Fabrication of high aspect-ratio microchannels on diamond surface by pulsed Bessel beams laser machining

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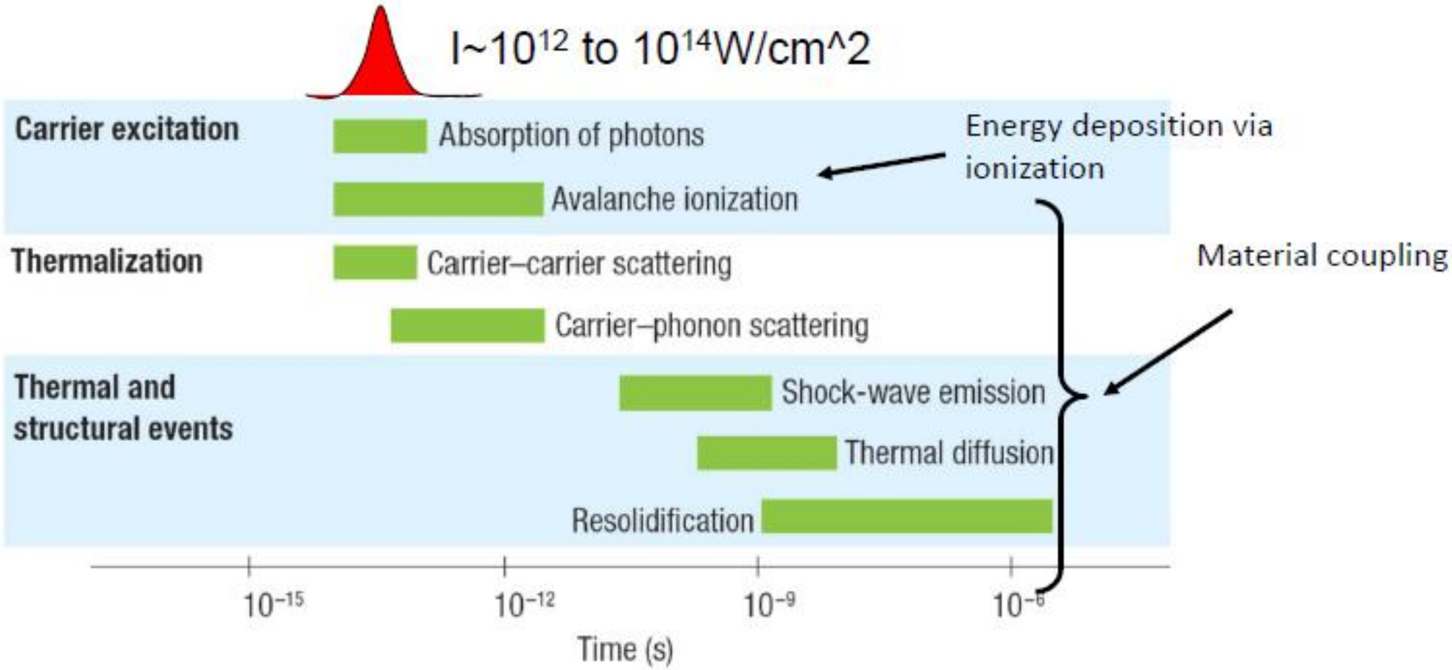
CNR IFN Istituto di Fotonica e Nanotecnologie

Outline

- Ultrafast Laser micromachining of transparent materials
- Finite energy Bessel beams and applications in laser micromachining
- The experiment: Laser writing on diamond surface
- Characterization of generated trenches and microchannels
- Conclusions

Ultrafast Laser micromachining

Femtosecond laser ablation is not a direct process.

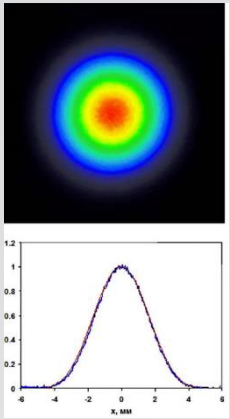


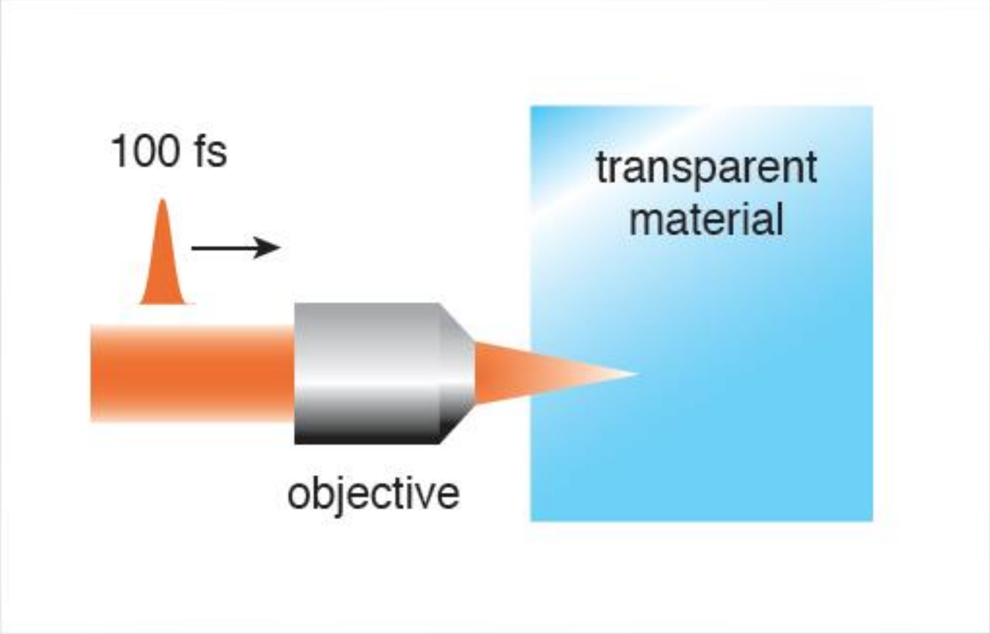
Gatass,R and Mazur,E. Nature Photonics,2,219 (2008)

