Nonlinearity Engineering: From Mode-Locked Lasers to Self-Assembled Nanostructures

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In nature, structure and functionality emerges from competing nonlinear feedback mechanisms subject to stochastic forces. These systems invariably operate far from thermodynamic equilibrium. However, physics of far-from-equilibrium systems are far from being understood. While this is ubiquitous all around us, its intentional use in human technology remains relatively rare. I assert that it is possible to exploit similar dynamics to achieve superior technological functionalities that compliment traditional engineering approach, which I refer to as Nonlinearity Engineering. Laser-material interactions is a particularly fertile platform to develop this approach and this talk will review several successful applications that address well-known and stubborn problems.

I will first discuss passive mode-locking, which constitutes a far-from-equilibrium steady state; both a great source of rich physics, apart from its well recognized technological importance for ultrafast optics.

Then, I will discuss several cases of complex laser-material interaction, each of which relies on a nonlinear and iterative mechanism. The first is Nonlinear Laser Lithography (NLL), which allows femtosecond laser-driven, self-organized structuring of materials (Ilday, et al., Nature Photon., 2013). NLL judiciously exploits positive nonlocal feedback between the material and the laser beam to initiate, and negative local feedback to regulate formation of nanostructures with unprecedented uniformity, at high speed, low cost on non-planar or flexible surfaces. Furthermore, NLL is a great model system for a broad class of self-organizing systems. In that vein, we now show how geometries of self-organized patterns can be controlled by the application of "structured noise".

Recently, we extended NLL to 3D by demonstrating self-organized functional 3D superstructures deep inside silicon chips, demonstrating the first in-chip phase-holograms for arbitrary wavefront control, lenses and gratings for beam steering, multilevel, erasable information storage, embedded microfluidic channels for cooling of microchips, through-Si vias for interconnects, microstructures for MEMS applications, slicing of a wafer into microns-thick plates for low-cost Si photovoltaics, and even arbitrary 3D sculpturing of the entire chip.

Applications of ultrafast laser-material processing are growing rapidly. However, its potential is limited by the low speeds at which material can be removed. Using simply more powerful lasers results in unwanted effects, such as shielding or collateral damage from heat accumulation. We recently managed to circumvent this limitation by exploiting iterative interaction between the pulses and the material to benefit from ablation cooling (Ilday, et al., Nature, 2016): If we send in pulses so rapidly that the heat left by a pulse does not have time to diffuse out of the volume to be ablated by the next pulse in the train, heating of the bulk of the target can be eliminated. We achieved 10-times higher ablation efficiency, while simultaneously reducing the ablation threshold by 1000 times as well as target heating.