Ultrafast diffraction-free beams for high-aspect ratio laser materials processing

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Abstract: Nondiffracting beams have brought exciting opportunities to control ultrafast laser processing of transparent materials. This tutorial will review the basics of non-diffracting beams, their applications and recently discovered fundamental mechanisms.

1. Introduction

Non-diffracting beams are a particular class of beams that are formed by an interference. If the crossing angle between interfering waves is maintained constant over propagation, the transverse intensity patter remains invariant, *i.e.* diffraction-free. Among those, ultrafast zeroth-order Bessel beams form a cylindrically-symmetric line of focus. As early as in 2010, our group demonstrated that they can be usefully exploited to generate high-aspect ratio nano-voids inside glass [1]. This approach have been decisive to develop stealth-dicing technology for high-speed glass cutting: it consists of forming a line of adjacent nano-voids at speeds up to 1 m/s, define fracture planes to induce glass cleaving. The talk will review the numerous approaches developed by worldwide groups, as well as the extension of this work with accelerating beams. which have a curved trajectory along the propagation and enable curved cutting [2].

2. Modeling of the ultrafast laser-matter interaction

However, the exact sequence leading to void formation with Bessel beams remained hitherto unclear. A key aspect is the energy density effectively deposited during laser-matter interaction. Experimentally-generated nano-plasmas are extremely small, typically between 200 and 400 nm in diameter. We will discuss the different modeling approaches of the Bessel-beam interaction within dielectrics and show their limitations in explaining the experimental diagnostics. We have recently developed a model that successfully overcomes these limitations, based on a kinetic approach for the laser-plasma interaction. This reveals that resonance absorption is one of the key physical phenomena that lead to the exceptionally high energy density deposited [3].

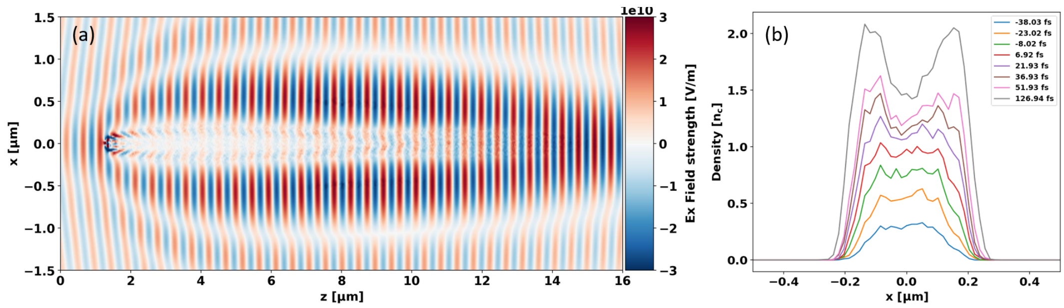

Fig. 1. (a) Particle-In-Cell simulation of the E_x field of a 100 fs Bessel pulse at 25 fs after its peak. (b) Plasma density evolution along the transverse x direction.

We used Particle-In-Cell simulations to model Bessel beam interaction with sapphire, achieving excellent agreement with experimental diagnostics: high absorption (50%), Bessel lobe shifts, plasma ellipticity, and second-harmonic generation. The simulations solve Maxwell's equations alongside particle trajectories, and we incorporated refraction index and Keldysh-based ionization models [5]. Figure 1(a) shows the electric field within the Bessel beam's central lobe 50 fs post-peak. Plasma formation repels the laser outward, shifting Bessel lobes.

Figure 1(b) shows an important result: the femtosecond Bessel beam has generated an over-critical plasma early during the pulse, leading to resonance absorption. This phenomenon efficiently converts the pulse into plasma waves at the critical surface. Localized field amplification and electron excitation by Landau damping enhance the plasma density. Our Particle-In-Cell simulations capture the physical effects due to non-Maxwellian electron distribution, such as the Landau effect, which was not possible with previous state-of-the-art simulations.

3. Nano-pillar generation in single shot

The extreme localization of femtosecond Bessel-beam generated plasma has been further exploited using radially-polarized first-order Bessel beams. They generate empty cylindrical plasmas (Fig. 2[left]). Figure 2 (right) shows the result of the single-shot interaction with sapphire exit surface: a vertically standing, high aspect ratio, nano-pillar has emerged from the sapphire sample. We have confirmed the different regimes of the process of laser-induced extrusion using Transmission Electron Microscopy, demonstrating that the nano-pillar is a mono-crystal. At low fluences, the plasma layer is so thin that the nano-pillar reaches the surface without phase change.

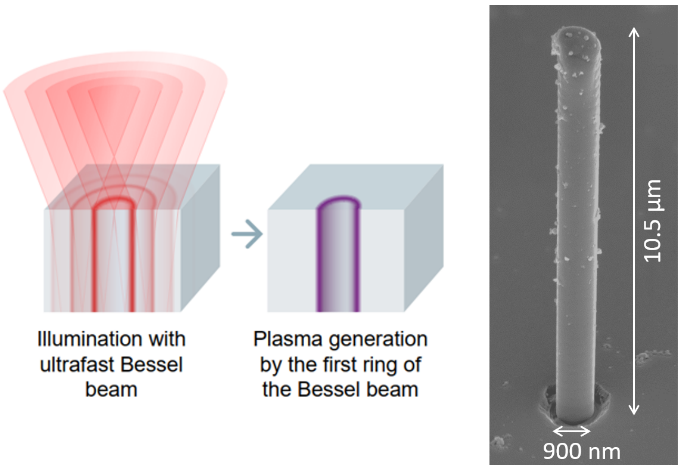

Fig. 2. (left) Cylindrical plasma formation concept. (right) Scanning Electron Microscopy image of a nano-pillar generated via laser-induced extrusion [4].

4. Conclusion

Ultrafast non-diffracting beams have enabled a number of new applications. This is because they are in ideal conditions to trigger extremely efficient energy deposition inside The high degree of confinement of plasmas generated by femtosecond high-angle Bessel beams is due to resonance absorption, which is an efficient collisionless mechanism, accounting for most of the absorption. The resulting energy density is enough to open voids inside dielectrics. Similar conditions are found for first order, radially polarized Bessel beams where a novel mechanism of laser-induced extrusion has just been discovered and is expected to lead to a number of new applications across photonics, phononics or material science.

References

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