

Pulse energy stabilization to enhance precision of ultrafast laser material processing

P. Sopena¹, M. Garcia-Lechuga^{2,3}, A. Wang¹, D. Grojo¹

1- LP3 (UMR 7341), CNRS, Aix-Marseille University, 163 Av. de Luminy, 13009, Marseille, France

2- Departamento de Física Aplicada, Universidad Autónoma de Madrid, 28049, Madrid, Spain

3- Centro de Microanálisis de Materiales, Universidad Autónoma de Madrid, 28049, Madrid, Spain

Main author email address: pol.sopena-martinez@univ-amu.fr

The concept of nonlinear resolution exploited in optical microscopy does not directly translate in ultrafast material processing. This is because the size and shape of the produced modifications are based on a threshold response so that the features perfectly map the beam contour at a fixed fluence independently of the nonlinearity of energy deposition [1]. Accordingly, one can obtain high-resolution patterns by threshold-based processes like ablation or structural change when working with very tightly focused beams at peak fluence close to threshold conditions. However, a drawback is a process reproducibility that becomes inherently highly sensitive to pulse-to-pulse energy fluctuations of the used laser sources. Supported by a noise model, we described and observed the asymptotic increase of the feature size fluctuation as we approach the fluence threshold. This trend clearly shows the contradiction existing between precision and reproducibility when aiming at high-resolution processing [2].

By controlling the level of laser fluctuations in an experiment, we demonstrate in this work the validity of the noise model by producing amorphous spots on crystalline Si with single femtosecond pulses. In this way, we can precisely assess the precision limits specific to our experiment and the stability performance of our laser. To exceed this limit and improve the pulse-to-pulse energy fluctuations there are several methods such as dynamically controlled Pockels cells [3] or Kerr interactions [4]. Alternatively, we propose a less intricate passive extra-cavity approach based on high-order nonlinear absorption of the beam through transparent dielectrics [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 dielectrics, such as ZnTe or sapphire, to our near-IR <200 fs laser source. We achieve the best compromise between absorption and stabilization for a ZnS crystal, showing a reduction of laser fluctuations of 1/3 (Fig. 1a). Later, with a laser fluctuation of 2% (SD, Gaussian noise), we demonstrate an improved features repeatability at near-threshold conditions that is unachievable without stabilization. In particular, the method allows reliable writing at energies just 1% above the threshold (Fig. 1b). The feature size obtained with large beams at these conditions is $\omega_0/10$, 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.

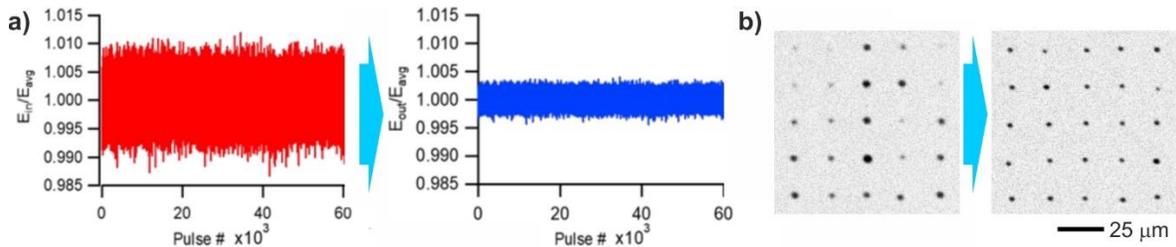


Figure 1. (a) Simulated reduction of pulse-to-pulse energy fluctuations that can be achieved by nonlinear absorption. (b) Example of demonstration of the improved machining repeatability near threshold on Si amorphization taking benefit from energy stabilization.

Acknowledgement: This work is funded by H2020 European Research Council (724480).

- [1] M. García-Lechuga, O. Utéza, N. Sanner and D. Grojo, “Evidencing the nonlinearity independence of resolution in femtosecond laser ablation”, *Opt. Lett.* **45**, 952 (2020).
- [2] M. García-Lechuga, G. Gebrayel El Reaidy, H. Ning, P. Delaporte and D. Grojo, “Assessing the limits of determinism and precision in ultrafast laser ablation”, *Appl. Phys. Lett.* **117**, 171604 (2020).
- [3] T. Oksenhendler, F. Legrand, M. Perdrix, O. Gobert and D. Kaplan, “Femtosecond laser pulse energy self-stabilization”, *Appl. Phys. B* **79**, 933 (2004).
- [4] S. Matsuo, L. Yan, J. Si, T. Tomita and S. Hashimoto, “Reduction of pulse-to-pulse fluctuation in laser pulse energy using the optical Kerr effect”, *Opt. Lett.* **37**, 1646 (2012).
- [5] R. H. Pantell and J. Warszawski, “Laser power stabilization by means of nonlinear absorption”, *Appl. Phys. Lett.* **11**, 213 (1967).