High Accuracy Micro-Displacement Sensor With Integrated Optics-based Detection Means

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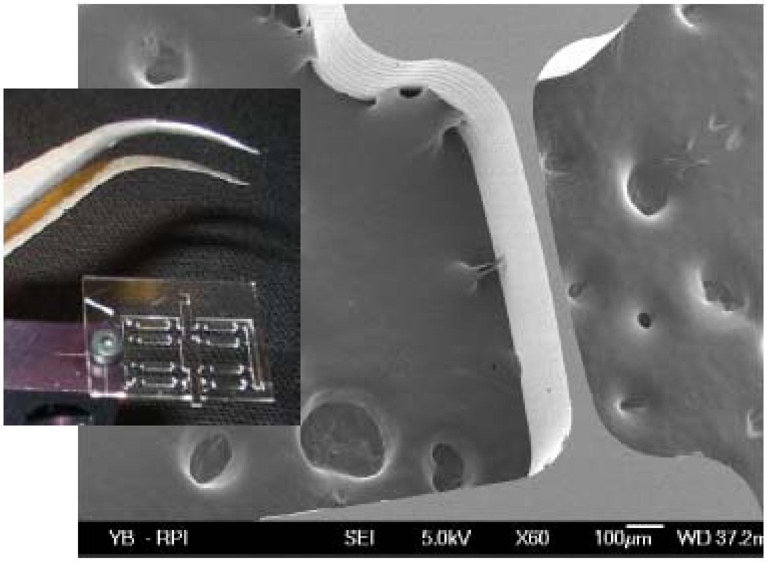

High Accuracy Micro-Displacement Sensor With Integrated Optics-based Detection Means[*]

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Abstract - **We present a high-precision monolithic glass micro-displacement sensor suitable for harsh or sensitive environment in general and electromagnetic radiation environment in particular. Our displacement sensor is made out of a single piece of glass through a two-steps process based on femtosecond laser illumination followed by chemical etching. This process is used to create for the first time integrated waveguided-optics and mechanical flexures within a three-dimensional glass body.**

Index Terms - MEMS, Optical MEMS, Flexures, harsh environment, MRI compatible sensor.

I. INTRODUCTION

Harsh environments are characterized either by high temperatures and large pressures, or unusual environmental conditions like vacuum, nuclear radiation or high electromagnetic fields. These environments are hostile for humans, but in turn, open wide opportunities for interventional robotics. However, to operate successfully, robots for harsh environment also require specific technologies for sensing and actuating that can survive these particular environmental conditions. For some applications, like inside Magnetic Resonance Instruments, it is also desired to have technologies that do not interfere with their environment.

This paper presents a monolithic micro-displacement sensor suitable for EM sensitive environment. It is based on glass technology and uses integrated optics to carry the sensing information.

II. SENSOR CONCEPT

The basic concept is to create a displacement sensor made of a single piece of fused silica glass where mechanical, structural and optical features are embedded in the same piece of material. The design objective is a miniaturized one degree-of-freedom structure with sub-micron sensing accuracy.

Sensors are made of two parts: the sensing head that interacts physically with the element to measure and the processing unit. The basic concept of our sensor is to decouple the sensing head from the processing unit. The transfer of information between the sensing-head and the processing unit is made using optical waveguides and fibers. The sensing information is exlusively carried by photons in the visible or near-infrared spectrum. Considering optical losses in waveguides (typically less than a fraction of one dB/km), the processing unit that is potentially sensitive to surrounding environmental conditions can be placed far away from the dangerous zone. Fig. 1 illustrates this concept of optical sensor with remote processing unit.

