Laser interaction with materials: introduction

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Laser-materials interaction is the fascinating nexus where laser physics, optical physics, and materials science intersect. Applications include microdeposition via laser-induced forward transfer of thin films, clean materials processing with femtosecond beams, creating color filters with nanoparticles, generating very high density storage sites on subpicosecond time scales, structuring solar cell surfaces for higher efficiency, making nanostructures that would be impossible by other means, and creating in-volume waveguiding structures using femtosecond laser filaments. © 2014 Optical Society of America

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Laser-materials interaction is the fascinating nexus where laser physics, optical physics, and materials science intersect. The range of laser-enabled applications is broad and has been exhibiting steady expansion during the last decades. The current and emerging applications include microdeposition via laser-induced forward transfer (LIFT) of thin films, clean materials processing with femtosecond beams, making color filters with nanoparticles, generating high-density storage sites on subpicosecond time scales, structuring solar cell surfaces for higher efficiency, making nanostructures that would be impossible by other means, creating volumetric waveguiding structures using femtosecond laser filaments, and laser space debris clearing.

Paper topics in this joint *Applied Optics*-JOSA B feature were specially selected from those submitted to or presented at the International Symposium on High Power Laser Ablation and Beamed Energy Propulsion in Santa Fe, New Mexico, 21–25 April, 2014.

Since 1998, the International High Power Laser Ablation Symposia have provided a unique forum for exchange of ideas on the physics and application of high power laser-materials interaction, including advances in relevant high power laser sources and problems of beam propagation and detection, in a collegial atmosphere. The High Power Laser Ablation (HPLA) series is one of the first scientific conferences to be organized around a broad physical phenomenon

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(laser ablation and its applications) rather than a single technology.

Since 2002, the International Symposia on Beamed Energy Propulsion have brought together organizations and individuals interested in developing beamed-energy propulsion vehicles, engines, schemes, and concepts into space transportation systems of the future. Beamed Energy Propulsion (BEP) includes microwave sources as well as lasers as drivers. These meetings offer an exceptional opportunity for researchers in the BEP field to present the current results of their studies.

In 2014, for the first time, we combined these meetings, in a similar way as the Conference on Lasers and Electro-Optics and the International Quantum Electronics Conference were combined, initially with parallel sessions. The venue for HPLA/BEP was the Hotel La Fonda in Santa Fe. We had 140 attendees from 18 countries, 56% from outside the United States.

This feature issue is aimed at scientists and engineers interested in understanding how pulsed lasers interact with different materials to produce new processes and new states of matter.

Numerous disciplines are reflected in the work presented here. These include laser physics, optical physics, optical physics and engineering, chemistry, nanoengineering, plasma dynamics, semiconductor physics, simulation and modeling, imaging optics, high power microwave source development, microwave optics, and microwave receivers.

In this collection of papers you will find research on passive phase locking of a large fiber array, making nanostructures on solid surfaces with femtosecond lasers, micromachining borosilicate glass with high order femtosecond Bessel beams, making dichroic laser-induced silver nanoparticle gratings within dense inorganic films, ZnO surface nanostructuring, transfer of microwave radiation in plasma waveguides produced by UV lasers in atmospheric air, supersonic laser propulsion, short pulse interactions in laser space debris removal, transient optical properties of materials excited by ultrashort pulses, replacement of chemical rocket launchers by beamed energy propulsion, and a summary of the European CLEANSPACE project.

JOSA B Papers

Bulgakova *et al.* present a comprehensive theoretical model of the spatiotemporal dynamics of ultrashort laser-induced modification of fused silica. The model incorporates two submodels: a Maxwell equation solver including the laser-induced plasma electric currents, and a model accounting for thermoelastic and plastic material response to the laser energy deposition. An ionization instability leading to periodic electron density nanogratings and micro- or nanobubbles is predicted. A map of absorbed laser energy is used as input for modeling the spatiotemporal dynamics of excited matter relocation and determining the final density-modulated structure that conditions the refractive index changes.

Gamaly and Rode provide a model for the transient permittivity of dielectrics excited by ultrashort pulses. They treat SiO_2 with 800 nm ultrashort excitation and obtain an analytical solution for electron number density during the laser pulse. They compare multiphoton and electron impact ionization mechanisms for the density buildup and conclude that electron impact dominates at the end of a 100 fs pulse. They find that reflectivity has a maximum and that the impact ionization coefficient has a nonlinear dependence on laser intensity, and they predict that circularly polarized light will produce 2 times higher impact ionization rate.

Zjilstra *et al.* report on development of a modeling tool called Code for Highly Excited Valence Electron Systems (CHIVES) and provide several examples highlighting the capabilities of the code. The computational tool is suitable for accurate *ab initio* molecular dynamics simulation of large crystal supercells. It makes possible observation of anharmonic effects and ultrafast structural phenomena, as, for example, coherent phonon decay in Sb and ultrafast fractional diffusion in Si.

