Generation of high-aspect ratio, dense nano-plasmas in solid dielectrics with femtosecond Bessel beams

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Transparent materials such as glass and sapphire are ubiquitous in modern technology. They are used for consumer electronics, substrates for microsystems, microchips, and encapsulation. However, most of the intended uses require deep drilling, which is extremely demanding for lithography. In this framework, ultrafast laser pulses are ideal since they allow materials to be processed in 3 dimensions from the material's bulk. In this context, Bessel beams provide novel opportunities for laser processing of transparent materials at an extremely high aspect ratio.

Bessel beams are generated from a circularly-symmetric interference of an infinite set of plane waves. The beam profile is quasi-propagation-invariant and defines a very high aspect ratio focal zone. Our group demonstrated in 2010 the formation of high aspect ratio (hundred: 1) nanochannels in glass with a single femtosecond laser pulse shaped as a Bessel beam [1].

High aspect ratio channels extending over the entire thickness of glass are a substantial benefit in the framework of the stealth-dicing technology: a series of nanochannels can be generated at high speed. In a second step, mechanical, thermal, or chemical stresses trigger a fracture along the modification plane. The uniformity of the channels generated via Bessel beams in glass makes it possible to cut glass with sub-mm thickness at speeds reaching 1 m/s. We extended this approach to cut 1 cm thick glass [2].

To further increase the efficiency and resolution of nanochannel formation, we used two-pulse illumination with delays in the sub-ns regime. We demonstrated the possibility of opening voids with only 100 nm diameter [3]. The analysis of the relative absorption of the pulses reveals that the first pulse already transforms the material into warm dense matter, which is a highly absorbing state in fused silica. This state confines energy deposition down to extreme transverse scales, well below the diffraction limit.

Remarkably, the Bessel beam, focused with a moderate numerical aperture of 0.4 can generate such extreme material states. We have investigated the formation of plasma using advanced simulation codes, including particle-in-cell. A combination of different diagnostics is comparable to experimental results. Our simulations reveal that the plasma generated within the pulse is of extremely small diameter and over-critical density. We identified several processes that are specifically linked to the use of Bessel beams.

In conclusion, ultrafast pulses shaped as Bessel beams correspond to ideal conditions to generate dense plasmas within solids, create extreme states of matter, and develop innovative technological means to process materials.

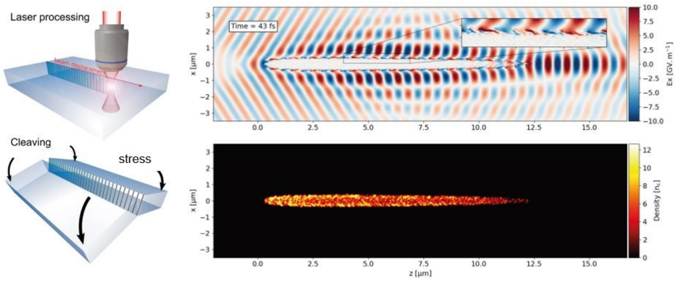

Fig 1: (left) Concept of the stealth dicing technology. (right) Numerical simulation of nanoplasma generation: electric field (top) and plasma density (bottom).

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