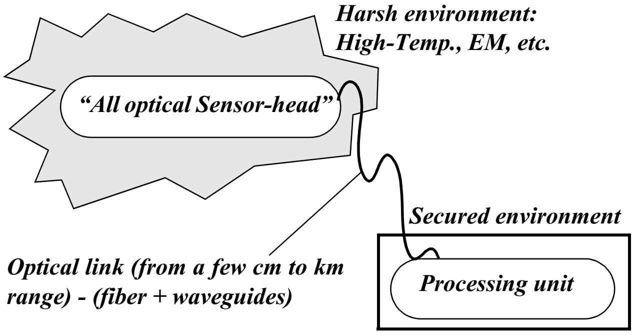

Fig. 1 - Concept of all-optical sensor with remote processing unit. An optical link is used to carry the information from the sensing unit to the processing unit.

Although it may be counterintuitive, fused silica glass is an interesting material for a micromechanical component. Fused silica is chemically stable (except in the presence of Hydro-Fluoric (HF) acid) and can survive high temperature conditions. It has a low density (2200kg/m^3) and a Young's modulus comparable to aluminum. Although the elastic limit is rather low (apparent elastic limit in the order of 50 MPa), various methods exist to increase this value by several order of magnitude [1]. It is usually assumed that surface flaws are responsible for the low strength of normal glass. By eliminating these flaws, one can substantially increase its strength. It was also shown that chemical etching and polishing greatly improved the elastic limit to a value ranging from 100 to 400 MPa [1].

III. MICRO-FABRICATION PROCESS

The sensor is fabricated with a two-step fabrication process based on femtosecond laser irradiation and chemical etching. This process allows the three-dimensional patterning of fused silica and the simultaneous introduction of sub-surface optical waveguides.

Femtosecond lasers [6] are characterized by unusual laser-matter interaction. The peak power is incredibly high. Intensities in the Terawatt/cm^2 or even Petawatt/cm^2 can be reached with relatively simple commercial systems. The

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femtosecond pulse-matter interaction is unusual in several ways. Any material can be turned into plasma. The deposition of energy is extremely fast (typically 10^{-13}s). The diffusion of heat away from the interaction region proper can be almost completely prevented. Furthermore the extreme optical intensities can lead to strong non-linearity.

Femtosecond laser illumination affects two properties of fused silica glass: it increases locally its refractive index [7] and also its HF chemical etching selectivity [8], [9]. It is a two-step process. As a consequence, material properties can be affected below its surface. For instance, it is possible to fabricate three-dimensional waveguides within the glass volume.

We have demonstrated the microfabrication of a variety of microstructures like trenches and tunnels [9]. The process consists of - first, exposing the glass with femtosecond laser illumination by rasterizing a desired pattern corresponding to the region to be removed - second, etching the glass in a low-concentration HF bath (typically 2.5 to 5 %). Fig. 2 shows a scanning electron microscope (SEM) picture of two micro-fluidic channels fabricated using this two-steps process.

Worth noticing, optical waveguides can be introduced during the first step of the process and at the same time as the pattern that defines the microstructure. Therefore, the relative positioning accuracy of waveguides relatively to microstructures only depends on the performance of the stages used to move the glass specimen under the laser beam. This is a unique characteristic: to the best of our knowledge, it is the only micromanufacturing process that allows the simultaneous integration of optical and structural functionalities. It opens new opportunities for fully integrated systems.

In this paper, we illustrate how this process can effectively be used in micro-robotics. We propose a new concept of micro-displacement sensor that integrates a flexure and an optical sensor that mimics the function of an encoder in traditional large-scale robotic systems.

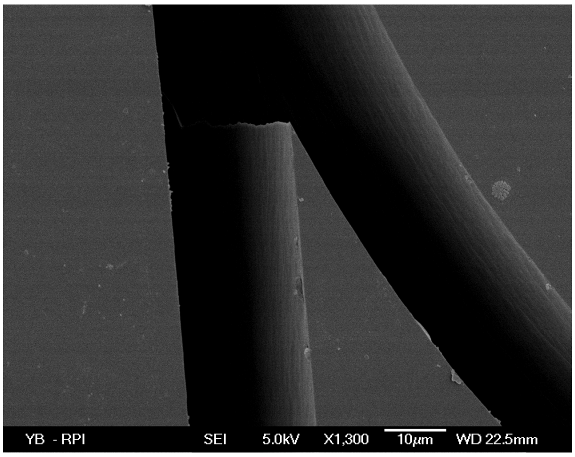


Fig. 2 - Two micro-machined branching channels. Typical aspect ratio is 1:30. This picture illustrates the use of femtosecond laser illumination followed by chemical etching.

IV. DESIGN AND SIMULATION

A. Kinematics

The kinematics is based on two identical four-bar mechanisms serially connected as shown on Fig. 3. This structure is well known in precision engineering [2]. A quick mobility analysis of this planar mechanism shows that the mechanism has a mobility of two. In the case of flexure mechanism, it would still work satisfactorily as a single linear drive because the two degrees of freedom are coupled by elastic forces as the two springs are serially mounted and share the load.

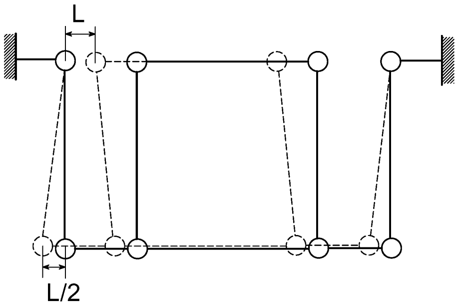


Fig. 3 - Compensated one degree-of-freedom (dof) linear stage. Circles represents one-dof planar joints (rotation axis normal to the plane). A quick mobility analysis shows a mechanism mobility of 2.

To have a more consistent behavior and superior performance, it is desirable to remove the additional mobility. To do so, various designs have also been proposed [2]. For instance, kinematic couplings based on a master/slave mechanism have been proposed [2]. Although these solutions are very elegant, their mechanical complexity makes them difficult and challenging to implement.

Another way, more practical, to compensate for this undesirable degree of freedom is to use a double-compound rectilinear kinematic as shown on Fig. 4. This can be easily achieved for instance by connecting the mirror image of the structure to the mobile platform. The practical design is shown on Fig. 5.

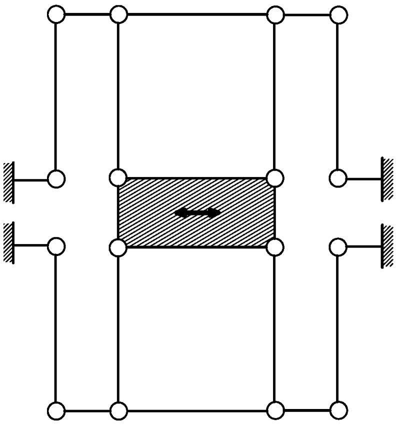


Fig. 4 - Double compound rectilinear kinematics. Circles represent one-dof planar joints (rotation axis normal to the plane). The mechanism mobility is now one.