Brouwer and Rethfeld present a model of nonequilibrium dynamics of conduction and valence band electrons, and of acoustic and optical phonons, by calculating the complete Boltzmann collision integrals for the respective distribution functions, using material properties of fused silica. The model includes Auger recombination and electron-phonon collisions and transient screening by electrons and holes. This allows them to determine electron thermalization times within and between the bands, in order to understand the applicability of the concept of temperature in the excited regions of fused silica, and to determine the effective parameters for electron-phonon coupling under conditions of strong electronic excitation.

Kanaev *et al.* report femtosecond KrF laser irradation of ZnO films in the high electron density excitation regime, below the ablation threshold but above the Mott density, corresponding to the electron-hole plasma regime. ZnO films prepared by pulsed laser deposition show nanoholes arranged in straight and zigzag lines, while solgel films show a flake-like structure with open porosity.

Cheng and Polynkin discusses experiments and simulations of self-focusing of intense, shaped femtosecond laser beams in transparent gaseous and condensed materials. Beam shaping provides an effective way to control and regularize locations of intense laser filaments within the beam profile. These regular filament distributions can be utilized for writing extended structures inside transparent dielectrics. Specific beam shapes include fundamental Bessel beams, vortex beams, high-order Bessel beams, and self-bending Airy beams. Vortex beams and Bessel beams of higher order propagating in the extreme nonlinear regime produce bottle-like distributions of filaments that can be used for making extended volumetric waveguiding structures. The application of Airy beams to materials processing has recently been shown to machine curved trenches with high aspect ratios.

Destouches *et al.* show how to generate polarization-sensitive, active color filters by scanning inorganic films with a homogeneous continuous wave laser to create buried unlimited gratings of metal nanoparticles in one step. The filters operate by a combination of plasmonic and waveguide resonances. The authors explain the mechanisms responsible for the generation of such nanostructures and show that the gratings can be extended by partially overlapping successive illuminations to create nanoparticle gratings with local tuning parameters over large areas.

Bulgakov *et al.* report on a new technique called blister-based laser-induced forward transfer (BB-LIFT) of nanoparticles by nanosecond lasers for gas phase analysis. This technique eliminates the need for a matrix by spreading the nanoparticles over a thin metal film that is deposited on a transparent substrate and illuminated from the back side. They transported silica-gold core-shell 150 nm particles spread on 100–200 nm Ni films on glass or quartz and found velocities of the order of 10–50 m/s.

AO Papers

Reif discusses laser-induced periodic structures (LIPSS) created after hundreds to tens of thousands of femtosecond laser pulses well below the ablation threshold. At first, spherical bubbles of 0.5–3 μm diameter are formed, which after further irradiation form ripples. Laser polarization dependence is seen only after agglomeration, aggregation, and coagulation of the bubbles into larger structures after many pulses. It is concluded that LIPSS formation is an evolutionary, active process more than a passive lithographic one.

Napartovich *et al.* discuss passive phase locking of an array of fiber lasers. Maximum array size is governed by nonlinear effects such as gain saturation and refractive index nonlinearity. Specifically, they compare an array of amplifiers in ring resonator configuration with spatially filtered feedback to an array of lasers with external feedback. They report a semi-analytical approach based on probability theory to describe the two systems for arrays up to size 20 and conclude that the second approach has better scaling.

Zvorykin *et al.* report a study of multiple filamentation of 248 nm, supercritical laser beams during propagation along a ~100 m path in various focusing geometries. The beam contained subpicosecond duration, 1 TW pulses combined with a quasi-steady 100 ns, 1 GW KrF pulse. They compare filamentation for a single laser pulse and a train of a few pulses with 5 ns interval, shorter than the electron relaxation time in the plasma. Despite filamentation, the beam demonstrated linear focusing.

Rezunkov reports a study of supersonic laser propulsion in an off-axis "Lightcraft-type" parabolic nozzle. He develops a theoretical model of the interaction of the laser ablation jet with supersonic gas flows and studies applicability of the jet for additional acceleration of supersonic flows in hypersonic engines.

Neely *et al.* report the formation of plasma mirrors capable of reflecting 70%–90% of incident energy using femtosecond beams having contrast of order 10^{12}. They consider the impact of their findings on laser space debris clearing.

Fukunari *et al.* report on the feasibility of replacing first stage engines and solid rocket boosters of the Japanese H2B rocket by a microwave rocket with a reed-valve airbreathing system. They found the payload could be increased 360%, reducing launch cost by 80%.

Esmiller *et al.* report on the European CLEAN-SPACE project, including the system architecture, intended for ground-based laser space debris removal.

Artusio-Glimpse *et al.* discuss the effect of radiation pressure on the motions of a semicylindrical transparent rod with a mirrored flat surface lying on a flat window through which the radiation comes. Radiation affects the equilibrium orientation as well as the oscillation frequency of the resulting rocking motion.