Femtosecond self-reconfiguration of periodic plasma patterns in dielectrics

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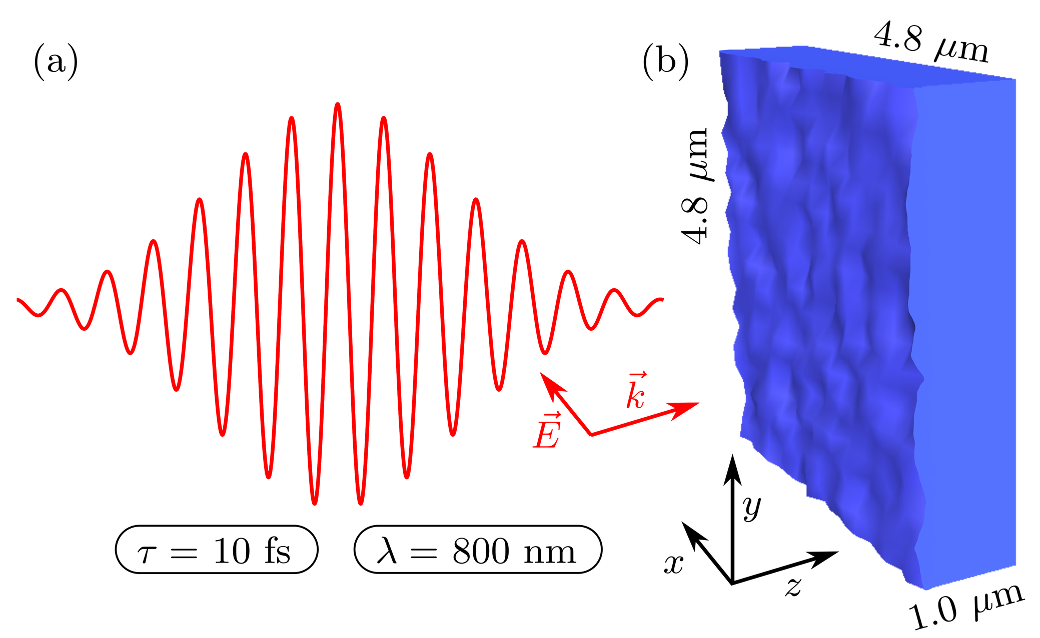
Self-organized nanogratings

Exposition of **solid materials** to **intense laser radiation** typically gives rise to nonlinear light-matter interaction processes. These **nonlinearities** are often associated with **instabilities** that lead to the formation of **self-organized periodic surface and bulk patterns.**

In particular, the formation of **self-organized subwavelength nanogratings** in laser processed dielectrics is numerically studied [1].

Inhomogeneous plasma formation in the material and its **feedback** relationship with the electromagnetic field lead to the formation of self-organized plasma patterns that are aligned **perpendicular** to the laser polarization and with a periodicity Λ of **half a wavelength λ** in the medium ($\Lambda \sim \lambda/2n$).