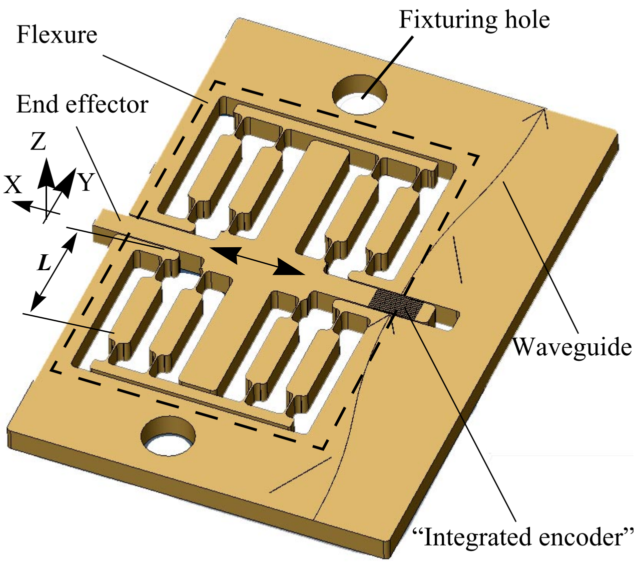


Fig. 5 - Complete design of the sensor. The material used is a fused silica. Two holes are used to mount the mechanism on a static platform. The sensor detection mechanism based on integrated optics is shown on the right side of the sketch. When a force is applied on the end-effector along the X-axis, the mechanism translates. By doing so, the “integrated encoder” - a structure made of several parallel waveguides - is successively aligned and misaligned with stationary waveguides on the support structure. These alignment/misalignment sequences create a modulation of the light signal transmitted through the device. The sensing mechanism is further described in section D.

B. Analytical model of the flexure

If a force is applied in the middle of a four bar structure made with notch hinges, the hinges are equally loaded. For small angles, the stiffness of the four bar structure can be approximated by [5]:

$$K_X \approx \frac{8Ebt^{2.5}}{9\pi l^2\sqrt{r}} \qquad (1)$$

Where E is the Young’s modulus, t the notch hinge thickness, b the thickness of the plate (along the z axis), l the distance from the notch hinge center to the next notch hinge center distributed along the Y axis and r the notch hinge radius.

Since the complete flexure is made of two bars in serial forming a first element connected in parallel to a symmetric element, the overall stiffness in the motion direction for the double compound is the same as the single stage one.

The angular excursion of simple notch hinges can be estimated by [5]:

$$\alpha_M \approx \frac{3\pi\sigma_l\sqrt{r}}{4E\sqrt{t}} \qquad (2)$$

where r is the notch hinge radius, t the hinge thickness along the x direction, E the Young’s modulus and σ_l the elastic limit.

Considering a given elastic limit σ_l, the range motion f for this mechanism is:

$$f = \frac{3\pi L\sigma_L\sqrt{r}}{2E\sqrt{t}} \qquad (3)$$

where l is the distance between two notch hinge centers along the Y direction and E the Young’s modulus. This result is simply twice the motion of a single stage mechanism.

The following dimensions with corresponding stiffness and range motion values were chosen based on this simple analytical model:

TABLE I: MAIN DESIGN PARAMETERS

σ_l MPa	L mm	t µm	r mm	E GPa	Poisson ratio	b mm
300	4.7	50	7	75	0.17	1

The analytical model predicts a maximum force of 200 mN for the maximum excursion while the predicted stiffness is 0.200 N/mm.

The elastic limit shown in Table 1 is conservative. It is known that this value can be higher after etching in HF [1]. Elastic limits in the range of 400MPa are expected. Furthermore, at the smaller scale, this elastic limit could be significantly increased. For glass fibers, elastic limits as high as a few GPa have been reported.

C. Finite Element Modeling

The analytical model is based on several assumptions. To refine and optimize the hinge shape, a finite element analysis was conducted for static and dynamic conditions. A close-up view of the static analysis is shown on Fig. 6.

For the simulation, the force applied on the structure along the X axis is the maximum force predicted by the analytical model to get the full excursion.

A relatively good agreement between analytical and FEA model is found. From the FEA, the force to get the full excursion is about 160 mN and the maximum stress was found to be 182 MPa as opposed to 200mN and 300 MPa as predicted by the analytical model.

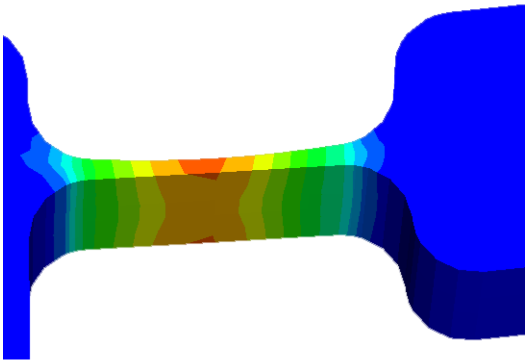
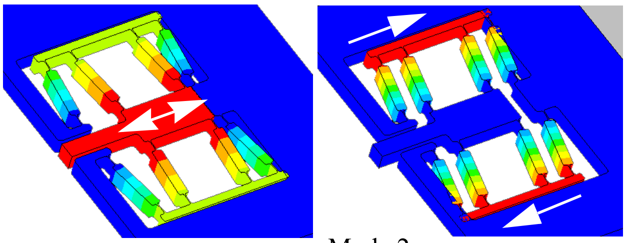


