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14. ABSTRACT

The 8th meeting of the International Symposium on High Power Laser Ablation was held in Santa Fe NM 18 -22 April 2010. This report describes the conference in detail and includes the book of abstracts. AFOSR partially supported the conference. Eighteen countries were represented; 51 oral papers and 44 poster papers were presented in 14 sessions. Sessions covered laser-matter interaction physics and modeling, short-pulse laser-matter interactions, nanoprocessing and engineering of materials, laser propulsion, plume dynamics, alkali halide, optically pumped and oxygen-iodine lasers, space applicatioins and PLD, MAPLE and processing of advanced materials. A unique panel session on the topic "What are the issues we should be putting more effort on in terms of understanding and/or overcoming technological roadblocks" was held.

15. SUBJECT TERMS
laser, plume dynamics, alkali halide laser, femtosecond laser-matter interaction, nanoprocessing

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U	U	U	NONE	93	Dr. Claude Phipps
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Support for High Power Laser Ablation 2010

Final Report
Contract FA9550-10-M-0001 (16 April 2010)

Submitted 27 May, 2010 by
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1. Objectives

The main objective of this contract is to provide critical support to High Power Laser Ablation 2010.

Since 1998, the International High Power Laser Ablation Symposium meetings 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. Our eighth meeting, just completed, was supported at a critical level by AFOSR, through this contract.

The HPLA series is one of the first physics conferences to be organized around a physical phenomenon (high power ablation) rather than a specific technology or application. HPLA addresses every aspect of the high power ablation of materials from the basic physics to the leading applications.

Our attendees are forefront specialists in the basic physics of laser-surface interactions, high-power lasers, materials science, femtosecond lasers and effects, beam propagation, beam forming, diagnostics and detection.

We provide a collegial atmosphere in which a wide array of specialists who might not otherwise meet can talk and learn from each other. All sessions are plenary, so that each attendee can hear all the oral papers. Two evenings of poster sessions are contemplated.

We heavily emphasize the physics involved in the laser-surface interaction to avoid missing the grand connections among these interesting applications. Groundbreaking physics is discussed for its own sake. We also devote some sessions to advances in the specific types of lasers (diode, solid state, rare gas photodissociation, etc.) which are of use in these applications. Applications discussed range from high-tech material processing to space propulsion to inertial confinement fusion.

Past keynote speakers have included luminaries such as Prof. Charles Townes, Prof. Yuri Raizer, Prof. Arthur Kantrowitz, Prof. Oleg Krokhin, Dr. Raymond Kidder, and Prof. Sadao Nakai.

2. Corporate Sponsor and Duties

For the first time, General Dynamics Information Technologies (GDIT) was our corporate sponsor. Their duties were hotel contract management, webpage preparation (http://www.usasymposium.com/hpla/default.htm), making conference announcements, setting and collecting registration fees, designing the exhibitor and sponsor programs, selecting and paying for audiovisual services, obtaining insurance for the event and onsite management.

3. Organizer and Duties

Dr. Claude Phipps, Photonic Associates, LLC was the conference organizer and chair. His duties included creating the 2000-name conference contact list from scratch (SPIE would not share this), creating the exhibitor and sponsor contact lists, selecting and inviting speakers, communicating with all authors, organizing the conference program, obtaining sponsorships and exhibitors, defining sessions, appointing session heads, chairing the conference, coordinating with GDIT, coordinating entertainment for the conference dinner including best poster awards, setting conference paper guidelines, editng and assembling conference proceedings, coordinating reviews of all papers, coordinating proceedings publication with the American Institute of Physics, executing the contract with AIP and selling the proceedings. The publication contract is between AIP and Dr. Phipps (GDIT is not involved).

4. Conference Location and Schedule

HPLA 2010 was held 18 – 22 April, 2010 at the Eldorado Hotel, Santa Fe. The schedule was as follows:

Sunday April 18
- 4:00 – 6:00 PM: Early registration
- 5:00 – 6:00 PM: Reception

Monday April 19
- 7:00AM: Continental breakfast and registration
- 8:00 AM – 12:00 PM: Technical sessions
- 9:00 AM – 12:00 PM: Setup for tabletop exhibits and Monday posters
- 11:40 – 1:40 PM: Lunch
- 1:40 PM – 5:30 PM: Technical sessions
- 8:00 – 10:00 PM: Poster session and table top exhibits

Tuesday April 20
- 7:30AM: Continental breakfast and registration
- 8:30 AM – 11:10 AM: Technical sessions
- 9:00 AM – 12:00 PM: Setup for tabletop exhibits and Tuesday posters
- 11:10 AM – 1:10 PM: Lunch
- 1:10 PM – 4:50 PM: Technical sessions
- 8:00 – 10:00 PM: Poster session and table top exhibits

Wednesday April 21
- 7:30AM: Continental breakfast and registration
- 8:30 AM – 12:40 PM: Technical sessions
- 12:40 PM – 2:40 PM: Lunch
- 2:40 PM – 4:25 PM: Technical sessions

Thursday April 22
- 7:30AM: Continental breakfast and registration
- 8:30 AM – 11:25 AM: Technical sessions
- 11:25 AM – 12:15 PM: Panel "What are the issues we should be putting more effort on in terms of understanding and/or overcoming technological roadblocks?" moderated by Prof. J. Thomas Dickinson
- 12:15 PM – 2:15 PM: Lunch
- 2:15 PM – 5:10 PM: Technical sessions
- 5:10 PM: Closing remarks by Dr. Phipps
- 6:00 – 9:00 PM: Conference dinner and best poster awards

5. Conference Topics, Program Committee, Sessions and Chairs

The complete program is provided in Appendix A. In that Appendix, papers highlighted in gold are those which will be included in the American Institute of Physics Proceedings but could not be given because of European and Russian airport closings due to the Eyjafjallajökull volcano. Appendix B is our book of abstracts. Appendix C lists our program committee (including a new member, Dr. Pete Latham, AFRL Kirtland), and Appendix D lists sessions and session chairs.

One of the most interesting events in the conference was the panel, organized by Tom Dickinson of Washington State, entitiled "*What are the issues we should be putting more effort on in terms of understanding and/or overcoming technological roadblocks*." Those participating in addition to Tom were Leonid Zhigilei, University of Virginia, Akos Vertes, George Washington University, Eugene Gamaly, Australian National University and Chunlei Guo, University of Rochester. In addition inputs were sent remotely by Razvan Stoian, Université St-Etienne, Michel Meunier, Polytechnique Montréal, and Carmen Afonso, Optics Insitute of the Spanish Research Council, Madrid. Some conclusions were

- The details of absorption processes and the processes that follow absorption are extremely important for understanding how heat is generated in materials
- All properties are time- and temperature-dependent, so that the spatio-temporal shapes of the incident laser beam must be considered
- Vortex beams have interesting properties
- Applications lead physics and chemistry
- The three types of models (electronic structure calculations, atomic level classical simulations and continuum hydro models) need to be rationalized
- We need the next 'flagship application'
- We need to understand the role of negative ions (are they as energetic as positive ones)
- We should consider group proposals to get funding for these studies

6. Conference Statistics

Table 1 gives the principal statistics for HPLA 2010.

Table 1. Statistics, HPLA 2010

Parameter	Value	Comment
Attendance	82	Would have been 102, absent the volcano
Volcano cancellations	20	
Countries represented	18	New countries: Egypt
Total papers presented	95	18 could not be presented due to volcano
Oral papers	51	
Poster papers	44	
Papers in AIP Proceedings	84	
Pages in AIP Proceedings	902	
Sessions	14	Including poster sessions

7. General Comments

This was the toughest year in the history of HPLA to hold a conference. The worldwide economic malaise caused potential sponsors and exhibitors to decline our invitations. Hundreds of contacts produced only two sponsors. At the same time, our new location in Santa Fe rather than Taos increased costs paid for hotel services as well as the attendee room rate ($149). A month before the conference, our main keynoter, Astronaut Donald Pettit, was sent to Kazakhstan to train for a Soyuz launch. Then the volcano happened. Our technical keynoter, Prof. Johannes Pedarnig of the Johannes-Kepler University, Linz, Austria could not attend. Ultimately, we lost half of our European attendance from this cause. The organizer put 450 hours into the conference, but we still had the lowest attendance in our history.

8. Costs supported by AFOSR

Table 2 lists the costs supported by this contract

Table 2. AFOSR support expenditures

Item	Cost
Audiovisual Expenses	$5,700
Exhibit Expenses	$1,700
Web Setup	$ 400
Supplies and Shipping	$ 500
Photonic Associates Fee (4%)	$ 330
Total	$8,630

All expenses except Photonic Associates' fee were in fact incurred by our corporate sponsor, General Dynamics Information Technologies, 5100 Springfield Pike, Suite 509, Dayton OH 45431, and paid to them (Photonic Associates, LLC check 1297). This information can be verified with Ms. Pamela Myers, 937-254-7950, extension 1135, pamela.myers@gdit.com.

Appendix A: HPLA 2010 Final Program

K	keynote		0:40
I	invited		0:25
R	regular		0:15
B	break		0:30
S	space		0:05
M	misc	you fill it in	

note: yellow shading in the schedule means a change. If the time for the talk is 0:00 it has been canceled with no subsitute presenter.

Sunday 4/18			
Reception	17:00	18:00	
Registration	16:00	18:00	

Abs No.	Monday 4/19/2010	Time	Interval	Author/Chair	Type	Title
	Introductory remarks: Claude Phipps	8:00	0:15	Claude Phipps	M	
	Dedication to Santa Fe 400th	8:15	0:30	Mayor David Coss	M	
	Session 2: Laser-matter interaction physics and modeling I	8:45	0:05	Thomas Dickinson	S	
98		8:50	0:25	Thomas Dickinson	I	Fundamental Studies of the Role of UV Laser Defect Production on the Modification of Surfaces: Single Crystal ZnO and CaF2
105		9:15	0:25	Aaron Lindenburg	I	High Intensity THz Interactions with Materials: New Aspects and Applications
	Break	9:40	0:30		B	
18		10:10	0:25	Leonid Zhigilei	I	Atomic-Level Simulations of Laser Interactions with Metals: Melting of Nanocrystalline Films and Generation of Crystal Defects
3		10:35	0:00	Andrei Rode	I	Transport of Light Absorbing Particles in Air with a Laser Pipeline
7		10:35	0:00	Tatiana Itina	I	Simulations of controlled spectral emission of Al plasmas generated by temporally tailored laser irradiation
126		10:35	0:00	Alfred Vogel	I	Controlled Nonlinear Energy Deposition in Transparent Materials: Experiments and Theory
63		10:35	0:15	Joern Bonse - Thomas Lippert will give	R	Damage Mechanisms in Thin Film and Bulk Polymers upon NIR Femtosecond Pulse Laser Irradiation: Sub-threshold Processes and Their Implications for Laser Safety Applications
29		10:50	0:25	Wayne Hess	I	Surface-specific Laser Matter Interactions and Dynamics
89		11:15	0:25	Akos Vertes	I	Nanophotonic Ion Sources
	Lunch on your own	11:40	2:00		M	
	Session 3: Laser-matter interaction physics and modeling II	13:40	0:05	Wayne Hess	S	
32		13:45	0:25	Peter Balling Joergen Schou will give	I	Fundamentals of Femtosecond Laser Ablation of Dielectric Materials
95		14:10	0:25	Irina Zavestovskaya	I	Laser Nanostructurization of the Metal and Alloy Surfaces
82		14:35	0:15	Ivan Oleynik	R	Large-scale Molecular Dynamics Simulations of Ablation and Spallation of Gold Irradiated by Femtosecond Laser Pulse
90		14:50	0:25	Vitaly Gruzdev	I	Laser-induced Modification of Energy Bands of Transparent Solids
	Break	15:15	0:30		B	
	Session 4: Short pulse laser-matter interactions I	15:45	0:05	Pete Latham	S	
		15:50				

1		15:50	0:00	Thomas Baumert	I	Temporal Femtosecond Pulse Tailoring for Nanoscale Laser Processing of Wide Band Gap Materials
53		15:50	0:25	Minghui Hong	I	Laser-material Interaction and its Applications in Surface Micro-nanoprocessing
13		16:15	0:25	Marta Castillejo	I	Wavelength Effects in Femtosecond Pulsed laser Ablation and Deposition
40		16:40	0:00	Jean-Philippe Colombier	I	Adaptive Pulse Shaping for Controlling Emission Lines in Ultrashort Laser Produced Plasmas
11		16:40	0:25	Eugene Gamaly	I	Ultra-fast Phase Transitions Induced by fs-lasers in Solids: Superheating Before the Entropy Catastrophe
9		17:05	0:00	Stephane Guizard	I	Femtosecond Laser Ablation of Dielectrics: Experimental Studies of Fundamental Processes
85		17:05	0:25	Alexander Rubenchik	I	Laser System for Space Debris Cleaning
	End, Dinner on your own	17:30				
	Poster Session	20:00	2:00		M	
		22:00				
	<u>Tuesday 4/20/2010</u>					
	Session 5: Short pulse laser-matter interactions II	8:30	0:05	**Haglund**	S	
113		8:35	0:25	Andrei Ionin	I	Non-linear Absorption and Ionization of Gases by Intense Femtosecond Laser Pulses
97		9:00	0:25	Katsumi Midorikawa	I	Attosecond Nonlinear Optics
	Break	9:25	0:30		B	
51		9:55	0:00	Klaus Sokolowski-Tinten	R	Short-pulse Laser Induced Transient Structure Formation and Ablation Studied with Time-resolved Coherent XUV-scattering
72		9:55	0:25	Luke Emmert	I	Single and Multiple Pulse Subpicosecond Breakdown in Dielectric Films
65		10:20	0:25	Shawn McGrane	I	Ultrafast Dynamic Ellipsometry and Spectroscopy of Laser Shocked Materials
110		10:45	0:25	Wataru Watanabe	I	Femtosecond Laser Produced Micro-modifications in Polymers
62		11:10	0:00	Wouter Wendelen	I	Space Charge Corrected Ultrashort Pulsed Laser Induced Electron Emission from a Cu Surface
	Lunch on your own	11:10	2:00		M	
	Session 6: Nano-processing and engineering of materials	13:10	0:05	**Dickinson**	S	
5		13:15	0:25	Koji Sugioka	I	Nanoaquariums Fabricated by Femtosecond Laser for Exploration of Dynamics and Functions of Microorganisms
56		13:40	0:25	Martin Ams	I	Directly Written DFB Waveguide Lasers using Femtosecond Laser Pulses
35		14:05	0:00	Juergen Reif	I	Long-time Feedback in Self-organized Nanostructures Formation upon Multipulse Femtosecond Laser Ablation
		14:05				
	Break	14:05	0:30		B	
31		14:35	0:25	Craig Arnold	I	High Throughput Direct-write Near-field Nanopatterning
16		15:00	0:25	James Fraser	I	Coherent Imaging of Laser Micromachining
2		15:25	0:25	Costas Grigoropoulos	I	Laser-Assisted Nanoprocessing

	Session 7: Laser Propulsion	15:50	0:05	**Andrei Ionin**	S	
22		15:55	0:00	**Hans-Albert Eckel**	I	Tailoring Laser Propulsion for Future Applications in Space
122		15:55	0:25	Leik Myrabo	I	Experimental investigation of axial and beamriding propulsive physics with TEA CO2 laser
33		16:20	0:15	John Sinko	R	Modeling CO2 Laser Ablative Impulse with Polymers
42		16:35	0:15	Claude Phipps	R	A Review of Laser Ablation Propulsion
	End	16:50				
	Dinner on your own	16:50				
	Poster Session	20:00	2:00		M	
		21:00				
	Wednesday 4/21/2010					
	Announcements	8:30	0:05	Claude Phipps		
127		8:35	0:25	Pavel Polynkin	I	Filamentation of beam-shaped femtosecond laser pulses
66		9:00	0:15	Leik Myrabo	R	Dedicated laboratory setup for CO2 TEA laser propulsion expts at RPI
	Session 8: Plume Dynamics	9:15	0:05	**Lunney**	S	
28		9:20	0:25	James Lunney	I	Plume Dynamics in Femtosecond Laser Ablation of Metals
39		9:45	0:25	Katsuya Oguri	I	Dynamics of Femtosecond Laser Ablation Plume Studied with Ultrafast X-Ray Absorption Fine Structure Imaging
25		10:10	0:25	Juergen Schou	I	Ablation Plume Dynamics in a Background Gas
	Break	10:35	0:30		B	
	Session 9: Alkali halide, other optically pumped lasers and oxygen-iodine lasers	11:05	0:05	**Hostutler**	S	
108		11:10	0:25	Michael Heaven	I	Theoretical and Spectroscopic Investigations of Alkali Metal – Rare Gas Photodissociation Lasers
93		11:35	0:25	Glen Perram	I	Frequency Dependent Optical Delay with Gain in the Cesium Diode Pumped Alkali Laser System
75		12:00	0:15	Vasudevan Nampoothiri	R	Optically pumped C2H2 and HCN Lasers with conventional cavities and based on h ollow core photonic crystals
134		12:15	0:25	William Latham	I	6.5 kW, Yb:YAG cereamic thin disk laser
	Lunch on your own	12:40	2:00		M	
		14:40				
	Session 10: Space applications	14:40	0:05	**Joergen Schou**	S	
8		14:45	0:25	Victor Apollonov	I	Long Conductive Guide for Energy Delivery from Space
80		15:10	0:25	Duane Liedahl	I	Analysis of Momentum Transfer due to Laser Ablation of Irregularly Shaped Space Debris
30		15:35	0:25	Stefan Scharring given by John Sinko	I	Laser Propulsion Standardization Issues
21		16:00	0:25	Alexander Bulgakov	I	Pulsed Laser Ablation of Compound Semiconductors: Vaporization Mechanisms and Cluster Generation
	End	16:25				
	Group Photo in Eldorado Bar by Fireplace	17:45		Please Be There!		
	Conference Dinner	18:00	3:00		M	
	including announcement of 3 best poster awards	21:00	0:00			

	Thursday 4/22/2010					
	Session 11: **PLD, MAPLE and processing of advanced materials**	8:30	0:05	**Obara**	S	
132		8:35	0:25	Richard Haglund	I	Resonant infrared pulsed laser deposition of organic and polymer materials for display applications
17		9:00	0:25	Thomas Lippert	I	Laser-induced Forward Transfer (LIFT): Application of a Dynamic Release Layer for the Transfer of Sensitive Materials
15		9:25	0:25	Gediminas Raciukaitis,Lucian Hand, Altos Photonics will give	I	Selective Ablation of Thin Films with Ultra-Short-Pulse Lasers for Solar Cells and Other Technical Applications
73		9:50	0:15	Ryan Pate	R	Resonant Infrared Matrix-assisted Pulsed Laser Evaporation of Inorganic Nanoparticles and Organic/Inorganic Hybrid Nanocomposites
12		10:05	0:15	Ludovic Rapp	R	Pulsed-laser Printing Process for Organic Thin Film Transistors Fabrication
	Break	10:20	0:30		B	
102		10:50	0:00	Arseniy Kuznetsov	R	Laser-induced Backward Transfer of Metal Nanoparticles
10		10:50	0:25	Chunlei Guo	I	Optical Alchemy with Lasers
	Panel: what are the issues we should be putting more effort on in terms of understanding and/or overcoming technological roadblocks	11:15	1:00	**Tom Dickinson**	M	
	Lunch on your own	12:15	2:00		M	
	Session 12: Advanced applications and diagnostics	14:15	0:05	**Lander**	S	
64		14:20	0:00	Maria Dinescu	R	Two Photon Polymerization of Ormosils
		14:20	0:25	Nigel Browning	I	Dynamic Trnsmission Electron Microscopy (DTEM)
128		14:45	0:25	Larry Shah	I	High power thulium lasers - the next family of high power lasers
125		15:10	0:00	Anatoly Boreysho	I	High Brightness Multi-Channel Laser Systems
	Break	15:10	0:30		B	
78		15:40	0:15	James Luke	R	High Energy Laser Diagnostic Sensors
69		15:55	0:00	Anatoly Napartovich	I	Analysis of a Problem of High Power Fiber Laser Combining for Arbitrary Large Optical Phase Differences
27		15:55	0:25	Dieter Schuoecker	I	Forming of Brittle Materials – A New and Valuable Application of Diode Lasers
57		16:20	0:25	Ilja Mingareev	I	Time-resolved White-light Interferometry for Ultrafast Metrology
120		16:45	0:25	Jose Ocaña	I	Laser Shock Processing of Metallic Materials
	End	17:10				
	Closing remarks	17:10	0:15	**Phipps**	M	
	End Conference	17:25				

	Monday evening poster session	20:00	22:00 Hostutler		
83			Shelly Gaston		Solar Pumped Laser Microthruster
70			Ronald Gilgenbach		High Current Cathodes Fabricated by KrF Laser Ablation
111			E. Golosov		Nanostructuring of Solid Surfaces by Femtosecond Laser Pulses
23			Bing Han	I	Investigation of Laser Propulsion for Transport in Water Environment
109			Michael Heaven		O2(a1Δ) Quenching in the O/O2/O3 System
130			Hideyuki Horisawa	I	High-Isp Mode of Pulsed Laser-Electromagnetic Hybrid Accelerator for Space Propulsion Applications
129			Hideyuki Horisawa		Low-Power Laser-Metal Interaction for Space Propulsion Applications
112			Andrey Ionin		Gas-flow Slab RF Discharge as a Source of Singlet Delta Oxygen for Oxygen Iodine Laser
68			Denis Kiselev		Use of Femtosecond Laser Filaments for Material Machining
19			Fumio Kokai		Growth of Polyhedral Graphite Particles and Carbon Nanotubes Filled with SiC Nanowires by Laser Ablation
117			Sergey Kudryashov		Femtosecond Laser Microstructuring of Transparent Materials and its Ophtalmological Applications
60			Tetsuya Makimura		Silica Nano-ablation using Laser Plasma EUV Radiation
4			Mahendra Maurya		Photorefractive Phase-shift of a Two Unidirectional Photorefractive Ring Oscillators Using Two Beam Coupling
106			Carrie Noren		Dynamic Pressure Recovery System for a Gas Laser
119			Minoru Obara		Comparison of Resonant Plasmon Polaritons with Mie Scattering for Laser-induced Near-field Nano-patterning: Metallic Particle vs Dielectric Particle
24			Leonid Pekker		An Analytical Model of Ablation in Gas Flow
123			Nikita Medvedev		Transient Dynamics of Electronic Subsystem of Aluminum Target Irradiated with an Ultrashort XUV Laser Pulse
124			Nikita Medvedev		Electronic Kinetics of Semiconductors under an Ultrashort VUV Laser Pulse Irradiation
74			Chris Walton	I	Formation of Micro and Nano Structures Using VUV 157nm Laser Radiation
133			Axel Maeyens		Femtosecond pulsed laser induced phase transitions studied by a hybrid continuum-atomistic model
131			Vitaly Gruzdev		Modification of material properties and response of nanostructures on transparent substrates by ultrashort laser pulses

	Tuesday evening poster session	20:00	22:00	Autric		
109				Michael Heaven		$O_2(a^1\Delta)$ Quenching in the $O/O_2/O_3$ System
92				Woody Miller		Effects of Mode Matching and Radial Intensity Distributions in Pulsed, Optically Pumped Rubidium Laser
94				Gordon Hager		A Three Level Analytic Model for Alkali Vapor Lasers
107				Glen Perram		The Effect of Residence Time on the Production of Singlet Oxygen in Microwave and RF Discharges
77				Claude Phipps		Applying the Phipps and Sinko Model to the ORION Problem
86				Claude Phipps		Can Lasers Play a Role in Planetary Defense?
87				Claude Phipps		"Catcher's Mitt" as an Alternative to Laser Space Debris Mitigation
46				John Remo		Laser Driven Compression Wave Equations of State and Momentum Coupling Measurements in Thick Solid Metallic Targets at 0.1 - 10 TW/cm2
43				John Remo	I	Laser and Z-pinch Simulation of High Energy Density Planetary Interactions
34				John Sinko		CO2 Laser Ablation Area Scaling with Flat Polyoxymethylene Targets
41				John Sinko		Update on CO2 Laser Ablation of Polyoxymethylene
52				Klaus Sokolowski-Titen		Coherent Acoustic and Optical Phonons in Laser-excited Solids Studied by Ultrafast Time-resolved X-ray Diffraction
71				Enrique Sterling		Z-pinch Discharge in Laser Produced Plasma
47				Timothy Suen		Separation of Copper Isotopes in the Laser Plume
6				Remi Torres		Study on Laser-induced Periodic Structures and Photovoltaic Application
101				Keshav Walia		Self Focusing of Laser Beams in Thermal Conduction Loss Predominated Plasmas
91				Irina Zavestovskaya		Nonlinear Mechanisms of Light Beam Absorption in Transparent Materials Under High Power Laser Action
79				Vasily Zhakhovsky		Spallative Ablation of Metals and Dielectrics by Ultrashort X-ray Lasers
81				Vasily Zhakhovsky		Pump-probe Exploration of Ultrafast Electron Processes in Metal Irradiated by a Femtosecond Laser Pulse
121				Osama Khalil		The Laser damage threshold for materials and the relation between solid-melt & melt-vapor interface velocities
67				Cristian Focsa	I	High-Power Laser Ablation Plasma Dynamics: From Experiment to Fractal Hydrodynamic Model
135				Luciano Velardi		Ion Beams by Laser Plasma for Modification of Polymeric Surfaces
136				Jack Yoh		Innovative drug injection via laser induced plasma

APPENDIX B
BOOK OF ABSTRACTS
INTERNATIONAL SYMPOSIUM ON HIGH POWER LASER ABLATION
ELDORADO HOTEL, SANTA FE, NM
19 APRIL – 22 APRIL 2010

Monday 19 April

Keynote I

[104] Pulsed-laser Deposition of Oxide Thin Films and Laser-induced Breakdown Spectroscopy of Multi-element Materials

Johannes D. Pedarnig [1, 2]

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New results of the Linz group on pulsed-laser deposition (PLD) of oxide thin films and on laser-induced breakdown spectroscopy (LIBS) of multi-element materials are reported. High-T_c superconducting (HTS) films with enhanced critical current density J_c are produced by laser ablation of novel nano-composite ceramic targets. The targets contain insulating nanoparticles that are embedded into the $YBa_2Cu_3O_7$ matrix. Epitaxial double-layers of lithium-doped and aluminum-doped ZnO are deposited on r-cut sapphire substrates. Acoustic over-modes in the GHz range are excited by piezoelectric actuation of layers. Smooth films of rare-earth doped glass are produced by F_2 – laser ablation. The transport properties of HTS thin films are modified by light-ion irradiation. Thin film nano-patterning is achieved by masked ion beam irradiation. LIBS is employed to analyze trace elements in industrial iron oxide powder and reference polymer materials. Various trace elements of ppm concentration are measured in the UV/VIS and vacuum-UV spectral range. Quantitative LIBS analysis of major and minor components in oxide materials is performed by calibration-free methods.