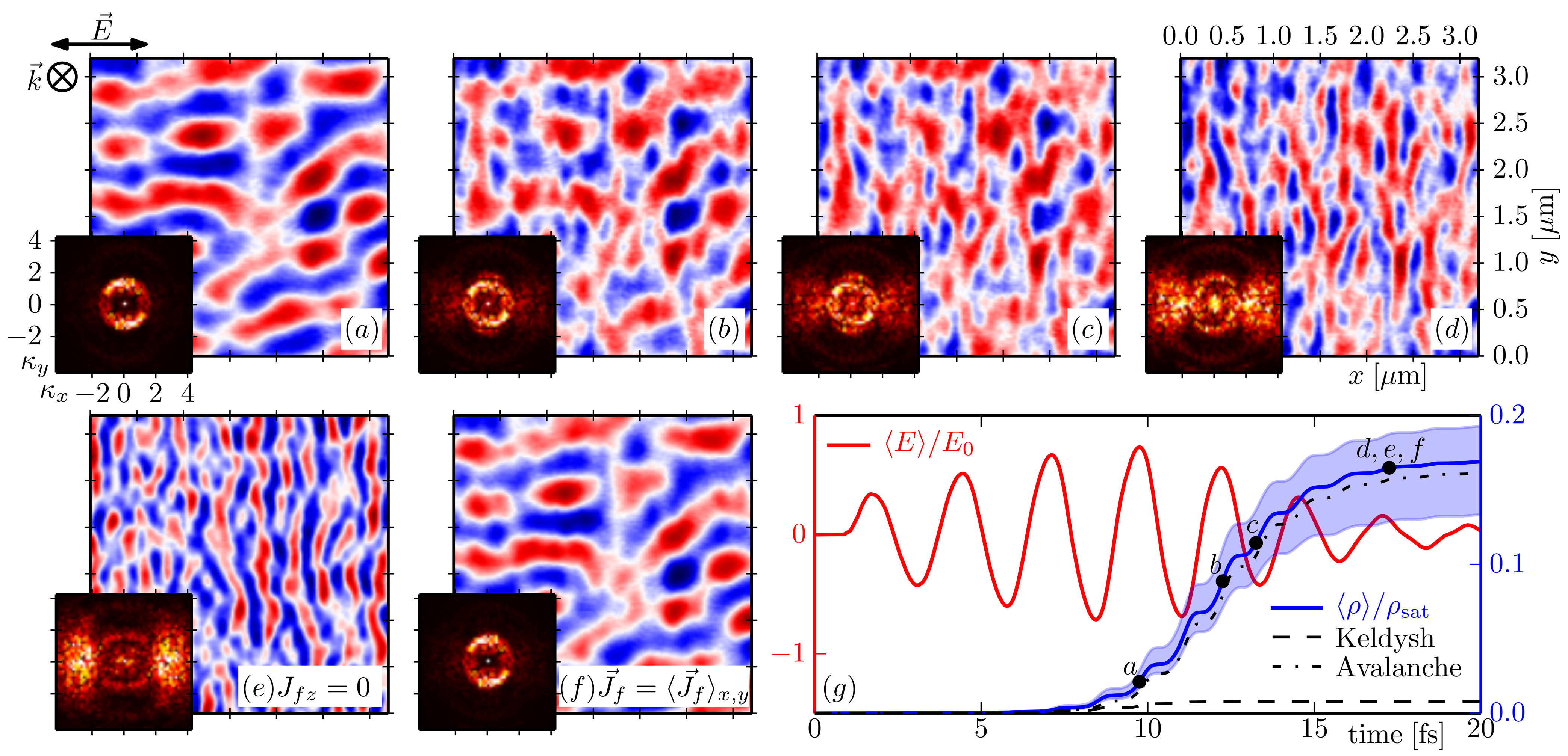
Simulations



We use the **finite-difference time-domain** (FDTD) method to solve Maxwell's equations. **A laser pulse is propagated through the rough surface of a fused silica sample.** The **field ionization** rates are calculated with Keldysh's formula. The **collisional ionization** rate is proportional to the intensity and the local plasma density. The Drude model is included to account for **losses due to the plasma.**

Plasma self-reconfiguration

The plasma initially grows inhomogeneously because of the surface roughness. The **first plasma structures are parallel to the light polarization** with a periodicity of $\Lambda \sim \lambda/n$ [see (a)]. As the plasma approaches its **critical density**, the structures progressively **self-reconfigure to perpendicular structures** with $\Lambda \sim \lambda/2n$ [see (b) - (d)].



