Ultrafast laser-induced extrusion in sapphire

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Ultrafast near-infrared laser pulses excel at generating localized and intense material transformations via nonlinear processes such as multiphoton ionization. Tailoring laser pulses, in space, time or polarization offers significant advantages to control light-matter interaction. Most applications of ultrafast laser pulses were hitherto related to ablative processes, removing material or modifying the bulk.

We will present a drastically novel femtosecond laser-induced phenomenon that is neither ablative or subtractive. We have discovered a process where positive structures are generated atop a sample by translating the matter over several micrometers using a single laser pulse, as reported in [1].
The key to this process is inducing a nanometrically-thin liquid layer in the shape of a cylinder inside sapphire, effectively cutting out a nano-rod with a 100 fs laser pulse shaped into a radially polarized zero-order Bessel beam, which features an elongated, hollow cylindrical focus. The pressure gradients generated are capable of pushing the material out, forming 800-nm diameter nano-pillar-shaped positive structures with a height of several micrometers on the surface.

We have identified 3 different regimes which were deeptly investigated using Transmission Electron Microscopy (TEM) to provide insights into the effective generation processes. Strikingly, all structures are mono-crystals. The actual generation processes range from material translation without phase change to a jet of liquid undergoing capillary instabilities before resolidification, resulting in a final wavy shape up to 15 µm in height.

From a fundamental perspective, our research shows that ultrafast laser pulses can create extreme temperatures on scales as small as 50 nm. On the applications side, our processing method offers a rapid approach to producing nanostructures with applications in areas such as metamaterials, photonics, phononics, and mechanical systems, supported by the demonstrated capability to create matrices of nano-pillars.

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[1] V. V. Belloni, et al., Laser Photonics Rev, **18**, 2300687 (2024)