Deciphering the complexity behind laser-induced self-organized nanopatterns

Jean-Philippe Colombier,[1] Eduardo Brandao,[1] Anthony Nakhoul,[1,2] F. Ali Banna,[1] Rémi Emonet,[1,3] Amaury Habrard,[1,3] François Jacquenet,[1] Florence Garrelie,[1] Marc Sebban[1]

[1] Université Jean Monnet, CNRS, Institut d'Optique Graduate School, Laboratoire Hubert Curien, Saint-Etienne, France
[2] Univ Lyon, Mines Saint-Etienne, CNRS, Centre SMS, Laboratoire Georges Friedel, UMR5307, F-42023 St-Etienne, France
[3] Institut Universitaire de France (IUF), Paris, France
*Corresponding author email: jean.philippe.colombier@univ-st-etienne.fr

When subjected to a series of ultrashort laser pulses, an initially smooth surface undergoes a progressive transformation into dissipative structures, empowering it to regulate energy flux and optimize entropy production rates. This phenomenon manifests as the spontaneous emergence of periodic patterns at various scales, with diverse shapes and varying aspect ratios. Consequently, numerous 2D patterns (stripes, labyrinthines, dots, triangles, hexagonal cavities, etc.) have recently been observed at various scales [1]. The theoretical challenge lies in developing an effective model with symmetry breaking, scale invariance, stochasticity, and nonlinear properties to replicate dissipative structures. Describing pattern growth requires nonlinear dynamics under far-from-equilibrium conditions, for which classical equations (Maxwell, Navier-Stokes, Fourier…) demand unknown transient material properties [2]. We have implemented a stochastic Swift-Hohenberg model that replicates hydrodynamic fluctuations near the convective instability threshold, inherent in laser-induced self-organized nanopatterns at the nanoscale. We will show that a deep convolutional network can learn the complexity of patterns, linking model coefficients to experimental parameters to design specific morphologies [3]. The model accurately predicts patterns, identifying laser parameter regions and potentially anticipating physics complexity evolution.

[1] A. Nakhoul, and J.P. Colombier, "Beyond the Microscale—Advances in Surface Nanopatterning by Laser-Driven Self-Organization", Laser & Photonics Reviews, In press (2024).
[2] A. Rudenko and J.P. Colombier, "How light drives material periodic patterns down to the nanoscale", Ultrafast Laser Nanostructuring: The Pursuit of Extreme Scales, 209-255 (2023).
[3] E. Brandao, A. Nakhoul S. Duffner, R. Emonet, F. Garrelie, A. Habrard, F. Jacquenet, F. Pigeon, M. Sebban. & J.P. Colombier, "Learning complexity to guide light-induced self-organized nanopatterns", Physical Review Letters, 130, 226201 (2023).

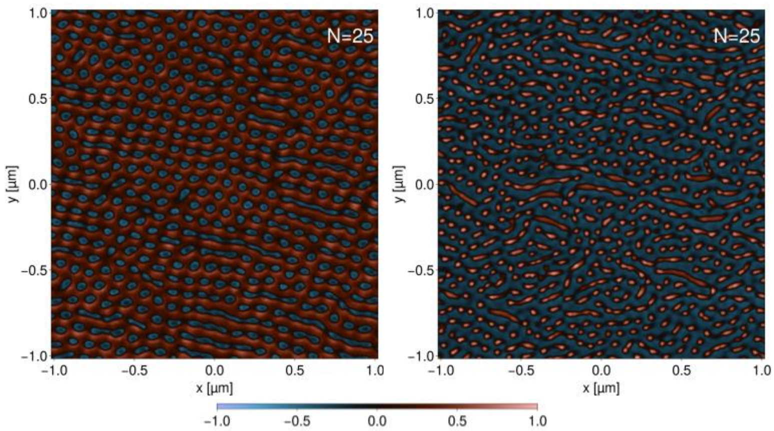

Figure: Examples of SEM images exhibiting the complexity of 2D LIPSS at the nanoscale obtained on irradiated Nickel for delayed double pulses (F = 0.18 J/cm² & Δt = 8 ps [left] and F = 0.26 J/cm² & Δt = 28 ps [right] for a pulse duration of 170 fs at λ = 1030 nm).