A monolithic micro-tensile tester for investigating silica micromechanics, fabricated and fully operated using a femtosecond laser

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A monolithic micro-tensile tester for investigating silica micromechanics, fabricated *and* fully operated using a femtosecond laser

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Abstract: We report on the use of femtosecond laser for fabricating, loading *and* in-situ measuring using third-harmonic signal generation a micro-tensile tester for characterizing silica and its polymorphic phases.
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Fused silica – the glassy phase of SiO_2 – is of particular interest for microsystems. Its unique mechanical (high strength, low coefficient of thermal expansion), optical (high transparency over a broad spectrum, low dispersion, etc.) and chemical properties (inert to most chemicals) makes it a particularly interesting substrate for micro-devices in which optical, mechanical and fluid-handling function can be combined all together or separately, thanks to the use of femtosecond micromachining [1]. At the micro and nanoscale, amorphous silica exhibits an unconventional behaviour such as pseudo-plastic failure and deformation [2,3]. However, the micromechanical behavior of fused silica as well as its polymorphic phases remains largely unexplored, due to the inherent experimental difficulties associated with it. Here, we propose a monolithic microscale tensile tester, entirely made of silica, for which the same femtosecond laser is not only used for fabricating the device, but also for operating it (loading the specimen) as well as for measuring *in situ* the induced deformation thanks to the use third-harmonic generation (THG). The tensile tester consists of two parts (shown in Fig. 1a): the loading cell (part a) and the displacement amplification sensor (part b). The tensile tester is fabricated using a femtosecond laser (Yb-fiber amplifier operated at 800 kHz with pulse energy of 375 nJ, 0.4 NA objective) and chemical etching according a process described elsewhere [4].

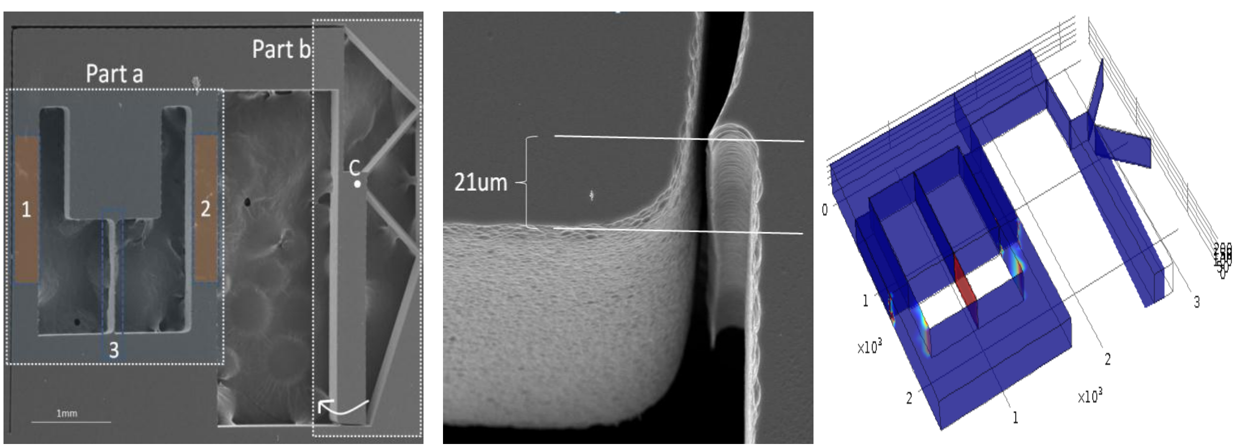

Fig 1:(a). Micro-tensile tester Scanning Electron Microscope image. The overall dimensions of the system are 2.5 mm ×2.9 mm. Part a is the loading cell unit and part b is the displacement amplification sensor. (b) Magnified view of the system's 21um displaced lever beam.(c) Finite element analysis image for the system loaded.