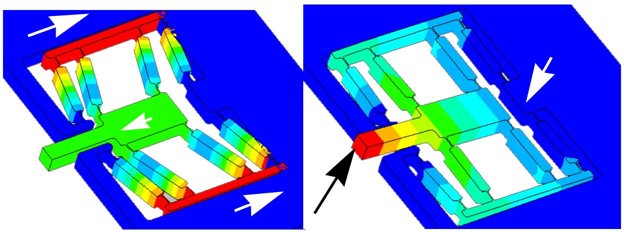
Fig. 6 - Finite element model of the notch type double compound flexure. In this simulation, the maximum stress (von Mises) in the hinges is 182 MPa.

The modes of vibration are shown in Fig. 7. The three first modes are in plane vibration and at frequencies below 1kHz. The next ones (mode 4 to 6) are related to out-of-plane vibrations and are found at much higher frequencies (3.5 to 5.1 kHz).



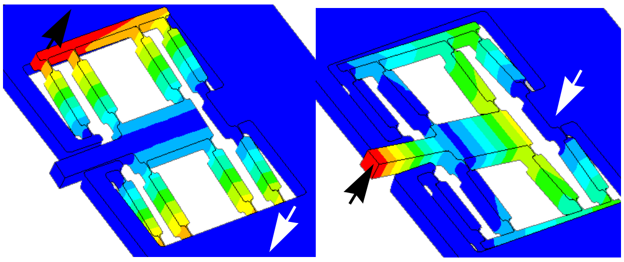
Mode 1 Natural mode **290 Hz**

Mode 2 In plane **740 Hz**



Mode 3 **880 Hz**

Mode 4 out of plane **3540 Hz**



Mode 5 out of plane **4180 Hz**

Mode 6 out of plane **5100 Hz**

Fig. 7 - Finite Element Analysis of the notch type double compound flexure: modal analysis.

These simulation results show the decoupling between the natural vibration mode and the higher order ones. It also shows the relatively average dynamic performance of the double compound rectilinear mechanism. The intermediate members of the symmetrical compensated rectilinear stages are the source of vibrations at lower frequencies.

D. Measurement principle: “integrated encoder”.

The measuring principle is based on transmitted light intensity modulation. A stationary optical waveguide, placed 100 microns below the surface, carries a light signal from a source to a photodetector. The waveguide is interrupted in its central portion by the mobile platform (see Fig. 5). The mobile platform contains a set of parallel waveguides regularly distributed.

When a force is applied on the end-effector (see Fig. 5), the movable platform translates along the X axis. By doing so, the set of parallel waveguides are successively aligned and misaligned with stationary waveguides integrated in the support structure (see Fig. 8). When a waveguide of the movable platform is aligned with the two stationary waveguides (step a and c on Fig. 8), the intensity of the transmitted signal is maximum. Conversely, when waveguides are misaligned (step b), the light is no longer guided and diverges, causing a steep loss of transmitted signal to the photodetector.

For a given separation between waveguides within the array, the signal sensitivity with respect to displacement can be compromised when the stationary input / output waveguides are aligned between any two waveguides in the array. The displacements over which this low signal configuration occurs can be minimized by decreasing the arrayed waveguide separation but only to the point where coupling between adjacent waveguides initiates. At this point the input signal amplitude is distributed among many waveguides within the array. To keep the low signal "dead-space" to a minimum while maintaining single waveguide transmission through the array a quadrature detection scheme can be implemented.

Absolute displacement would involve maintaining a fringe count relative to a zero displacement position. The latter "home" position can be referenced to a single waveguide trio (input, bridge, output waveguides) separate from the array and made to be aligned at zero displacement.