Acknowledgements:

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Session 2: Laser-matter interaction physics and modeling I
Thomas Dickinson, chair

[98] Fundamental Studies of the Role of UV Laser Defect Production on the Modification of Surfaces: Single Crystal ZnO and CaF_2

Tom Dickinson

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UV-Laser interactions with wide bandgap insulators and semiconductors has generated a number of examples of point defect production, surface and bulk modification, etching and re-deposition processes, as well as numerous PLD related applications involving the emitted particles. In metal containing compounds such as oxides and halides, aggregation of metals into nanoparticles has been observed. In this talk we examine the fundamental mechanisms required to explain the formation of such nanoparticles. We examine these modifications in oriented single crystals of semiconducting ZnO with a band-gap of ~3.4 eV We first discuss results on interactions of strongly absorbing 248 nm (5 eV), 193 nm (6.3 eV), and 157 nm (7.8 eV) excimer laser light with high purity ZnO surfaces in UHV. Using time resolved quadrupole mass spectroscopy, we show examine atomic and molecular emissions (Zn, O, and O_2) generated at fluences below plasma formation threshold. Although the atomic Zn emission is robust, more total oxygen is observed to leave the surface. One possible emission mechanism we are pursuing is the ejection of O by localized electron hole pair annihilation. Accompanying exposure of these single crystals to 193 nm light is coloration: i.e. gray to black spots (some preliminary evidence is showing detectable but less coloration at 248 nm); we show conclusively that this coloration is due to surface metallic zinc in the form of nanoparticles, typically 10-20 nm in diameter. We discuss formation mechanisms and the role of strong interactions of the laser with these nanoparticles. Finally, we show preliminary results on the production of defects in the VUV region of the spectrum induced by 157 nm light that results in significant and novel first order interactions with the laser light itself. This may enter into the processes that lead to Ca metal nanoparticles generated by 157 nm exposure.

[105] High Intensity THz Interactions with Materials: New Aspects and Applications

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Topics: Physics of laser-matter interactions; Femtosecond and attosecond effects

Abstract: We describe recent results studying the interaction of ultrashort high field THz pulses with a variety of materials ranging from small band gap and wide band gap semiconductors/insulators to perovskite ferroelectrics. Evidence for THz-induced breakdown and impact ionization processes on ultrafast time-scales are observed. Combined Thz-pump/X-ray probe ultrafast measurements are described which capture the atomic-scale displacements associated with THz-driven materials. We also present several novel aspects of plasma-mediated ultrafast THz emission, in which we demonstrate attosecond level control of the half-cycle THz polarization and investigate the coupling of femtosecond-laser-generated plasmas through THz emission spectroscopy.

[18] Atomic-Level Simulations of Laser Interactions with Metals: Melting of Nanocrystalline Films and Generation of Crystal Defects

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Relevant topics: Fundamental Theory; Simulations; Physics of Laser Matter Interactions

Abstract: Atomic-level computer modeling has the ability to provide detailed information on the complex processes induced by short pulse laser irradiation of metal targets and can assist in the advancement of laser-driven applications. Recent results obtained in simulations of laser interactions with metal targets (Au, Ni, Cr, AuCu bilayer) [1-4] are reviewed in the presentation with a particular focus on the laser-induced generation of crystal defects and the role of the microstructure of the target on the material response to the fast laser energy deposition. In particular, the mechanisms and driving forces responsible for the generation of point defects (vacancies and interstitials) in femtosecond laser interactions with Cr target [4] will be discussed based on the results of molecular dynamics simulations. The simulations are designed to investigate the relative contributions of the thermally-activated generation of vacancy-interstitial pairs during the laser-induced temperature spike and the production of the point defects at the advancing solid-liquid interface during the solidification process. The implications of the computational predictions for atomic mixing and damage accumulation in multi-pulse irradiation regime are discussed. To address the role of the microstructure of the irradiated target on laser-induced phase transformations, the results earlier simulations of short pulse laser melting of single crystal films and bulk targets [1,5] are compared with computational predictions obtained for nanocrystalline Au films [2]. The effect of nanocrystalline structure on the melting process is investigated for a broad range of laser fluences. At low laser fluences, close to the threshold for the complete melting of the film, the initiation of melting at grain boundaries is found to steer the melting process along the path where the melting continues below the equilibrium melting temperature and the crystalline regions shrink and disappear under conditions of substantial undercooling. The unusual melting behavior of nanocrystalline films is explained based on thermodynamic analysis of the stability of small crystalline clusters surrounded by undercooled liquid [2]. The physical processes responsible for the material ejection in laser ablation will also be briefly discussed based on the results of simulations performed for bulk Ni targets [1].

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[3] Transport of Light Absorbing Particles in Air with a Laser Pipeline

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Topics: Physics of Laser-Matter interaction, Advances of Laser Trapping

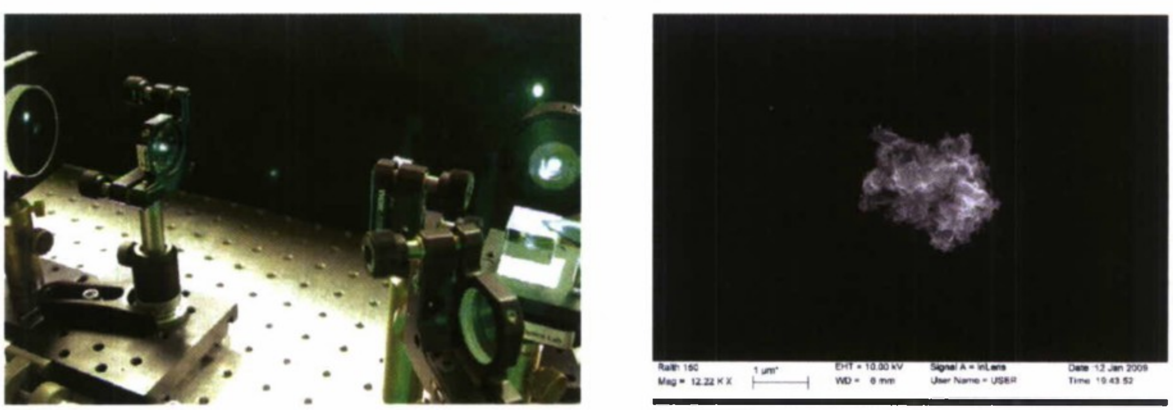
We developed an optical pipeline for laser-guiding particles in air using optical vortex beams. We employ photophoretic forces for catching particles in air and transport them over a meter-long distance by a laser beam. The photophoretic forces appear when a surface of an air born particle is heated nonuniformly by an incident light, so that the gas molecules rebound off the surface with different velocities creating an integrated force on a particle.

The main difficulty associated with the use of thermal forces in gases is the stability of trapping, because absorbing particles are repelled from the intensity maximum of the laser beam. We overcome this difficulty by employing counter-propagating doughnut-shaped optical vortex beams, which offer stability and robustness of trapping [1,2]. The optical trap was formed by the standing wave of two counter-propagating vortex beams with opposite topological charges, creating a radially symmetric and azimuthally homogeneous intensity distribution in the trap volume. The distinguishing feature of this approach is that particles are trapped at the intensity minimum of the beam, thus with minimal heating and minimal intervention into the particle properties, which is important for direct studies of particle properties and for air trapping of live cells.

We used agglomerates of carbon nanoparticles produced by a high-repetition-rate laser ablation technique to illustrate trapping of particles in air [3]. The nanoclusters were trapped and agglomerated in larger chunks, which could be collected from the trap for diagnostics of the content, see Fig. 1(b). The size of the aggregates of the nanoclusters was varied from 0.1 μm up to 100 μm in our experiments, mainly depending on the laser power and the cross-section size of the beam.

The scheme offers two principal degrees of freedom for optical manipulation of trapped particles, by changing the polarization and by changing the distance between the focal planes of two optical vortex beams. This feature presents a unique possibility of using the vortex beam as an optical pipeline for transport of absorbing particles over large distances in gas environment.

The ability to capture absorbing particles suspended in gases by contact-less optical means opens up rich and diverse practical opportunities. The new approach will be of direct importance in the areas of air pollution and environmental protection, and will allow simulating on the processes studied in atmospheric and planetary sciences in laboratory scales.



(a) (b)

Fig. 1. Trapping of particles in air with counter-propagating optical vortices. (a) The scattered light from the agglomeration of carbon nanoparticles is clearly seen in the centre. (b) SEM image of a particle collected from the trap on a Si wafer; the scale bar is 1 μm.

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[7] Laser Applications for Nanotechnology: Insights from Numerical Modeling

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Abstract

Laser-produced nanoparticles have found many applications in bio-photonics, medicine and in the development of photovolvatic cells. Many experiments have been performed demonstrating the formation of these particles from solid targets in vacuum, in the presence of a gas or a liquid. However, it is still difficult to predict the size distribution of these particles. Therefore, we have performed an extensive numerical modeling of the involved physical processes. The developed models allow us to compare the relative contribution of several processes involved in the cluster

production by laser ablation: (i) direct cluster ejection from a target under rapid laser interaction, (ii) condensation/evaporation; (iii) fragmentation/aggregation processes during cluster diffusion; and (iv) diffusion and coalescence if nanoparticles are deposited on a substrate. The calculation results of both hydrodynamic and molecular dynamics simulations demonstrate that an exposure of a target to a short or ultra-short laser pulse leads to an explosive target decomposition and to the ejection of nanoparticles [1,2]. These cluster precursors are formed during rapid target expansion through both thermal and mechanical processes. Collisions with background species affect the cluster size distribution. The influences of the parameters, such as initial cluster temperature and size, background temperature and density, on the cluster evolution are analyzed. The diffusion-limited aggregation process is shown to depend both on laser-dependent cluster density and on the properties of the background gas or liquid leading to a significant increase in particle size. If particle density is high enough, the final size distribution is also affected by the substrate material properties due to the particle diffusion and coalescence occurring after the nanoparticle deposition.

In addition, laser-induced phase explosion process is shown to play an important role in the first stage of the formation of the periodic structures on the surfaces of some materials. Cluster ejection leads to the formation of the caotically-modumlated relief that is then transferred into periodic structures upon the action of several laser pulses.

These calculation results can be used to explain many recent experimental observations.

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[126] Controlled Nonlinear Energy Deposition in Transparent Materials: Experiments and Theory

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Using a novel experimental technique that detects transient laser effects as small as 50 nm [1], we recently demonstrated that low-density plasmas and nanoeffects can be produced not only using ultra-short laser pulses but also, in a much more cost-effective way, by means of temporally smooth nanosecond pulses of short wavelengths [2]. We also showed that luminescent plasmas of high energy density are formed when tightly focused femtosecond pulses of > 100 nJ pulse energy are focused into transparent materials and determined the corresponding plasma pressure and temperature [3]. Our experiments thus reveal that controlled nonlinear energy deposition with widely tunable energy densities is possible in a large part of the parameter space spanned by wavelength (UV to IR) and pulse duration (fs to ns). Only ns breakdown at IR wavelengths is intrinsically characterized by an abrupt jump from 'no absorption' to brightly luminescent, dense plasma. The tunability opens exciting perspectives for laser material processing, precision manufacturing, and surgery of cells and tissues.

Modeling of controlled nonlinear energy deposition requires a change of paradigms: it is no longer sufficient to determine breakdown thresholds but one needs to be able to calculate the dependence of energy density and material temperature from laser parameters to assess the resulting phase transition and ablation effects. We present a model that fulfils these requirements. Besides considering photoionization, avalanche ionization, recombination, and diffusion losses, it also considers heating through residual linear absorption and via collision losses and recombination of the free electrons produced by nonlinear absorption, as well as its counteraction by heat diffusion out of the focal volume. Sufficiently high temperatures result in thermal ionization accelerating the ionization avalanche.

The predictions of the advanced model are in excellent agreement with our experimental results achieved with fs, ps and ns pulses at various wavelengths from 347 to 1064 nm. They also explain the different ablation behavior of tailored fs pulses with positive and negative cubic phase from that of unshaped pulses [4]. The good agreement encouraged creating a map of the (λ,τ) parameter space in which the dependence of target temperature on laser energy is calculated for each (λ,τ) value. This 'tunability' map for the magnitude of laser effects is very useful in guiding the choice of laser parameters for a large variety of applications.

Finally, we demonstrate the tuning of nanosecond laser material interactions from the generation of nanoeffects to larger, disruptive effects on various examples ranging from cell surgery and corneal intrastromal dissection to the writing of waveguides or patterns in glass.

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[63] Damage Mechanisms in Thin Film and Bulk Polymers upon NIR Femtosecond Pulse Laser Irradiation: Sub-threshold Processes and Their Implications for Laser Safety Applications

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<u>Topics</u>

Physics of Laser Matter Interactions, High Power Laser Application and Diagnostics, Laser Safety

<u>Abstract</u>

Ultrashort pulse lasers are the most important experimental tools for investigating fast evolving processes in physics, chemistry, and biology. The availability of reliable laser systems enabled applications in medicine and micromachining based on new regimes of light-matter interactions. Therefore, in-depth knowledge of laser-induced damage thresholds (LIDT) and damage mechanisms of optical materials is essential specifically to improve the laser protection abilities of the user against the high-intensity radiation emitted by femtosecond laser systems. This contribution describes different approaches for the measurement of LIDT of thin film and bulk polymer samples. The dependence of LIDT on the band gap energy of bulk samples and on the laser pulse duration will be discussed. In addition to ex-situ microscopic characterizations, in-situ real-time reflectivity (RTR) measurements with picosecond and nanosecond temporal resolution were performed on thin polymer films on a timescale up to a few microseconds. A model for polymer thin film damage will be presented indicating that irreversible chemical modification processes take place already below the fluence threshold of macroscopic damage. On dye-doped bulk polymer filters (as used for laser goggles), transmission studies using femtosecond and picosecond laser pulses reveal the optical saturation behavior of the material and its relation to the threshold of permanent damage. Implications of the sub-threshold processes for laser safety applications will be discussed for thin film and bulk polymer damage.

[29] Surface-specific Laser Matter Interactions and Dynamics

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Topic: Physics of Laser Matter Interactions

Abstract:

Understanding the chemical dynamics of electronically excited species in solids is essential to forming mechanistic models relevant to photocatalysis, radiation chemistry, and energy transfer. Irradiation of solid surfaces by UV, or higher energy photons, produces energetic species such as holes and free electrons, that relax to form electron-hole pairs, excitons, and other transient species capable of driving surface and bulk reactions. Photo-stimulated desorption, of atoms or molecules, provides a direct window into many important processes and is often indicative of electronic excited state dynamics of bulk and surface states. We use femtosecond and nanosecond lasers to excite specific surface sites (e.g. terraces, step edges, corners) of nano-structured wide-gap ionic crystals and measure velocities and state distributions of desorbed atoms or molecules under highly controlled conditions. Photon energies are chosen to excite specific surface structural features that lead to particular desorption reactions. The photon energy selective approach takes advantage of energetic differences between surface and bulk exciton states and probes the surface exciton directly. We have demonstrated that desorbed atom product states can be selected by careful choice of laser wavelength, pulse duration, and delay between laser pulses. Excited state chemistry in solids is inherently complex and greater understanding is gained using a combined experiment/theory approach. Our experiments are designed specifically to test theoretical models based on the results of *ab initio* calculations.

Application of this approach to controlling the yield and state distributions of desorbed species requires detailed knowledge of the atomic structure, optical properties, and electronic structure. To date we have thoroughly demonstrated surface-selective excitation and reaction on alkali halides. However, the technological applications of alkali halides are limited compared to oxide materials. Our current efforts focus on technologically important materials such as metal oxides. Oxides serve as dielectrics in microelectronics and form the basis for exotic semi- and super-conducting materials. Although the electronic structure of oxides differs considerably from alkali halides, it now appears possible to generalize the exciton model for laser surface reactions to these interesting materials. Our recent studies have explored nanostructured samples grown by chemical vapor deposition or thin films grown by reactive ballistic deposition (RBD) in addition to cleaved single crystal surfaces.

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Nanophotonic Ion Sources

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Topics: Photonics, Near-field Effects, Physics of Laser Matter Interactions

Near-field effects in laser light-nanostructure interactions result in highly confined and enhanced electromagnetic fields. These strong fields and elevated radiation intensities can efficiently couple the laser energy to the local environment. Recently, ion production from adsorbates has been demonstrated at elevated laser intensities from laser-induced silicon microcolumn arrays (LISMA) that have features commensurate to the wavelength of radiation. Ion production from LISMA exhibited nanophotonic properties, such as strong polarization and laser incidence angle dependence. Activation of the ions, laser desorbed from LISMA structures, show fragmentation compatible with the presence of both low and high energy channels.

To expand the limited range of accessible geometries and aspect ratios of microcolumns for photonic ion production, silicon nanopost arrays (NAPA) are nanofabricated. The nanopost heights, H, diameters, D, and periodicities, P, are varied in the 200-1500 nm, 50-600 nm and 200-1200 nm ranges, respectively. Upon irradiation by a UV laser pulse, posts with subwavelength diameters show resonant ion production at high aspect ratios (H/D). For example, a post height of 1200 nm and a post diameter of 200 nm, i.e., H/D = 6, resulted in a 55-fold increase in the ion yield compared to the H/D = 1 case. As the diameters of the posts decrease, the resonances shift to higher aspect ratios. These resonances are linked to the near-field enhancements of the laser intensity around the posts, as well as to energy dissipation and redistribution in these structures.

To explore the desorption and activation of adsorbates on NAPA surfaces, we study the survival yields of preformed ions with a single decomposition channel (thermometer ions). For a wide range of laser fluences, ions desorbed from NAPA with post diameters from 200 to 500 nm the survival yields do not change. In contrast, NAPA with post diameters of 100 nm exhibit a dramatic decrease in survival yields as the laser fluence is increased, indicating a different desorption mechanism for the thinner posts. In particular, radial energy redistribution in these posts is limited, as the heat conduction length is larger than their diameter. As a consequence, upon laser irradiation, the surface temperature of these posts sharply increases. Similar to LISMA, biomolecular ions with multiple decomposition channels show the presence of both low and high energy processes on NAPA.

The nanophotonic interactions are also explored by changing the incidence angle and plane of polarization of the electromagnetic field in the ion production experiments. Dramatic increase in the ion yield is observed when the laser beam is changed from s- to p-polarized and ion yields, irrespective of polarization, vanish under right angle illumination conditions.

LISMA and NAPA systems constitute an entirely new class of ion sources that work on the basis of photonic interactions. Their properties enable fast switching and modulation of ion production and provide control over the internal energy of the generated ions. Further development and insight into photonic ionization promise to eliminate the need for additional ion activation, while reducing the size of the ion source. Eventually, photonic ion sources can be integrated with micromachined mass spectrometers and microfluidic devices.

Session 3: Laser-matter interaction physics and modeling II
Wayne Hess, chair

[32] Fundamentals of Femtosecond Laser Ablation of Dielectric Materials

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Topics: Physics of Laser Matter Interactions, Femtosecond and Attosecond Effects, Simulations

The modeling of laser-excited dielectric materials requires a detailed description of the electronic excitation. Dielectric materials do not absorb visible light by traditional linear absorption, so the dynamical generation of conduction-band electrons strongly couples to the absorption. The generation of free electrons is initiated by strong-field excitation and followed by multiplication through impact ionization by energetic electrons heated by inverse bremsstrahlung. With free electrons present, absorption of the remaining part of the light pulse becomes much more efficient.

There has been a lot of effort in modeling the ablation threshold of dielectrics. The level of detail has varied considerably, where the most advanced models are computationally demanding and not suitable for an extension to include propagation of light into the bulk. As a consequence Rethfeld [1] has proposed a multiple-rate-equation (MRE) model, which includes the most dominant physical effects, with less demand on the computation time. In the MRE model, electrons in the valence band are excited to the conduction band by strong-field ionization followed by one-photon excitation leading to an increased energy of the conduction-band electrons. When the energy of an electron in the conduction band is sufficiently high, impact ionization can occur, and two electrons with a low kinetic energy are generated.

In the present work [2], the MRE model is expanded to include propagation of the optical fields into the material in a one-dimensional model. The excited electrons are assumed to behave as a free-electron gas described by a Drude model. The model is generic and based on a few key para-meters: the wavelength and the pulse duration of the light, and the band gap of the dielectric medium. The inclusion of light propagation allows for a determination of ablation depths. Simulations have been made for varying wavelengths, pulse durations and band gaps of the materials, see, e.g., the figure to the right.

The dependence on key parameters obtained from the simulations as well as the underlying physical explanation will be discussed. In addition, simulated results will be compared to an ongoing experimental investigation of single-shot ablation on a range of dielectric materials.

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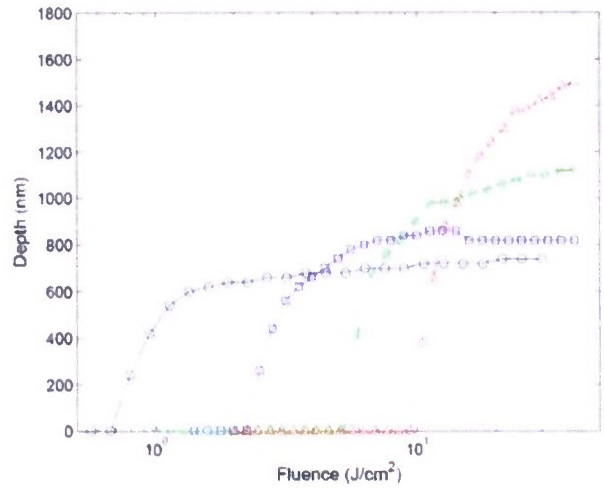

The calculated ablation depth as a function of laser fluence for varying band gaps [2]. The band gaps are: Black circles 3 eV, blue squares 5 eV, green diamonds 7 eV and red triangles 9 eV.

The calculated ablation depth as a function of laser fluence for varying band gaps [2]. The band gaps are: Black circles 3 eV, blue squares 5 eV, green diamonds 7 eV and red triangles 9 eV

[91] Laser Nanostructurization of the Metal and Alloy Surfaces

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Topics: Physics of Laser-Matter Interaction, Nanoengineering, Fundamental Theory

Abstract

Rapid development of the ultrashort pulses lasers opens up possibilities for new applications of material precision treatment as compared to conventional lasers. Nanostructuring of the metal surface layers makes use of femtosecond laser pulses with the intensities close to the threshold ones, where one observes the metal melting in a small volume without any significant ablation.