Ultrafast Laser micromachining

high intensity at focus…

Gaussian laser profile



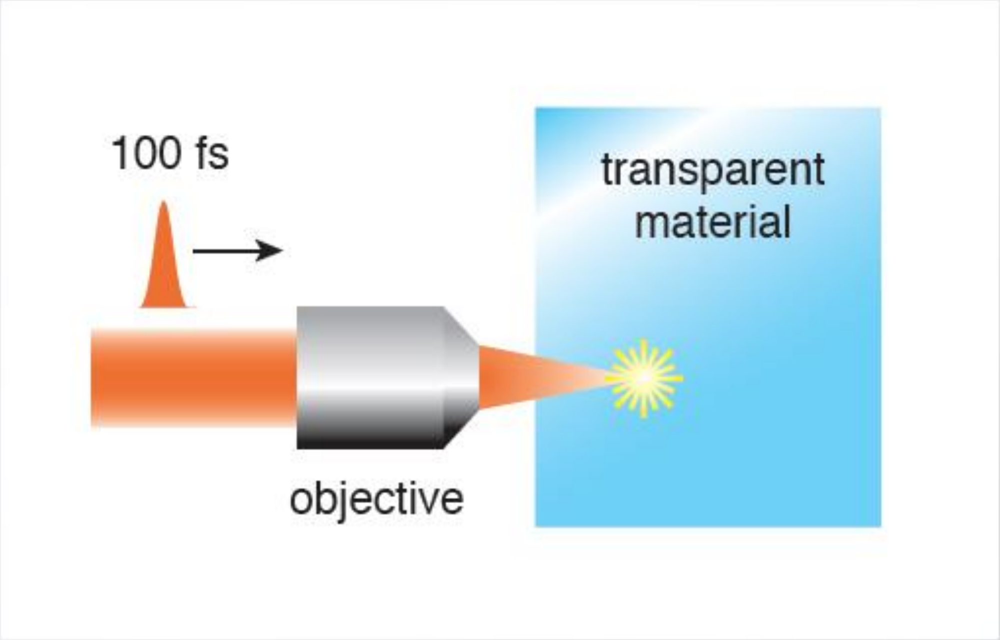


High rep.rate laser
kHz or MHz

→ Large number of laser pulses in the same spatial point

Ultrafast Laser micromachining

…causes nonlinear ionization…



Local confinement of the absorption

Laser intensity > threshold intensity for material modification ⟹ Nonlinear processes

Carrier excitation from valence band to conduction band leads to an increase of electronic density till critical plasma density

