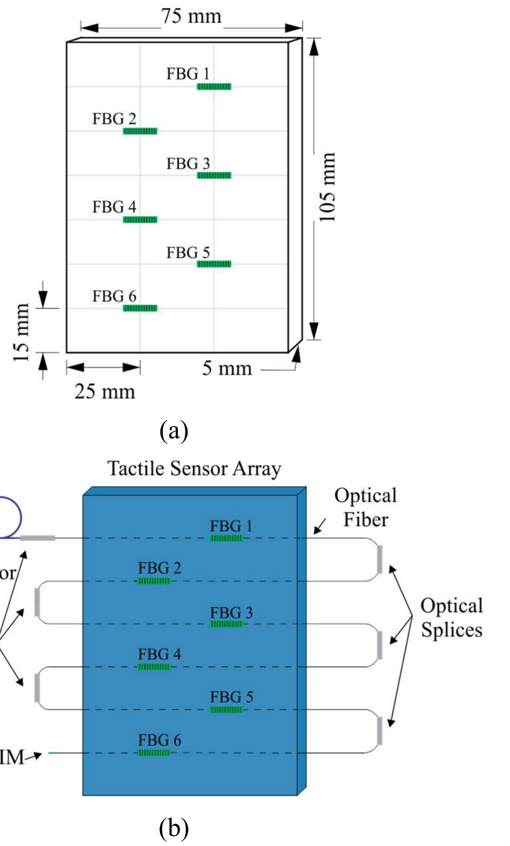

Fig. 3. Diagram showing: (a) the vertical and horizontal distance between the FBGs in the sensor array; (b) the fiber connections of the sensor array.

After the production of the silicone elastomer sheet embedded with the FBGs, the fiber tips were connected producing a set of six FBGs in series (Fig. 3 (b)). For the sensor array interrogation, one of the free fiber tips is connected to a fiber coupler which is also connected to a superluminescent LED (Superlum PILOT-2, centered at 1558.2 nm with a FWHM of 73.8 nm) and to an optical interrogation monitor (Ibsen I-MON 512E, 970 Hz maximum sampling rate, resolution < 0.5 pm). The acquired spectral data is sent to a computer where the Bragg wavelengths of the six FBGs are recorded. Fig. 4 shows a diagram of the interrogation unit.

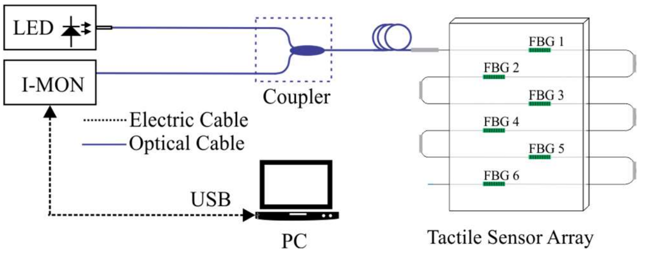

Fig. 4. Interrogation unit connected to the sensor array.

D. Test of the sensor array

Tests were carried out with the application of different loads in the central position of the sensor array placed over a flat and stiff surface. Loads up to 250 g, with steps of 25 g and delay of ∼ 5 s, were applied on a circular contact area with diameter of 20 mm by the *z*-stage system shown in Fig. 5. The responses of the six FBGs to the applied loads were measured in repeatability and intermediate precision conditions [10] at a controlled room temperature of (22.0 ± 0.5) °C in three up and down cycles.

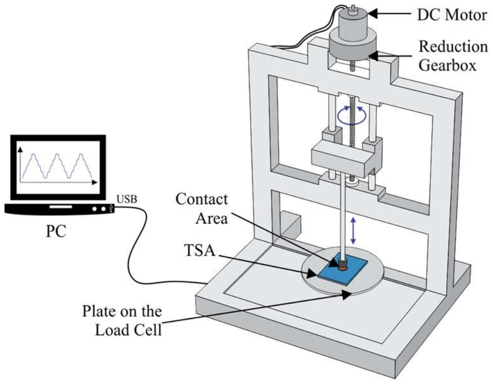

Fig. 5. Schematic of *z*-stage system.