Modification of the structure and phase properties of the metal and alloy surface layers under superfast cooling velocities are widely used to produce superfine crystalline and amorphous structures with an application of the laser pulses of ultrashort duration. After the end of the laser pulse the melt is rapidly crystallized due to the heat propagation into the specimen depth. Due to superfast colling (10^9 K/s and higher) the size of the produced crystallites may be compared with an interatomic spacing. An amorphous layer may be formed, if the cooling velocity exceeds the freezing rate.

In case of a femtosecond laser pulse the material heating and melting processes take place under essentially nonlinear and non-equilibrium conditions. However, the kinetics of the melt cooling after the action of a supershort laser pulse is defined, finally, by the velocity of heat propagation into the material depth, and for the metals this velocity makes about 10^{13} - 10^{15} K/s. So, the time of cooling makes the value more than 10^{-12}s. This means that one can make use of a heat model applied in classical consideration of the crystallization kinetics.

The crystallization kinetics of metals from the melt under superfast cooling velocities realized in the treatment of the materials by ultrashort laser pulses has been studied. An explicit solution to kinetic equation for the size distribution function of crystalline phase nuclei at the fast cooling of the melt

was analyzed analytically and numerically. The use has been made of physical preconditions for the crystallization process practically realized at superfast cooling: the existence of a sufficiently large number of crystal nuclei of supercritical size and a plate-type shape of the nuclei. An average size of crystallites has been defined, as well as the volume fraction of crystallized phase. The amorphyzation criterion for the melt cooling velocity is determined.

The presented expressions for the crystal nuclei size and the new phase volume have been used to describe the experiments on micro- and nanostructuring of the metal surface layers under the action of femtosecond laser pulses.

The work was supported by the Grant 09-02-06186 of Russian Foundation for Basic Research, and by Grants of Russian Academy of Science.

[82] Large-scale Molecular Dynamics Simulations of Ablation and Spallation of Gold Irradiated by Femtosecond Laser Pulse

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Topics: Physics of Laser Matter Interactions; Femtosecond and Attosecond Effects; Simulations

In this talk we present results of large-scale molecular dynamics simulations of ablation and spallation processes in gold thin films produced by the ultrashort laser pulse with duration $\tau < 1$ ps, and incident fluence ~1 J/cm^2. In order to capture reach physics of materials response, it is critical use the realistic samples of 1 μm thickness which contain 0.1 billion atoms. The major processes considered in this work are the two-temperature electron-ion thermalization, the formation of the high pressure zone, followed by the propagation of strong rarefaction and compression waves. We specifically discuss the atomic-scale details of the propagation of the rarefaction wave which produce the nucleation of bubbles, cavitation and ablation of subsurface layer [1]. Concurrently, in the same simulation run, the compression wave is transformed to shock wave propagating towards the rear side of foil, followed by the formation of cracks and rear-side spallation of target. The MD simulations were capable of capturing the complex interplay between the processes of spallation and ablation in gold: dynamics of spallation depends on shock wave profile originated from the pressure profile in ablated zone formed at early stage of laser energy absorption. Such strong inter-connection between spallation and ablation can only be revealed if simulation includes the entire dynamics of the materials response at the time and length scales close to those observed in experiment. The key to achieving realistic description of the complex atomic-scale processes taking place during ablation and spallation is the availability of robust interatomic potentials that are capable of to reproduce properties of bulk gold at wide range of pressures and densities. Due to failure of existing embedded atom potentials (EAM) to simulate the properties of gold at extreme conditions, we used in simulations new analytical EAM Au potential which was fitted to reproduce the density functional theory cold pressure curves [2]. In addition to observing complex atomic-scale processes during ablation and spallation, the MD simulations provide quantitative data: cavitation strength of molten Au, the ablation and spallation thresholds, the strain rate in spallation zone at the spallation threshold, the spall strength of solid Au. Comparison with available experimental data including the crater depth and the ablation threshold will also be presented.

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[90] Laser-induced Modification of Energy Bands of Transparent Solids

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Presentation: invited

Topic: 1 – Fundamental Theory; 2 – Physics of Laser Matter Interactions

Abstract:

The main focus of this presentation is to theoretically analyze the fast variations of energy spectrum of electrons in non-metal crystals induced by high-intensity laser radiation. The main mechanisms of the energy-spectrum changes are attributed to laser-induced variations of electron states. Being subjected to action of laser radiation, the electrons cannot be characterized by the time-independent Bloch functions. It means that the energy spectrum determined for the steady electron states (i.e., corresponding to the initial material before the laser action) is modified. We identify the following modification mechanisms:

pondermotive potential resulted from the laser-driven electron oscillations;

specific high-frequency Franz-Keldysh effect attributed to laser-induced modification of the crystal potential;

excitation of electrons from valence to conduction band.

We analyze and discuss each of those mechanisms and consider the interplay between them. In particular, the pondermotive potential results in increase or oscillatory variations of effective band gap. This effect was considered by Keldysh in his model of the photo-ionization [1]. Later we demonstrated that this type of band-structure modification can be more complicated [2] leading to flattening of energy bands. The classical Franz-Keldysh effect (FKE) [3] results in exponential spreading of electron states into the forbidden band and the corresponding decrease of the band gap. Our analysis shows that the classical description of FKE is not acceptable in the case of interest, i.e., when the band structure is modified by the same radiation that is absorbed by the electrons. Analyzing the specific formulation of FKE for the high-intensity laser action, we demonstrate that the band-structure modification by the pondermotive potential dominates in multiphoton regime at low laser intensity, but FKE always dominates at high laser intensity in the tunneling regime. The high-frequency FKE can result in a variety of effects, e.g., band-gap collapse in semiconductors and specific shifts of the cutoff of white-light generation spectrum in wide-band gap solids. We discuss the possible modifications of laser-induced electron processes resulted from the modifications of the energy bands in transparent solids.

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Key words: Franz-Keldysh effect, Keldysh formula, photo-ionization, laser-induced breakdown, wide band-gap dielectrics.

Session 4: Short pulse laser-matter interactions I
Pete Latham, chair

[1] Temporal Femtosecond Pulse Tailoring for Nanoscale Laser Processing of Wide Band Gap Materials

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Topics:

Femtosecond and Attosecond Effects
Nanoengineering
Physics of Laser Matter Interactions

Abstract:

Ultrashort laser pulses are a promising tool for processing wide band gap materials for a variety of applications ranging from precision micromachining even below the wavelength of light to medical surgery. It is the transient free-electron density in the conduction band playing a fundamental role for sub picosecond pulses [1] [2] [3] that after coupling to the lattice lead to phase transitions or the creation of voids.

In our work we make use of temporally asymmetric femtosecond pulses of identical fluence and identical statistical pulse duration in order to control two distinct ionization processes, i.e. photoionization and electron-electron impact ionization. Control leads to different final electron densities / energies as the direct temporal intensity-profile and the time inverted intensity-profile address the two ionization processes in a different fashion. This results in observed different thresholds for material modification in fused silica as well as in reproducible lateral structures being an order of magnitude below the diffraction limit (down to 100 nm at a NA of 0.5) being robust with respect to laser fluence variations [4] [5]. These findings are supported by our recent experiments: we used chirped pulses with comparable pulse duration and observed that the asymmetric temporal frequency ordering had no significant influence on the ablation thresholds. In addition, experiments with geometrically overlapping focal regions did not show incubation effects on the creation of the nanostructures. In order to get a conclusive picture we currently extend our studies on time resolved plasma dynamics [6] to spectral interference measurements with shaped laser pulses. Aiming at optimizing the temporal pulse shapes further, we started to simulate the free electron creation under the constraint of minimizing the spatial structure. Minimizing the spatial structure and at the same time maximizing the spectrochemical sensitivity for fs-LIBS [7] completes our experiments exploiting temporal pulse tailoring for material processing.

Here I will shortly describe our temporal pulse shaping approach and discuss the experiments sketched above.

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[53] Laser-material Interaction and its Applications in Surface Micro-nanoprocessing

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Abstract:

In this talk, dynamic laser-material interaction will be reviewed to achieve high quality micro- & nano-scale surface processing. How to achieve small heat affected zone (HAZ) is one of the key issues. Process optimization of the laser-material interaction can provide us novel approaches to overcome the optical diffraction limit for sub-wavelength resolution. Hybrid laser processing can lead to the laser precision engineering of difficultly processed substrates, such as wafer thinning, micro-drilling of heat sensitive polymer and singulation of ultra-thin devices. Combined with AFM and NSOM means, laser processing resolution can be pushed further down to sub-50nm. To solve the other technical bottleneck of slow laser nanoprocessing speed, parallel (multi-beam) and maskless laser processing techniques are developed. Potential applications and technical challenges for the laser-material interaction to cater for 22nm and beyond laser nanolithography, based on high efficiency less debris laser produced plasma (LPP) EUV light source and flexible laser manipulation of atom deposition will also be discussed.

Keyword: laser-material interaction, surface micro-processing, nanofabrication.

[13] Wavelength Effects in Femtosecond Pulsed laser Ablation and Deposition

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Topics: 1 - Femtosecond & Attosecond Effects; 2 - PLD, MAPLE & Processing of Advanced Materials; 3 - Physics of Laser Matter Interactions

Abstract:

Ultrafast pulsed laser irradiation of solid materials is used for surface and bulk structuring and for deposition of nanostructured films or nanoparticles of a wide variety of materials. Ultrashort femtosecond (fs) laser pulses promote efficient material removal with reduced heat transfer and high

deposition rates of nanometer scale particles free of microscopic particulates. Therefore their use is highly attractive for the micro- and nano-structuring of substrates and for the fabrication of nanostructured deposits. However most of the studies to date have been performed with light pulses centered around the peak wavelength of the Titanium:Sapphire laser around 800 nm. Analysis of the process over a broader range of wavelengths can provide important information about the processes involved and serve as experimental tests for advanced theoretical models.

This talk will present our recent [1,2] and on-going research on the effect that laser wavelength of fs pulses has on: a) the nanostructuring induced in biopolymer substrates, and b) on the characteristics of nanostructured deposits grown by pulsed laser deposition from semiconductor targets. Laser irradiation with 90 fs pulses at 800, 400 and 266 nm of biopolymers is examined in self-standing films of gelatine, chitosan, and blends with synthetic polymers, and is shown to result in the formation of a modified layer with sub micrometric structures. The size and uniformity of the observed features are strongly dependent on irradiation wavelength and on the characteristics of the biopolymer (water content and mechanical strength). On the other hand, nanostructured deposits of semiconductors TiO_2 and CdS were grown on Si (1 0 0) substrates by laser ablating a target in vacuum or in oxygen using 80 fs pulses at the three wavelengths as above. A clear tendency is observed consisting on the production of smaller nanoparticles with a narrower size distribution at shorter wavelengths of the fs pulses.

The mechanisms governing the observed trends with fs laser wavelength, together with the implications of the above findings for the application of organic and semiconductor nanostructured substrates in biomedicine and photonics will be discussed in the presentation.

Acknowledgements: The skilled research of my collaborators, most recently S. Gaspard, R. de Nalda, M. Oujja, S. Pérez, M. Sanz and W. Walczak is thankfully acknowledged.

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[2] M. Sanz, M. Walczak, R. de Nalda, M. Oujja, J.F. Marco, J. Rodriguez, J.G. Izquierdo, L. Bañares, M. Castillejo, *Appl. Surf. Sci.* **255** (2009) 5206.

[40] Adaptive Pulse Shaping for Controlling Emission Lines in Ultrashort Laser Produced Plasmas

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Topic(s): 1 – Simulations ; 2 – PLD, MAPLE and Processing of Advanced Materials ; 3 – High Power Lasers Applications & Diagnostics ; 4 – Physics of Laser Matter Interactions

Abstract :

We discuss the possibility to influence and optimize the optical emission of the different ion species in the ablation plume induced by laser-irradiated aluminium surfaces. For laser fluences exceeding the ablation threshold, temporal tailoring of laser pulses was used to optimize the relative weight a spectroscopic line with respect to the neighbouring spectral components and thereby to gain extended control over spectral composition. Consequently, evolutionary algorithm and adaptive pulse shaping were applied to control intensity ratios of selected emission lines in the induced Al plasma plume. Furthermore, deposition of thin films is performed using the different temporally optimized and femtosecond light distributions. Morphological characterization and the particle distribution on sizes estimated by measurements on the corresponding deposited films are investigated for PLD applications [1].

Hydrodynamics simulations have been performed to correlate intensity envelopes of the laser fields and thermodynamical states reached by the emerging plasma phase. We will discuss the efficiency of energy coupling as a function of different intensity envelopes and the resulting temperature, density and ionization rates since the energy delivery rate is an essential factor that predetermines the material thermodynamic evolution [2]. Subsequently, we examine probable thermodynamic paths for material ejection under the laser action. The plasma composition is calculated as a function of time and the neutral/ion species ratios typical of LIBS signals are compared with experimental results. Moreover, the calculations allow to investigate the efficiency of nanoparticles generation from materials subjected to different heating rates, in comparing the ejection features of a confined liquid shell. With support from these numerical simulations of the hydrodynamic advance of the excited matter, experiments revealed that controlling intensity envelopes of ultrashort laser pulse, emerging plasma phase in a hot state generates a specific spectral emission which can serve as a guideline for optimal control of its formation and kinetic evolution.

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* presenting author - invited paper

[11] Ultra-fast Phase Transitions Induced by fs-lasers in Solids: Superheating Before the Entropy Catastrophe

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The advent of fs-lasers and novel diagnostic techniques (ultra-short x-ray, optical and electronic probes) during the last decades made possible the studies of transient material transformation induced by ultra-short powerful lasers. However, there is a controversy in interpretation of the entirety of experiments. There are papers interpreting the fall-off of x-ray probe intensity as evidence of a non-thermal lattice melting solely by electronic excitation. On the other hand probing of the fs-laser excited ice, Al, Bi and Ga demonstrate that the melting time is much longer than time needed for the electron-to-lattice equilibration thus evidencing the purely thermal character of the ultra-fast melting.

It was established that the ultimate stability limit of a superheated crystal is achieved when entropy of a crystal equals to that of it's liquid (entropy catastrophe) [1]. The entropy catastrophe value mainly depends on point defects concentration and lattice temperature [2]. The point defects and lattice heating are two major sources for the catastrophic disordering of a crystal in equilibrium. I demonstrate that the point defects formation time in fs-laser excited solid is the longest of all relaxation times. Therefore a swiftly heated solid can be brought to the entropy catastrophe state before the point defects formation only if a lattice is superheated well over the melting enthalpy. Analysis of experiments on fs excitation of different solids reveals this salient feature of ultra-fast transformation.

I demonstrate that characterization of the transient processes in a laser-excited solid through the changes in entropy, the most fundamental measure of disorder, allows consistent explanation of the diverse experiments without controversy [3]. The entropy catastrophe criterion unequivocally determines that the ultra-fast melting commences when the lattice is superheated over the equilibrium melting point while the point defects are so far absent. The main parts of electron and lattice distributions are established before electron-to-lattice energy transfer time, thus making entropy a legitimate concept for description of ultra-fast processes. The salient feature of the ultra-short laser-solid interaction is that the generation of non-equilibrium point defects appears to be the longest of all characteristic times. Thus ultra-fast catastrophic disordering, i.e. melting, becomes only possible when the lattice is superheated in the absence of defects in a purely thermal mode.

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3. E. Gamaly, *Entropy catastrophe: stability limit for solids overheated by ultra-short laser assuring thermal mechanism of rapid melting*, EMRS 2008 Spring Meeting, Symposium B, Strasbourg, May 26-30, 2008

Topics: Fundamental theory; Femtosecond effects; Physics of laser-matter interaction

[85] Laser System for Space Debris Cleaning

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Presenter: ***Alexander Rubenchik***, rubenchik1@llnl.gov

Topic: Applications – Laser Space Debris Mitigation and Planetary Defense

The use of a ground based laser for space debris cleaning was investigated by the ORION project in 1996. Since that study the greatest technological advance in the development of high energy pulsed laser systems has taken place within the NIF project at LLNL. The proposed next laser system to follow the NIF at LLNL will be a high rep rate version of the NIF based on diode-pumping rather than flashlamp excitation; the so called "LIFE" laser system. Because a single "LIFE" beamline could be built up in a few year time frame, and has performance characteristics relevant to the space debris clearing problem, such a beamline could enable a near term demonstration of space debris cleaning. Moreover, the specifics of debris cleaning make it possible to simplify the LIFE laser beyond what is required for a fusion drive laser, and so substantially reduce its cost. Starting with the requirements for laser intensity on the target, and then considering beam delivery, we will flow back

the laser requirements needed for space debris cleaning. Using these derived requirements we will then optimize the pulse duration, the operational regime, and the output pulse energy of the laser with a focus of simplifying its overall design. Anticipated simplifications include operation in the heat capacity regime, eliminating cooling requirements on the laser gain slabs, and relaxing B-integral and birefrigence requirements. Estimates of laser size and cost will be presented.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Monday Evening Poster Session
Tony Hostutler, chair

[83] Solar Pumped Laser Microthruster

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Presenter: Alexander Rubenchik, rubenchik1@llnl.gov
Topic: Laser Ablation Propulsion

Abstract:

The development of microsatellites requires the development of engines to modify their orbit. It is natural to use solar energy to drive such engines. For an unlimited energy source the optimal thruster must use a minimal amount of expandable material to minimize launch costs. This requires the ejected material to have the maximal velocity and, hence, the ejected atoms must be as light as possible and be ejected by as high an energy density source as possible. Such propulsion can be induced by pulses from an ultra-short laser. The ultra-short laser provides the high-energy concentration and high ejecta velocity. We suggest a microthruster system comprised of an inflatable solar concentrator, a solar panel, and a diode-pumped fiber laser. We will describe the system design and give weight estimates. The comparison with ion thrusters and direct pumping by the diodes will also be presented.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

[70] High Current Cathodes Fabricated by KrF Laser Ablation

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Session: High Power Laser Applications and Diagnostics

Abstract:

High current (1-10 kA) electron beam cathodes for accelerators and microwave sources have been fabricated at the University of Michigan by several laser ablation techniques:

1) Projection Ablation Lithography (PAL) cathodes, 2) Ablation Line Focus (ALF) cathodes, and 3) Metal-Oxide-Junction (MOJ) cathodes. Laser-ablative micromachining techniques (PAL and ALF) have been utilized to generate microscopic features on metal substrates that provide electric field

(beta) enhancement for Fowler-Nordheim emission and plasma cathodes. Since these laser-ablated patterns are directly written on the substrate metal they exhibit much higher thermal conductivity for higher current capability and increased damage thresholds.

The ablation laser is a KrF excimer laser with a per-pulse energy of 600 mJ and pulselength of 20 ns. Laser-ablative deposition has been applied to deposit arrays of hafnium-oxide islands (metal-oxide junctions) for triple-point cathodes. Triple-point is defined as the interface between metal, dielectric and vacuum. We exploit the electron emission feature of triple-points to develop high current cathodes. The KrF laser ablates a solid target of hafnium metal in a background gas of 20% O_2 / 80% Ar at 100 mTorr. Contact lithography is employed to fabricate arrays of HfO_2 islands on metal substrates. Plasma plume diagnostics by gated optical emission spectroscopy reveal neutral and singly-ionized hafnium in the ablation plasma plume. Hafnium-oxide film diagnostics include XEDS, SEM, TEM, profilometry, ellipsometry and x-ray diffraction (XRD). Hafnium-oxide deposition rates are about 0.06 nm/pulse. Cathode experiments were performed on the MELBA-C accelerator: V = -300 kV, pulselength = 0.5 microsecond. Data will be presented for PAL, ALF and MOJ cathodes. For MOJ cathodes, three cases were compared: 1) pure Hf metal, 2) pure HfO_2, 3) HfO_2 island on metal substrate. Effects of laser ablated particulate will be discussed.

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[111] Nanostructuring of Solid Surfaces by Femtosecond Laser Pulses

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Experimental results on femtosecond laser surface nanostructuring of various solid materials – aluminum, titanium, and silicon – under dry and wet surface conditions are presented. The fabricated nanostructures exhibit both quasi-periodic and irregular surface relief features.In particular, on atomically flat silicon and mechanically polished titanium multi-shot fabrication of one-dimensional sub-wavelength ripples with spatial periods in the range of 200-500 nm, visualized by means of scanning ion-electron microscope, are observed. In contrast, on mechanically polished Al surfaces two-dimensional nanostructures appeared even after single laser shot. Depending on laser dose (laser fluence multiplied by the number of shots), in the case of titanium surfaces evolution of surface nanoscale structures (spallation sites, trenches etc.) developing into the above mentioned one-dimensional sub-wavelength nanoripples can be seen. The physical mechanisms underlying the femtosecond laser fabrication of such nanostructures and their applications in biomedicine and optoelectronics are discussed.

[23] Investigation of Laser Propulsion for Transport in Water Environment

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Topics: Laser Ablation Propulsion, Physics of Laser Matter Interactions, Simulations.

Abstract: Problems that cumber the development of the laser propulsion in atmosphere and vacuum are discussed. Based on the theory of interaction between high-intensity laser and materials, as air

and water, it is proved that transport in water environment can be impulsed by laser. The process of laser propulsion in water is investigated theoretically and numerically. It shows that not only the laser induced plasma shock wave, but also the laser induced bubble oscillation shock waves and the pressure induced by the collapsing bubble can be used. Many experimental results show that the theory and the numerical results are valid. The numerical result of the contribution of every propulsion source is given in percentage. And the maximum momentum coupling coefficient C_m is given. Laser propulsion in water environment can be applied in many fields. For example, it can provide highly controllable forces of the order of micro-Newton (μN) in microsystems, such as the MEMS (Micro-electromechanical Systems). It can be used as minimally invasive surgery tools of high temporal and spatial resolution. It can be used as the propulsion source in marine survey and exploitation.

[109] $O_2(a^1\Delta)$ Quenching in the $O/O_2/O_3$ System

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Abstract:

Rapid quenching of $O_2(a^1\Delta)$ in $O(^3P)/O_2/O_3$ mixtures has been observed. Oxygen atoms and singlet oxygen $O_2(a^1\Delta)$ molecules were produced by 248 nm laser photolysis of ozone. $O_2(a^1\Delta)$ quenching was followed by detecting the 1268 nm fluorescence from the *a-X* transition. Temporal profiles for the oxygen atoms $O(^3P)$ were monitored by means of the O+NO chemiluminescent reaction. Fast and slow decays of $O_2(a^1\Delta)$ were observed. The fast decay was observed when O atoms were present in the system. An attempt was made to model the fast decay using the three body quenching process $O_2(a^1\Delta) + O + O_2 \rightarrow 2O_2 + O$ suggested by Braginskiy *et al.* (*J. Phys. D: Appl. Phys.* **38** (2005) 3609). The near gas kinetic rate constant obtained from this analysis ($(1.1\pm0.1)\times10^{-31}$ cm^6/s) was inconsistent with data obtained from flowing afterglow experiments, indicating that additional quenching species are generated by the ozone photochemistry. Rate constants for quenching of $O_2(b^1\Sigma)$ by CO_2 ($(6.1\pm0.5)\times10^{-13}$ cm^3/s) and O_3 ($(1.9\pm0.2)\times10^{-11}$ cm^3/s) were measured as a test of the kinetic analysis techniques.

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[129] Low-Power Laser-Metal Interaction for Space Propulsion Applications

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Topics:
Laser-matter Interaction Physics and Simulations, Laser Ablation Propulsion

Abstract:
The micro-Newton thrust generation was observed through low-power continuous-wave laser and aluminum foil interaction without any remarkable ablation of the target surface. To evaluate the thrust characteristics, a torsion-balance thrust stand capable for the measurement of the thrust level down to micro-Newton ranges was developed. In the case of an aluminum foil target with 10 micrometer thickness, the maximum thrust level was 15 micro-Newtons when the laser power was 20 W. It was also found that the laser intensity, or laser power per unit area, irradiated on the target was significantly important on the control of the thrust even under the low-intensity level.

[130] High-Isp Mode of Pulsed Laser-Electromagnetic Hybrid Accelerator for Space Propulsion Applications

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Topics:

Laser Ablation Propulsion, Optically-pumped Lasers

Abstract:

A fundamental study of a newly developed rectangular pulsed laser-electromagnetic hybrid thruster was conducted, in which laser-ablation plasma was induced through laser beam irradiation onto a solid target and accelerated by electrical means instead of direct acceleration only by using a laser beam. The performance of the thrusters was evaluated by measuring the mass shot and impulse bit. As results, significantly high specific impulses ranging from 5,300 ~ 7,100 sec were obtained changing with the charge energies of 0.1 to 8.6 J, respectively. In addition, typical thrust efficiency varied from 11.8 to 21.3% depending on the charge energy.