Ultrafast Laser micromachining

and 'microexplosion' causes microscopic damage…

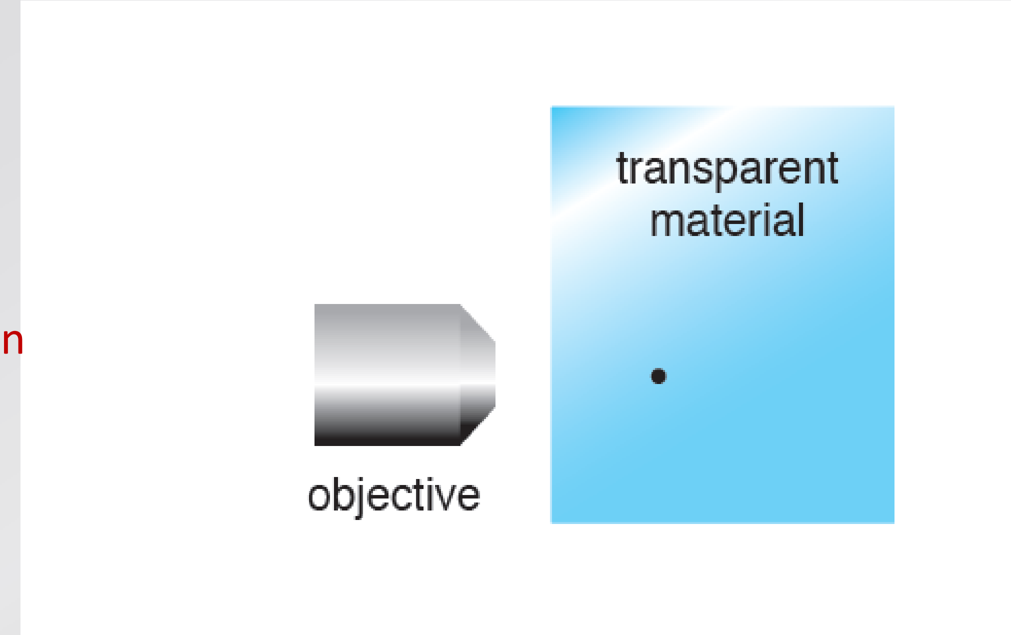
Plasma expansion and
Shock wave

⬇

Thermal expansion

⬇

Permanent modification
of the material



100 fs: laser energy transferred to electrons

10 ps: energy transfer to ions

100 ps: plasma expansion

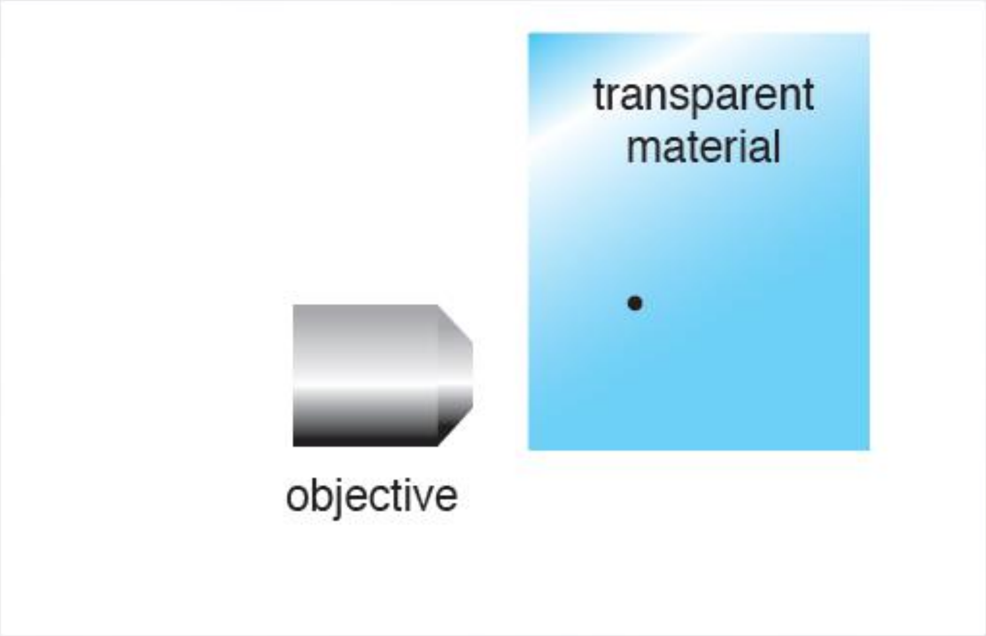
10–100 ns: shock propagation

1 μs: thermal expansion

1 ms: permanent structural damage

Ultrafast Laser micromachining

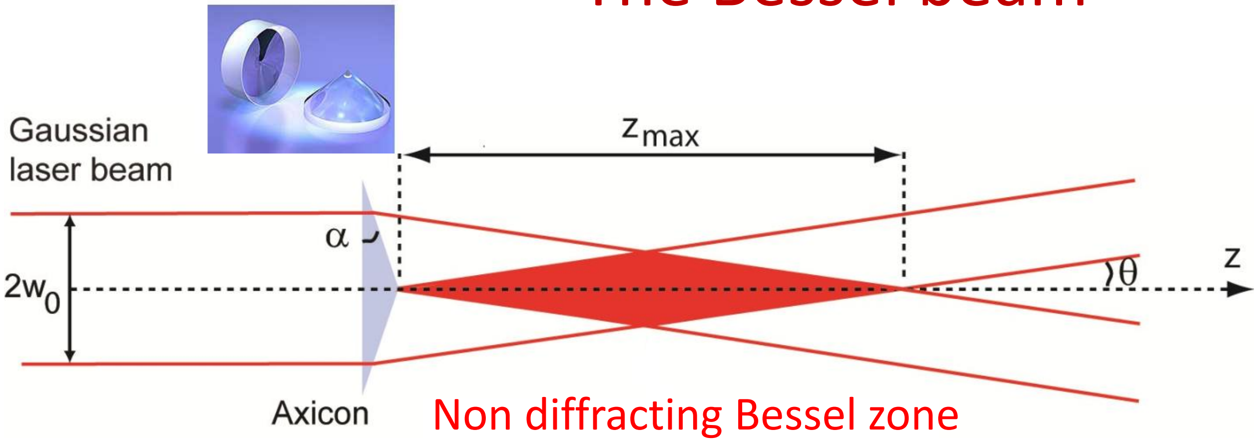
translate sample

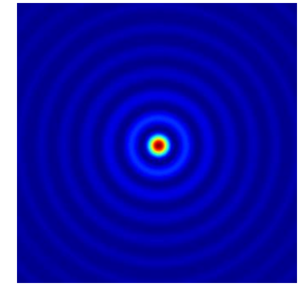


Three dimensional structures can be obtained

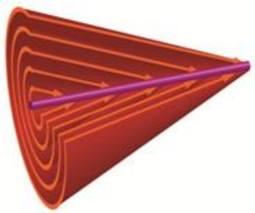
The essential components that can be fabricated with this tecnology in transparent materials are the optical waveguides and microfluidics channels

