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Laser-based fabrication of a displacement sensor with an integrated high-accuracy position sensor

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Abstract

We present a high-accuracy force or displacement sensor made only of fused silica. This device merges integrated optics and micro-mechanics in a monolithic substrate. It differs from previous micro force sensor works in that the measured variable is acquired optically, rather than electrically. The device was manufactured using a combination of femtosecond laser pulses and chemical etching. A single manufacturing step was used to define both the optical and the mechanical features. This approach dramatically simplifies the overall fabrication and eliminates alignment issues associated with sequential fabrication processes. Our displacement sensor is composed of a mobile platform and a fixed frame. These components are linked together through sixteen high-aspect ratio double-compound flexures. This design firmly restrains the motion of the platform along a single axis. The range of motion exceeds 1-millimeter. Integrated waveguides are used to measure the displacement of the displacement with accuracy better than 50-nm.

Introduction

Over the last decade, we have seen the emergence of glass micromachining techniques based, in part or in full, on the use of femtosecond laser pulses. Femtosecond lasers were initially used to micromachine glass through direct ablation. It was shown that, when compared to other glass machining processes, the use of femtosecond laser pulses results in fewer and less severe collateral damage.^{1,2} Yet for most cases the defects were still present which prevented the use of direct laser ablation for the fabrication of glass microdevices. Shortly thereafter, Hirao and his coworkers showed that one could locally change the index of refraction of glasses using femtosecond laser pulses.³ The technique was immediately used to create three-dimensional optical waveguides. More recently it was shown that for some glass compositions, the femtosecond process that creates a local change in the index of refraction, also locally affects its resilience to hydrofluoric etching.⁴

Femtosecond-based index and chemical resilience changes are still poorly understood. These effects are being actively studied by the authors,⁵ as well as by others. Despite this incomplete understanding of the underlying material phenomena, numerous R&D groups have used these processes to fabricate simple optical elements. A few have shown that these femtosecond processes can be combined to create more complex glass-based microdevices. While it appears that not all glass compositions are appropriate for the machining of complex devices, a compelling case can be made in the case of fused silica (or fused quartz), a glassy material where significant index change (of the order of a fraction of 1%) and a large change in HF etching resilience can be locally created using femtosecond laser pulses.

In order to demonstrate this point we recently manufactured a fused silica mesoscale linear translation stage⁶ with characteristic similar or superior to that found in microdevices manufactured with traditional MEMS techniques. In this paper we present recent developments associated with the manufacturing of this type of devices.

Microstage design and fabrication

There is an overabundance of linear stage designs, including subgroups that include means to measure the position of the stage. Here we selected a design where the stage position is read optically through an array of waveguides. The mobility is provided by flexures acting as elastic mode compliant elements. The design objective was to create a device with mesoscale displacement capability (1-mm range) combined with an integrated sub100-nanometer sensing accuracy capability.

The device is made from a single piece of amorphous fused silica into which the mechanical, structural and optical features are monolithically integrated. The key elements - flexures, frame, moving platform, waveguide array, and input/output fiber ports are shown in Figure 1.

This is a rather generic device that can be configured to be used as a position/displacement sensor, a force sensor, a viscosity or lubricity sensor, accelerometer, vibration etc.

