

# Ultrafast laser writing stabilized by nonlinear absorption

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The concept of nonlinear resolution exploited in optical microscopy does not directly translate in ultrafast material processing since the size of the produced modifications is primarily defined by an incoming fluence threshold independently on nonlinear energy deposition [1]. This leads to feature geometries corresponding to the beam contour at this threshold condition. Such description holds for processes like ablation or structural modification. Accordingly, high-resolution patterns can be achieved when working with very tightly focused beams at peak fluence close to these conditions. However, supported by a noise model and ablation experiments we described how the process becomes increasingly unreliable due to pulse-to-pulse energy fluctuations as we approach the fluence threshold. This quantifies the inherent contradiction between precision and reproducibility in such a configuration [2].

Varying the level of laser energy fluctuations in our experiment, we demonstrate in this work the validity of the noise model to describe the production of amorphous spots on crystalline Si with single femtosecond pulses. In this way, we can precisely assess the precision limits imposed by the laser stability performance. To surpass this limit there are several methods to reduce pulse-to-pulse energy fluctuations. These include dynamically controlled Pockels cells [3] or Kerr interactions [4]. Alternatively, we propose a more straightforward passive extra-cavity approach based on high-order nonlinear absorption of the beam through transparent materials [5]. We show this simple configuration can be accounted in the model and results in a reduction of the feature size fluctuations through energy stabilization.

In this regard, we first study the stabilization response of several materials (including ZnSe, Si, or sapphire) to our femtosecond laser source (1030nm, <200fs). The best compromise between absorption and stabilization is found for a ZnS crystal, proving a reduction of laser fluctuations of 1/5. Then, using an incoming laser fluctuation of 2% (SD, Gaussian noise), we demonstrate an enhanced feature repeatability and writing performance at near-threshold conditions that are unachievable without stabilization [6]. In particular, the method allows reliable writing at energies just 1% above the threshold. The feature size obtained with large beams at these conditions is one tenth of the beam spot, which should directly translate in stable features of around 10 nm with tightly focused beams. In this regard, the implementation of our simple scheme holds potential for contributions in the most demanding precision manufacturing applications. These today remain addressed by extreme UV lithography and/or focused ion beam and likely represent the next challenge of ultrafast laser processing.

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