The Bessel beam

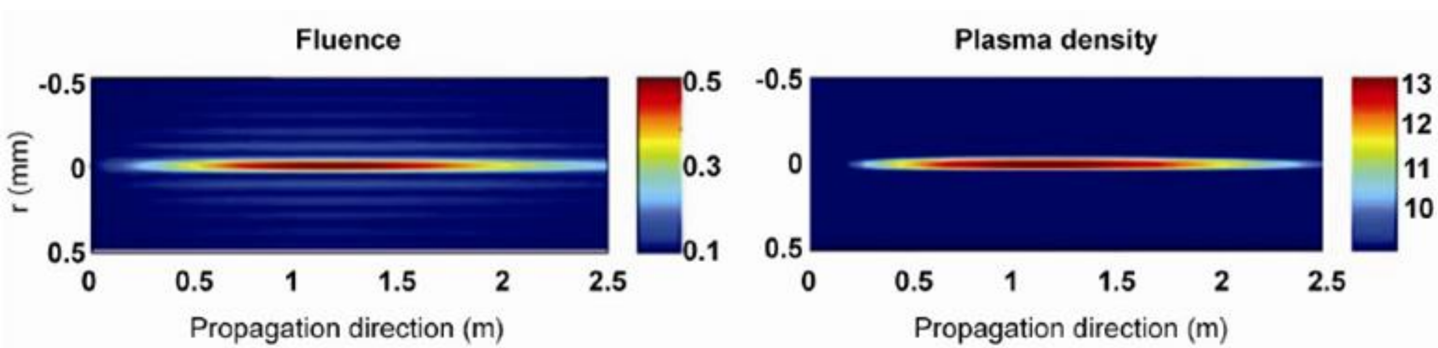




Conical-flow energy inwards the central lobe of the beam



Bessel beam can be seen as a superposition of plane waves distributed over a cone

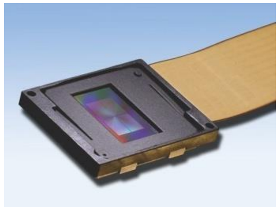


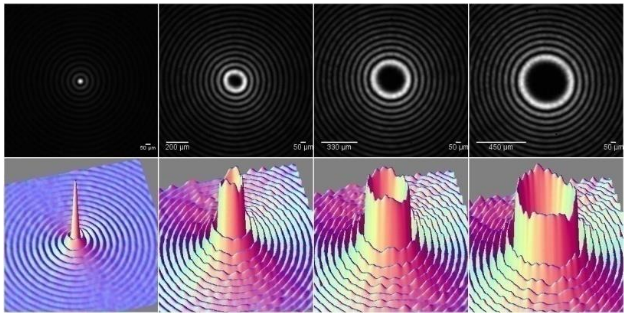
PRA 77, 043814 (2008)

In transparent materials the plasma track generated by the Bessel lobe is the main support for the nonlinear absorption of laser energy → high aspect-ratio material modification

Applications of Bessel beams to laser machining

The spatial light modulator (SLM): Versatile device for BB generation of any orders and features

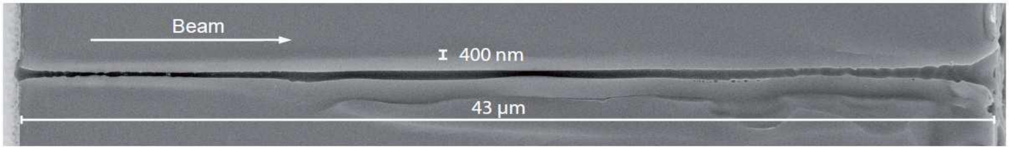




High order Bessels have additional azimutal phase

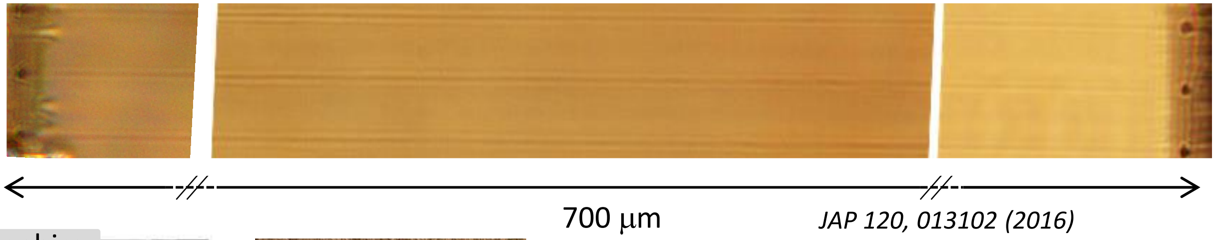
APPLICATIONS

Void nanochannels for nanofluidics



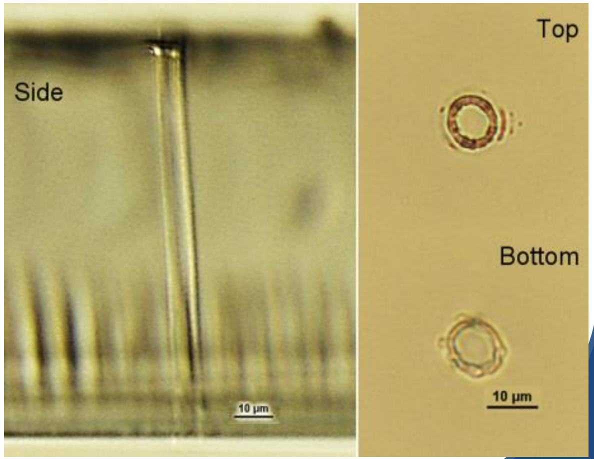
APL 97, 081102 (2010)
EJPD ST 199, 101 (2011)

Single shot high aspect ratio guiding microstructures

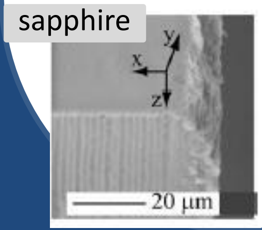


JAP 120, 013102 (2016)