V-groove shapes consisting of voids created in the glass during the machining are used to reflect off unguided light when waveguides are not aligned. This allows us to increase the signal-to-noise by preventing unguided light from reaching the photodetector.

Using a model that predicts the light coupling between two waveguides, the actual sensor position is known from the amount of light transmitted through. This is a very sensitive detection mechanism.

This loss of transmitted signal is a function of the lateral displacement. For multi-mode waveguides, the coupling intensity can be evaluated by this simple expression (in dB):

$$L_{lat} = -10\log\left[1-\frac{8x}{3\pi a}\right] \qquad (4)$$

where x is the lateral misalignment and a is the waveguide dimension.

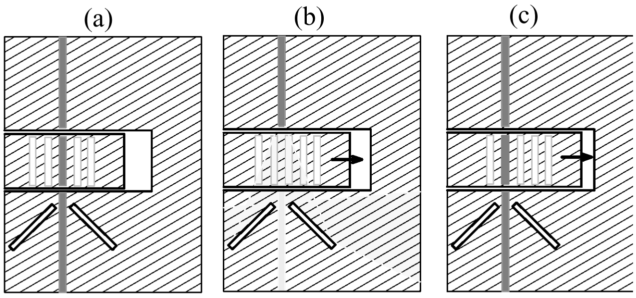


Fig. 8 - Motion measurement principle: a) the waveguides are all aligned, the transmitted signal is maximum. b) the middle waveguide is translated right, the waveguides are no longer aligned and significant signal losses is observed c) after moving further to the right, the waveguides are again aligned, the transmitted signal is again maximized.

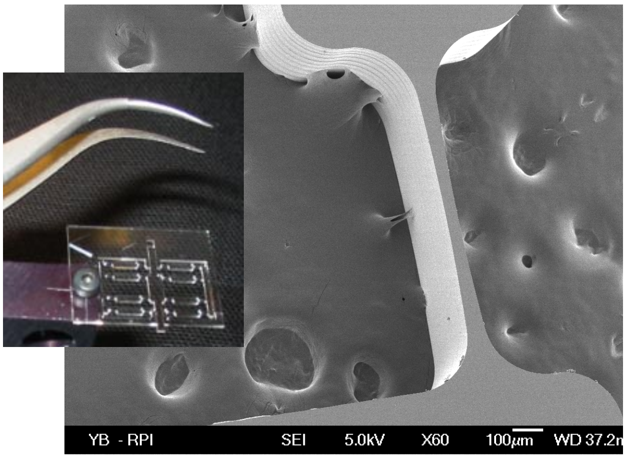


Fig. 9 - Microfabricated prototype. Scanning Electron Microscope picture of one hinge. Insert: overview of the microsensor with a tweezer next to it

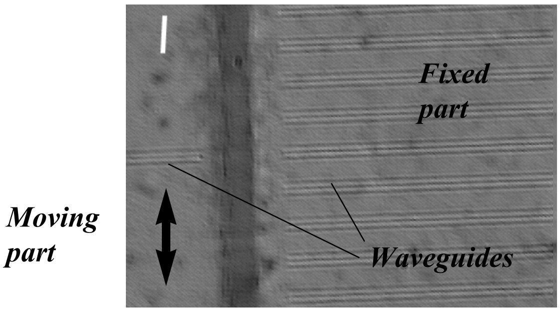


Fig. 10 - Optical microscope view of the sensing element (scale bar 30 microns). When the waveguide are aligned, the transmitted signal is maximized.

V. EXPERIMENTAL RESULTS

Close-up views of a prototype displacement sensor is shown on Fig. 9 and Fig. 10. The picture shows the interface between a stationary and a mobile waveguide. This prototype contains only one waveguide on its movable platform and was designed for testing the sensing mechanism. Waveguides are 8 microns wide and are placed at 100 microns below the surface. A V-groove shape consisting of two rectangular voids is placed to reflect off unguided light.