To load the microscale beam (thin bar 3 in part a of Fig. 1a), we use the *same* femtosecond laser to re-expose the specimen but only in the zones 1 and 2. Indeed, as demonstrated in [5], laser exposure induces a net volume expansion in the operating regime described above. Here, we take advantage of this effect to generate a net expansion of the two loading bars (bars 1,2 in part a of Fig. 1a). By writing a given number of adjacent planes - each of them consisting of multiple lines writing across the specimen thickness, the applied load can be tuned to virtually any desired level. As an illustration, in the example shown in Fig. 1(a, b, c), 800 planes where written with an energy deposition (net fluence) of 7 J/mm^2. The corresponding stress of 280 MPa in the test beam (label 3 in Fig. 1a) is achieved as predicted and measured with polarized light microscopy (Fig. 2a) and is consistent with the stress of 277MPa calculated using the finite method analysis (Fig. 1c).

To measure the beam elongation resulting from the stress load, the displacement is mechanically amplified using a flexure-based lever mechanism (part b in Fig. 1a). This mechanism consists of two beams (mounted 45 degrees to the long lever beam) that form a hinge with a remote rotation center (C indicated in part b of Fig. 1a). This hinge is connected to the main load cell. When a load is applied, the load cell induces a mechanical moment on the hinge that pivots. Using this mechanism, the beam elongation creates a corresponding amplified motion of the elongated beam. The amplification ratio here is eleven.

Finally, we use the same laser, yet at much lower pulse energy so that no modification is made on the material, to accurately measure the displacement of the lever amplification beam. To do so, we use third harmonic generation [6] (THG) induced by the femtosecond beam while scanning the beam across the specimen. At this stage, we estimate the measurement accuracy to be in the order of a micron and possibly less. (Fig. 2b illustrates a THG scanned signal acquired across a test pattern made of predefined trenche sizes.)

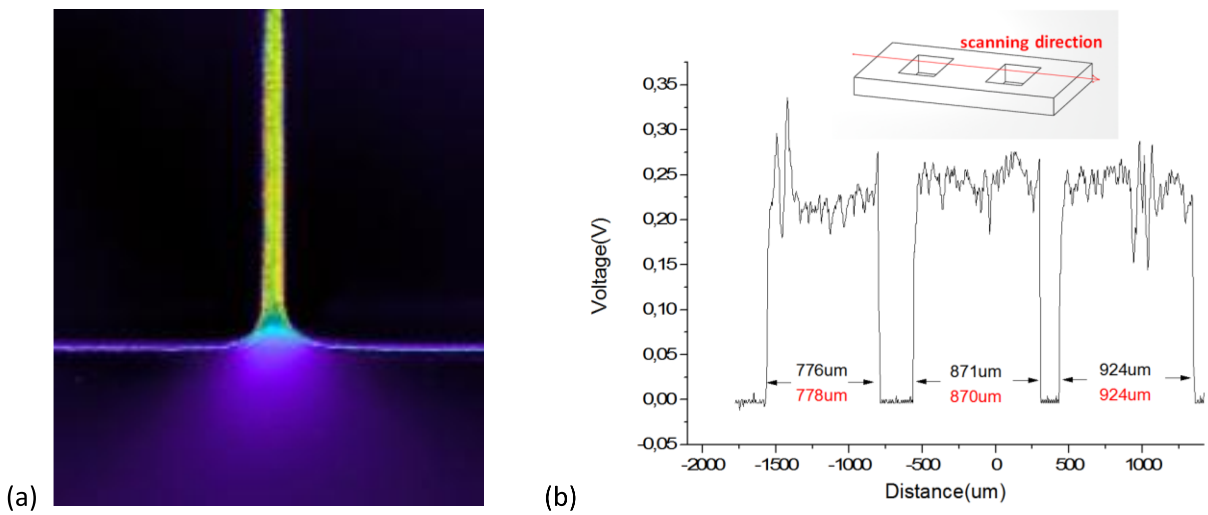

Fig.2:(a) Birefringence image of the test beam (beam 3) acquired with a CRI PolScope (50x objective). As can be seen the stress is uniformly distributed as expected. Beam width is 5 microns. (b) Illustration of a THG signal scan across the surface of a calibration pattern made of known-size grooves. The back labels are extracted from the THG trace. The red one are measured with a conventional microscope.

In summary, we have demonstrated that the same femtosecond laser can be used not only for fabricating a miniaturized tensile tester with fine flexures, but also for loading the device as well as for performing *in situ* measurements using THG. This instrument and measurement approach opens up new perspectives for investigating size effect on material mechanical properties. This approach is particularly suitable for investigating the mechanics of silica polymorphic phases at the micro- and nano- scale which is, for now, largely unknown.

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