Tubular microstructures



Appl. Phys. A 120, 385 (2015)



Fast single pass cutting

Appl. Phys. A 120, 443 (2015)
PATENT PCT/EP2013/003508

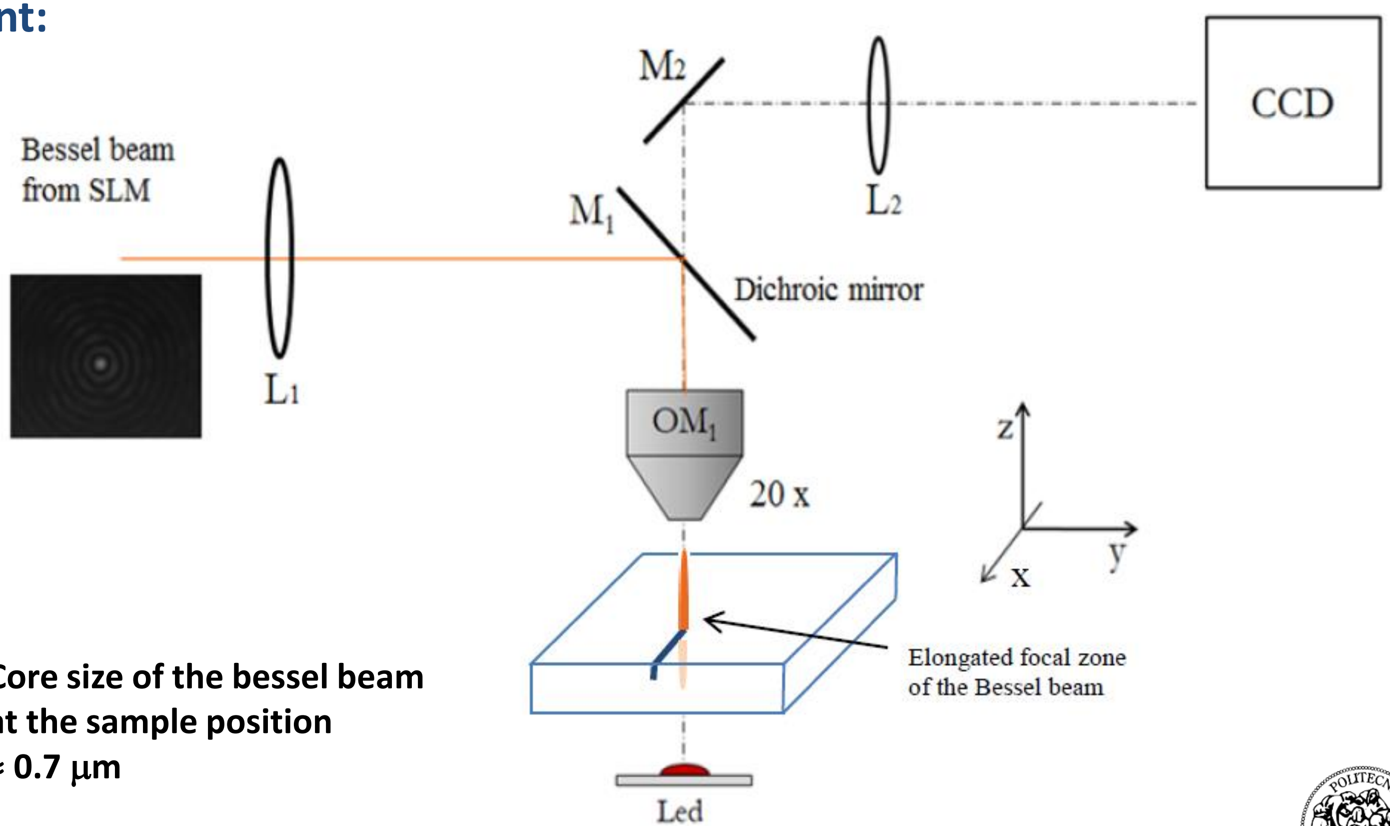
Surface machining of diamond

Why diamond ?: Highest thermal conductivity, high mechanical hardness, wide bandgap, very good optical properties as well as chemical resistance, high level biocompatibility

Idea: To exploit the long focal length of the Bessel beam to obtain high aspect ratio ablated microstructures