[112] Gas-flow Slab RF Discharge as a Source of Singlet Delta Oxygen for Oxygen Iodine Laser

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Results of experimental and theoretical study of singlet delta oxygen (SDO) production in transverse gas flow RF slab discharge for an electric discharge oxygen-iodine laser are presented. The electric discharge facility operating in both pulse-periodic and CW mode was manufactured: gas flow duct including multi-path cryogenic heat exchanger, dielectric slab channel, and slab electrode system incorporated in the channel for RF discharge ignition. Experiments on SDO production in transverse gas flow RF discharge were carried out. SDO production depending on gas mixture content, gas mixture, gas flow velocity, low-frequency modulation of RF power and RF discharge power was experimentally studied. It was shown that SDO yield increased with gas pressure decrease, gas flow deceleration and helium dilution of oxygen at the same input power. CW RF discharge was demonstrated to be the most efficient for SDO production at the same averaged input power of RF discharge. SDO yield was demonstrated to be not less than 10%.

[19] Growth of Polyhedral Graphite Particles and Carbon Nanotubes Filled with SiC Nanowires by Laser Ablation

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Abstract:

Nanocarbon materials have received widespread interests in basic and applied research fields. Laser ablation can produce various nanocarbon materials such as single- and multi-walled carbon nanotubes, single-walled carbon nanohorn aggregates, and polyhedral graphite (PG) particles. In addition, laser ablation can be used to form nanocarbon composites such as metal-encapsulated carbon nanocapsules, single-walled carbon nanohorn aggregates hybridized with carbon nanocapsules, and carbon nanotubes (CNTs) filled with copper nanowires. We present a simple way to grow PG particles and CNTs completely filled with naowires of silicon carbide based on laser ablation of graphite containing silicon in the presence of high-pressure Ar gas atmosphere. All the grown CNTs contain SiC nanowires and no empty CNTs were present. Laser ablation of graphite/Si targets was performed using a continuous-wave Nd:YAG laser (500 W peak power) at room temperature. The deposits produced by the laser ablation were examined scanning and transmission electron microscopy. Depending on the Si content (0.1–70 at%) and Ar gas pressure (0.1–0.9MPa), the products showing different morphologies were obtained. Unlike laser ablation of pure graphite in which the growth of PG particles occurs at high Ar gas pressures of 0.5–0.9 MPa, for low Si contents of 0.1–5 at%, PG particles with diameters of 100–1000 nm were grown even at a low pressure of 0.1 MPa. The reason for the enhanced formation of PG particles is unclear. However, one possibility is that a Si atom could bind to a carbon atom and act as a seed to enhance the formation of carbon clusters and/or graphitization. On the other hand, for higher Si contents, one dimensional structures of amorphous SiC nanowires and CNTs containing SiC nanowires were produced. In particular, at high Ar gas pressures of 0.7–0.9 MPa, SiC-filled CNTs (10–60 nm thick and 0.5–30 μm long) were efficiently grown. A selected area diffraction pattern showed spots corresponding to crystalline SiC. The number of graphitic layers around SiC nanowires was up to 25, depending on the ratio of graphite and Si in the targets. For the formation of these SiC-filled CNTs, high resident density of

vaporized carbon and Si is thought to be essential in a space confined by Ar gas. From the TEM observation of traces of molten composite particles at the ends of filled CNTs, we believe that the growth of SiC-filled CNTs were self-induced from molten particles with specific carbon-Si compositions together with separation of the SiC nanowire and graphitic layers.

Three topics: PLD, MAPLE, and Processing of Advanced Materials, Nnaoengineering, and High Power laser Applications and Diagnostics

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[117] Femtosecond Laser Microstructuring of Transparent Materials and its Ophtalmological Applications

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Presenting author: ***Sergey Kudryashov***

Section: *Biomedical Applications*

Abstract: At tight focusing (high NA > 0.5) femtosecond lasers with sub-critical peak powers are known to enable fabrication of sub-micron voids inside transparent materials. Such voids could serve as optical memory bits or photonic crystal units, while their continuous sequences make channels and other internal structural elements of microfluidic devices. However, due to the fast temporal and very short spatial appearance scales for such voids, their fabrication mechanisms (rupture of molten material or plastic deformation of solid exterior by TPa-level shock wave) and parameters (laser intensity, deposited volume energy density) are not well understood yet. Interestingly, at supercritical peak powers tightly focused femtosecond laser pulses typically produce in bulk dielectrics not point-like, but elongated (filamentary) damage structures, which should, however, appear at similar laser intensities and deposited energy densities, thus enabling evaluation of the key quantities and enlightening the underlying physical fabrication mechanisms for both these damage structures.

In our experiments on bulk micro-structuring of PMMA by tightly (NA = 0.65) focused 744-nm, 120-fs laser pulses with supercritical powers we observed inside the material prominent filamentary damage structures with their volumes linearly increasing versus increasing laser energy (power). This fact indicated homogeneous energy density inside the structures during fs laser filamentation in PMMA with its upper bound corresponding thermal decomposition of the material. Ultrasonic probing demonstrates formation of sub-critical plasma in the corresponding transient filaments, enabling alternative evaluation of the deposited energy density, which is in agreement with the abovementioned one. The potential physical mechanism of femtosecond laser nano- and micro-scale modification of transparent materials at tight focusing is discussed.

Finally, femtosecond laser micro-perforation of eye tissues – cornea and sclera – has been successfully performed in the similar manner opening, in the latter case, new perspectives in eye surgical applications of femtosecond lasers.

This work was supported by Russian Foundation for Basic Research under the project # 08-04-12068-ofi.

[60] Silica Nano-ablation using Laser Plasma EUV Radiation

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Topics: Nanoengineering, Advances in promising new laser technologies, Physics of Laser Matter Interactions

Abstract: Investigating interaction of intense extreme ultraviolet (EUV) light with solid surfaces and induced phenomena becomes very much challenging, although extensive studies have been carried out on interaction of EUV light at intensities below ablation thresholds. As application of the intense EUV light to a novel technology, one could expect direct light nanomachining. We have investigated micro- and nano-machining of transparent materials using laser-produced EUV light. In the present paper, we report nano-ablation of silica glass and ablation process.

EUV light with a pulse duration of 10 ns were generated by irradiation of Ta targets with 532-nm Nd:YAG laser light at 600 mJ/pulse. EUV light radiated from the laser-produced plasma were focused on silica glass plates using an ellipsoidal mirror, which is designed to focus EUV light at around 10 nm efficiently. The optics has an advantage that it can focus a wide range of EUV light compared to normal incident mirrors such as Schwartzchild mirros employed in EUV lighography. We have achieved a fluence as high as 1 J/cm^2.

In order to fabricate nano-trenches, a silica glass plate was irradiated with EUV light through windows of a line and space mask. We demonstrated fabrication of nano-trenches with a width of 50 nm. It should be noted that the feature size is more precise than that estimated from the thermal diffusion length for the 10-ns EUV pulse (i.e. 80 nm). Furthermore, the ablated area has a depth of 470 nm after ten shots of irradiation. Atomic force microscope analysis revealed that the irradiated regions have a root mean square roughness of 1 nm. Thus, the EUV irradiation technique have a significant feature of direct nanomachining.

The ablation occurs at fluences (F) beyond a ablation fluence (F_0) and ablation depth per pulse (D) obeys the law $D = 1/a \ln (F/F_0)$, where 'a' is an effective absorption coefficient. These results suggest that absorbed energy is accumulated in the absorbed region without energy diffusion until ablation occurs. It is notable that the accumulated energy density estimated from 'a' and 'F' is almost comparable to the biding energy of silica glass. In addition, time-resolved mass spectroscopy revealed that silica glass is broken into atomic ions and atomic neutrals after ablation. Because Si^+ and O^+ ions have a kinetic energy of 10^6 cm/s, non-thermal process such as Coulomb explosion may be driving force behind the ablation. Such non-thermal process enables us to fabricate nano-structures on silica glass.

[4] Photorefractive Phase-shift of a Two Unidirectional Photorefractive Ring Oscillators Using Two Beam Coupling

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Topic(s): Physics of Laser Matter Interactions

Abstract:

The interest in photorefractive materials has been increased in the last three decades due to wide range of applications, such as storage of volume holograms, image amplification, real-time optical signal processing, image processing, correlators, associative memories, information processing, optical neural networks , beam coupling, phase conjugation, resonators, pattern formation etc. Several experimental and theoretical investigations show that a photorefractive medium can act as an amplifier in a Photorefractive ring oscillators .In the present paper, we have analyzed the photorefractive phase shift for a primary and secondary cavity of a coupled photorefractive unidirectional ring resonators under the assumptions of the plane-wave approximation and steady state oscillation. The coupling in a coupled unidirectional ring resonators is achieved by a pair of photorefractive two-beam coupling gain media (photorefractive crystals A & B) which are pumped by an external laser beam and the oscillating beam which passed through crystal A & B respectively. In such a case, crystal A acts as a gain element for a primary cavity while crystal B, loss element. For the secondary cavity the crystal B acts as a gain element. We have also studied the two types of steady state oscillations (in the first case both cavities oscillate simultaneously while in the second primary cavity oscillate but not the secondary). The effects of parameters characterizing the photorefractive medium and the pump intensity on the photorefractive phase-shift have been also studied and it has been found that the strength of the photorefractive phase-shift in one resonator will be affected by changing the characterizing parameters of the other resonator, i.e., the changing the parameters of primary cavity will change the photorefractive gain and phase-shift of the secondary cavity.

[106] Dynamic Pressure Recovery System for a Gas Laser

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A diffuser, with the purpose of recovering pressure from a gas laser system, was designed and studied. A diffuser is used in a gas laser system to transition the laser cavity's low pressure to the ambient pressure outside the device. Diffusers use a series of shocks in a duct to recover the pressure of the laser effluent. The static pressure increases as the flow passes through each shock. This diffuser uses a series of oblique shocks followed by a normal shock to accomplish the pressure recovery. The diffuser studied here is made up of a constant-area supersonic section and a constant-angle subsonic section. This diffuser was studied with non-reacting flows on a small scale test stand with non-reacting flows and on a larger test stand. The efficiency of the diffuser was compared to a baseline diffuser with static and stagnation pressure measurements. Computational Fluid Dynamic (CFD) modeling was also performed, allowing insight to the fluid mechanics involved.

Topics: Advances in oxygen iodine lasers, Advances in laser technology

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[119] Comparison of Resonant Plasmon Polaritons with Mie Scattering for Laser-induced Near-field Nano-patterning: Metallic Particle vs Dielectric Particle

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Presenter: ***Dr. Mitsuhiro Terakawa***

Topics: Near-field Effects, Nano-processing and Engineering of Materials, Short-pulse Laser-matter Interactions

Abstract:

This paper describes the comparative study of near-field nano-processing of glass and silicon by use of metallic nano-particle and dielectric nano-particle excited by an 820 nm near-infrared femtosecond laser pulse. Near electromagnetic field around metallic nano-particle and dielectric particle shows quite unique properties on the substrate to be near-field processed. It is found that the existing thought that the use of the metallic particle is better than the dielectric particle in a much smaller particle size region than excitation wavelength is NOT always correct. As for near-field enhancement on low refractive index glass substrates by the dielectric particle with appropriate refractive index, an enhancement factor at the TE1 (magnetic dipole mode) resonance mode is found to be higher than that induced by gold particle even at the TM1 (electric dipole mode) resonance mode of gold particle. Conversely, on a high refractive index substrate like silicon, the near-field enhancement factor becomes larger by use of the gold particle at the same particle size. This significant change of the enhanced field intensity stems from the different nature of power flow based on the image charge induced in the substrate. These results indicate that the best combination of the particle and substrate for efficient localized near-field nano-processing is important for selecting either the metallic or dielectric particle. The obtained result gives a useful means for the particle selection and understanding of near-field interaction physics with substrate for efficient nano-processing of the substrate surface. Finally, these theoretical results have been verified by experiment.

This work is supported in part by a Grant-in-Aid for the Global Center of Excellence for High-Level Global Cooperation for Leading-Edge Platform on Access Spaces from the Ministry of Education, Culture, Sport, Science and Technology, Japan.

[24] An Analytical Model of Ablation in Gas Flow

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Topics: Simulation, Laser Ablation Propulsion

Abstract:

The physics of the Knudsen layer, formed near the vaporizing (ablative) surface is of great interest for a number of applications such as capillary discharges, plasma thrusters, vacuum arcs, laser ablation, etc.

Anisimov [1] was the first to consider details of the vaporization process for a case of vaporization of a metal exposed to laser radiation. In his model, Anisimov used mass, momentum, and energy conservation laws to determine the parameters of his bimodal velocity distribution function. The assumption of his model are: (1) no absorption of laser radiation in the ablated gas, (2) the gas flow velocity at the external boundary of the Knudsen layer is equal to the sound velocity, (3) the temperature of the gas in the bulk region (beyond the Knudsen Layer) is constant, i.e. there is no conductive heat flux to the ablative surface; (4) all particles that hit the ablative surface arc absorbed by it. The primary result of his work was the calculation of the maximal flux of returned atoms to the evaporating surface, which was found to be about 18% of the flux of vaporized atoms.

Since then, the Anisimov method has been extended to the certain cases of half-space evaporation problem [2], and evaporation into dense plasmas [3-7], where the flow velocity at the outer boundary of the Knudsen layer was assumed to be smaller than the speed of sound and dependent on the properties of the bulk gas (plasma). In all these models, the authors still assume no conductive heat flux to the ablative surface and complete absorption of particles by the ablative surface. This can be significant because in these models [3-7] the temperature in the plasma core is assumed to be much greater than the temperature of the ablative surface and, therefore, the thermal conduction can be significant and has to be included in a Knudsen layer model.

Pekker et al [8] used a new bimodal velocity distribution function in the Kinetic layer and built a more general Knudsen layer model that takes into account the conductivity of the bulk gas and can therefore be used to simulate flows with large temperature gradients. However, as with all other bimodal velocity distribution function model, the condensation coefficient of the model [8] was assumed to be equal to unity.

Recently Pekker [9] extended the model [8] to the case of an arbitrary condensation cocfficient. He also assumed a constant accommodation coefficient that specifies the fraction of diffuse and specular collisions of incident particles on the ablative surface. This model allowed the author to formulate gas-surface boundary conditions that can be used for CFD modeling of ablation process, which takes into account thermal conduction and incorporate arbitrary condensation and accommodation coefficients.

The motivation behind this work is to extend model [9] to the case of gas flow and to formulate the boundary conditions for numerical simulation of fluid dynamics with ablative surface. This model can be applied for laser ablation in gas flow as well.

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[124] Electronic Kinetics of Semiconductors under an Ultrashort VUV Laser Pulse Irradiation

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Topics:
Short-pulse Laser-matter Interactions 1, Short-pulse Laser-matter Interactions 11, Laser-matter Interaction Physics and Simulations

Abstract:
In the presented work, the theoretical research was done in order to investigate the transient electronic dynamics within a solid semiconductor (silicon) under irradiation with an ultrashort VUV laser pulse with the photon's energy of $\hbar\omega = 92$ eV and the Gaussian pulse duration of $\tau_L = 10$ fs), according to the parameters used in experiments with a new Free Electron Laser (FLASH) in DASY (Hamburg, Germany) [1].

The new Asymptotical Trajectory Monte-Carlo (ATMC) code [2] was created to describe the photon penetration into the material accomplished with the electronic excitation and all following processes with electronic subsystem (in the conduction and the valence band). The main goal of this work was to obtain the transient energy distribution of the excited and ionized electrons within a solid silicon target. The Asymptotical Trajectory Monte Carlo method was modified where necessary and extended in order to take into account the electronic band structure and Pauli's principle for electrons excited into the conduction band. Secondary excitation and ionization processes, made by free electrons as well as by holes in valence band, were included and simulated event by event as well.

We demonstrate that the final kinetic energy of free electrons is much less than the total energy provided by the laser pulse, due to the energy spent to overcome ionization potentials.

From the energy distributions of electrons and holes, we found the mean kinetic energy of free electrons to be equal about a half of the minimum energy required for secondary electron creation (which for Si is equal to the real band gap value of the material E_{gap}) just after the laser pulse. Quite similar is the situation in the valence band with holes: they end up with the energy in between energy gap and their own minimum of the energy necessary for a creation of secondary electron (which is different from the electronic one). Both values can be found from the analysis of the static band structure of the material.

It was found that the final total number of electrons excited by a single photon is significantly less than $\hbar\omega/E_{gap}$.

We introduce the concept of an '*effective energy gap*' for collective electronic excitation, which can be applied to estimate the free electron density after high-intensity VUV laser pulse irradiation. The effective energy gap depends on the properties of material (like the band structure and the density of states) and photon energy, but not on the intensity of the laser pulse.

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[74] Formation of Micro and Nano Structures Using VUV 157nm Laser Radiation

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Topic(s): Nanoenginering, Near-Field Optics.

Abstract:

Electromagnetic radiation from an F_2 laser emitting at 157nm interacts strongly with most materials. Due to the relatively large photon energy of 7.9eV shallow absorption depths and concomitant low ablation thresholds are observed during laser processing. Thus the F_2 laser is an appropriate choice for surface patterning when good depth resolution is required.

In this work we report on near-field laser ablation experiments at 157nm. In order to pattern the surface of dielectrics they have been intentionally deposited with metal and semiconducting micro and nano particles such that the incoming laser beam interacts with the obscuring particles. We discuss the formation of seeded conical and prismatic structures with specific attention to the attainable resolution, geometrical properties and plasmonic effects. The so called plasmonic metamaterial structures will be discussed from a negative refractive index perspective.

[131] Modification of Material Properties and Response of Nanostructures on Transparent Substrates by Ultrashort Laser Pulses

Authors:

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Abstract:

The objective of this combined experimental and theoretical research is to study the ablation mechanisms of nanoparticle modification by ultrashort laser pulses. The experimental part considers several groups of nanostructures built from spherical particles deposited on semiconductor and dielectric substrates. Density of the particles varies from low (with mean inter-particle distance of 1-10 μm) to high (with mean inter-particle distance less than 0.5 μm). We investigate different geometries of the nanostructures – from random or quasi-random particle distribution to ordered

linear and 2D patterns. Those nanostructured and the corresponding empty substrate surfaces are irradiated with single 150-fs laser pulses at 775-nm wavelength and different levels of laser fluence. Several different interaction regimes are observed in the experiments ranging from complete nanoparticle removal by the laser pulses and melting at high intensity to very gentle size reduction via non-thermal ablation at lower intensity. The removed particles frequently form specific sub-micrometer-size pits on the substrate surface at their locations. Dependence of the size reduction on laser fluence has been studied. Special attention is paid to the processes of laser-induced ionization of metal and non-metal nanoparticles resulting in charging them positively.

The experimental effort is supported by simulations of the nanoparticle interactions with high-intensity ultrashort laser pulse. The simulation employs specific modification of the molecular dynamics approach applied to model the processes of non-thermal particle ablation following laser-induced electron emission. This technique delivers various characteristics of the ablation flow from a single nanoparticle including energy and speed distribution of emitted particles, variations of particle size and overall dynamics of its ablation. The simulations confirm existence of the distinct regimes of laser-nanoparticle interactions depending on laser intensity and wavelength. A distinct difference between dynamics of ablation of metal and non-metal particles is demonstrated.

Tuesday 20 April
Session 5: Short pulse laser-matter interactions II
Richard Haglund, chair

[113] Non-linear Absorption and Ionization of Gases by Intense Femtosecond Laser Pulses

Andrey A. Ionin (presenter),[1*] ***Sergey I. Kudryashov,***[1)] ***Yurii N. Ponomarev,***[2)] ***Leonid V. Seleznev,***[1)] ***Dmitry V. Sinitsyn,***[1)] ***Boris A. Tikhomirov,***[2)] ***and Vladimir D. Zvorykin***[1)]

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High-power hybrid femtosecond laser facility consisted of a front-end Ti:Sapphire laser system and a set of excimer KrF laser amplifiers is now under development at the Lebedev Institute. Peak power comes up to a few TW right now. Recent experiments on applications of high-intensity femtosecond pulses for studying multiphoton and tunnel ionization of different gases, their multi-filament propagation in air are discussed. Mechanisms of non-linear absorption and ionization of pure atomic argon and molecular nitrogen gases by UV femtosecond laser pulses were studied using photogalvanic and photoacoustic technique. The effect of the intermediate Rydberg resonance, its dynamic Stark perturbation and ponderomotive upshift of the first ionization potential of argon atoms and nitrogen molecules by the intense laser pulses has been revealed by observing an increase of a power slope of ion yield from three to four at increasing laser intensity. The photoacoustic technique was also applied for studying the effect of tunnel ionization of air by femtosecond laser pulses with sub-critical peak power in the range of intensity ~0.5-20 PW/cm^2. Saturation of ultrasonic signals at near-atomic laser fields, which is well described by ADK model, is observed.

[97] Attosecond Nonlinear Optics

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Femtosecond and Attosecond Effects, Physics of Laser Matter Interactions

Abstract:
The observation of nonlinear optical processes in the soft X-ray region has been a very attractive and challenging area of research in quantum electronics since the first observation of second-harmonic generation and two-photon excitation in the visible range in 1961. No observation of nonlinear optical process with soft X-ray photons, however, had been reported because of a lack of intense short wavelength light sources. This situation has changed recently due to the advent of an intense coherent EUV and soft X-ray (XUV) source based on high-order harmonic generation. Now, an instantaneous brightness of high harmonics becomes of the order of 10^8 times higher than that of synchrotron orbit radiation in the XUV region. When such a harmonic pulse is focused with an off-axis parabolic multilayer mirror, the focused intensity attains 1×10^{14} W/cm^2, which is sufficient to induce nonlinear optical phenomena in the XUV region .

In this presentation, I review the generation of intense XUV attoscond pulses and its application to nonlinear multiphoton processes in atoms and molecules. Intense attoseocnd pulses produced by phase-matched high harmonic gneration enables the observation of those mulitpoton processes in the XUV region.

[51] Short-pulse laser induced transient structure formation and ablation studied with time-resolved coherent XUV-scattering

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ABSTRACT : XUV- and X-ray free-electron-lasers (FEL) combine short wavelength, ultrashort pulse duration, spatial coherence and high intensity. This unique combination of properties opens up new possibilities to study the dynamics of non-reversible phenomena with ultrafast temporal and nano- to atomic-scale spatial resolution.

In this contribution we wish to present results of time-resolved experiments performed at the XUV-FEL FLASH (HASYLAB/Hamburg) aimed to investigate the nano-scale structural dynamics of laser-irradiated materials. Thin films and fabricated nano-structures, deposited on Si_3N_4-membranes, have been excited with ultrashort optical laser pulses. The dynamics of the non-reversible structural evolution of the irradiated samples during laser-induced melting and ablation has been studied in an

optical pump – XUV-probe configuration by means of single-shot coherent scattering techniques (i.e. diffraction imaging [1]).

In a first set of experiments we investigated the formation of *laser induced periodic surface structures* (LIPSS) on the surface of thin Si-films (thickness 100 nm). In a simplified view LIPPS are generated as a result of interference between the incident laser pulse and surface scattered waves which leads to a periodically modulated energy deposition. Time-resolved scattering using femtosecond XUV-pulses (with a wavelength of 13.5 nm and 7 nm) allowed us to directly follow LIPSS evolution on an ultrafast time-scale and with better than 40 nm spatial resolution. The observed scattering patterns show almost quantitative agreement with theoretical predictions [2] and reveal that the LIPSS start to form already during the 12 ps pump pulse.

In the second set of measurements we studied picosecond and femtosecond laser induced ablation and disintegration of fabricated nano-structures. Correlations of coherent diffraction patterns measured at various time delays to the pattern of the undisturbed object, show that order in the structure is progressively lost starting from short length scales. This structural rearrangement progresses at close to the speed of sound in the material. Under certain circumstances (e.g. adequate sampling) it became also possible to reconstruct real-space images of the object as it evolves over time [3]. The possibility of femtosecond single-shot imaging of ultrafast dynamic processes with nanoscale resolution provides yet more details of the physical processes involved.

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TOPICS: Physics of Laser Matter Interactions, Femtosecond and Attosecond Effects

[72] Single and Multiple Pulse Subpicosecond Breakdown in Dielectric Films

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Abstract:
Experimental and theoretical progress on subpicosecond laser pulse breakdown in dielectric films is reviewed. The single pulse threshold fluences can be related to fundamental material properties, and scaling laws with respect to pulse duration and material bandgap are discussed. Multiple pulse thresholds are controlled by native and laser induced defects. A phenomenological model is introduced that describes the accumulation and relaxation of such defects. The model is able to explain the experiments and can be used to assess relevant defect parameters.