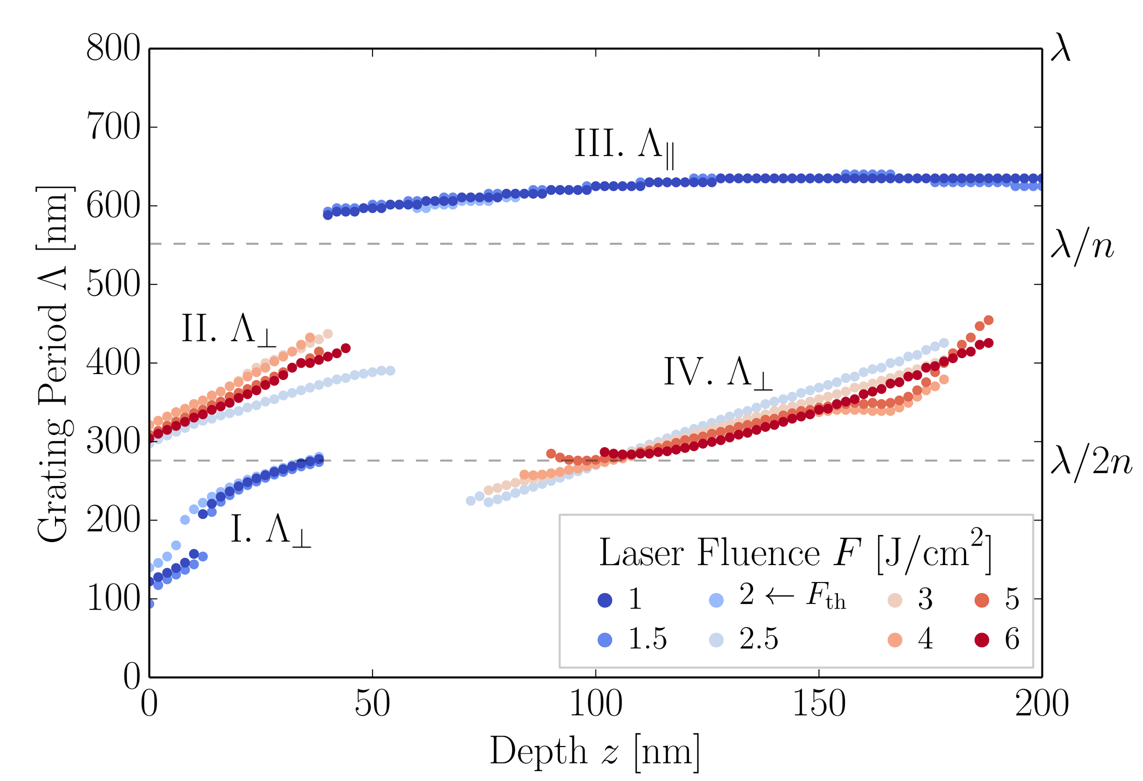
Reflections of the laser field against local plasma maxima (in red) are **central** in this self-organization process. Figures (e) and (f) show the final plasma structures obtained by **turning off**, respectively, **longitudinal or transverse** reflections during the simulation. We conclude from these results that **self-reconfiguration is mainly caused by the transverse reflections.** Recent studies simulated the growth of similar structures when *longitudinal* reflections dominate, but found important disagreements with experimental evidence [2].

Plasma patterns

At **sub-threshold** laser fluence, the plasma density is low, **intrapulse feedback** (reflections) is negligible. The plasma structures result from **interference patterns** (Sipe theory). Structures I correspond to the **near-field** interference pattern, and structures III to the **far-field** [3].

Above the fluence threshold, only structures perpendicular to the light polarization remain. The formation of a **transverse standing wave** locks the periodicity of these structures around half a wavelength in the medium **λ**/2n.