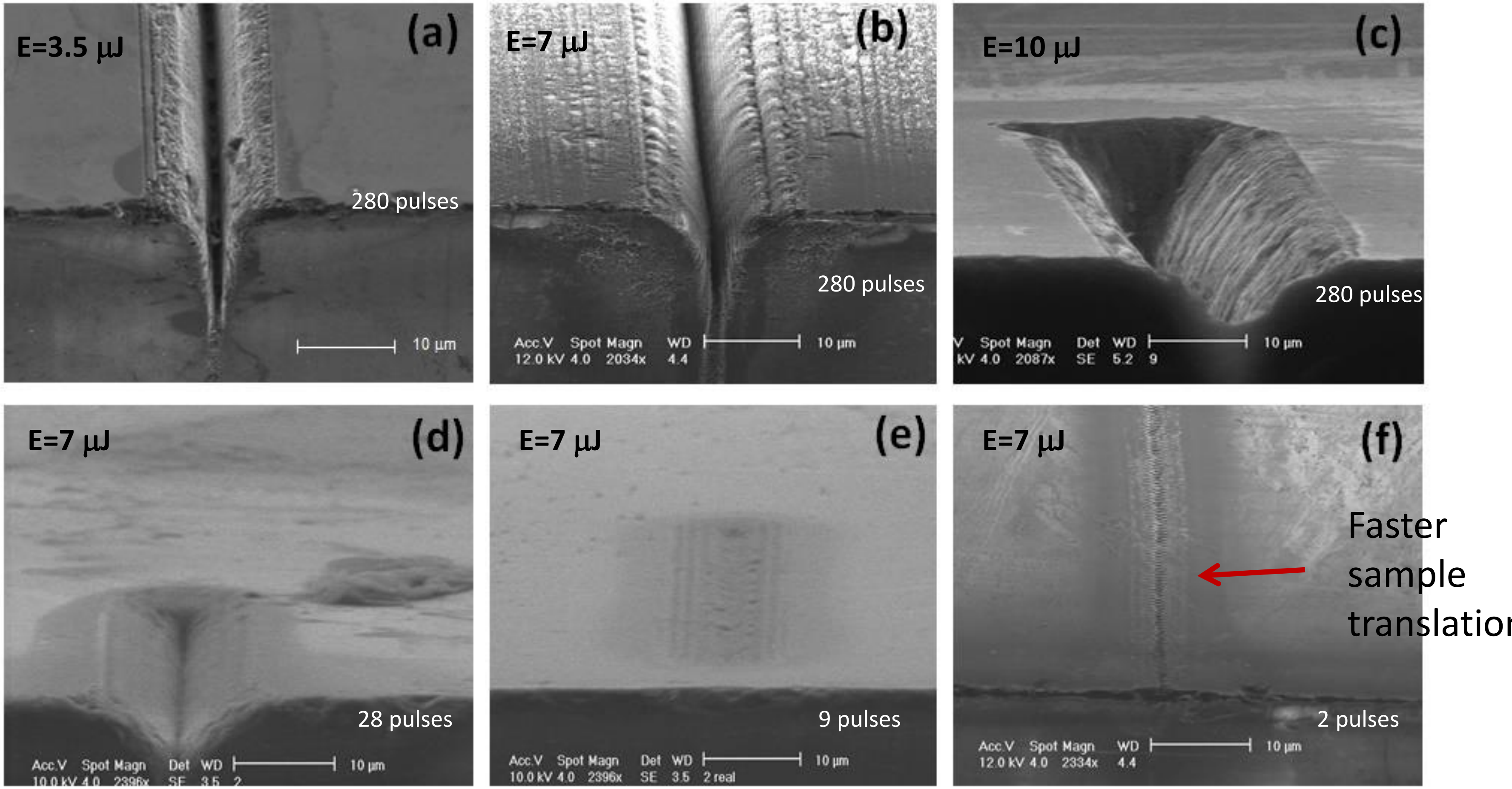
The experiment:

Ti:Sapphire laser
200 fs pulses
λ=800 nm



Core size of the bessel beam at the sample position ≈ 0.7 μm

SEM images of surface microtracks



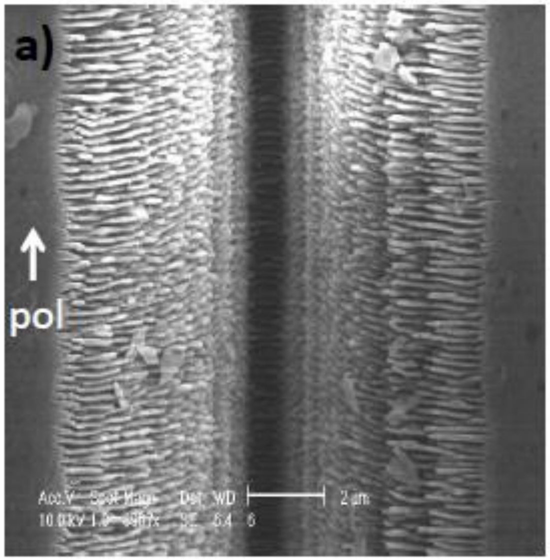
➡ High aspect-ratio tracks featured by a deeper central trench "digged" by the BB central core during the nonlinear absorption process.

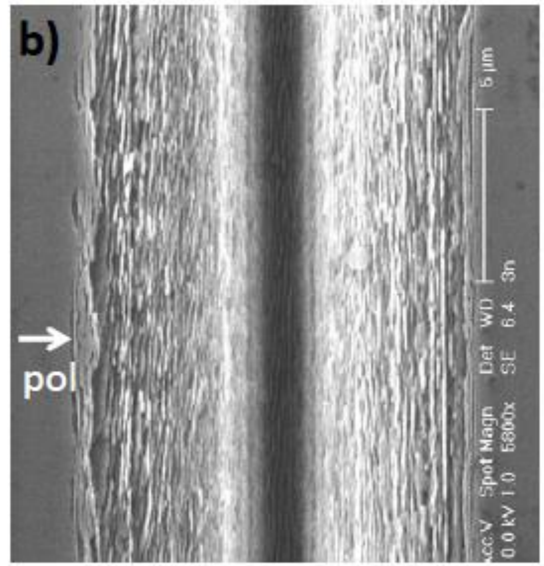
Depth dictated by writing speed – Width dictated by energy

➡ If energy is too high a strong nonlinear absorption of the whole beam (core + rings) occurs

Evidence of microchannels

E=3.5 μJ





Presence of an homogeneous **microchannel** of about 1.5 μm width, at the very center in depth of the 3D V-shaped trench.