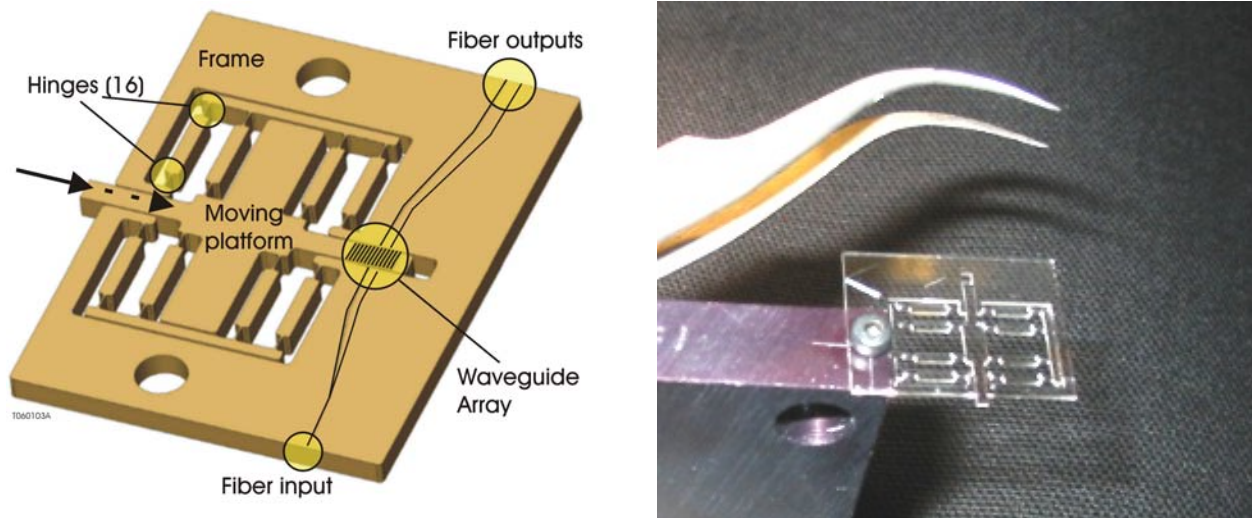


Figure 1: Stage with encoder- schematic with key component overlaid (left), the real device with tweezers (right)

The device was manufactured using two of the femtosecond-based processes introduced above. For clarity we call the femtosecond-process resulting in a local index change *femtoWrite*TM, and the femtosecond-process resulting in a local change in chemical reactivity *femtoEtch*TM.

Although this may be counterintuitive, fused silica glass is a good material for micromechanical applications. Besides its well known optical transparency, which extends from the UV to the mid-infrared, fused silica is chemically stable (except in the presence hydrofluoric acid) and can endure very high temperatures. It has a low density (2200 kg/m³) and a Young's modulus comparable to that of aluminum. While theoretically fused silica has a very high elastic limit of several GPa, its strength is limited in practice to much lower values - typically 50 MPa. This low experimental value is due to the presence of surface flaws, which lead to cracks formation and ultimately material failure. By eliminating these flaws, one can substantially increase the glass strength. Methods that reduce or eliminate surface flaws based on this principle exist to increase this value significantly.⁷ In the case of fused silica, it was shown that chemical etching and polishing can greatly improved its fracture strength up to a few 100 MPa.

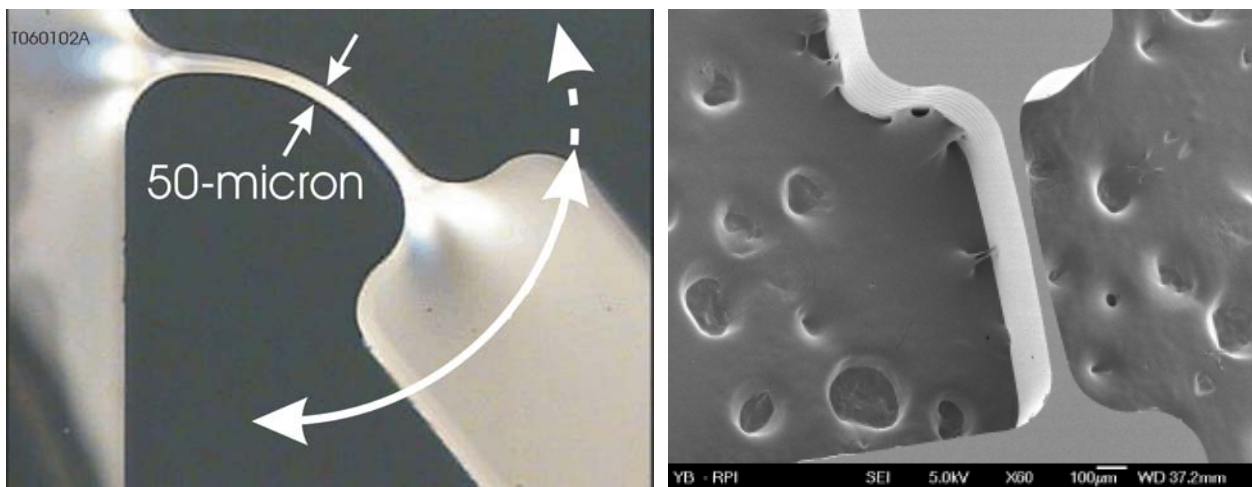


Figure 2: Hinge manufactured with the femtoEtch process. The width of the neck is approximately 50-micron. The range of motion is 120 degree (limited only by the glass frame).

The ultimate elastic limit value is highly process dependent. In our case, we found that our *femtoEtch* process leads to extremely high fracture strength: we consistently obtained values in excess of 500 MPa and in some cases in excess of 2 GPa. As a result we were able to manufacture hinges with much higher displacement/size ratio or with superior mechanical performance. An example of micro-hinge fabricated with our process is shown in Figure 2.

