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Precision and controllability of ultrafast laser processing over the spectrum

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High-peak power compact femtosecond lasers allow strong-field interactions that are the basis for high-precision laser processing. However, a relatively narrow region of the spectrum remains exploited today in this field. We study femtosecond laser interactions in various bandgap materials at non-conventional driving wavelengths up to the mid-infrared part of the spectrum.

The range of nonlinear responses accessible by radiation tuning allows revisiting questions as important as the achievable precision in surface machining technologies. In particular, we establish that the concept of nonlinear resolution 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 in dielectrics and beam contours at a strict threshold-intensity [1]. This is because any observable based on a threshold-based response (as ablation) simply ruins all potential benefits that could be expected on resolution from the nonlinear confinement of absorption. Another important consequence is that the achievable precision and repeatability can be directly derived from the level of determinism of the interaction. By comparing the results of a simple 'noise' model accounting for laser fluctuations and statistical analyses of ablation experiments, we quantify the degradation of the machining repeatability with increased pulse duration [2]. In this way, we assess the precision limits in laser machining. Overall, these works indicate that stable UV sources must provide a direct route to reach the nanoscale resolutions routinely achieved in lithography.

At the opposite side of the spectrum, ultrashort infrared laser pulses open for internal structuring of semiconductor materials that are extremely challenging to process in the three dimensions (3D writing). Our first proposed solution used hyper-focused beams to demonstrate permanent modifications in the bulk of silicon with sub-100-fs pulses [3]. For more practical alternatives, we rely today on optimizations in the time domain. We investigate the picosecond regime limiting the nonlinearities and improving the process reliability by provoking progressive thermal band gap closure to assist pulse energy deposition [4,5]. Another approach is to rely on transient accumulation strategies. To this aim, we generate and apply ultrafast trains of pulses at up to Terahertz repetition-rates [6]. An important aspect also addressed by our experiments is the unusually high sensitivity of 3D writing in semiconductors to the temporal contrast of the pulses [7]. This causes laser-technology dependent results and represents an important finding for a comprehensive reading of the literature on this topic. Taken these approaches together, we introduce unique multi-timescale control parameters exploited for improved energy coupling and for demonstrations of reliable 3D laser writing deep inside silicon chips that would not be possible otherwise.

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