Topics: Physics of Laser Matter Interactions, Femtosecond and Attosecond effects.

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[65] Ultrafast dynamic ellipsometry and spectroscopy of laser shocked materials

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Abstract:

Single shot ultrafast dynamic ellipsometry (UDE) is used to provide simultaneous temporal and spatial resolution of surface motion and transient refractive index dynamics. Interferometric measurements at two angles and two polarizations in our experimental implementation provide 3 ps temporal resolution, sub-nm spatial resolution to movement in the shock direction, and 5 micrometer resolution along one transverse spatial dimension. This is coupled to UV-NIR transient absorption spectroscopy and used to study the dynamics of laser shocked materials. UDE allows determination of the particle velocity, shock velocity, and shocked refractive index. Transient absorption allows determination of electronic excitations or band structure changes that occur under strong shock loading (10's of GPa).

[110] Femtosecond laser produced micro-modifications in polymers

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Topics: Femtosecond and Attosecond Effects, Physics of Laser Matter Interactions, Femtosecond Laser Processing

Abstract:

Femtosecond laser micromachining has been proven to be a powerful technique to microstructure practically any material with small thermal damage inside the materials. When femtosecond laser pulses are tightly focused within a transparent bulk material, nonlinear absorption can be induced in the focal volume and lead to highly localized energy deposition resulting a range of possible changes in material properties. This highly localized modification gives femtosecond laser micromachining a unique three dimensional micro-modification capability, and has been used to create volume optical storage, waveguides, gratings, and microfluidic devices. Femtosecond laser micromachining

technology has been employed to fabricate photonic structures in various polymer materials. Focusing femtosecond laser pulse creates different types of modifications such as void, cavity, refractive index change, and scattering damage inside polymer materials. The control of modifications is crucial in the applications of femtosecond micromachining.

In this talk, interaction of ultrashort laser pulses with polymers has been investigated [1-6]. The 800-nm femtosecond laser pulses at 1 kHz repetition rate were focused into polymer materials with an objective lens. The morphology and properties of structural modifications are investigated depending on the focusing conditions, the materials, scanning speeds as well as the laser parameters. The mechanisms of the refractive index modifications are discussed. The possible reasons for the changes in refractive index are attributed to change in density (compaction), photodecomposition, and tensile stress. The fabrication of photonic devices in polymer materials, including waveguide devices and diffractive optical elements is demonstrated. The selective modification of the refractive index in polymers is a promising method for the fabrication of three-dimensional integrated optical devices.

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[62] Space Charge Corrected Ultrashort Pulsed Laser Induced Electron Emission from a Cu Surface

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Abstract:
Ultrashort pulsed laser induced electron emission is reduced significantly by a space charge effect. Emitted electrons create a negative space charge above the surface, which generates an electric field that pushes electrons back into the target [1]. In this study, a one dimensional Particle In Cell (PIC) method [2] is employed to study the effective ultrashort pulsed laser induced electron emission from a Cu surface, corrected by this space charge effect.

The PIC-method uses electron macroparticles with a certain weight, position and velocity to represent an amount of electrons in a one dimensional grid. These macroparticles move according to the local electric field, which is calculated based on Gauss' law. Electron emission is implemented at the boundary as the sum of thermionic and multiphoton photoelectron emission, as formulated by the Fowler-Dubridge theory [3].

These flux terms have been used in several theoretical papers concerning laser induced electron emission processes, such as coulomb explosion and early stage plasma formation [4-6]. The temperature dependence was based on the two temperature model [7].

The present results indicate that without an externally applied electric field, the space charge effect reduces the electron emission by several orders of magnitude. This leads to believe that the formulations of electron emission fluxes in theoretical research concerning laser induced electron emission related phenomena, significantly overestimate the actual electron emission.

Input for the PIC-model includes the electron energy evolution, the material work function and the electron emission velocity distributions. The determination of these input parameters is crucial in order to obtain accurate results that can be used to make quantitative predictions. Whereas we used the Fowler-Dubridge theory coupled to the two temperature model, the input parameters can be calculated more accurately by solving the Boltzmann equation or by quantum mechanical calculations. These two methods can also be employed to test the validity of the Fowler-Dubridge theory, which uses assumptions that might not be correct in the extreme conditions under consideration. When reasonable approximations for the input parameters are adopted, the PIC-model can be employed for calculating the space charge corrected amount of emitted electrons, which is essential for the studies of electron emission on the target. The effectively emitted electron velocity distributions can be used in theoretical studies concerning the early stage plasma formation.

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Session 6: Nano-processing and Engineering of Materials
Tom Dickinson, Chair

[5] Nanoaquariums Fabricated by Femtosecond Laser for Exploration of Dynamics and Functions of Microorganisms

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<u>Abstract:</u>
Observation of microorganisms by an optical microscope with a high NA objective lens and a high speed camera is currently a challenging subject for cell biologists, since most of them are composed of a unit cell and thereby it is very important to explore their dynamic movement and physiologic energy generation mechanisms to understand the potential ability and function of the unit cells composing organisms including human beings. Thus, we proposed to use microchips, referred to as nanoaquariums, possessing 3D microfludic structures fabricated by femtosecond (fs) laser for exploration of dynamics and functions of microorganisms. The nanoaquariums have several advantages over conventional observation methods using a glass slide with a coverslip or a Petri dish, such as great reduction of observation times, ability of 3D observation, control of movement

directions, easy integration of functional microcomponents into the observation site for highly functional observation, etc.

Our technique for fabrication of nanoaquarium consists of the following four steps: (1) 3D direct writing inside the photosensitive glass by fs laser (1045 nm, 370 fs, 200 kHz), (2) thermal treatment to form the modified regions at the laser exposed regions, (3) wet chemical etching in dilute HF solution to selectively remove the modified regions, and (4) post thermal treatment to smooth the etched surfaces. By this technique, 3D hollow microstructures with smooth internal surfaces can be formed inside the photosensitive glass.

In this talk, we demonstrate to fabricate several kinds of nanoaquariums with different structures and different functions for observation of a variety of microorganisms. The nanoaquarium possessing a simple microchannel embedded in the glass microchip performs minute and 3D analysis of rapid motion of Euglena gracilis"s flagellum. One of the advantages of our technique is that some functional microcomponents can be easily integrated into the microfluidics for highly functional observation. Integration of a movable microneedle for physical stimulation is used to understand the information transmission process in Pleurosia leavis. Integration of a micropump generates water flow in the embedded microchannel circuit, resulting in observation of rheotaxis behavior of various aquatic microorganisms. In the meanwhile, the fs laser exposure to the photosensitive glass followed by thermal treatment grows a crystalline phase of lithium metasilicate at the laser exposed regions and then changes color into brown. This modification can be utilized for spatially selective formation of cut-off filters of visible light in the photosensitive glass. By covering a part of embedded microchannels with the optical filters, light illumination effect in Phormidium assemblage to the seeding root is investigated for mechanism study on growth promotion of Komatsuna vegetable.

Topics: Laser Micromachining, Biomedical Applications, Femtosecond and Attosecond Effects

[56] Directly Written DFB Waveguide Lasers using Femtosecond Laser Pulses

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Topics: High Power Lasers Application and Diagnostics, Femtosecond and Attosecond Effects

Abstract:

Significant attention has been directed to the use of laser pulses for fabricating optical components on or inside various materials since the introduction of ultrashort pulsed lasers in the 1980s. In particular, it was demonstrated in 1996 that tightly focused femtosecond Ti:Sapphire laser pulses can induce a local internal increase in the refractive index of bulk transparent glasses. By translating a sample through the focal point of a focused femtosecond laser beam and varying the writing geometry and femtosecond laser properties, various 2D and 3D optical waveguide devices (bulk glass analogues of optical fibres) with different characteristics have been fabricated in many transparent materials. Not only can this direct-write technique be carried out rapidly, it is readily compatible with existing fibre systems, it does not require a lithographic mask and it can be conducted in a regular laboratory environment with the minimum of sample preparation.

At the CUDOS at Macquarie we employed novel femtosecond laser beam delivery techniques in order to fabricate low loss photonic waveguide devices for application in technologies such as telecommunications and quantum information science. After trialling various passive devices including waveguides, evanescent couplers and waveguide-Bragg gratings (WBGs) in undoped

glasses, we transferred our technologies into rare-earth-doped media to create waveguide lasers (WGLs). In our most recent experiments we fabricated a waveguide laser in Ytterbium doped phosphate glass based on the distributed feedback (DFB) architecture. The device lased at 1.032 μm with an output power of 102 mW and a bandwidth < 2 pm. The pump power threshold was approximately 115 mW and the optical efficiency was over 17%. Such a device represents the first demonstration of an efficient, high power monolithic WGL created entirely using the femtosecond laser direct-write technique. Given the flexibility of the femtosecond laser direct-write technique for creating structures on a per pulse basis, there also exists the potential to develop novel DFB designs to create multiple laser output lines. In this paper a review of our ongoing activities in monolithic WGL fabrication will be presented. In particular we report on lifetime studies of WGLs, focussing on the relative effects of thermal- and photo-annealing on WGL performance.

[35] Long-time Feedback in Self-organized Nanostructures Formation upon Multipulse Femtosecond Laser Ablation

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Topics: Physics of Laser Matter Interactions; Femtosecond and Attosecond Effects; Nanoengineering

Abstract:

Self-organized nanostructures (ripples) on the target surface are observed after multi-pulse femtosecond laser irradiation. From numerous experimental data it appears obvious that successive pulses result in a positive feedback in the self-organization process. We report on a series of experiments on different targets (CaF_2, Si) to investigate this feedback in more detail, in particular its dynamics. We study the influence of time separation between successive pulses on both the size and complexity of the nanostructures and on the size of the modified surface area. Taking into account the dependence of structure formation on the total *applied* irradiation dose, total pulse number and laser parameters (pulse energy, pulse duration, focussing) are kept constant throughout all experiments.

By varying the pulse separation between 1 ms and 1 s (rep. rate between 1 kHz and 1 Hz), we find that both modified area as well as pattern feature size and complexity decrease with increasing pulse-to-pulse delay. The effect is similar to a reduction of *effective* irradiation dose with increasing intervals. Vice versa, the coupling efficiency between laser and target increases with increasing repetition rate.

Assuming the structure formation to be the result of relaxation from surface instability induced by the laser impact, we can understand the observed behaviour in the following way: the stronger the perturbation is from the preceding pulse the better is the coupling of the succeeding one, thus resulting in a positive feedback. Then, the decrease of coupling with increasing intervals should correspond to a decay of induced perturbation/instability.

Since we observe a change of structural features even between 0.5 s and 1 s intervals, this indicates an unexpectedly long "lifetime" of the instability, at the order of seconds.

But not only temporally do we observe such "long-range" effect of the laser induced instability. Also spatially, we see a persisting modification of the crystalline structure well beyond the ablation spot, though no apparent surface morphology can be seen. Mapping the band-to-band photoluminescence from silicon, we find a spatial modulation in a region significantly larger than irradiated. This indicates a dramatic increase of non-radiative recombination compared to unaffected material.

[31] High Throughput Direct-write Near-field Nanopatterning

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Topic: 1 – Nanoengineering; 2 – Near-field Effects

Abstract: Near-field intensity enhancement enables laser modification of materials with feature sizes below the classical diffraction limit. Incorporating such effects into direct write techniques allows for the creation of arbitrary patterns with nanoscale resolution, but is typically limited by their serial nature, making them unsuitable for manufacturing operations. In this presentation, we review direct-write strategies with an eye toward increasing the throughput to enable more rapid processing. In particular, we examine the applicability of optical trapping to position near-field focusing elements near the substrates of interest. In this experiment, a CW laser is used to optically trap and position an array of liquid-dispersed microspheres near a substrate using 2-d Bessel beams. A second, pulsed laser is directed through the bead array and modifies the surface below. Both ablative and non-ablative transformations are possible and direct manipulation of the bead or substrate enables the accurate control of the feature placement. The constant optical scattering force in the propagation direction created by the Bessel beam on the microsphere is balanced by the net repulsive interaction near the surface thereby creating an equilibrium spacing between the two, regardless of large scale surface features. This effect enables nanoscale direct-write over rough or curved surfaces and the parallelization of the process using arrays of beads, each with identical spacing above the surface. In addition, the harmonic nature of the interaction potential and the liquid environment allows the microsphere to be displaced from its equilibrium position only to quickly return with large damping. This effect has important implications for ablative and chemically enhanced processes.

[16] Coherent Imaging of Laser Micromachining

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Topics: coherent imaging, process monitoring and control, laser ablation

Abstract:

We adapt the medical imaging modality optical coherence tomography to serve as a real time metrology to observe laser machining dynamics *in situ*. The coherent imaging technique is practical for a wide-range of machining light sources (quasicontinous wave ytterbium fiber laser, ultrafast diode-pumped regenerative amplified oscillator) and can evaluate cuts with sustained rates as high as

47 kHz and integration times as short as 7 μs. Imaging light is provided by a broadband 1320±35 nm superluminescent diode light source. Coaxial machining and imaging light are combined to observe depth-reflectivity profiles in holes as they evolve. High aspect ratio features are easily monitored with ~10 μm resolution. Sensitivities higher than 100 dB allow weak features to be observed in the presence of strong specular reflection. Use of infrared imaging light allow simultaneous monitoring of both surface and subsurface changes in semiconductors, even in the presence of intense plasma emission and machining laser backscatter.

In the thermal cutting process, coaxial imaging, machining and assist gas delivery (oxygen) allow optimization of machining parameters for stainless steel. Microsecond refilling between laser pulses in percussion drilling is attributed to the steel melt and solidification cycle, and show a significant degree of pulse to pulse variability. The stochastic variation can be overcome using *in situ* feedback to improve blind hole depth accuracy by over an order of magnitude. In contrast to thermal cutting, ultrafast pulses achieve dramatically different real-time dynamics with little evidence of melt or hole refilling and highly deterministic ablation speeds. Doppler image processing provides access to submicron morphology changes. Ultrafast light sources can also provide wide spectral bandwidth thus allowing coherent imaging to be achieved with machining light backscattered from the sample. We use a compact, modelocked fibre oscillator coupled to a single-pass ytterbium double-clad fiber amplifier to achieve simultaneous imaging and machining with only one light source.

[2] Laser-Assisted Nanoprocessing

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Topics: Nanoengineering, Near-field Effects

Pulsed lasers were coupled to near-field-scanning optical microscopes (NSOMs) for nanoprocessing, nanomachining, nanolithography and nanodeposition. Experiments have been conducted on the nanoscale surface and structural modification of metals, polymers and semiconductor materials. Ablation nanolithography and patterning has been demonstrated. NSOM-based ablation is also applied to nanoscale chemical analysis via Laser-Induced Breakdown Spectroscopy (LIBS). The mechanisms of ablation in the near field were investigated. Detailed comparison with ablation by tightly focused femtosecond laser beam ablation was conducted.

In-situ SEM monitoring of the samples under laser processing was achieved, fully integrated into a dual beam system. To understand the structural evolution, nanoscale laser processing was carried out inside a TEM, hence achieving high-resolution *in-situ* monitoring. New concepts are being pursued for the high throughput nanoprocessing as well as towards the directed growth and assembly of nanostructures.

Session 8: Laser Propulsion
Andrei Ionin, Chair

[22] Tailoring Laser Propulsion for Future Applications in Space

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Presenter: ***Hans-Albert Eckel***

Topic: Laser Ablation Propulsion

Abstract: Pulsed laser propulsion may turn out as a low cost alternative for the transportation of small payloads in future. In recent years DLR investigated this technology with the goal of cheaply launching small satellites into LEO with payload masses on the order of 5 to 10 kg. Since the required high power pulsed laser sources are yet not at the horizon, DLR focused on new applications based on available laser technology. Space-borne, i.e. in weightlessness, there exist a wide range of missions requiring small thrusters that can be supported by laser propulsion. This covers space logistic and sample return missions as well as position keeping and attitude control of satellites.

First, a report on the proof of concept of a remote controlled laser rocket with a thrust vector steering device integrated in a parabolic nozzle will be given. Second, the road from the previous ground-based flight experiments in earth's gravity using a 100-J class laser to flight experiments with a parabolic thruster in an artificial 2D-zero gravity on an air cushion table employing a 1-J class laser and, with even less energy, new investigations in the field of laser micro propulsion will be reviewed.

[122] Experimental Investigation of Axial and Beam-Riding Propulsive Physics with TEA CO2 laser

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Abstract. A twin Lumonics K922M pulsed TEA CO_2 laser system (pulse duration of approximately 100 ns FWHM spike, with optional 1 μs tail, depending upon laser gas mix) was employed to experimentally measure both axial thrust and beam-riding behavior of Type #200

lightcraft engines, using a ballistic pendulum and Angular Impulse Measurement Device (AIMD, respectively. Beam-riding forces and moments were examined along with engine thrust-vectoring behavior, as a function of: a) laser beam lateral offset from the vehicle axis of symmetry; b) laser pulse energy (~12 to 40 joules); c) pulse duration (100 ns, and 1 μs); and d) engine size (97.7 mm to 161.2 mm). Maximum lateral momentum coupling coefficients (C_M) of 135 N-s/MJ were achieved with the K922M laser whereas previous PLVTS laser (420 J, 18 μs duration) results reached 15-30 N-s/MJ—an improvement of 4.5x to 9x. Maximum *axial* C_M performance with the K922M reached 440 N-s/MJ, or about ~3.2x larger than our *lateral* C_M values. These results are sharply higher than previously reported for long pulse (e.g., 10-18 μs) CO_2 electric discharge lasers.

Keywords: Lasers, lightcraft, laser propulsion.

[33] Modeling CO_2 Laser Ablative Impulse with Polymers

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Topics: Physics of Laser Matter Interactions, Laser Ablation Propulsion, Fundamental Theory

Abstract: Laser ablation impulse generation research has lacked a cohesive strategy for linking the plasma and vaporization regimes. Existing models, formulated for ultraviolet laser systems or metal targets, appear to be inappropriate or impractical for applications requiring CO_2 laser ablation of polymers. A method for linking the vaporization and plasma regimes is proposed, and the implications of its use are discussed in detail. Several predictions are made using related models for laser ablation impulse generation by vaporization, and the results are compared. The range of behaviors suggested by including common approximations are considered. Key control parameters are also considered, along with major propulsion parameters needed for laser ablation propulsion modeling. Assessment of the validity of the models is performed using existing literature data on laser ablation propulsion.

[42] A Review of Laser Ablation Propulsion

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Topic: Laser Ablation Propulsion

Abstract: We review the 30-year history of laser ablation propulsion from the transition from earlier pure photon propulsion concepts of Oberth and Sänger through Kantrowitz's original laser ablation propulsion idea to the development of air-breathing "Lightcraft" and advanced spacecraft propulsion engines. The polymers POM and GAP have played an important rôle in experimental realizations. Liquid ablation fuels show great promise, made possible by the realization of low vapor pressure, viscous polymers or, alternatively, by the use of thin liquid films.

Laser Ablation Propulsion is a broad field with a wide range of applications. Laser-induced re-entry of space debris or launch to low planetary orbit use a laser system which is distant from the propelled object, for example, on another spacecraft, the Earth or a planet. In contrast, other applications use a laser that is part of the spacecraft propulsion system on the spacecraft. Propulsion is due to the ablation jet created when an intense laser beam (pulsed or CW) strikes a condensed matter surface and produces a vapor or plasma jet. The advantages of this idea are 1) that specific impulse I_{sp} (proportional to the exhaust velocity) of the propulsion engine covers a broader range than is available from chemistry because of the very high target temperatures which can be attained and 2) I_{sp} can be varied to meet the instantaneous demands of the particular mission. This gives better energetic efficiency than can be had with fixed velocity. Practical realizations lead to lower mass and greater simplicity for a payload delivery system, while ground-based launch concepts can dramatically reduce launch cost by using low-cost energy and facilitating high launch frequency.

We provide a detailed overview of the underlying theory, buttressed by extensive experimental data. The primary problem in this area has been the absence of a way to predict thrust and specific impulse over the likely parameter space of laser space propulsion. Earlier workers, e.g., Pirri, developed laser-surface interaction theory primarily as an aerodynamic problem for the vapor regime in atmosphere with some connection to the plasma regime. Phipps, *et al.* addressed the pure plasma regime in vacuum with a treatment that permitted ablation pressure predictions within a factor of two over an extremely broad range of pulse duration from 100ps to 1ms and wavelength from 0.25 to 10.6 micrometers, but with intensity limits that exclude the extremes of inertial confinement fusion (ICF) and very short pulses. The theory of Lindl covers the ICF regime. For the lower-intensity vapor regime, below the plasma transition, Sinko has developed a useful, fluence-dependent model which predicts impulse delivered for pulsed CO_2 lasers ablating polymers.

We briefly discuss a method we developed which combines the vapor and plasma treatments, which laser space propulsion workers can apply to field applications such as laser plasma thrusters and ORION-like systems. with a smooth transition from one regime to the other. This result is treated in greater detail by another paper at this conference. We conclude with a section on future directions.

[127] Filamentation of beam-shaped femtosecond laser pulses

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Topics:Laser-matter interaction physics and simulations, Short-pulse laser-matter interactions

Abstract: We discuss recent experiments and numerical simulations on filamentation of beam-shaped femtosecond laser pulses in gaseous and condensed media. Exotic beam shaped that we have investigated so far include Bessel and Airy beams. In the case of Bessel beams, the diffraction-free nature of these beams allows for the creation of extended plasma channels in air. For particular pulse duration, an extension of the generated plasma channels have been observed, that was accompanied by an efficient nonlinear conversion of the incident Bessel beam into a bright broadband radiation that propagates along the beam axis. This effect can potentially be applied to the generation of energetic optical pulses with the pulse duration in the few-cycle range. In the case of filamentation of femtosecond Airy beams, the self-bending property of these beams allows for the creation of curved filaments. In this unusual filamentation regime, the linear self-bending property of the beam competes against the nonlinear Kerr lens. This competition leads to interesting propagation effects such as bifurcations of the plasma channels generated by self-bending beams in air. Furthermore, the supercontinuum emission by curved filaments is angularly resolved in the far field, thus allowing a detailed characterization of this emission along the optical path, a property that may add longitudinal resolution to various remote spectroscopy applications. Future experiments with other exotic beam shapes, such as parabolic beams and spiraling beams, will be also discussed.

[66] Dedicated Laboratory Setup for CO2 TEA Laser Propulsion Experiments at Rensselaer Polytechnic Institute

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Abstract. Laser propulsion research progress has traditionally been hindered by the scarcity of photon sources with desirable characteristics, linked to specialized flow facilities in a dedicated laboratory environment. For TEA CO2 lasers, the minimal requirements are time-average powers of >100 W, and pulse energies of >10 J with short duration (e.g., 0.1 to 1 μs); furthermore, for the advanced pulsejet engines of interest here, the laser system must simulate pulse repetition frequencies of 1-10 kilohertz or more, at least for two (carefully sequenced) pulses. A well-equipped laser propulsion laboratory should have an arsenal of sensor and diagnostics tools (such as load cells, thrust stands, moment balances, pressure and heat transfer gages), Tesla-level electromagnet and permanent magnets, flow simulation facilities, and high-speed visualization systems, in additional to standard optics and gas supply systems.

Just such a laboratory has been created at Rensselaer Polytechnic Institute. In this paper we introduce this cutting-edge Laser Propulsion Laboratory, one of the few in the world to be uniquely set up for beamed energy propulsion (BEP) experiments. The current BEP research program is described, along with the envisioned research that will exploit expanded facilities, currently under development. Of

course, a non-trivial element in this research is the vision and strategy that dictates work actually pursued in the lab, because at this point in history, the opportunities are limitless.

Keywords: Laser Ablation Propulsion, High Power Lasers Application and Diagnostics, Physics of Laser Matter Interactions.

Tuesday evening Poster Session

[109] $O_2(a^1\Delta)$ Quenching in the $O/O_2/O_3$ System

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Abstract: Rapid quenching of $O_2(a^1\Delta)$ in $O(^3P)/O_2/O_3$ mixtures has been observed. Oxygen atoms and singlet oxygen $O_2(a^1\Delta)$ molecules were produced by 248 nm laser photolysis of ozone. $O_2(a^1\Delta)$ quenching was followed by detecting the 1268 nm fluorescence from the *a-X* transition. Temporal profiles for the oxygen atoms $O(^3P)$ were monitored by means of the O+NO chemiluminescent reaction. Fast and slow decays of $O_2(a^1\Delta)$ were observed. The fast decay was observed when O atoms were present in the system. An attempt was made to model the fast decay using the three body quenching process $O_2(a^1\Delta) + O + O_2 \rightarrow 2O_2 + O$ suggested by Braginskiy *et al.* (*J. Phys. D: Appl. Phys.* **38** (2005) 3609). The near gas kinetic rate constant obtained from this analysis ($(1.1\pm0.1)\times10^{-31}$ cm^6/s) was inconsistent with data obtained from flowing afterglow experiments, indicating that additional quenching species are generated by the ozone photochemistry. Rate constants for quenching of $O_2(b^1\Sigma)$ by CO_2 ($(6.1\pm0.5)\times10^{-13}$ cm^3/s) and O_3 ($(1.9\pm0.2)\times10^{-11}$ cm^3/s) were measured as a test of the kinetic analysis techniques.