Flexures

There are various ways to provide mobility. We selected a flexure-based approach. Flexures offer a smooth and continuous displacement. They are free from wear issues. The flexure approach provides mobility along one axis while providing good stiffness along the other axis. Most importantly flexures are straightforward to manufacture monolithically with our laser-based processes, which greatly simplifies the assembling procedure.

Flexures are typically associated with small displacements. One can combine flexures to increase the associated displacement range (This does generally come at a price of reduced out of plane stiffness). We selected a design calling for a combination of several flexures known in the trade as double-compound rectilinear system. Mechanical stresses and resonance frequencies were calculated using an analytical model and optimized using commercial FEM CAD software.

Waveguide array and position readout

We used the variation of signal intensity resulting from lateral displacement between facing waveguides as the principle for the mobile platform position readout. The basic implementation calls for three waveguide segments, created with the *femtoWrite* process. An input waveguide is created in the frame. It brings an optical signal from the light source to the boundary separating the frame from the mobile platform. A second waveguide segment is located in the mobile platform. Its position is selected so that at rest it is aligned with the input waveguide. A third waveguide is created in the frame. It brings the optical signal from the mobile platform to the photodetector. This third segment is aligned with the second segment.

This basic design was shown to operate as expected. However with this design the sensing range is limited to approximately the width of the mode-field diameter associated with the waveguides. In order to increase the displacement sensing range, the single waveguide found in the mobile platform was replaced with an array of parallel waveguides, as illustrated in Figure 3. We also improved on the early position readout accuracy by writing an additional pair of input and output waveguides. These pairs are spaced to operate in a quadrature mode (Full quadrature implementation will require four input and output waveguides). A quadrature-type implementation provides information about the direction of motion, and in conjunction with a proper choice of waveguide size, can effectively linearize the optical signal response to the displacement of the platform. Using this approach, we can measure the stage position with a resolution equal or better than 50 nanometers (This positioning accuracy is presently limited by our experimental setup and not by the microstage itself).

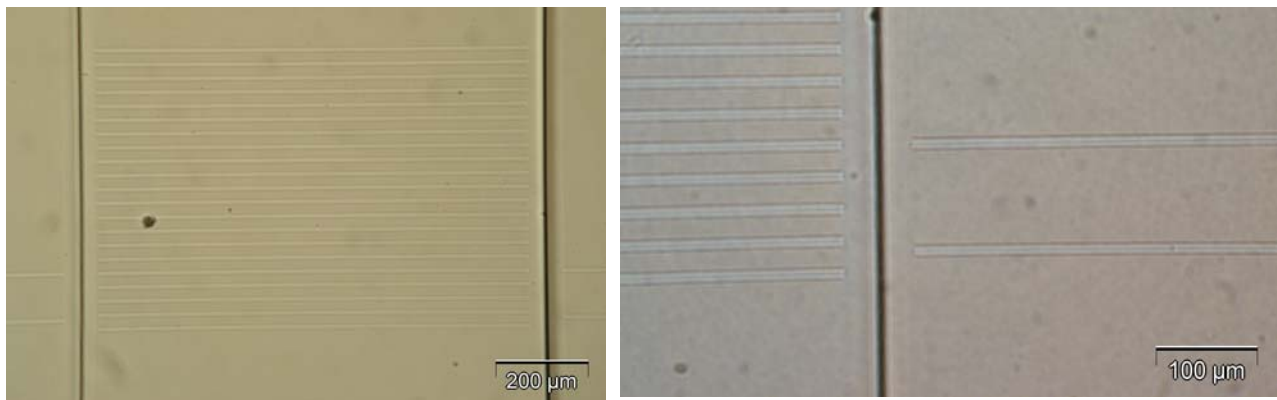


Figure 3: Waveguide array of waveguide in moving platform – Full array (left); detail (right)

Input/output fiber interfacing

Ancillary optoelectronic components such as light sources (diode lasers, LED, etc.) and photodetectors can be bonded directly onto the glass substrate, as illustrated in Figure 4.

For some applications it is desirable to have these optoelectronic components placed at a remote location. In such a case, it is convenient to link the optoelectronics components with the stage/frame assembly via optical fibers. We tested several ways to interface optical fibers with our fused silica devices.

