



# Space-time domain solutions for direct inscription in bulk silicon with ultrafast lasers

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### LMI-I-3

#### Internal structuring of silicon using ultrafast lasers

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An important challenge in the field of three-dimensional (3D) ultrafast laser processing is to achieve permanent modifications in the bulk of silicon (Si) and narrow-gap materials. High-energy infrared femtosecond laser pulses fail when conventional laser machining configurations are used [1,2].

By comparisons between ultrafast plasma images, 3D energy density maps inside the samples and nonlinear propagation simulations of tightly focused infrared pulses [3], we identify the strong nonlinear and plasma effects in the pre-focal region causing a strict clamping of the intensity that can be delivered inside Si [4].

To circumvent this limitation, we describe a solution inspired by solid-immersion microscopy to achieve hyper-tight focusing of the pulses. We describe the details of a proof-of-concept experiment demonstrating femtosecond optical breakdown inside Si and discuss the associated local refractive index changes measured by infrared phase microscopy [4].

The complexity of these optimizations in the space domain suggests that more practical solutions may likely arise with the use of longer pulses for reduced beam power. We concentrate our attention on the picosecond regime for which non linear effects persist and cause a non-monotonic evolution of the peak delivered fluence as a function of the incoming pulse of the energy. This is a situation somehow more complex than the clamping of the intensity observed in the femtosecond regime. However, we also find reduced energy thresholds for 3D writing inside silicon that is highly desirable.

Finally, we describe the range of possibilities that are already accessible with the fabrication of optical waveguides [5] and diffraction grating [6], structures based on positive- and negative-tone laser-assisted chemical etching [7] and a demonstration of 3D data inscription deep inside silicon using nanosecond and picosecond lasers. This directly translates in Si some of the 3D writing technologies originally developed in transparent dielectrics and has the potential to change the way Si microsystems are today designed and fabricated.

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