A laser diode (750 nm) is used as the light source. At this wavelength the waveguides are multimodes. In this particular case, the coupling losses are almost linear and can be described with the formula presented in the previous paragraph. A micrometer with sub-micron resolution is used to translate the mobile platform laterally relatively to the stationary waveguide. The micrometer position is sensed with a Keyence sensor that has a resolution of 0.1 microns. The light intensity is measured with a photodector and the signal acquired through a LabView interface. Results are shown on Fig. 11.

This result demonstrates the principle of this micro-displacement sensor. Repeatable sub-micron displacements were measured. Our current measurements were limited by the resolution of the sensor use to characterize the structure. We suspect that the resolution of the glass sensor is at least below 100 nm. Further experimental work will be done to fully characterize the structure.

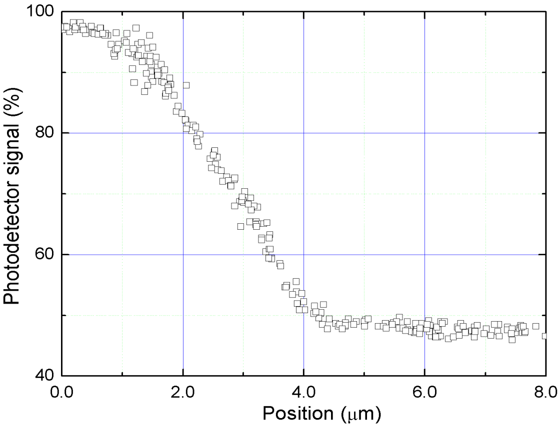


Fig. 11 Photodetector signal as a function of the position. The signal rapidly decreased when the waveguides are no longer aligned. The signal is not filtered.

VI. CONCLUSION

A new concept of micro-displacement sensor suitable for harsh environments has been proposed. For the first time, we show the simultaneous introduction of integrated waveguided optics and micromechanical flexures within a three-dimensional glass body. This result opens new opportunities for interventional robotics in particular robots operating in an EM sensitive environment.

Unlike their macro-counterpart, microrobots lack “direct-joint” sensing capabilities. As a consequence, many microsystems work in open loop. The ability to incorporate optical sensing and mechanical functionalities in a common platform has the potential to solve these issues. We expect this technology to play a significant role in microrobotics by providing a platform for fully integrated micromechanisms with embedded sensors.

REFERENCES

[1] Horst Scholze, “Glass: Nature, Structure and Properties”, Springer-Verlag publishers, 1990.

[2] S. T. Smith, D.G. Chetwynd, *Foundations of Ultraprecision Mechanism Design*, ed. Gordon & Breach Publishers.

[3] R.V. Jones, Parallel and rectilinear spring movements, J. Sci. Instrum., 28, 38-41, 1951.

[4] S. T. Smith, PhD Thesis, University of Warwick, 1988.

[5] S. Henein, “Conception des guidages flexibles”, Press Polytechniques et Universitaires Romandes, 2001.

[6] X. Liu, D. Du, G. Mourou,“Laser Ablation and Micromachining with Ultrashort Laser Pulses” IEEE Journal of Quantum Electronics, 33: 1706-1716 (1997).

[7] K. M. Davis, K. Miura, N. Sugimoto, K. Hirao,”Writing waveguides in glass with a femtosecond laser”, Opt. Lett. 21, 1729 (1996).

[8] A. Marcinkevicius, S. Juodkazis, M. Watanabe, M. Miwa, S. Matsuo, H. Misawa, J. Nishii, “Femtosecond laser-assisted three-dimensional microfabrication in silica”, Optics Letters, 26, 277 (2001).

[9] Y. Bellouard, A. Said, M. Dugan, P. Bado, “Fabrication of High-Aspect Ratio, Micro-Fluidic Channels and Tunnels using Femtosecond Laser Pulses and Chemical Etching”, Optics Express, 12:2120-2129(2004).