III. Results and Discussions

Fig. 6 shows the response curves of the 6 FBGs to loads applied at the center of the sensor array. The detected wavelength shifts are only associated to mechanical deformations as the temperature was controlled during the experiments. Data symbols are the arithmetic mean of 15 measurements under repeatability conditions. The error bars are the combined uncertainties obtained from the experimental standard deviations of mean in repeatability and intermediate precision conditions, the I-MON interrogator uncertainty in the measurement of the wavelength, uncertainties related to the elastomer thermal expansion and the z-stage system [10]. Lines connecting the data points correspond to a first order polynomial fit to the response curve, with correlation coefficients higher than 0.99.

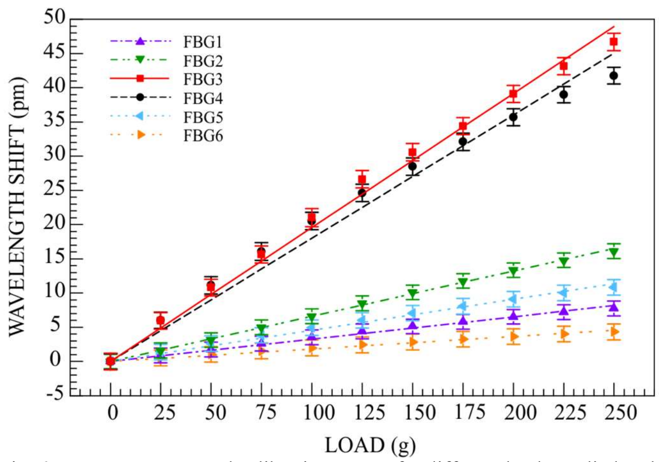

Fig. 6. FBGs responses and calibration curves for different loads applied at the central position of the tactile sensor array.

As shown in Fig.6, loads applied at the central position of the array produce Bragg wavelength shifts in the spectra of the 6 FBGs. These coupled responses allow the application of the sensor array instrumented with a reduced number of sensors in tactile sensing [2, 7]. Both, the linearity of the system and the coupled FBG responses, are suitable characteristics for the application of compressive sensing in the force mapping [7]. Additionally, all six FBGs experience wavelength shifts for the range of applied loads that can be measured by the interrogation unit and are within the range delimited by the spectral separation between the central wavelengths of the FBGs (~ 3 nm).

As expected, FBGs sensitivities depend on the distance of the grating from the point of load application. FBGs 3 e 4, the FBGs closest to the position of the load application, showed the highest sensitivities, (0.1958 ± 0.0027) pm/g and (0.1801 ± 0.0041) pm/g, respectively. On the other hand, FBGs 1, 2, 5 and 6 are less sensitive to loads applied at the center of the sheet, (0.0327 ± 0.0004) pm/g, (0.0661 ± 0.0004) pm/g, (0.0455 ± 0.0007) pm/g and (0.0183 ± 0.0003) pm/g, respectively. As the placement of the FBGs at the fabrication stage is visually controlled, differences in the distance and orientation of the gratings with respect to the point of load application result in different sensitivities for these gratings.

IV. Conclusion

The versatility of a 3D printer was successfully used for the production of the sensor array. The mold is manufactured in a single block and the technique is adequate to create narrow slits to insert the optical fiber. The slits make possible the fiber placement at the middle of the sheet thickness, mechanically protecting the gratings. The quality of the manufactured mold as well as the non-adherence between the ABS and the silicone elastomer resulted in a smooth sensing surface for the sensor array.

The FBGs have shown coupled responses, a feature necessary for the sensor array application in *quasi*-distributed sensing with a reduced number of transducers. Preliminary tests allowed the establishment of a measuring interval of operation for the tactile sensor. This range might be adjusted according to the application by changing the proportions of silicone and quartz powder of the prepared mixture used to encapsulate the FBGs. Experiments are under way aiming for a complete characterization of the sensor array and for a benchtop application.

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