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[92] Effects of Mode Matching and Radial Intensity Distributions in Pulsed, Optically Pumped Rubidium Laser

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Topic Area: Advances in promising new laser technologies (DPAL), Optically pumped lasers

Abstract: The Diode Pumped Alkali Laser (DPAL) offers great promise for high power applications and is based on optical excitation on the D_2 $^2S_{1/2} - {}^2P_{3/2}$ line, collisional relaxation to the upper laser level, $^2P_{1/2}$, and subsequent lasing back to the ground state on the D_1 line. A pulsed, optically pumped rubidium laser operating at 794 nm has been demonstrated and characterized to study the effects of varying pump beam spot size and resonator mode volume on observed slope efficiency. Peak pump intensities as high as 5 x 10^8 W/cm^2 have been used to bleach alkali sample at high concentrations and demonstrate scaling to more than 100 x threshold. The temporal dynamics after short, 10 ns, excitation reveal kinetic and optical limitations. Overall system performance is compared with

analytic and computation models that include the broad spectral pump width (~ 0.1 cm^{-1}) convolution with the narrower atomic absorption profile.

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[94] A Three Level Analytic Model for Alkali Vapor Lasers

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Topic Area: Advances in promising new laser technologies (DPAL), Optically pumped lasers

Abstract: A three level analytic model for optically pumped alkali metal vapor lasers is developed considering the steady-state rate equations for the longitudinally averaged number densities of the ground $^2S_{1/2}$ and first excited $^2P_{1/2}$ and $^2P_{3/2}$ states. The threshold pump intensity includes both the requirements to fully bleach the pump transition and exceed optical losses, typically about 200 W/cm^2. Slope efficiency depends critically on the fraction of incident photons absorbed and the overlap of pump and resonator modes, approaching the quantum efficiency of 0.95-.098, depending on alkali atom. For efficicent operation, the collisional relaxation between the two upper levels should be fast relative to stimulated emission. By assuming a statistical distribution between the upper levels, the limiting analytic solution for the quasi-two level system is achieved. Application of the model and comparisons to recent laser demonstrations are presented.

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[107] The Effect of Residence Time on the Production of Singlet Oxygen in Microwave and RF Discharges

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Topic Area: COIL, DOIL, EOIL and Other Unusual Sources

Efficient, high power, discharge pumped oxygen-iodine laser performance requires high $O_2(a)$ yield at moderate oxygen pressure. The $O_2(a)$ yield, defined as $Y = [O_2(a)] / ([O_2(X)] + [O_2(a)])$, in a pure oxygen discharge is limited by the balance between the electron impact production and the inverse, super-elastic rate: $e^- + O_2(X)$ ⍰ $e^- + O_2(a)$. The yield theoretically peaks at about 37% for a reduced electric field of E/N ~ 10 Td, corresponding to an electron temperature of about 1.1 eV. However, self sustained O_2 discharges tend to operate at somewhat higher E/N than ideal for $O_2(a)$ production. The present experimental study examines the dependence of $O_2(a^1\Delta, b^1\Sigma)$, highly excited atomic oxygen, and gas temperature on the residence time in both microwave and radio frequency discharges and presents the relative yields as a function of specific energy deposition. A discussion of the second order kinetics which limits the yield suggests vibrationally excited, ground state oxygen may limit scaling.

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[77] Applying New Laser Interaction Models to the ORION Problem

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Topic: Applications: Laser Space Debris Mitigation and Planetary Defense

Abstract: Previously, Phipps, *et al.* developed a model that permitted laser ablation impulse predictions within a factor of two over an extremely broad range of pulse durations and wavelengths in the plasma regime. For the lower-intensity vapor regime, below the plasma transition, Sinko has developed a useful, fluence-dependent model which predicts impulse delivered for pulsed lasers on polymers at a specific wavelength. Phipps subsequently developed an alternate model which treats elemental solids in the vapor regime, and that only requires knowledge of basic material parameters and vapor pressure vs. temperature data. These data, except for optical absorptivity, are wavelength-independent. A simple technique combines either vapor model with the plasma model to form a complete model that moves smoothly through the vapor to plasma transition.

In this paper, we apply these models to show the optimum momentum coupling fluence on target, at the transition from the vapor to the plasma regimes, for aluminum (a typical debris material) and polyoxymethylene (representing polymeric debris). The application of this work is the ORION laser space debris mitigation concept. This is an improvement over previous work, in which this optimum was only estimated from the plasma ignition threshold. We present calculations showing how impulse delivered to debris targets in the ORION concept varies with pulse duration, and the ablation depth on debris targets, which must be small enough to avoid debris fragmentation, at a maximum fluence determined by nonlinear optical effects in the Earth's atmosphere.

[86] Can Lasers Play a Rôle in Planetary Defense?

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Topic: Applications: Laser Space Debris Mitigation and Planetary Defense

Abstract: It is now well-established that a NEO in the 1 to 5-km size range extinguished the dinosaurs, although such events have an impact interval on the order of 100M years. Smaller "snowball" objects with diameters of tens of m may fragment in the atmosphere, but could still create extensive damage due to blast and heat. From a risk point of view, these objects are of two types: asteroids in stable orbits which can be tracked and long period comets. Among the latter, comet nuclei which have not yet been detected constitute the main hazard. These "dirty snowballs" typically have albedo of a few percent. Such objects in the 0.1 to 1 km size range may not be detected before approaching within 1 to 10 A.U. of Earth and, since their approach velocity may be 30-60 km/s, that situation leaves on the order of 100 days to respond.

Beginning with the NASA/Los Alamos Workshop on Near Earth Object Interception in 1991, lasers have been considered a means for deflecting near-Earth objects (NEO's) discovered to be on a collision course with Earth. However, such meetings have usually concluded that the most effective response is a standoff nuclear detonation, physically delivered to the NEO.

This paper finds significant advantages in retargeting, probability of success and even precise target location which are possible with the laser alternative. What makes this possible is discarding earlier

assumptions about laser mirror size. In this study, we assume a 20-km-diameter mirror, which would be a thin foil space-based structure. With our choice of laser parameters, the laser would necessarily be space-based also, to avoid nonlinear optics effects in the atmosphere.

If the NEO has optical scattering coefficient ε into 2π sterradians, the range to detection Z_{DET} is given by $(1+ Z_{DET}) Z_{DET} = 1.9E\text{-}10\ D_A D_R/\lambda[\varepsilon/(S/N)]^{1/2}$ in units of A.U., S/N indicates the necessary detector signal to noise ratio and D_A, D_R are the asteroid and detection receiver diameters. We consider a 100-m cometary object with a highly elliptical orbit originating in the Oort cloud which is discovered on first approach at 30km/s. With $\varepsilon = 25\%$ at λ=550nm, D_R=10m and S/N = 1.5, detection can occur at 3.3 A.U., giving 190 days to act on the object. Where r_o is the distance of closest approach to Earth and v_o is the object's incident velocity, we wish to impart a change dv_o which will make the cometary object arrive just 214 seconds later, and miss the Earth. We will discuss the assumed astrodynamics which yielded this requirement.

Assuming a momentum coupling coefficient C_m = 5 dyn-s/J, a 2.2MW repetitive pulse 1.06μm laser (f = 0.7Hz with 3MJ, 100ps pulses) will deflect the object sufficiently to avoid collision.

[87] "Catcher's Mitt" as an Alternative to Laser Space Debris Mitigation

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Topic: Applications: Laser Space Debris Mitigation and Planetary Defense

Abstract: Other papers in this conference discuss the ORION concept for laser space debris mitigation. An alternative concept nicknamed "Catcher's Mitt" has been proposed. In this concept, a block of low density solid material is placed in a precessing, elliptical, near-equatorial orbit to sweep out near-Earth space between about 400km and 1100km altitude where the hazardous debris objects reside. The concept could work by vaporizing or trapping the objects, or slowing them enough for re-entry on passing through the "mitt."

The most hazardous debris objects are those between 1 and 10-cm diameter, which are difficult or impossible to detect and track using conventional technology and much more numerous (about 300k objects) than the larger debris objects. The latter are few enough to be catalogued, and to be evaded.

Calculations we will present in this presentation show very serious problems with this approach.

To compete with ORION, an alternative must intercept 300k objects in two years. Given the above altitude range, the number density is 2.9E-6/km³. To succeed, it is necessary to have a reaction rate R = 4.7E-3/s over this time. With a typical interception velocity v_o = 10km/s, the required cross section is σ = 161km^2, or a square object 12.7km on a side. The typical incident areal mass density M/A is 10kg/m² (1g/cm²). To slow the object by Δv in a slab of aerogel with mass density 1kg/m³, the thickness of the mitt must be 90 cm, giving a total mass of the "mitt" of 146Gg or 146 ktonnes. Current spacelift technology would require a launch vehicle with 3.6 Mtonnes mass and 78 billion pounds liftoff thrust.

The second major problem with the concept is ram pressure at the required 400km perigee, which would lead to a lifetime on orbit of 56 hours. Even though atmospheric density at this altitude is just 3.7E-15 g/cm³, the pressure at orbital speed is 438N/km². To counter this, an engine must be present which continuously delivers about 10kN thrust averaged over an entire orbit, for two years. If perigee is raised until this thrust becomes reasonable (e.g., 4N at 1000km), the mitt fails to address the debris problem except for the small subset of very elliptical or very high altitude debris orbits.

As an alternative, we also consider the design of a much smaller "mitt" which would protect a single spacecraft.

[46] Laser Driven Compression Wave Equations of State and Momentum Coupling Measurements in Thick Solid Metallic Targets at 0.1 - 10 TW/cm^2

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Abstract: An experimental methodology was developed to obtain the equations of state (EOS), momentum coupling coefficients (CM) and strain rates for a series of high energy density laser impact experiments in the 100 GW/cm2 (λ = 1064 nm) to 10 TW/cm2 (λ = 527 nm) range on a variety (Al, Cu , Ti, Fe, Ni) of thick (≈ 1 - 3 mm) solid metallic targets. At intensities of ~ 7 TW/cm2 plasma pressures and temperatures reached several hundred GPa and over two million K in the Al targets while the corresponding rear surface pressures exceeded 30 GPa with an average shock wave transit velocity ~ 6 - 7 km/s. Target response was initiated by a surface ablation blow-off plasma compression that subsequently generated an impulsive wave whose effects on the target included elastic and plastic deformations and in some cases phase transformations, mechanical failure (fragmentation), and debris generation (spallation). Instead of using the very expensive Visar interferometer that requires an impedance matching window, a simple probe laser/fiber optic system was used to measure rear surface particle velocity. This probe laser reflected from the diamond polished rear surface of the target and monitored the rear surface deformation, shock wave emergence, and particle velocity in real time with ~ 3 GHz resolution. The target thickness prevented front surface laser irradiation from effecting, by changing the rear surface reflectivity, the rear surface reflection detected. In the 10 TW range electromagnetic pulse noise generated from the target chamber initially overwhelmed the detector signal, but an analysis of the EMP pulse frequencies and identification of the noise origins led to appropriate shielding configuration changes that overcame this problem. Direct measurement of the transit time of the compression waves and rear surface particle velocities allow determination of the rear surface Hugoniot pressure, EOS and CM. These values obtained using the laser are compared to those using high pressure gas gun. Such laser generated high pressure compression wave and optical measurements on large and thick targets are important for understanding high energy density equations of state in general and mediating materials properties modeling in the meso-scale range where inhomogeneities and phase boundaries play a critical role. The values for Fe under high pressure are useful in planetary astrophysics modeling of planetary cores and high velocity impact.

[43] Laser and Z-pinch Simulation of High Energy Density Planetary Interactions

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Invited paper

Abstract: This analysis addresses issues using high energy laser, soft X-ray and black body radiation to simulate high velocity impact and related high energy density (HED) plasma interactions. Different intensity transport mechanisms induce quantitatively different equations of state (EOS) and associated macroscopic responses for a given intensity (energy transport /area-time) value. This

effect is significant at intensities used to generate HED interactions (~ several GPa) that are about an order of magnitude or more greater than the vaporization energy of target material ($\geq 10^7$ J/kg). Effects of HED interactions also characterize warm dense matter states in the temperature range from ~ 0.1 to 30 eV at densities of ~ 10^{-3} to 10 g/cm^3 ; the upper range of these values, 0.5 to 30 eV and 0.5 to 10 g/cm^3, are expected to exists in some planetary cores and planar shock waves. Typically this plasma region is generated by intensities from ~ 10^{16} to 10^{22} W/m^2 depending on target material properties and irradiation wavelength(s). An analytic methodology is presented that computes, for equivalent intensities, different isothermal sound speeds, pressures, temperatures, densities, and continuity relationships and their gradients in plasma, ablation and hydrodynamic regions of solid targets generated via mechanical impact, laser radiation, and soft X-ray/black body energy transport mechanisms. The different intensity transport mechanisms for the same intensity value can significantly affect (by ~ 0 to 100%) the EOS and macroscopic response depending on intensity and type of the HED interaction as compared with ideal plasma calculation. Computations based on analytic derivations using empirical relationships between pressure and temperature as a function of intensity on a range of intensities from 10^{16} to 10^{20} W/m^2 are presented. Dynamic (macroscopic) variables critical for comparative modeling of HED interactions that are effected by different intensity transport mechanisms include macroscopic responses such as ablation rates, ejection velocities,impulse transfer/ momentum coupling, opacity, turbulent mixing lengths and Reynolds and Peclet numbers. Form of the HED intensity is a significant factor in modeling astrophysical, planetary, nuclear fusion, near-Earth hazard mitigation, and related HED phenomena. An example is laser, soft X-ray or black-body radiation to simulate high velocity (~ 10 km/s) planetary impacts effects on material properties and Richtmyer-Meshkov mixing.

Topic: High Energy Laser Interactions with Materials

[34] CO_2 Laser Ablation Area Scaling with Flat Polyoxymethylene Targets

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Topic: Laser Ablation Propulsion, Physics of Laser-Matter Interactions, Fundamental Theory

Abstract: One of the remaining subjects of interest for laser ablation propulsion study is whether special benefits or challenges exist when applying a particularly large or small laser spot area to a target. This subject is of high importance for topics including laser removal of space debris, micropropulsion, and design of laser propulsion vehicles. Analysis of spot area-dependent effects is complex since ablation phenomena differ between atmosphere and vacuum conditions. Progress has also been impeded by the difficulty of setting control parameters (particularly fluence) constant while the spot area is adjusted. It is virtually impossible for one group to address small- and large-area effects using a single high-power laser system. Recent collaborative experiments using 100-J class and 10-J class CO_2 lasers have advanced the understanding of laser propulsion area scaling. Experiments were conducted below the threshold for plasma formation. The dependence of various laser propulsion parameters on the laser spot area has been investigated within areas covering approximately 0.5-50 cm^2 on the target.

[41] Update on CO_2 Laser Ablation of Polyoxymethylene

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Topics: Laser Ablation Propulsion, Physics of Laser Matter Interactions

Abstract: Polyoxymethylene (POM) propellants have been studied since the 1970's, and perhaps represent the most promising match of a propellant to the CO_2 laser for laser propulsion studies. Applications range from ground-launch of laser propulsion vehicles at atmospheric pressure to space-based laser ablation propulsion microthrusters. In this paper we broadly update the state of understanding of CO_2 laser ablation of POM based on new experiments conducted in Japan and Germany, with a focus on the basic physics of ablation of flat POM targets. Measurements using 10 J-class and 100 J-class lasers are compared to previous literature results for ablation of POM. Emphasis is placed on the influence of control parameters on ablation, especially the incident laser fluence and ambient pressure. New results highlight the influence of the ambient pressure on ablation physics from the vaporization threshold to the plasma regime, and clarify the role of the fluence in determining ablation behavior in air and vacuum environments. Imparted impulse and ablated mass were measured at the target using piezoelectric force sensors, impulse pendulums, and

scientific balances. The new experimental investigations cover orders of magnitude in fluence (10^{-2}-10^{3} J/cm^2) and ambient pressure (10^{-3}-10^{5} Pa).

[52] Coherent acoustic and optical phonons in laser-excited solids studied by ultrafast time-resolved X-ray diffraction

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ABSTRACT: Upon excitation of a solid with ultrashort laser-pulses the optical energy is initially stored in the electronic subsystem and subsequently transferred to the lattice in a few picoseconds. Both, electronic excitation and lattice heating can induce rapid atomic motion in the irradiated material. In this work we apply ultrafast time-resolved X-ray diffraction to directly study coherent acoustic and optical phonons in a number of different materials. Femtosecond X-ray pulses at 4.51 keV (Ti K_a) and 8 keV (Cu K_a) produced by irradiating the corresponding target materials with high intensity laser-pulses served as probe pulses in an optical pump – X-ray probe experiment. We measured transient changes of intensity and angular distribution of Bragg-diffracted X-rays as a function of pump-probe time delay. Using thin, crystalline films as samples to be excited with 100 fs laser pulses we were able to generate well-defined excitation conditions and to exclude the influence of carrier diffusion and heat conduction.

In Ge and Au we investigated coherent acoustic phonons which are often described with the model of Thomson et al. [1]. In this model the acoustic response of the lattice is attributed to the increase in pressure induced by both, electronic excitation and quasi isochoric heating of the material. It was the particular goal of this study to clarify the interplay of the electronic and thermal driving forces. For Ge our measurements reveal that the relative strength of the electronic pressure decreases with increasing laser fluence. For larger laser fluences the thermal pressure exceeds the electronic one, and only at low excitation strength the electronic pressure becomes the dominant driving force, as predicted by theory [1]. For the case of Au the data are well described within the established theoretical framework using the known values for those material parameters which determine the laser-induced pressure, namely the energy relaxation time and the electronic and lattice Grüneisen parameters.

In Bi we studied coherent A_{1g}-optical phonons which can be excited via the so-called displacive excitation mechanism (DECP) [2]. Previous work performed at the Sub-Picosecond Pulse Source [3] has allowed us, for the first time, to quantitatively measure the transient laser-induced changes of the potential energy surface which underlie DECP. In the present work we have extended our studies of coherent optical phonons to higher excitation fluences. For those fluences the experimental data reveal an extreme softening of the A_{1g}-mode in Bi down to frequencies of about 1 THz, only 1/3 of the unperturbed A_{1g}-frequency. The observed softening follows qualitatively the predictions of density functional theory calculations [4]. For even higher fluences the measured diffraction signals no longer exhibit an oscillatory behaviour. Our experimental observations present strong indication that upon intense laser-excitation the Peierls-transition which determines the equilibrium structure of Bi can be reversed and the material transformed into a transient ordered state of higher symmetry

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TOPICS: Physics of Laser Matter Interactions, Femtosecond and Attosecond Effects

[71] Z-pinch Discharge in Laser Produced Plasma

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ABSTRACT: There are many reports of using fast, high current electrical discharges in laser produced plasma (LPP) with the aim of compressing and heating the plasma to make a pulsed X-ray source for time-resolved microscopy. The LPP is formed in the anode-cathode gap by laser ablation of one of the electrodes and acts to trigger the discharge. The interaction of the high current and the self-induced magnetic field leads to radial compression of the plasma to form a micro Z-pinch. This technique has also been explored for the generation of radiation at 13.5 nm for extreme ultraviolet lithography.

In this paper we describe the results of an experiment to investigate to behaviour of a relatively low power discharge in a LPP. Instead of forming the LPP on one of the electrodes, we formed it on a separate rotating aluminium target and allowed a portion of the plasma to flow into the gap through a 3 mm diameter aperture in the grounded electrode of a coaxial discharge cell. In this way we can load the discharge with nearly-collimated plasma of controllable line density. The LPP was produced with a 20 ns excimer laser. The discharge was supplied by a 1.5 μF capacitor charged to 1 kV and is self-triggered when the plasma column reaches the live electrode. The discharge was underdamped with a period of 2 μs and a peak current of 3.5 kA. Slits in the outer coaxial electrode provided optical access for time-resolved ICCD imaging and UV/visible emission spectroscopy.

The time-resolved imaging shows that Z-pinching of the plasma occurs but compression is limited by the onset of a sausage instability. Emission spectroscopy shows that the plasma temperature and degree of ionisation increase as the charging voltage and discharge current are increased. With no discharge, only Al I emission lines are observed, while at 800 V strong emission on Al II and Al III lines is seen. However, it seems that in order to reach the plasma conditions for strong EUV emission a faster discharge with higher current is required.

Topics: Advanced Materials Processing, Propulsion, Laser Applications and Diagnostics

[47] Separation of Copper Isotopes in the Laser Plume

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Topic: Physics of Laser Matter Interactions

Although several studies have reported isotope enrichment during laser ablation, the phenomenon is not well understood. Research into the mechanisms underlying this phenomenon would help advance the basic science of laser material interactions, specifically with regard to the development of the ablation plume. In addition, a better understanding of isotope separation within the plume could be important to the use of laser ablation for chemical characterization.

In this study, isotopic separation was observed during ablation of standard copper samples by a nanosecond Nd-YAG laser, frequency quadrupled to 266 nm. A time-of-flight mass spectrometer, orthogonal to the direction of the laser plume, was used to measure the isotopic composition of the plasma at different delay times in order to obtain a temporal profile as the plume expanded. The fraction of ^{63}Cu in the plasma detected by the mass spectrometer reaches a maximum of 0.85 around 10 μs after the laser is fired before falling back to the natural abundance ratio of 0.69. As reported in the literature, the ion peaks are centered at two different delay times, representing fast and slow ion energy distributions. The time of maximum isotopic enrichment appears near the falling edge of the fast ions and the rising edge of the slow ions. A mechanism based on the electric field between the electrons and ions is proposed to explain the separation of isotopes in the plume.

[6] Study on Laser-induced Periodic Structures and Photovoltaic Application

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Topic(s) : Physics of Laser Matter Interactions ; Simulations ; Nanoengineering

Abstract: Laser-induced periodic structures on surface can be understood as a universal phenomenon, which occurs for a broad range of wavelengths and different laser polarizations. The interference of a diffracted optical wave with the incident beam gives rise to the optical interference fringes. The smaller structures called "ripples" are similar to the capillary waves with a sub-micrometer periodicity (close to the laser wavelength). They are formed at low energy density and/or number of pulses. For higher energy densities and number of pulses those capillary waves tend to collapse to form a more hydrodynamically stable structure, like "beads". The absorption of light on these beads is not uniform: the ablation is maximized in the valley between the beads which tends to amplify the phenomena and creates more erected structures (cones, spikes). We study the formation of the first ripples and the following transformation of these ripples into spikes as a function of laser parameters, such as energy density, numbers of shots, and laser polarization. We fabricate

micrometer silicon spikes by irradiating a silicon surface with 800 nm, 100 fs laser pulses from crystalline silicon (100) and mc-Si targets placed under vacuum (10^{-5} mBar). The surface treated by the laser turns to black when choosing the appropriate parameters. We investigate the optical properties of the surface (reflectance, transmittance and absorption) in the visible and near-IR range. The obtained results show that we can decrease the optical reflectance down to 3% in the near-UV and visible range, compared to a non-texturized silicon surface. This effect can be used for photovoltaic applications. After laser processing, the front side of the samples is boron-implanted by Plasma Immersion Ion Implantation (PULSION® tool developed by IBS) to create the 3D p+ junction. The different photovoltaic efficiencies are characterized by I(V) curve and by Light Beam Induced Current (LBIC).The significant improvement of the photocurrent is discussed in the paper, and the results are analysed based on the developed numerical model.

[101] Self Focusing of Laser Beams in Thermal Conduction Loss Predominated Plasmas

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Topic: Laser-matter Interaction

Abstract: In the present paper, the self focusing of laser beams in thermal conduction loss predominant plasmas is studied by moment theory approach. Moment theory has been adopted in place of paraxial ray approximation and variational approach which have so far been the basis for most of the analysis of self focusing. We have set up the nonlinear differential equation for beam width parameter of the main beam and is solved numerically by using Runga Kutta method. Effect of increase in value of intensity on the beam width parameter is studied. It is observed from the analysis that increasing the value of intensity brings about reduction in self focusing length on account of increase in nonlinearity.