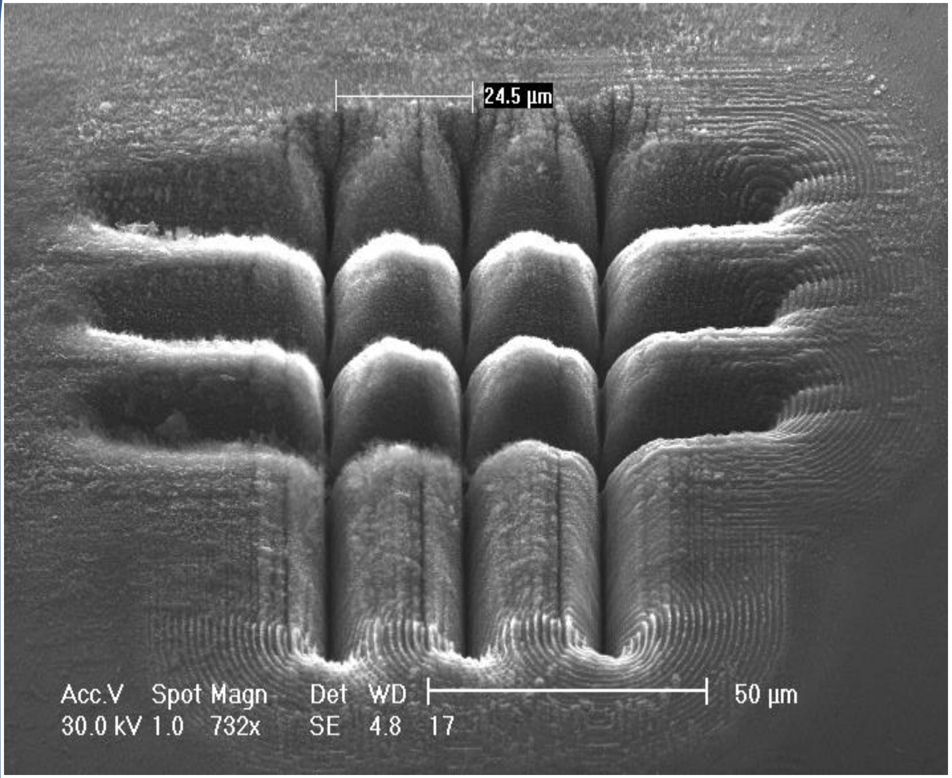
Nanogrooves orthogonal to laser polarizations with a periodicity of the order of $\lambda/2n$ attributed to the interaction between the laser pulse and a laser-induced plasma

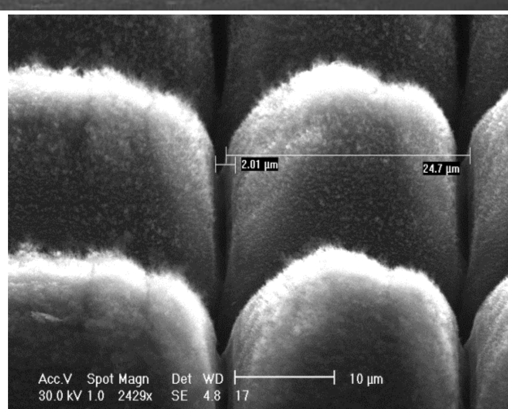
Roughness highest at the side walls of the trenches