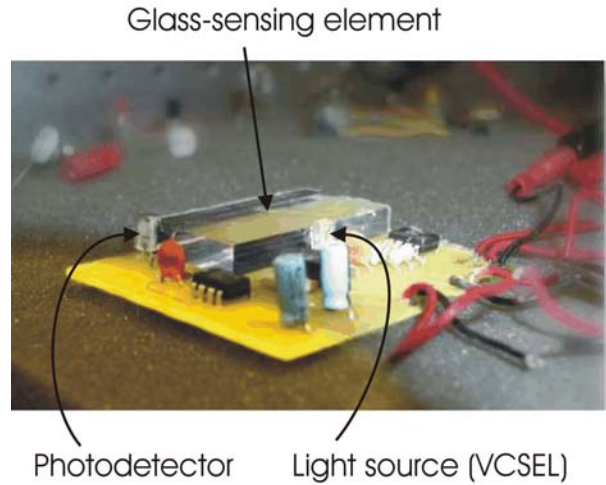


Figure 4: Micromachined glass substrate with directly bonded optoelectronic components

While conceptually simple, the interfacing requires significant manufacturing precision. Sub-micron accuracy is essential when using single mode fibers whose core diameters are smaller than 10-microns.

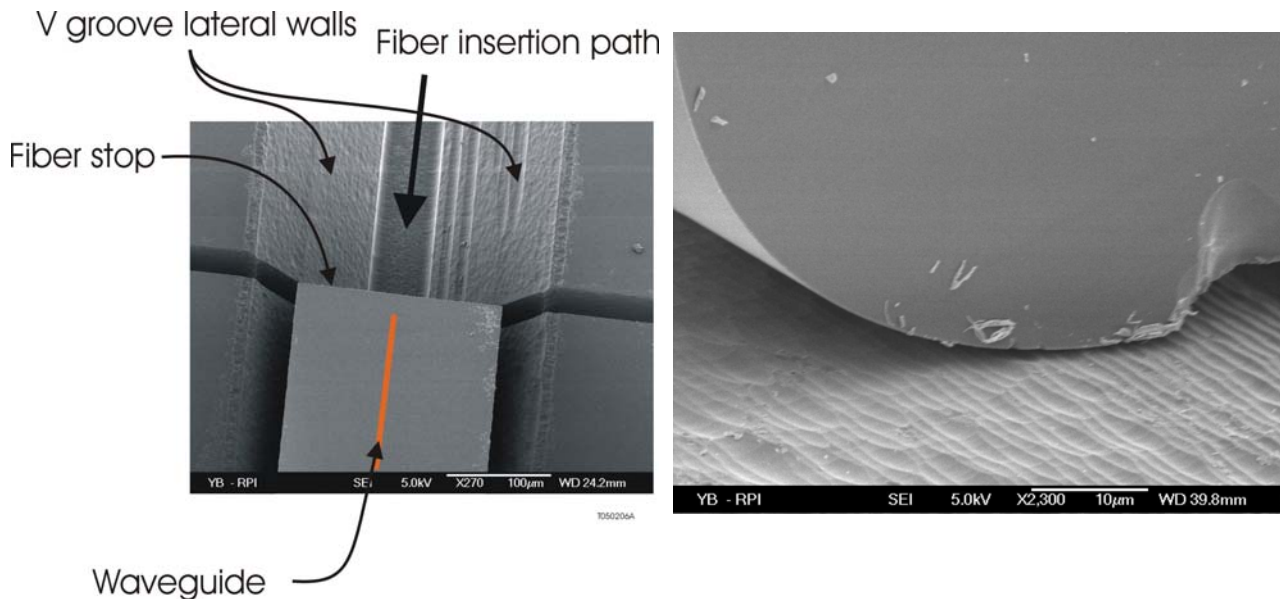


Figure 5: (Left) Overview of a V-groove and a fiber stop machined with the *femtoEtch* process. (Right) detail view of a SMF28 fiber resting against one of the walls of the V-groove

We have demonstrated two approaches to interface single-mode fibers to our single-mode waveguides. In a first phase, we manufactured V-grooves, which are used to position accurately optical fibers with respect to waveguides.

Some examples are shown in Figure 5. A related approach based on anisotropic etching of silicon is commonly used in the design of telecommunication components.

In our case, the V-groove boundaries and the associated waveguide (superimposed on Figure 5 left) are defined in a continuous laser-based manufacturing process. Specifically, there is no need for repositioning of the work piece. Consequently, this manufacturing technology is intrinsically very precise: the accuracy depends mainly on the performance of the motorized stages used to move the specimen under the laser beam. Note that there is a fiber stop located at the end of the V-groove: The fiber front face rests against this fiber stop.

