Growth of laser-induced surface nanostructures

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Nanostructured damage patterns

Strongly organized laser-induced periodic surface structures (LIPSS) can be fabricated on any type of solid with intense femtosecond laser pulses, near the ablation threshold. LIPSSs allow us to:

- Time material’s optical properties (color, reflectivity, etc.).
- Make a surface super-hydrophilic.
- Study intense light-matter interactions on a femtosecond time scale.

The Sipe-Druce theory can predict the triggering of LIPSSs growth by solving the analytical solutions of Maxwell’s equations for the propagation of an incident plane wave through a random rough surface.

![Fig. 1: Propagation and symmetry breaking of an incident plane wave.](image)

Various LIPSS morphologies can be predicted and fabricated depending on the laser properties (wavelength λ, polarization) and on the material’s optical behavior (dielectric, metallic).

Dielectric behavior

Sipe-Druce theory predicts structures oriented parallel to the incident light polarization for a material with dielectric optical properties (Re(λi) > Im(λi)), where λi is the complex refractive index. The predicted LIPSSs periodicity Λ is equal to λi/Re(λi).

Metallic behavior

For a strongly absorbing material, a metallic behavior (Re(λi) < Im(λi)) structures oriented perpendicular to the incident light polarization are predicted. The predicted LIPSSs periodicity Λ is equal to λi.

![Fig. 2: Analytical solution of the Sipe-Druce theory in the frequency domain for a typical dielectric (silicon, n = 3.5 + 0.001i].](image)

![Fig. 3: Analytical solution of the Sipe-Druce theory in the frequency domain for a typical metal (aluminum, n = 1.8 + 0.9i).](image)

Full wave simulations

The finite-difference time-domain (FDTD) method, while more involved than the Sipe-Druce analytical (but approximate) solution, provides deeper insights. For instance, the simulation results are:

- Available in the spatial domain.
- Available over all the simulation domain and the important bulk region.
- Accurate for high frequency structures.
- Easily extensible to account for other processes (feedback mechanism for instance).

The surface roughness is modelled by a randomly generated binary function over the material surface. Specifically, one random computational cell out of ten is filled with material.

![Fig. 4: Geometry used in the FDTD simulations. Dimensions are indicated in terms of numbers of computational cells.](image)

Constructive & destructive feedback

Self-organization effects can be included with the addition of a feedback mechanism. This is achieved by modifying the surface morphology in the FDTD simulations according to the field spatial distribution before sending another laser pulse. By repeating this process for a number of pulses, the surface morphology and the field distribution gradually build an equilibrium.

Growth on metals

To grow self-organized structures on a material with metallic behavior, the surface modification process has to be ablation-like, meaning that material is removed where the energy is maximum. The energy is maximum under the surface minima, with LIPSSs acting as divergent lenses.

![Fig. 5: Fourier transforms of the average field intensity under the surface. In subfigures (a) to (f), γ/ω = 1 and a transition from a dielectric to a metallic behavior is observed with the densification of the generated plasma.](image)

Growth on dielectrics

An inverse mechanism is used to grow LIPSSs on materials with dielectric behavior. photo-expansion. In this case, material is added where the energy is larger, over the surface maxima acting as convergent lenses in this case.

![Fig. 7: Incident light is mostly directed to red spots. Amplitude growth (constructive feedback) on materials with metallic behavior is achieved by deeper ablation under the surface minima.](image)

Self-organization and growth

An ablation-like feedback mechanism is implemented to grow structures oriented perpendiculare to the light polarization on a material with metallic behavior. Every part of the bulk which receive more light intensity than a certain threshold is removed between each laser pulse.

![Fig. 8: Growth of LIPSSs on a Drude metal with (ωp/ω, γ/ω) = (8, 1) and ablation. Surface morphology is shown for pulse numbers 1, 3, 5, 8.](image)

To grow structures oriented parallel to the light polarization on dielectrics, an expansion-like feedback mechanism is used and implemented with the same threshold method as for ablation, except the surface position modification is applied with an opposite sign.

![Fig. 9: Growth of LIPSSs on a dielectric with (ωp/ω, γ/ω) = (1.7, 1/16) and expansion. Surface morphology is shown for pulse numbers 1, 2, 3, 4.](image)

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References

Full wave simulations and crossed LIPSSs are discussed in:

Derivation of Sipe’s analytical solutions are in:

More on feedback applied to LIPSSs growth: