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Femtosecond laser processing of fused silica: from process characterization to applications in optomechanics

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Abstract: Non-linear laser-matter interaction offers the possibility to structure dielectric materials in three dimensions. Among dielectrics, fused silica has brought particular attention because of its suitability for a variety of applications from optofluidics to integrated optics and from optical components to mechanics and optomechanics. Multiple aspects of this laser-matter interaction remains elusive. Here we discuss some aspects of it from the viewpoint of micromechanics.

1. Introduction

Recent progresses in femtosecond laser processing of fused silica have opened up tremendous opportunities not only for integrated optics [1] but also - when combined with chemical etching [2] - for the fabrication of micro-channels and trenches [3].

As demonstrated in various publications (see for instance ref [4],[5],[7]), the laser-matter interaction with silica is inherently coupled with micro-mechanical side-effects, such as localized stress concentration as well as possible densification effects. Here, we summarize recent findings in our research effort to understand the nature of these micro-structural changes.

2. Densification versus volume expansion

In [6,8], we have shown experimental evidences based on Raman spectra evolution [11] and on nanoindentation as well as stress-induced birefringence measurements that suggested that densification occurs in the laser-affected regions in the regime where no nanogratings [8] are found. On the other hand, we recently observed using a method based on micro-cantilever deflection [9] that laser affected zones eventually expand when nanogratings are forming but still with some local indication of densification in the material as suggested by Raman spectra (increase of the D2-peak). Recent observations from J. Canning et al. [3] reconciles this apparent contradiction. Indeed, they reported the existence of porous structures inside nanogratings lamellas suggesting the formation of gas pores during laser exposure that would inherently pressurize the surrounding remaining glass matrix and thus explains, the signal observed with the Raman that hints toward the formation of lower SiOx rings formation (see Fig. 1).

3. Consequences of localized stress surrounding laser affected zones

Volume variations within laser-affected zones and the stress build-up resulting from it seem to affect various properties of the material. In [13], we observed a saturation of the etching efficiencies as we were reaching high energy deposited levels in patterns consisting of multiple adjacent lines. In particular, it was reported that there is an actual optimal level where etching rate is maximized, above which the etching efficiency declines. This observation was later confronted with volume expansion measurement [9] which emphasized the correlation between stress and etching rate. More intriguing (as a sequel of the work in [10] and briefly outlined in [12]), writing path dependence in complex patterns made of multiple lines on final etched structures (see Fig. 2) demonstrate that pressure building up during laser exposure is sufficient to induce irreversible densification effects. Indeed, preliminary observations in [9] suggests stress level within the range of 400-500 MPa around nanogratings and most likely much higher in nanogratings lamellas.

3. Conclusion

In this short communication, we summarized recent findings demonstrating stress generation in femtosecond laser exposed patterns possibly leading to localized densification. A direct practical consequence is that for precise control of final shapes and patterns written with femtosecond lasers, it is of utmost importance to carefully monitor the stress evolution during writing. Studying stress evolution in and around laser-affected patterns is not only interesting for better understanding femtosecond laser-interaction with fused silica but also for developing novel optomechanical as well as micromechanical devices and microdevices in general.

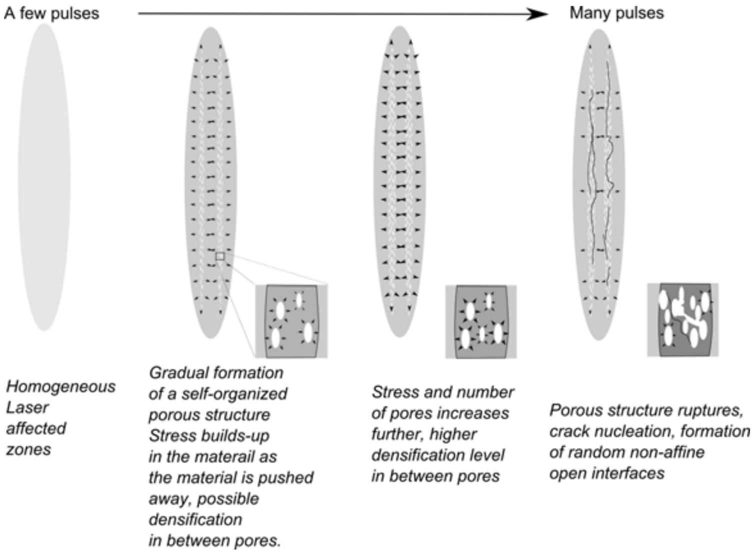

Fig. 1 A possible scenario for the gradual stress build-up and eventual stress-relaxation taking place during laser exposure of fused silica. In this scenario, porous material gradually forms during laser exposure leading to the generation of highly pressurized zones in the material eventually leading to localized densification in the matrix structure surrounding the nanopores (adapted from [9]).

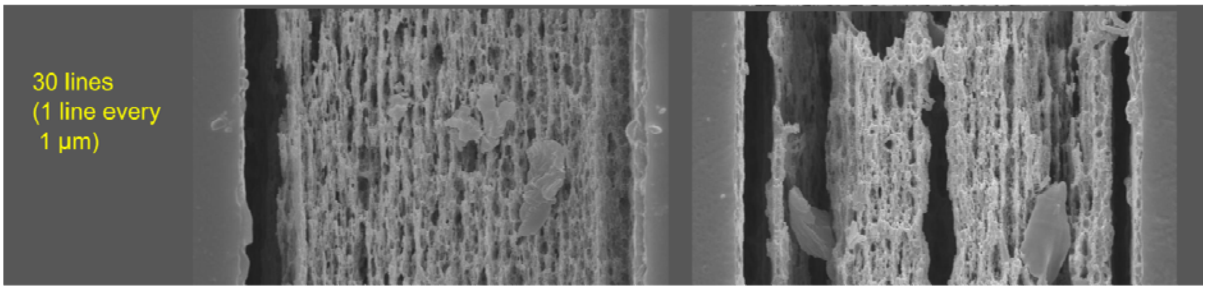

Fig. 2 Illustration of path dependant etching patterns (adapted from [12]). Both patterns are rigourously identical in term of laser exposure conditions but obtained with different ordering in the sequence of lines written in the material. In the left image, lines were written one after another from left-to-write, while on the right image, lines were written sequentially from the extremities and gradually moving toward the center.

4. References

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