[91] NONLINEAR MECHANISMS OF LIGHT BEAM ABSORPTION IN TRANSPARENT MATERIALS UNDER HIGH POWER LASER ACTION

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Topics: Physics of Laser-Matter Interaction, High Power Lasers Application, Fundamental Theory

Abstract: Analysis of the nonlinear mechanisms of light beam absorption in transparent materials under high power and ultrashort pulses laser action are presented. The processes of the nonlinear absorption and ablation of the transparent materials such as nitride semiconductor, sapphire and others under terawatt/cm^2-laser irradiation with ultrashort pulses are considered.

It is well known that laser ablation of the TW/cm^2 range laser irradiation with ultrasort pulses is suitable technique for surface processing and machining of semiconductors and isolators, particularly of hard and inert semiconductor nitrides. It means that there is an effective nonlinear mechanism of the power irradiation absorption in the transparent frequency region at TW/cm^2-range of power

density. For GaN the value of an effective absorption c oefficient of an induced light absorption is about of $2.5x10^4$ cm^{-1}. The linear absorption coefficient in GaN at 400 nm is less than 100 cm^{-1}.

A comparison of the ablation threshold has been performed for different transparent materials under very similar irradiation conditions. GaN epitaxial layers on the sapphire substrates, sapphire and silica-based glasses are tested. It was determined the laser-induced damage threshold (LIDT) and result shows the correlation of the LIDT with energy bandgap and other material characteristics. The threshold appears to grow as about third power of the energy bandgap. Existence of such a dependences allows to determine the type of a nonlinear mechanism of the absorption.

According to the general theory of the nonlinear ionization of the atoms and solid materials the character of the nonlinear ionization under a field action is determined as the intensity I as the irradiation frequency ω. The important parameter of this theory is adiabaticity parameter γ wich depends on the strength and frequency of the electric field. If $\gamma >> 1$ (high value of ω and moderately high fields) the simulteneous absorbtion of the several photons - multiphoton mechanism is realized. If $\gamma << 1$ (high value of the laser power and the case of low frequencies) there is realised the tunneling mechanism of absorption in the electric field.

For *GaN* $E_g \approx 3.43$ eV and for $I = 40$ TW/cm^2 and $\omega = 10^{15} s^{-1}$ $\gamma \sim ½$. For other transparent materials under investigation parameter γ are much smaller than for GaN since the bandgap of GaN is the smallest one. It means that for the ablation processes in GaN and in all presented experimental results at terrawatt laser power it is realized the tunneling mechanism of absorption.

Using the dependencies of the tunneling probability on ω, I and the energy bandgap we was determined the LIDT dependence on E_g^3 which is in good agreement with experimental results. The corresponding increasing of the absorption coefficient was determined. For GaN we had estimated α about $10^4 cm^{-1}$ that is also in good agreement with the experimental results.

Thus it was shown that the type of nonlinear absorption depends crucialy on the laser treatment regimes (multi-TW/cm^2 range femtosecond laser pulse ablation) as well as on semiconductors and isolators energy bandgaps.

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[79] SPALLATIVE ABLATION OF METALS AND DIELECTRICS BY ULTRASHORT X-RAY LASERS

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Topics: Fundamental Theory, Physics of Laser Matter Interactions; Simulations

Abstract: The report presents theory and experiments on ablation of wide-gap LiF crystal by soft X-ray laser (XRL) in Kansai Photon Science Institute with 90 eV photons and pulse duration $\tau = 7$ ps. The Ag XRL was operated with a single target, without using the additional amplifier target to generate the completely coherent XRL beam. The XRL beam with energy □~ 1 □μJ and the horizontal and vertical divergences of 12□5 Mrad^2, respectively, was focused on a LiF crystal of 2 mm thick and 20 mm diameter, by using a spherical Mo/Si multilayer mirror of 1050 mm radius of curvature. It is found that a crater appears on a surface of LiF for XRL fluence, exceeding the ablation threshold F_{abl} □≈ 10 mJ/cm^2 in one shot, or 5 mJ/cm2 in each of the three XRL shots. This is substantially below the ablation thresholds obtained with other lasers having longer pulse duration and/or longer wavelength.

The theory explains why experimental ablation threshold F_{abl} is remarkably small, it is order of magnitude smaller than F_{abl} for XRL with long pulse $\tau = 1.7$ ns and several orders of magnitude smaller than F_{abl} for dielectrics irradiated by infrared or visible light lasers with short or long pulses. The explanation is based on *spallative ablation* mechanism. Until now *spallative ablation* is exclusively attributed to metals and semiconductors irradiated by ultrashort laser pulses with optical photons ~ 1 eV. Discovery of *spallative ablation* started from surprising fact of non-monotonous reflection (Newton rings) found in outstanding experiments done by Sokolowski-Tinten et al., PRL, 1998. It turns out that the phenomenon of Newton rings is quite general - it was found in all checked metals and semiconductors without any exception. But despite many attempts with similar lasers it has never been seen in dielectrics. Explanation of the phenomenon (Inogamov et al., JETP Lett., 1999) introduces *spallative ablation* into the list of the most important ablation mechanisms.

This report demonstrates that *spallative ablation* takes place in dielectrics if infrared or optical lasers are replaced by picosecond X-ray laser. We believe that low energetic *spallative ablation* is very important for future application of ultrashort XRL for micromachining of any materials, from metals to dielectrics.

The work of NAI, VAK, YVP, VVZ is supported by RFBR (09-08-00969-a).

[81] Pump-probe Exploration of Ultrafast Electron Processes in Metal Irradiated by a Femtosecond Laser Pulse

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Topics: Fundamental Theory, Physics of Laser Matter Interactions; Femtosecond and Attosecond Effects

Abstract: New experimental, theoretical and simulation results about ultra-short pulse laser - matter interaction are presented. Two terawatt laser sets ($Ti:Al_2O_3$, 800 nm, $\tau = 10 - 40$ fs and $Cr:Mg_2SiO_4$, 1240 nm, $\tau = 100$ fs) and pump-probe technique of optical measurements are used. Pump-probe technique can explore a target after pump with extremely short time steps between successive measurements. Theory is based on short-time two-temperature electron-ion (2T) hydrodynamic and long-time molecular dynamic simulations.

For metals having high reflectivity the absorbed fluence F_{abs} is small, and the accurate measurement of reflection coefficient is essential for theoretical interpretation of experimental results. Experiments

and simulations point out to qualitative differences in optical response to pump between simple, noble and transition metals related to their band structures. Probing within 1-100 ps time range gives the depth of heated zone and rate of electron heat propagation into bulk at 2T stage. Also such probing data contain information describing strength $\sigma^*(T_{nucl};\ dV/Vdt\ )$ of a melt at different temperatures defined by F_{abs} and at extremely high expansion rate $dV/Vdt \sim 10^{10}\ s^{-1}$. Increasing of F_{abs} increases temperature T_{nucl} in nucleation (cavitation) zone and, thus, decreases strength σ^* of melt to resists stretching. At present the strength of molten metals is poorly known. New data on spall strength of liquid and solid metals are presented.

Pump-probe micro-interferometry provides information on plume formation and its structure for more early stage than it can be measured by other optical methods for sub-picosecond range or by time-of-fight mass-spectrometer many microseconds later. This technique can explore the displacement of a free rear-side surface of foils as well. Since the wave profile is formed in frontal layer during a short 2T stage the thin foils with thickness of several heating depths (microns) are used to get experimental data about 2T stage, because the rear-side expansion is controlled by a profile of acoustic/shock wave coming to the rear-side from irradiated frontal side.

Thick foils are necessary for measuring of spall strength in solid state because the rear side is not affected by the frontal 2T heating and melting. We reach the strain rates $dV/Vdt \sim 10^{10}\ s^{-1}$ which is extremely higher than more common experimental techniques. By our approach we measure spall strength for simple acoustic profiles (using thick foils) and for real complicated wave profiles (using thin foils) carrying information about fast non-equilibrium 2T electron-ion processes depending on band structure of metal.

[121] The Laser Damage Threshold for Materials and the Relation Between Solid-melt & Melt-vapor Interface Velocities

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Abstract: Numerous experiments have demonstrated and analytic theories have predicted that there is a threshold for pulsed laser ablation of a wide range of materials. Optical surface damage threshold is a very complex and important application of high-power lasers. Optical damage may also be considered to be the initial phase of laser ablation. In this work it was determined the time required and the threshold energy of a layer of thickness Δ to heat up. We used the Finite Difference method to create simulation programs for the process of laser-target interaction in three cases. Namely, the case before melting begins using a continuous wave (C.W) laser source and a pulsed laser source, the case after the first change of state (from solid to melt), and the case after the second change of state (from melt to vapor). And also study the relation between the solid-melt and melt-vapor interface velocities to have a commonsense of the laser ablation process.

We conclude that Damage threshold varies nonlinearly with laser pulsewidth and target material properties. In this work it was determined the time required and the energy required for a layer of thickness Δ to heat up, to melt, and to evaporate. The effect of changing the distance between the source and the target was considered also. The absorption of laser radiation leads to heating of the target at or near the surface in the case of good conducting metals due to the high conductivity, so the heat diffuse in the surface. The conductivity will be reduced with temperature, so laser heating will be concentrated in the molten area which will speed up the heating process. For a low intensity laser beam and with melt removal process, local melting can be achieved by using a pulsed laser with narrow pulse-width and high peak intensity. And at last we studied the relation between the solid-melt and melt-vapor interface velocities to have a commonsense of the laser ablation process and we

observed that the distance between the two interfaces decrease with time at high power to almost move with the same velocity to represent a process act as sublimation process.

[67] High-Power Laser Ablation Plasma Dynamics: From Experiment to Fractal Hydrodynamic Model

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Topics: 1. Physics of Laser Matter Interactions, 2. Fundamental Theory, 3. PLD, MAPLE and Processing of Advanced Materials

Studying the dynamics of plasma plumes generated by pulsed laser ablation presents fundamental interest, as getting better understanding of the complex laser-matter interaction and subsequent elementary processes taking place in the transient expansion, and is also important for application fields like analytical or materials sciences. High-power laser ablation involves complex phenomena, from the interaction of laser radiation with the target material, to laser beam absorption in the ablation plume, to hydrodynamics and electrical processes in the expanding plasma. In order to get better insight on this complexity, it is desirable to know directionality, velocity and other parameters of ejected plasma plume far from the irradiated target.

During the last several years, we developed systematic studies on these issues, both experimental, using optical (space- and time-resolved emission spectroscopy, fast ICCD imaging) and electrical (Langmuir probes, mass spectrometry) methods, and theoretical, in the frame of a fractal hydrodynamic model. Various lasers have been used to irradiate at high fluence (up to 1 kJ/cm^2) different types of samples, from simple model targets (Cu, Al) to chalcogenide glasses (with high potential in developing wavelength conversion devices, Raman and parametric amplification, laser sources for mid-IR, etc.) or ceramics used as dielectric walls in Hall Effect Thrusters for space propulsion [1-3].

The fractal hydrodynamic model developed in a non-differentiable space-time [4, 5] successfully reproduced the splitting of the plasma plume in two structures and their mean velocities. Moreover, the (quite surprising) oscillatory structure of the ionic current recorded by the Langmuir probe (for various targets, laser fluences, and probe positions) has been related to the ion plasma frequency and electron-ion collision frequency, while the continuous component of this transient ionic current was shown to match the ion implantation model proposed by Lieberman [6].

We present an overview of this experimental and theoretical work, with particular focus on new theoretical results.

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[136] Innovative drug injection via laser induced plasma

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Abstract: A laser based reusable microjet injector has been developed. Although needles and syringes are mostly used to deliver therapeutics transdermally among various delivery methods, they have significant limitations that include needle phobia due to pain, contamination from re-use of needles in developing countries, and creation of large volumes of medical waste [1,2]. For these reasons, several kinds of liquid jet injectors have been considered to deliver drugs and vaccines in place of needles. Nevertheless, they did not gain popularity due to the potential for cross-contamination from splash back during injection, poor reliability of delivered dose and depth, and the fact that they are still painful for patients [3-5]. As an alternative to minimize pain and stabilize administrated drug dose, pulsed microjet injectors have been studied that can achieve injection in a few nanoliters of drug dose and provide time-varying jet velocity [6]. With this type of new injector, the amount of splash back responsible for cross-contamination would be notably reduced, and a drug delivery process would consist of several time-varying injections such that the microjets are precisely controlled by real-time-monitoring of delivered dose and penetration depth.

We propose a new microjet injector using laser pulses which can achieve time-varying microjets of small doses. This laser based device has notable advantages: i) it can collect extremely high energy in a tightly confined small region with excellent controllability and repeatability, and ii) it can be miniaturized through the use of optical fiber such that one can in principle administrate drug into currently non-approachable treatment sites in human body [7]. We focused a laser beam inside the liquid contained in the rubber piston of micro scale. The focused laser beam causes explosive bubble growth, and the sudden volume increase in a sealed chamber drives a microjet of liquid drug through the micronozzle. In this research, the exit diameter of a micro-machined nozzle was 125 μm and the injected microjet reached an average velocity of 264 m/s before its breakup (Fig. 1). The measured microjet diameter was comparable to the nozzle exit and the measured jet velocity was high enough to penetrate human soft tissue.

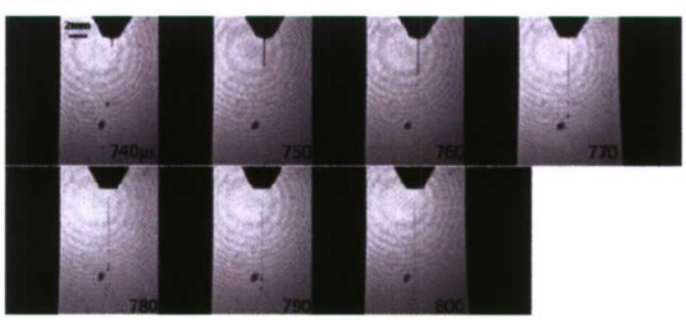

Fig. 1 Sequential images of microjet evolution.

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Wednesday 21 April

Session 7: Plume Dynamics
James Lunney, Chair

[28] Plume Dynamics in Femtosecond Laser Ablation of Metals

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Topics: 1 - Physics of laser-matter interactions; 2 - Femtosecond and Attosecond effects; 3 - PLD, MAPLE and processing of advanced materials

Abstract: Femtosecond laser ablation is widely used for micro-machining of solids, deposition of novel materials and as a direct route to nanoparticle formation. There is much current research on the dynamics of the ablation plume; both to obtain a better understanding of the ablation physics and to optimize the applications. It is now well established that a femtosecond laser ablation plume has two main components: a faster-moving plasma part and a slower nanoparticle plume which contains most of the ablated material.

In this paper we describe the results of a range of experiments to comprehensively characterize the ablation plume produced by laser irradiation of a metallic target (Ni or Cu) with ≈300 fs pulses at 527 nm in high vacuum. Both single-pulse and double-pulse irradiation was used. The laser ablation depth was measured using white light interferometry. The dynamics of the plasma part of the ablation plume was measured using Langmuir ion probes and time-resolved imaging and spectroscopy of the plasma self-emission. The ion probe measures the shape, velocity distribution and total ion charge in the plasma plume. The expansion of the nanoparticle plume was measured by imaging nanoparticle blackbody-like radiation. The shape of the overall ablation plume was recorded by depositing a thin film on a transparent substrate and measuring the thickness distribution.

For single-pulse ablation we find that the ablation depth varies from ≈20 nm at 0.1 J cm^{-2} to ≈100 nm at 0.7 J cm^{-2}. The expansion of the plasma plume is well described by the Anismov isentropic model of plume expansion. The average ion energy in the forward direction is ≈80 eV and the plume becomes somewhat more forward-peaked as the fluence is increased. Both from the deposition measurements and the time-resolved imaging, we find that, just above the ablation threshold, the nanoparticle plume is also well described by the Anisimov expansion model. However, at higher fluence it seems that expansion is somewhat restricted, perhaps due to the pressure exerted by plasma.

For double-pulse ablation we find that as the second pulse is delayed beyond ≈20 ps the ablation depth is reduced and the ion yield is increased. This behaviour is due to absorption of the second pulse in the nascent plasma plume produced by the first pulse. It seems that the pressure exerted by

the reheated plasma is acting as a tamper which impedes the fragmentation and ablation of deeper layers of material.

[39] Dynamics of Femtosecond Laser Ablation Plume Studied with Ultrafast X-Ray Absorption Fine Structure Imaging

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Topic(s): 1 – Particle generation via femtosecond laser ablation; 2 – High power lasers application & diagnostics; 3 – Physics of laser matter interaction

Abstract: Laser ablation induced by a femtosecond laser pulse has attracted a lot of attention as a promising material processing technique for a precise micromachining, novel material synthesis, high-quality thin film growth, and even nanosurgery of cells and tissue [1] . The wide variety of its applications to laser-processing technique has stimulated interest in the ablation dynamics, in particular, the ejection and the expansion dynamics of ablated particles in the ablation plume during the initial stage of femtosecond laser ablation. One of the characteristic of femtosecond laser ablation is that the ablation starts from a highly nonequilibrium states, which is achieved by the confinement of significant quantities of the laser energy deposited in the material before thermal conduction. This mechanism is completely different from conventional nanosecond laser ablation [2]. However, experimental approaches for clarifying the dynamics of femtosecond laser ablation are very limited, because there are still considerable difficulties involved in identifying ablation particles experimentally and measuring their physical properties such as temperature, pressure, velocity, and density, which evolve on picosecond to sub-nanosecond temporal scale and sub-micrometer to micrometer spatial scale.

For this purpose, we have developed an ultrafast x-ray absorption fine structure (XAFS) imaging system with both picosecond temporal resolution and micrometer spatial resolution [3]. The combination of XAFS spectroscopy and a time-resolved imaging technique is a powerful tool for investigating a femtosecond laser ablation process. One reason is that XAFS spectroscopy provides the information on the local electronic state that is sensitive to a chemical bonding or a local atomic structure. This enables us to investigate a laser ablation process where phase transformation, bond breaking, and particle ejection occur instantaneously. The other one is that the time-resolved imaging enables us to obtain the spatial distribution of an ablated material, which changes every moment through the ablation process. Our system was realized by combining the XAFS spectroscopy based on a femtosecond-laser-produced plasma soft x-ray source and the soft x-ray imaging based on a Kirkpatrick-Baez (KB) microscope. This system provides one-dimensional dynamic images of a femtosecond laser ablation plume with a temporal resolution of about 30 ps and a spatial resolution of about 10 μm. We used this system to measure the femtosecond-laser ablation plume of aluminum that is induced in the 10^{13} to 10^{15} W/cm^2 irradiation intensity range. We successfully identified singly and doubly charged aluminum ions, neutral aluminum atoms, and aluminum nanoparticles in the ablation plume by measuring spectral fine structures in the vicinity of the L-shell absorption edge of aluminum, and the temporal and the spatial evolution of the plume. This result confirms that the nanoparticles are generated in the initial stage of the ablation and travel in a in a vacuum as a condensed liquid phase with high temperature. Our experimental results also strongly suggest that the photomechanical fragmentation process, which was theoretically

proposed [4], is the dominant mechanism for the nanoparticle generation via femtosecond laser ablation well above the ablation threshold.

[25] Ablation Plume Dynamics in a Background Gas

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Topics: Physics of laser-matter interactions; PLD, MAPLE and processing of advanced materials.

Abstract: The production of thin films by pulsed laser deposition (PLD) with nanosecond pulses is carried out largely in a background gas of low pressure, e.g. for an oxide film in an oxygen atmosphere, for a nitride film in a nitrogen atmosphere etc. Laser ablation in background gases is also important for other experiments or techniques, such as nanoparticle formation and laser machining. The use of a background gas is well-established and has been studied extensively. However, most of the existing treatments of the plume expansion use complex numerical modeling for specific target/background gas systems and the results obtained are usually difficult to apply for other target/background gas combinations. In the present work, we will analyze the propagation dynamics of a silver ablation plume in different background gases on the basis of the model of Predtechensky and Mayorov (PM).

The starting point is the PM gas-dynamical model of [1], which provides a relatively simple and clear description of the essential hydrodynamics and can be used for target plumes as well as for gases of different atomic mass [2]. PM make the approximation that all the plume material is located in a thin, expanding shell on which the swept-up background gas is compressed as a thin shell as well. Both shells expand together against the pressure of the background gas. This simple approach leads to a clear description of the plume expansion in dimensionless units, for which the underlying equations can be solved analytically. The model describes the full history of the expansion from nearly free propagation of the plume near the target, through a regime of point-blast-wave behaviour before coming to a complete halt. It also describes how the initial kinetic energy of the plume is dissipated into kinetic and thermal energy of the background gas. Eventually when the plume has stopped, the initial kinetic energy of the plume is completely converted into thermal energy of the plume and background gas. The limitations of the model will be discussed as well.

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Session 9: Alkali halide, other Optically Pumped Lasers and Oxygen-iodine Lasers
David Hostutler, Chair

[108] Theoretical and Spectroscopic Investigations of Alkali Metal – Rare Gas Photodissociation Lasers

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Abstract: Alkali vapor lasers pumped by diode lasers are currently being investigated in several laboratories. One problem with this type of device is the poor matching of the relatively broad linewidth of the pump source with the very narrow absorption lines of the atom. Previously, pressure broadening has been used to increase the fraction of the pump laser radiation absorbed. It is also possible that the formation and excitation of alkali metal-rare gas dimers (M-Rg) could be used to achieve the desired spectral broadening. The interactions between $M(^2S)$+Rg pairs are weak, and the potential energy curves exhibit shallow minima that are characteristic of van der Waals bonds. The $M(^2P)$+Rg interactions are much stronger, having characteristics that suggest the formation of incipient chemical bonds. Excitation of the continuum regions of the $M(^2P)Rg \leftarrow M(^2S)Rg$ transitions offers attractive possibilities for utilization of broad band pump radiation in an alkali vapor laser, and laser action has been demonstrated in Cs/Ar and Cs/Kr mixtures. To further explore this concept we are mapping out the M-Rg potential energy curves using ab initio theoretical methods, in parallel with laser excitation and dispersed fluorescence spectroscopy.

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[93] Frequency Dependent Optical Delay with Gain in the Cesium Diode Pumped Alkali Laser System

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Topic Area: Advances in promising new laser technologies (DPAL), Optically pumped lasers

Abstract: Anomalous dispersion in the cesium Diode Pumped Alkali Laser system has been investigated by observing the dependence of the optical delays of a pulsed probe beam on the D_1 line of Cs in the presence of strong optical excitation on the D_2 line. A full dependence of the observed delays on frequency tuning across the hyperfine structure has been observed, with delays of up to 30 ns observed. A narrow band (< 300 kHz) diode laser is modulated to produce 10 ns pulses at 1 kHz repetition rates. Delays are observed as the laser is tuned across a 50 GHz scan of a cesium sample at 80 - 120 °C. A theoretical analysis of the hyperfine structure and impact on the real part of the index of refraction from the Kramers-Kronig relation is developed and compared to the experimental results.

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[75] Optically pumped C2H2 and HCN lasers with conventional cavities and based on hollow core photonic crystal fibers

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Abstract: Lasing in C_2H_2 and HCN are demonstrated in conventional gas cell/cavity geometries and with hollow core photonic crystal fibers when optically pumped in the 1.5 mm region by a ns optical parametric oscillator. Two lasing transitions in the mid-IR region (3 mm) are observed.

[134] 6.5kW, Yb:YAG Ceramic Thin Disk Laser

William P. Latham[(b)]***, Tim C. Newell***[(b)]***, Ahmed Lobad***[(a)], and ***Don Stalnaker***[(a)],

Abstract: The operation of a 1030 nm, single, thin disk laser which produced 6.5 kW of laser output power with a 57% slope efficiency is reported. The Yb:YAG ceramic gain element is 200 μm thick, bonded to a 1 mm, undoped, ceramic YAG cap. The gain element is pumped by diodes at 940 nm. The maximum incident pump intensity was 5 kW/cm^2, which yielded an output intensity of 2.6 kW/cm^2 of multimode laser radiation. Rigrod analysis suggests that the laser operates with inhomogeneous gain saturation. This is attributed to the enhanced, spatial-hole-burning effect when the gain element is adjacent to a mirror. The pump threshold and output intensities were independent of pump spot size, which validates area scaling. Observed thermal lensing contributions include thermal-expansion-induced disk flexure, pump-edge-induced temperature profile and a strong thermal imprint of the cooling nozzle due to the direct jet impingement on the high reflection (HR) coated side. Weak absorption of the 1030 nm intracavity intensity in the undoped cap and/or the anti-reflection (AR) coating led to excess heating that limited the extracted power intensity. These results suggest ceramic Yb:YAG can be scaled to higher powers using optimized thin disk elements and improved disk thermal management techniques.

