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Energy stability limits of precision in ultrafast laser material processing

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In laser manufacturing, precision is a key aspect when aiming at small and controllable modifications for specific applications. The size and characteristics of the produced features are defined by the delivered spatio-temporal energy distribution to the material. This makes the achievable stability and controllability of the laser conditions a critical technological question. By experiments, we study the importance of this limit and explore laser stabilization schemes to improve material processing performances.

In recent work, we established that the concept of nonlinear resolution is not applicable for femtosecond laser ablation. Consequently, there is a systematic one-to-one mapping between produced ablation features in dielectrics and beam contours at a strict threshold intensity [1]. Here we show that the same conclusion holds also for silicon surface amorphization with 200-fs pulses. This confirms an observable based on a deterministic threshold-based response and a resolution problem that is totally independent of the nonlinear confinement of absorption [1].

An important consequence of this strict threshold response is the possibility to derive the processing repeatability by using a simple ‘noise’ model to account for pulse-to-pulse energy fluctuations [2]. By simulating laser fluctuations in an experiment, we demonstrate the validity of the model to describe the repeatability of the produced amorphization features. In this way, we can assess the practical precision limits specific to our experiment and the stability performance of our laser.

From this, we explore concepts to exceed this limit. There are various methods to improve laser stability including dynamically controlled Pockels cell [3] or Kerr interactions [4]. Here, we propose a very simple extra-cavity method based on passive propagation through nonlinearly absorbing materials [5,6]. Using our 200-fs pulses, we measure nonlinear absorption in dielectrics (incl. Al₂O₃ and SiO₂) with band gaps from about 3 eV to 10 eV. We compare the measurements to a stabilization model assuming pure multiphoton absorption. The results show that all materials are not equally performing as some materials introduce important beam distortions depending on the required laser power for absorption. By optimized engineering of the experimental arrangement, we demonstrate how the achievable reduction of pulse-to-pulse energy fluctuation translates into an improvement of the repeatability and resolution in material processing.

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