Depth of nanogrooves from AFM ~**150-200 nm**

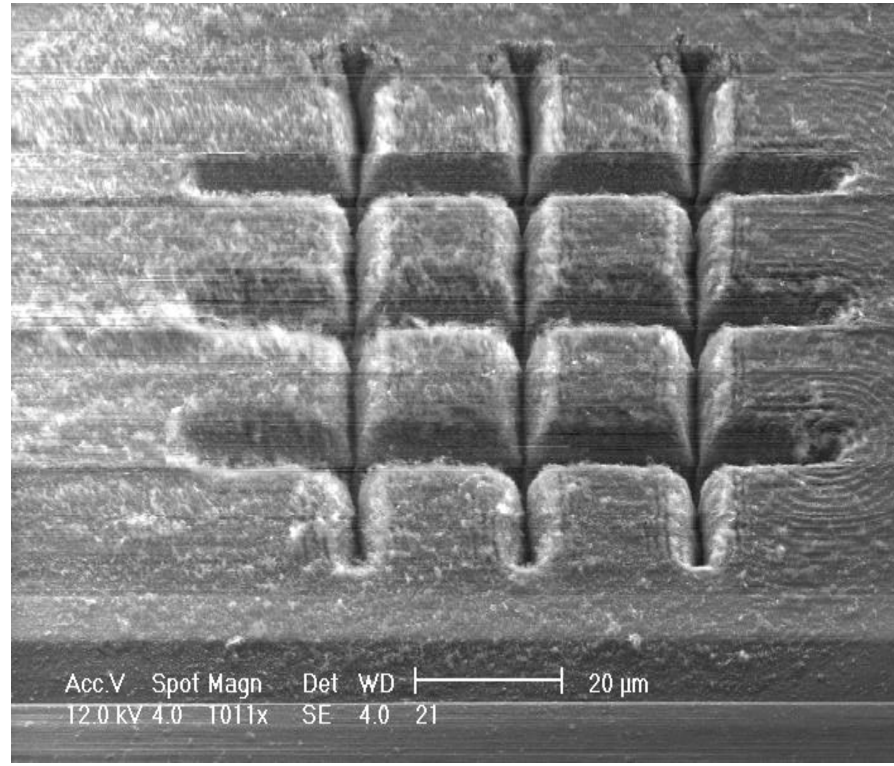
MICROPILLARS

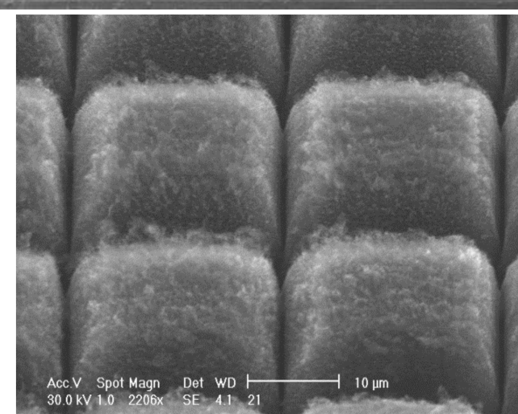
3.5μJ, 200fs





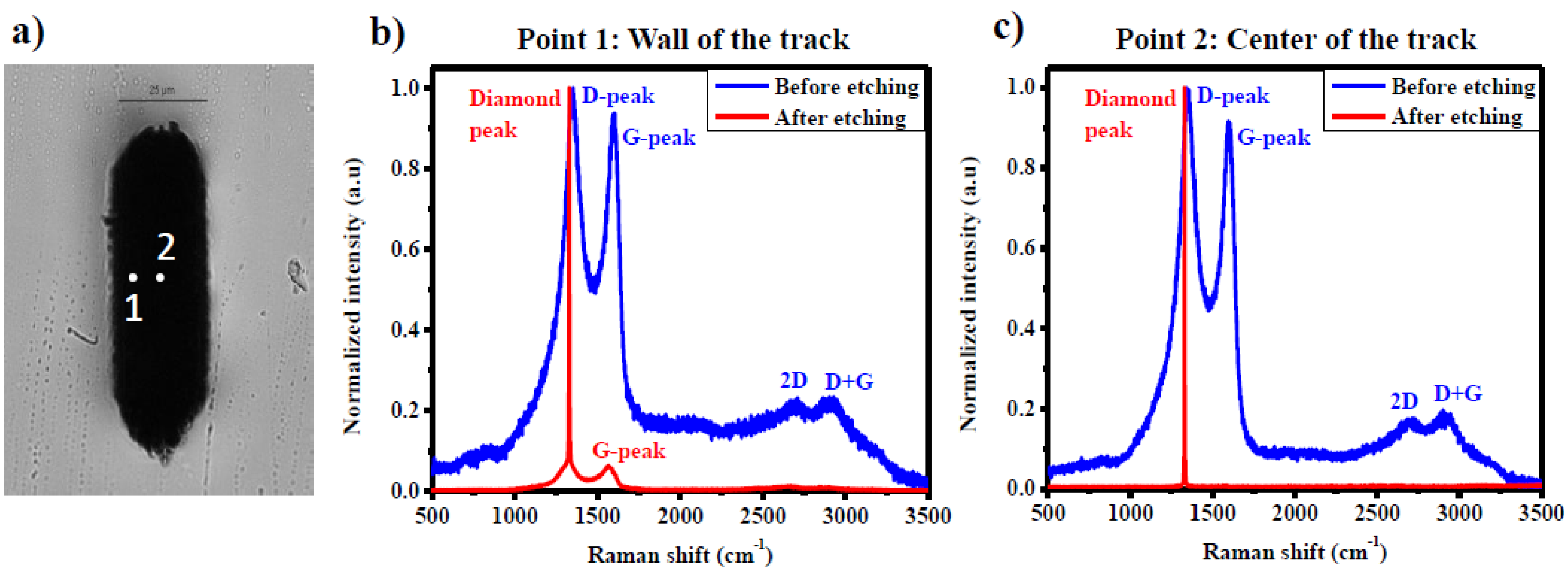
5μJ, 1ps





Micro-Raman spectroscopy

Show the formation of graphitic-like phase on the tracks after the laser irradiation



- G-peak at 1598 cm^{-1} and D-peak at 1351 cm^{-1} typical of nanocrystalline and amorphous carbon

Here nanocrystalline graphite

- Second-order Raman peaks (at 2700 (2D peak) and 2900 (D+G peak)) is also indicative of ordering of the graphitic-like phase

→ The graphitic-like layer turns out to be almost completely removed after the chemical etching

Conclusions

- Possibility to **create microstructure/microtrenches on monocrystalline diamond** by laser transverse writing **in single pass** using femtosecond micron-sized Bessel beams

- Possibility to **tailor the cross section of the trenches** that can be generated (with arbitrary length) at the diamond surface

→ fabrication of ad hoc **smooth and deep microfluidic channels** potentially useful for microfluidics applications, biosensing or analytical tasks, depending for instance on the size of the cells and biomolecules to be detected.

- Possibility to **write in a controlled way nanometer-sized substructures** inside the trenches of a microfluidic chip: added value especially for biosensing applications

⇩

Based on their biomechanical properties, cells to be isolated often present a different adhesion to particular nanorough surfaces, or nanogrooves orientation.

O. Jedrkiewicz et al. Opt. Mat. Express **7**, 290408 (2017)