

Three Dimensional Writing of Material Functions by femtosecond laser: Science and Technology.

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The femtosecond laser direct writing (FLDW) allows 3D highly localized permanent modifications because of light absorption in transparent material through a highly non-linear absorption of a converging beam. Up to date no other manufacturing process has the potential to integrate 3D multifunctional devices made in a single monolithic chip and within a variety of transparent materials. The absorption step corresponds to strong electron excitation from valence to conduction bands. Then, electrons relax through various processes that leads to structural modifications of the materials and their physical properties that could be useful for elaborating many applications.

During the presentation, I will give some examples of these effects and the consequences on the properties. A part of the effects are not specific of the femtosecond laser (ultra-brief pulses or very high intensity):

- Change of fictive temperature of glasses that leads to isotropic refractive index change,
- Physico-chemical transformations like oxide decomposition, phase separation, congruent or non-congruent crystallization for producing optically non-linear properties, amorphisation useful for optical waveguide elaboration,
- Chemical migration,
- Glass densification by shock wave produced by sudden increase of specific volume at the center of focal volume,
- Stress field for inducing remote anisotropic index change, change of mechanical properties,

Another part of the effects is specific of such type of laser.

- Coulomb explosion inducing cavitation,
- Self-organized nanostructures like nanogratings, so useful for creating anisotropic index change at the micron scale,
- Redox effect on transition metal or noble metal that leads to luminescence and dichroism (nanoparticle precipitation), respectively,
- Action of the fs laser polarization, action of the pulse front tilt.

An example is given in the figure, useful for integrated optics, it is the combination of the control of the direction of an optically non-linear crystals and of nanogratings forms by self-organized chemical separation of the glass into SiO_2 and LiNbO_3 .

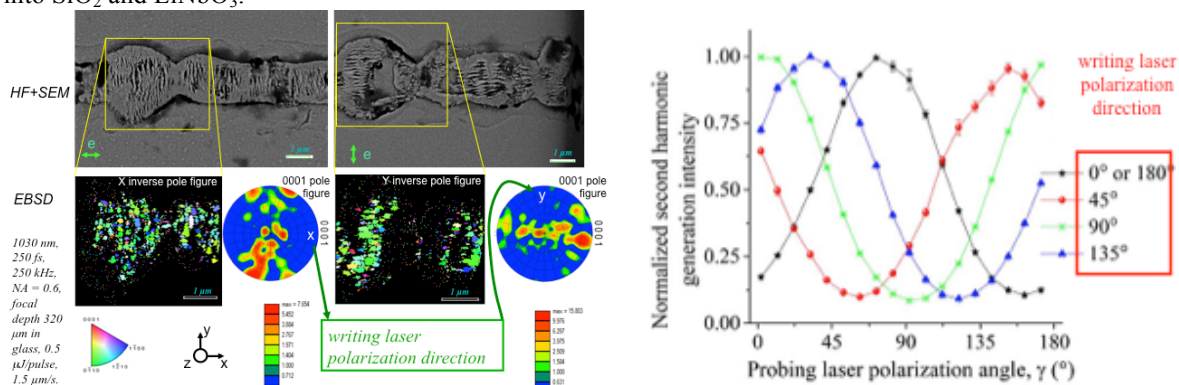


Figure 1 : Example of integration of two functions: SHG and birefringence. SHG (picture on the right) is carried by the LiNbO_3 nanocrystals produced by laser irradiation (see EBSD) in $33\text{Li}_2\text{O}-33\text{Nb}_2\text{O}_5-34\text{SiO}_2$ glass. Birefringence is carried by the nanogratings of SiO_2 and LiNbO_3 quasi-periodic modulation in the direction of the writing laser polarization (see SEM). At low pulse energies, the assembling nanostructure + texture turns with the writing laser polarization. The polar crystal axis is always perpendicular to the writing laser polarization. [1, 2]

[1] Cao J, Lancry M, Brisset F, Mazerolles L, Saint-Martin R, Pommellec B. Femtosecond Laser-Induced Crystallization in Glasses: Growth Dynamics for Orientable Nanostructure and Nanocrystallization. *Crystal Growth & Design*. 2019;19(4):2189-205.

[2] Cao J, Pommellec B, Brisset F, Helbert A-L, Lancry M. Tunable angular-dependent second-harmonic generation in glass by controlling femtosecond laser polarization. *J Opt Soc Am B*. 2016;33(4):741-7.