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Wavelength Influence on Precision Femtosecond Laser Processing

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High-peak power compact femtosecond lasers allow strong-field interactions that are the basis for high-precision laser processing. However, such lasers are typically operated in a very narrow spectral (515 nm – 1030 nm). In this work, we present a comprehensive study on modifications in dielectrics (fused silica and sapphire) and semiconductors (silicon) induced by femtosecond pulses (< 200 fs) covering a spectral range from 258 nm to 4000 nm. The determination of the wavelength-dependent fluence modification thresholds (ablation and amorphization) and 3D modification topographies allow to discuss the effect of drastically changing nonlinear ionization responses. It also serves to fully evaluate the potential of the wavelength as control parameter to improve machining performances, including resolution and precision.

In the first part, we explore the influence of the laser wavelength on spatial resolution. We demonstrate that the concept of nonlinear resolution, highly exploited in multiphoton microscopy, is not applicable for femtosecond laser ablation. Independently of the nonlinearity of interaction, we find a systematic one-to-one mapping between femtosecond laser ablation features and beam contours at a strict threshold-intensity [1], as shown in Figure 1. This is because the physical mechanism of ablation is a threshold-based response, which prevents all potential benefits in terms of resolution that could be expected from the nonlinear confinement of absorption. An important consequence of this strict threshold response is the possibility to derive the processing repeatability by accounting for pulse-to-pulse energy fluctuations. We present a simple and general model for aprioristic evaluation of machining repeatability, experimentally validated by generating reproducible features as small as 1/10 of the diffraction-limited spot size with a stable 200-fs laser source [2]. Additionally, here we propose a very simple extra-cavity method for laser stabilization and improved processing performances. It is based on passive propagation through nonlinearly absorbing materials leading a scheme that can be implemented in most material processing configurations [3].

Secondly, we explore the influence of laser wavelength on topographic and structural changes. In dielectrics, we observe that the quality of the processed regions (debris ejection and formation of rims) is independent of the laser wavelength and is only affected by the material properties. Also, this study reveals deeper drilling in the infrared range but limited to conditions close to the fluence threshold (Figure 2 (a)). At high fluences, a comparable crater saturation depth is found for all tested wavelengths. In crystalline silicon, we experimentally explore strategies to increase the thickness of the laser-induced amorphous layer, aimed at applications for surface waveguide writing on silicon. Our results show that with infrared pulses, amorphous layers with thickness larger than the previously reported upper limit of 70 nm can be achieved (c.f. Fig. 2(b)-(c)). Moreover, multiple pulse irradiation and the use of a SiO2 cover layer were found to be beneficial for the formation of thick amorphous layers [4]. Form these optimizations, the maximum obtained thickness reaches >120 nm making a critical step towards the requirement for laser direct writing of silicon photonic circuits [5].

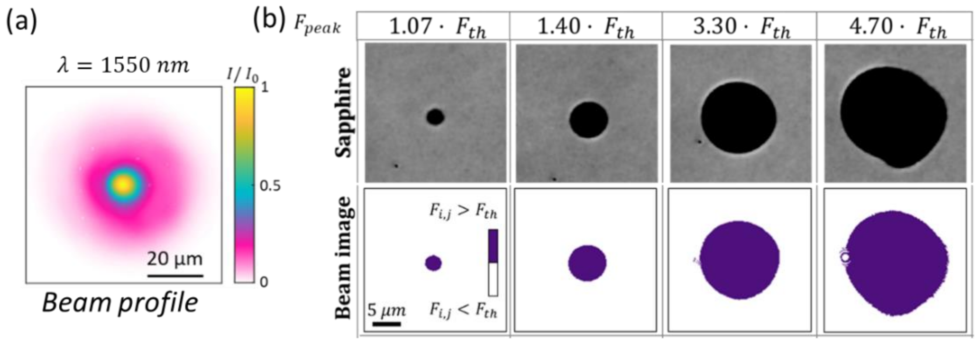

Figure 1: Comparison between laser beam profiles at the sample surface and corresponding crater shapes for a 1550-nm single femtosecond laser pulse. (a) Beam image produced at the focal position after directly focusing a 1550-nm laser beam. (b) (Top) Confocal microscopy images of the surface modifications on sapphire at the indicated excitation level. (Bottom) Beam portion above the ablation fluence threshold at the indicated excitation level. Pixels having values above the fluence threshold are represented in color and pixels below the threshold in white.

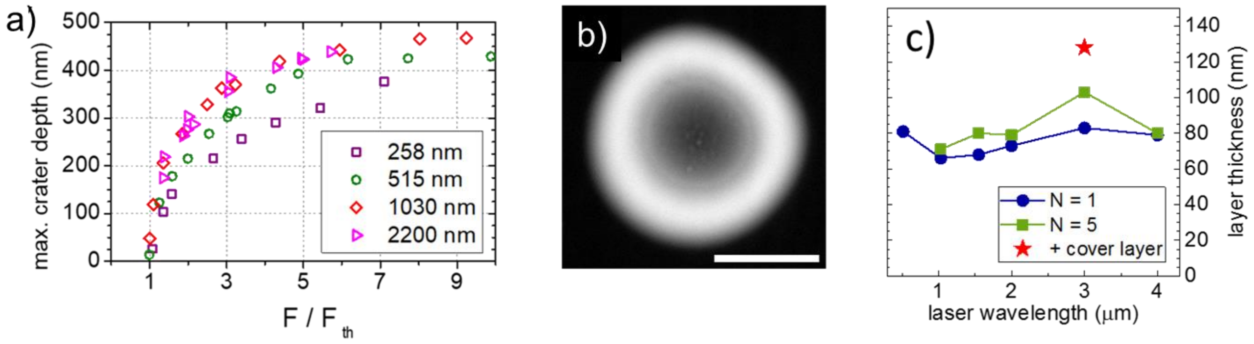

Figure 2: (a) (c) Maximum crater depth produced in fused silica upon single-pulse irradiation at different excitation levels above the fluence threshold for ablation. (b) Optical microscopy image of an amorphous spot in crystalline silicon, formed upon exposure to a single laser pulse at λ = 3000 m. The bright ring and darkening in the spot center is not caused by sample damage but a consequence of interference of the illumination light reflected at the two interfaces of the amorphous surface layer. The experimental reflectivity analysis indicates a thickness of 80 nm (lateral scale bar 10 µm). (c) Maximum thickness values of the laser induced amorphous layer as a function of laser wavelength, for single pulse (N = 1) and multiple pulse (N = 5) irradiation. The red symbol marks the maximum thickness achieved by using the presence of a silicon dioxide cover layer.

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