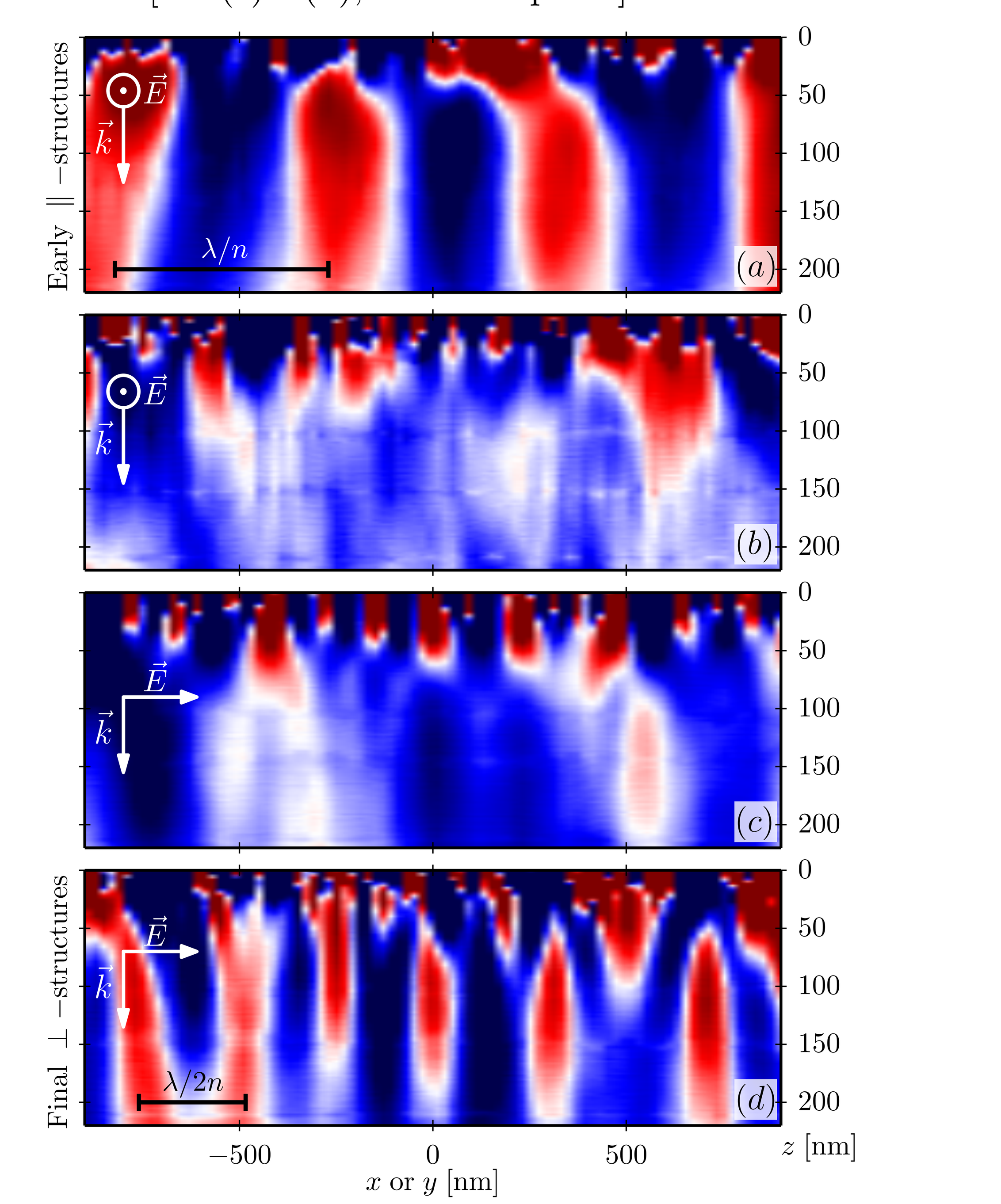
This is the **first description** of the formation of laser-induced surface nanogratings that can account for **all main experimentally observed structures.**



Explanation of the self-reconfiguration

Transverse mode coupling between the propagating laser beam and the plasma structures **still in formation** causes the **orientation shift**. The initial parallel structures [see (a), in the *yz* plane] couple with a **TE mode.** This configuration is **unstable** because the maxima of the field intensity, therefore maximal ionization, do not match the maximal plasma density spots. This **negative feedback loop** between the plasma and the field drives the parallel structures towards a **flat** distribution [see (b)].

In contrast, the **perpendicular** structures couple with a **TM mode that is stable**, so these structures **overwrite** the previous ones [see (c) - (d), in the *xz* plane].



Acknowledgments

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Fonds de recherche sur la nature et les technologies Québec

Calcul Québec

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