# Advanced Beam Shaping for Ultrafast Laser Materials Processing

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The relentless pursuit of novel materials and nano-structures to cater to the needs of next-generation technologies necessitates innovative processing strategies to overcome current limitations. To this end, the use of complex and structured light, modulated in phase, amplitude, and polarization, has emerged as a promising approach to control laser-matter interactions. The unique capabilities of ultrafast laser pulses in generating extreme states of matter at nanometric scales are further enhanced through the shaping of ultrafast laser pulses, thereby creating new avenues for material processing. Here, we will present recent findings highlighting three distinct areas where advanced beam shaping techniques enable access to novel regimes of laser-matter interactions.

Firstly, we will focus on the manipulation of the polarization states of a Bessel beam along its propagation path. By employing laser-produced spatially-variant waveplates, we successfully generated ultrafast Bessel beams exhibiting a polarization rotation up to 90° over the beam length. This approach enabled us to demonstrate laser-written nano gratings with chiral activity [1]. The acquired knowledge in this area will serve as a foundation for designing new optically active optical components and flat optics.

Secondly, we will present the latest results concerning the single-shot production of vertically-standing nanopillars using higher-order Bessel beams of very high angles [2]. These advancements in nanopillar fabrication contribute to the development of new high aspect ratio nanostructures. It opens a new pathway for generating positive nano-structures from materials bulk. The ease of fabrication and single-shot regime opens a number of potential applications for photonics, metamaterial or phononics components.

Lastly, we will address the ablation process in the GHz regime. The extremely high repetition rate of this regime allows for a very efficient vaporization of materials. But the areas irradiated by the laser that are below the vaporization threshold leads to excessive burr. It originates from the melting around the ablation crater, adversely affecting the process quality. To overcome this limitation, we demonstrate the effectiveness of high-precision flat-top beam shaping in reducing the amount of molten material and achieving quasi-perfect ablation of silicon with very high ablation rate.

In conclusion, our findings showcase the significance of advanced beam shaping techniques for ultrafast laser materials processing, offering innovative solutions to challenges posed by traditional processing methods. These developments hold immense promise for ushering in new materials and nanostructures, facilitating the realization of cutting-edge technologies.

[1] Jiafeng Lu, Mostafa Hassan, François Courvoisier, Enrique Garcia-Caurel, François Brisset, Razvigor Ossikovski, Xianglong Zeng, Bertrand Poumellec, Matthieu Lancry; "3D structured Bessel beam polarization and its application to imprint chiral optical properties in silica" APL Photonics 8 (6): 060801 (2023) https://doi.org/10.1063/5.0140843
[2] Valeria V Belloni, Luc Froehly, Cyril Billet, Luca Furfaro, Francois Courvoisier, "Generation of extremely high-angle Bessel beams" Applied Optics 62,1765-1768 (2023).