The SEM photograph (Figure 5 right) shows a portion of a 125-micron diameter optical fiber resting against a V-groove wall. The quality of the contact surface was found adequate for single-mode fiber–waveguide alignment

In a second phase, we manufactured fiber insertion holes with the accuracy needed to interface efficiently single-mode fibers with single mode waveguides. This type of approach is rarely used in the industry although it is conceptually simple. In our case the same laser that is used to manufacture the waveguide via the *femtoWrite* process is also used to define the boundaries of the insertion hole. There is no repositioning of the work piece and the relative alignment between the waveguide and the main axis of the insertion hole is intrinsically very precise. However, we note that, if no special care is taken, the walls of the insertion hole will be slightly tapered. This taper may affect the optical coupling between the fiber and the waveguide. The taper results from the etching geometry: While the main etching front propagates down the principal axis of the insertion hole, a secondary, much slower, radial attack of the unexposed fused silica occurs. As a result the insertion hole input diameter is slightly larger than the diameter found at the bottom of the insertion hole. This effect can be pre-corrected if necessary. To simplify fiber insertion we generally add a first section that is strongly tapered as shown in Figure 6.

Furthermore we also generally add a secondary well connected to the primary well through a horizontal duct. The function of this secondary well is to provide an escape path for excess adhesive, air bubble, etc. that tend to disrupt the optical coupling efficiency when no special precautions are taken.

The two fiber attachment techniques presented above can be combined when needed.

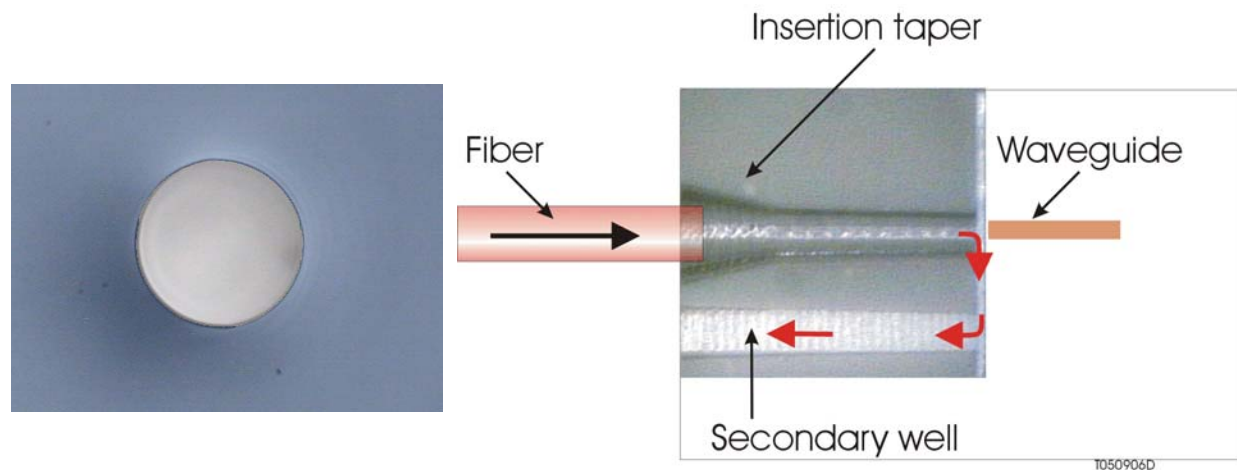


Figure 6: A top view (left) and side view (right) of two fiber insertion holes machined with the *femtoEtch* process. The side view shows an input tapered segment and a secondary well. The overlaid arrows illustrate the escape path for the unwanted material.

Conclusions

Overall activity in glass micromachining has historically been very limited. However the recent development of manufacturing processes based on femtosecond lasers is creating a commercial opportunity. We believe that in the next few years glass microdevices/sensor will play a much more important role than is generally envisioned today. The manufacturing of the mesoscale linear stage with its high-accuracy integrated optical readout presented here would not have been possible a few years ago. Due to remarkable developments in glass micromachining capabilities, it is now feasible.

Other desirable material characteristic can be implemented in fused silica microdevices. For example we recently combined our ability to manufacture with the *femtoWrite* process low-loss single mode subsurface waveguides with a thermal poling process to create nonlinear and electro-optically active waveguided devices.⁸

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