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Session 10: Space Applications
Jørgen Schou, Chair

[8] Long Conductive Guide for Energy Delivery from Space

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Topic: Launching by Laser and Applications for Launching Technology

Abstract. The goal of the project is to accomplish a circle of experimental, engineering and technological works on creation of long conductive guide for energy delivery from space. High repetition rate pulse-periodic laser system and the most important components for the project realization will be presented. Optical system for long range energy delivery will by discussed as well. Some new applications of energy delivery system will be highlighted. Relying on a wide cooperation of different branches of science and industry organizations it is possible to use the accumulated potential for the orbital scale experiments in our days.

[80] Analysis of Momentum Transfer Due to Laser Ablation of Irregularly Shaped Space Debris*

Duane A. Liedahl (Presenter),[a] ***Stephen B. Libby,***[b] ***Donald W. Phillion,***[c] and ***Kevin B. Fournier***[d]

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Topics: Laser remediation of space debris, High Power Lasers Applications and Diagnostics, Physics of Laser Matter Interaction, and Laser Ablation Propulsion

Abstract: Proposals for ground based laser remediation of space debris rely on the creation of appropriately directed ablation driven impulses to either divert the fragment or drive the fragment into an orbit with a low enough perigee for burn-up. For a spherical fragment, the ablation impulse is a function of the orbital parameters and the laser engagement angle. If, however, the target is irregularly shaped and arbitrarily oriented, significant new impulse effects come into play. Here we present an analysis of these effects and show how they can be accounted for in optimizing the laser engagement scheme.

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[30] Laser Propulsion Standardization Issues

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Topic: Laser Ablation Propulsion

Abstract: It is a relevant issue in the research on laser propulsion that experimental results are treated seriously and that meaningful scientific comparison is possible between groups using different equipment and measurement techniques. However, critical aspects of experimental measurements are sparsely addressed in the literature. In addition, few studies so far have the benefit

of independent confirmation by other laser propulsion groups. In this paper, we recommend several approaches towards standardization of published laser propulsion experiments. Such standards are particularly important for the measurement of laser ablation pulse energy, laser spot area, imparted impulse or thrust, and mass removal during ablation. Related examples are presented from experiences of an actual scientific cooperation between NU and DLR. On the basis of a given standardization, researchers may better understand and more clearly contribute their findings in the future, and compare those findings confidently with those already published in the laser propulsion literature. Relevant ISO standards are analyzed, and revised formats are recommended for application to laser propulsion studies.

[21] Pulsed Laser Ablation of Compound Semiconductors: Vaporization Mechanisms and Cluster Generation

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Pulsed laser ablation (PLA) has proven to be an efficient and flexible method for synthesis of nanoclusters and nanostructures. However, controllable production of nanoclusters with desirable properties is still challenging, especially for multi-component materials when there is an additional parameter to control, cluster composition, which strongly affects cluster properties. This work is devoted to experimental and theoretical studies of nanosecond PLA of compound semiconductors (InP, ZnO, CdTe) important for various applications such as fabrication of solar cells and optoelectronic devices. Particular attention is given to characterization of the cluster formation process.

The experiments were performed with IR (1064 nm), visible (532 nm) and UV (193 nm) ns-laser pulses under vacuum conditions. Neutral and positively charged clusters in the PLA plume were analyzed by time-of-flight mass spectrometry. By comparing two methods of ionization, electron impact and photo-ionization, relative stability of neutral compound clusters was investigated. The cluster composition was found to depend essentially on laser wavelength. In particular, stoichiometric $(ZnO)_n$ clusters (up to n = 34) are efficiently formed under IR PLA while shorter wavelengths result mainly in off-stoichiometric clusters (zinc rich). In_nO_m clusters are indium-rich for all wavelengths though IR PLA produces clusters in much more abundance. Ablation of Co-doped semiconductors was investigated in order to reveal synthesis ways for nanostructures with magnetic properties. Formation mechanisms of the observed clusters and possibilities to control their size and composition under PLA conditions are discussed.

Based on the analysis of abundances and velocities of the plume particles, we show that, depending on laser fluence, different mechanisms dominate in particle desorption/ablation from the irradiated surface. Two models have been developed to describe adequately the ablation process, electronic and thermal ones. The thermal model has been refined to account for material composition changing in a surface layer as a result of different volatility of the components. The optical response of the sample is described by a multilayer model within a concept of effective medium. A model of non-thermal particle emission has been developed which assumes emission enhancement due to non-radiative recombination of the laser-induced *e-h* pairs. Modeling allows to get a deep insight into the complicated dynamics of melting and solidification processes of compound semiconductors. The temporal and spatial scales of surface layer depletion by a volatile component have been determined. Multi-pulse irradiation regimes have been investigated showing saturation of material composition at the surface and uncovering the mechanism of stoichiometry reversal by irradiation control.

Additional abstract information

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Topics (in order of preference) :

1. Physics of Laser Matter Interactions
2. PLD, MAPLE and Processing of Advanced Materials
3. Simulations

Thursday, April 22
Session 11: PLD, MAPLE and Processing of Advanced Materials
Minoru Obara, Chair

[132] Resonant Infrared Pulsed Laser Deposition of Organic and Polymer Materials for Display Applications

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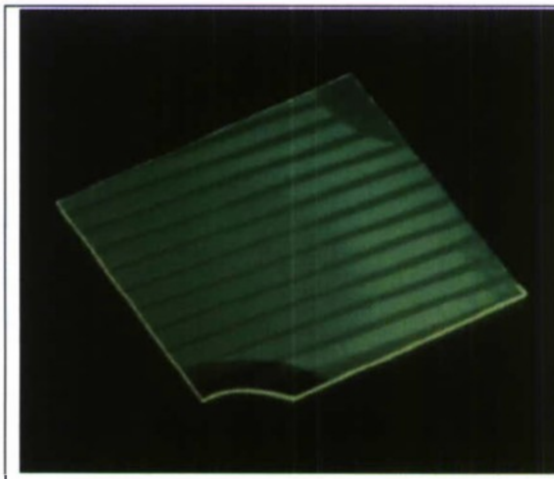
Topic: PLD and MAPLE of Advanced Materials

Abstract: We report recent progress in using resonant infrared pulsed laser deposition (RIR-PLD) to deposit thin films of model small-molecule organic, polymers and nanoparticles relevant to display applications, such as organic light-emitting diode (OLED) technology. The functions of thse generic materials include light emitters, hole-transport layers, barrier layers and transparent conductors. Deposited films are characterized by visible and scanning electron microscopy, Fourier-transform infrared spectrometry, photo- and electroluminescence spectroscopy and four-point probe conductivity measurements.

Thin-film deposition by RIR-PLD is enabled by resonant excitation of a localized, intra-monomer vibrational mode of the target material, such as a C-H stretch; with proper choice of laser parameters such as pulse duration, fluence and pulse repetition frequency, this leads to low-temperature volatilization and deposition of intact small molecules, polymers and nanoparticles. Because the mid-IR photons have energies well below those required to break the bonds connecting monomer units, RIR laser irradiation volatilizes polymers without photochemical fragmentation. Resonant infrared matrix-assisted pulsed laser evaporation (RIR-MAPLE) produces similarly efficient, non-destructive deposition of polymers, biological macromolecules and carbon nanotubes.



Photoluminescence image of an Alq_3 film deposited by RIR-PLD, overlaid by an RIR-MAPLE deposition of TiO_2 nanoparticles deposited through a shadow mask. The bright stripes show the forward-scattering effect of the TiO_2 nanoparticles due to their high index of refraction, enhancing the apparent brightness of the Alq_3 emission.

We also show how film properties are affected by the choice of mid-IR laser, and compare results from picosecond, tunable free electron lasers with varying temporal pulse structures (FEL), Er:YAG laser and picosecond and nanosecond optical parametric oscillators (OPO). These comparisons suggest that one might design appropriate laser systems for RIR-PLD and RIR-MAPLE compatible with commercial or industrial requirements at reasonable cost.

[17] Laser-induced Forward Transfer (LIFT): Application of a Dynamic Release Layer for the Transfer of Sensitive Materials

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Topic: PLD, MAPLE and Processing of Advanced Materials

Abstract: Laser induced forward transfer (LIFT) is a positive direct write process which enables the transfer of a material using photon energy from a laser beam as the driving force[i]. A dynamic release layer (DRL) which absorbs the laser radiation can be used as the transformer of this energy into the required mechanical push, protecting the transfer material from excessive irradiation, and degrading itself in the process[ii]. Various materials, e.g. metals or polymers, can be used as DRL, but recently polymers have attracted great attention. One possible approach is the application of triazene polymers which decompose upon laser irradiation mainly in gaseous fragments which transfer the material "mechanically" to a receiver. This allows to transfer sensitive materials, such as organic/polymeric materials or biomaterials, with precision patterning and a minimum thermal and UV photon load. This approach has been used to transfer a pixel of a functional LED polymer[iii], nanocrystal quantum dots[iv], metals[ii], living cells[v], various biomaterials, sensor polymers[vi], and ceramics[vii]. The LIFT process allows to transfer layers with typical sizes in the range of micrometer (may be even nanometer) to millimeter, with nanometer to micrometer thickness. The transfer can also be achieved with pixels consisting of multilayers and pixels of different materials can deposited in on layer onto a receiver. We will discuss the transfer mechanism, advantages and limitations of the LIFT process using a dynamic release layer.

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[15] SELECTIVE ABLATION OF THIN FILMS WITH ULTRA-SHORT-PULSE LASERS FOR SOLAR CELLS AND OTHER TECHNICAL APPLICATIONS

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Abstract: Permanent growth of the thin-film electronics market (flat panel displays, photovoltaics, flexible & organic electronics) stimulates the development of versatile technologies for patterning thin-film materials on rigid and flexible substrates. Photolithography and wet etching are common used technologies of semiconductor patterning for microelectronics. Large area applications of semiconductor thin films such as photovoltaics, however, needs high speed and simple to use technique Furthermore, the patterning process must be reliable to preserve or improve the device properties. Ultra-short laser processing with its flexibility is one of the ways to achieve the high quality material etching but the optimization of the processes is required to meet specific needs of the applications. Laser scribing is an important step to preserve high efficiency of photovoltaic devices on large areas.

The presentation covers the range from basic investigations of laser ablation in thin films to applications of laser scribing for the integrated interconnects in photovoltaic elements. Modeling of the energy transition between the layers and temperature evolution was performed to understand the processes. Absorption of the laser radiation by a film itself or at boundary in between is responsible for localization of excitation and final morphology of the patterns. Selection of the right laser wavelength makes it possible to keep the energy coupling in a well defined volume at the interlayer boundary.

Lasers with the picosecond pulse duration were applied in selective ablation of conducting, semi-conducting and isolating films in the complex multilayered of amorphous Si and Cu(InGa)Se_2 (CIGS) thin-film solar cells deposited on flexible and rigid substrates. The wavelength of laser radiation was adjusted depending on optical properties both of the film and the substrate.

The selective removal of indium-tin oxide (ITO) and CIGS layers was achieved without a significant damage to the underneath layers in the ITO/CIGS/Mo/PI solar cell system. In the solar cell system with a thick ITO top-contact, the 355 nm laser radiation was mainly absorbed at the interface ITO/CIGS, and the most upper layer was removed by the "lift-off" process rather than evaporation. Overlap of laser pulses should be carefully controlled to avoid micro-cracking and peeling of the top-contact layers induced by the laser pulses. In the solar cell system with a thin ZnO top-contact, it was possible to selectively ablate grains of the CIGS from the molybdenum back-contact when the 355 nm laser radiation was used. The ZnO top-contact was not affected even close to the rims of trenches. The reason is an optimum relation between absorptance in CIGS and ZnO layers.

Use of the high repetition rate lasers with picosecond pulse duration offers new possibilities for high quality and efficiency patterning of advanced materials for thin-film electronics.

Topics: Processing of Advanced Materials , Physics of Laser Matter interactions

[73] Resonant Infrared Matrix-assisted Pulsed Laser Evaporation of Inorganic Nanoparticles and Organic/Inorganic Hybrid Nanocomposites

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Topic(s): PLD, MAPLE and Processing of Advanced Materials

Abstract: Matrix-assisted pulsed laser evaporation (MAPLE)[1] is increasingly becoming an attractive approach for fabricating thin-films from a variety of different material systems[1,2,3,4], with the ultimate intent of realizing devices using this technique. Contemporary MAPLE has mostly been achieved using ultraviolet (UV-MAPLE)[1,4] and resonant infrared (RIR-MAPLE)[2,5] systems, wherein RIR-MAPLE uses infrared lasers to produce organic-based thin-films with minimal photochemically-induced degradation[4]. RIR-MAPLE requires that the ablating laser wavelength be strongly resonant with bond vibrations in the host solvent matrix of the target, making it necessary to have a tunable laser, like a free electron laser (FEL), or to limit the types of materials that can be deposited because only certain solvent matrices possess the requisite, resonant bonds with a fixed-wavelength laser[2].

In this research, RIR-MAPLE using a table-top 2.94 μm laser that is resonant with hydroxyl bonds has been used to deposit different classes of inorganic nanoparticles, including Au nanoparticles, CdSe and PbS colloidal quantum dots (CQDs), and oxide nanoparticles. In addition, RIR-MAPLE has been used for thin-film deposition of different organic/inorganic hybrid nanocomposites using these inorganic nanoparticles, including poly[2-methoxy-5-(2'-ethylhexyloxy)-1,4-(1-cyanovinylene)phenylene] (MEH-CN-PPV)-CdSe CQD nanocomposites and poly(methyl methacrylate) (PMMA)-Au nanoparticle nanocomposites. The unique contribution of this research is that emulsion matrices incorporating water have been used to deposit thin-films of materials that require solvents without resonant bond energies, thereby significantly expanding the types of materials that can be deposited using RIR-MAPLE. By creating an emulsion of solvent and water in the target, RIR-MAPLE at 2.94 μm can deposit most material systems without tuning the laser source because the hydroxyl bonds in the water component of the emulsion matrix are resonant with the 2.94 μm laser. Further, materials that require drastically different solvents can be sequentially deposited, facilitating the realization of organic/inorganic hybrid nanocomposite thin-films. This approach to RIR-MAPLE has been initially demonstrated by the ability to create MEH-CN-PPV/CdSe CQD nanocomposites with controllable internal morphologies[6]. In addition to the structural characterization of the inorganic nanoparticle and hybrid nanocomposite thin-films deposited using this RIR-MAPLE technique, preliminary device demonstrations will be presented through optical and electrical characterization. Thus, the table-top RIR-MAPLE technique presented herein is one possible route to fabricating hybrid nanocomposite thin-films for optoelectronic device applications.

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[12] Pulsed-laser Printing Process for Organic Thin Film Transistors Fabrication

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Chosen topic: **PLD, MAPLE and Processing of Advanced Materials**

Abstract: Organic Thin-Film Transistors (OTFTs) are witnessing a considerable increase of interest because they offer unique opportunities in low-cost microelectronics. The two major applications that motivate this research are radio frequency identification tags (RFID) and flexible displays. In this context, the development of facile and cheap fabrication processes represents a task of major importance. Laser-based processes offer versatile alternatives toward organic devices operating on flexible supports where usual techniques, such as inkjet or roll-to-roll printing, cannot be used because of the lack of solubility of the organic semiconductor or in the case of complex device architectures.

Our objective is to develop a laser printing technique, i.e. Laser-Induced Forward Transfer (LIFT) as spatially-resolved material deposition method. The LIFT technique removes a small piece of a thin layer previously deposited on a transparent substrate using a single laser pulse and transfers it on another substrate. This simple, single step, direct printing technique allows surface micro patterning or localized deposition of material. It can be applied to sensitive materials without altering their properties but it also allows to direct-write multilayer systems in a solvent-free single step, without requiring any shadowing masks or vacuum installation.

Our results present the fabrication for the first time of Organic Thin Film Transistors in different configurations using this technique. Source and drain electrodes and gate are laser-printed using metallic materials, nano-particles ink and organic conductor polymer. The organic semiconductors are polymer and oligomer chosen for their remarkable high performance and operational stability in time. The challenge was to transfer very thin layers of functional materials and to obtain well-resolved deposit patterns. This is particularly critical in the case of the electrodes in order to control the OTFT channel dimensions. We have compared with the same transistors vacuum evaporated to demonstrate the performance and the viability of the LIFT technique for OTFT devices. This experimental study is supplemented by electrical characterization of the deposits and the transistor patterns and demonstrates the full efficiency of the transistors, showing well-defined linear and saturation regimes in the I-V curves.

In addition and in order to understand the basic mechanism of the transfer, it was interesting to carry out time resolved visualizations. The dynamic of the process has been investigated by shadowgraphic imaging from the laser irradiation pulse to 1.5 μs, under atmospheric conditions. We have determined the velocity of the transferred material and discussed the influence of the distance between the donor and acceptor substrates on the deposit functionality. We have also demonstrated the utility of an absorbent protective layer, called Dynamic Release Layer (DRL) during the ejection to facilitate the material transfer. The DRL is used in LIFT technique to absorb the laser energy and to preserve the deposit from thermal and photochemical damages caused during the interaction. The high directivity of the ejected material offers the possibilities of high spatial resolution for the fabrication of micro-structures in LIFT technique.

[102] Laser-induced Backward Transfer of Metal Nanoparticles

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Abstract: A novel approach for the fabrication of metallic micro- and nanostructures based on femtosecond laser-induced backward transfer of metallic nanodroplets is developed. The controllable fabrication of high quality spherical gold micro- and nanoparticles with a radius between 100 nm and 800 nm is realized. These particles can be deposited onto different substrates and into arbitrary 2D and 3D polymeric microstructures. Several applications of this technique for the realization of plasmonic components and metamaterials will be demonstrated.

[10] Optical Alchemy with Lasers

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Topic: 1 – Femtosecond & Attosecond Effects; 2 - Nanoengineering

Abstract: For centuries, it had been the dream of alchemists to turn inexpensive metals into gold. Certainly, it is not enough from an alchemist's point of view to transfer only the appearance of a metal to gold. However, the possibility of rendering a certain metal to a completely different color without coating can be very interesting in its own right. In this work, we demonstrate a femtosecond laser processing technique that allows us to create, for the first time, a variety of colors on a metal that ultimately leads us to control its optical properties from UV to THz.

Session 12: Advanced Applications and Diagnostics
Mike Lander, Chair

[36] Dynamic Transmission Electron Microscopy (DTEM)

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In response to a need to be able to observe dynamic phenomena in materials systems with both high spatial (~1nm) and high temporal (~10ns) resolution, a dynamic TEM (DTEM) has been developed at Lawrence Livermore National Laboratory (LLNL). The high temporal resolution is achieved in the DTEM by using a short pulse laser to create the pulse of electrons through photo-emission (here the duration of the electron pulse is approximately the same as the duration of the laser pulse). This pulse of electrons is propagated down the microscope column in the same way as in a conventional high-resolution TEM. The only difference is that the spatial resolution is limited by the electron-electron interactions in the pulse (a typical 10ns pulse contains $\sim 10^8$ electrons). To synchronize this pulse of electrons with a particular dynamic event, a second laser is used to "drive" the sample a defined time interval prior to the arrival of the laser pulse. The important aspect of this dynamic DTEM modification is that one pulse of electrons is used to form the whole image, allowing irreversible transitions and cumulative phenomena such as nucleation and growth, to be studied directly in the microscope. The use of the drive laser for fast heating of the specimen presents differences and several advantages over conventional resistive heating *in-situ* TEM – such as the ability to drive the sample into non-equilibrium states. So far, the drive laser has been used for *in-situ* processing of nanoscale materials, rapid and high temperature phase transformations, controlled thermal activation of materials and work is underway to develop the technology for imaging live biological samples (currently being implemented on a new DTEM at UC-Davis). In this presentation, a summary of the development of the existing DTEM, its current and future applications to materials/biological structures, and the potential improvements in spatial and temporal resolution that can be expected through the implementation of upgrades to the lasers, electron optics and detectors used in the DTEM will be discussed.

Aspects of this work are performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory and supported by the Office of Science, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering, of the U.S. Department of Energy under Contract DE-AC52-07NA27344, by DOE NNSA-SSAA grant number DE-FG52-06NA26213 and by NIH grant number RR025032-01

[123] High Power Thulium Fiber Lasers

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Abstract

Recent years have seen a phenomenal rise in the capabilities of high power fibers lasers. 10 kW is now achievable and already the race is on to break the 100 kW mark. This has been enabled with the development of high power 970 nm pump diodes, ideally matched for efficiently exciting the 1060 nm transition in Yb-doped silica fibers. In the shadow of this remarkable development we are now witnessing a similar growth pattern for a sister to this laser, the 2 um thulium optical fiber laser. This laser possesses rather unique characteristics. Pumped by 790 nm diodes, the excitation scheme uses a cross-relaxation process that results in two-for-one photon generation with slope efficiencies approaching 70%. Powers approaching the kW level are now achievable. This talk summarizes the development of this unique laser source in the MIR, and speculates on its future applications in the medical, manufacturing and defense arenas. In particular we describe new experiments where we exploit the broad > 200 nm spectral bandwidth, and the advantages this laser brings to operating in the pulsed regime. We characterize the capabilities of conventional gratings, fiber Bragg and volume Bragg gratings and Guided Mode Resonant Filters to lock and tune the output spectral width to a bandpass as small as 50 pm, tunable from ~1950 nm to ~ 2150 nm. This spectral region covers many sharp atmospheric absorption lines in the atmosphere. We describe the first long range (1 km) atmospheric transmission tests with a tunable high power (200 W) thulium fiber laser. The capability to lock a number of these lasers to specific wavelengths each with < 100 pm linewidths opens the option of spectrally combining many lasers within the overall spectral bandwidth. We examine the benefits of this approach to reaching 100 kW power levels. In the pulse regime we describe the generation of nanosecond, picosecond and femtosecond pulses in oscillator and MOPA configurations. We discuss near-term potential applications in medicine, in laser-materials processing and in stand-off sensing technologies. This work is supported by an MRI program from the JTO HEL program, and a MURI from the ARO.

[78] High Energy Laser Diagnostic Sensors

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Topics: nanoengineering, high power lasers application and diagnostics, fiber lasers, CO_2 lasers, wavefront sensor, temperature sensor, irradiance sensor

Abstract: Recent advancements in high energy laser (HEL) sources have outpaced diagnostic tools capable of accurately quantifying system performance. Diagnostic tools are needed that allow system developers to quantify the parameters that define HEL effectiveness. The two critical parameters for quantifying HEL effectiveness are the irradiance on target and resultant rise in target temperature. Most remote sensing techniques use the bidirectional reflectance distribution function

(BRDF) to characterize reflected laser energy. The BRDF relies on reflecting properties of the material surface, which can change rapidly due to HEL heating making the technique impractical. Other issues with off-board sensing methods include interference from products of laser interaction (i.e. smoke and outgassing), limited engagement angles and atmospheric distortion. On-board sensors overcome the limitations of off-board techniques but must survive high irradiance levels and extreme temperatures. Additionally, the direct measurement technique must be non-intrusive so that it has minimal impact on the optical and thermal signatures of the target.

The AEgis Technologies Group and RTI International have developed sensors for diagnostics of high energy laser beams and for the measurement of the thermal response of the target. The conformal sensors consist of an array of quantum dot photodetectors and resistive temperature detectors. The sensor arrays are lithographically fabricated on flexible substrates and can be attached to a variety of laser targets. Two types of sensors have been developed. The first, the temperature and irradiance sensor matrix (TISM), is designed to be attached to the front side of the laser target, and measures both the laser irradiance and the target temperature. The open mesh architecture allows 90% of the beam to impact the surface. A critical component of the program is development of a protective coating that ensures sensor survivability at high irradiance levels for operational lifetimes on the order of 10 seconds. The protective coating must also allow transmission of a portion of the incident light to a microsensor that provides a calibrated measure of the incident irradiance.

The second type of sensor is designed to be attached to the back side of a relatively thin target. An array of a few hundred temperature sensors measures the temperature profile on the back side of the target, and an inverse heat conduction model is used to calculate the temperature and heat flux on the front side.

We have developed a nanoparticle adhesive that is used to bond the sensor array to the target. This adhesive has high thermal conductivity, and the sensor array remains attached to the target up to the melting point of the target.

Experimental results from our high energy laser testing will be presented.

Potential applications for this conformal microsensor technology include diagnostics for directed energy sources and evaluating the aimpoint accuracy of tracking lasers. A possible non-laser application of this type of sensor array would be to evaluate mirror pointing accuracy in concentrating solar power systems as part of an active control system.

[27] Forming of Brittle Materials – A New and Valuable Application of Diode Lasers

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Topic(s): High Power Lasers Application and Diagnostics

Abstract: If brittle materials, as glass or light weight or refractory metals, as e.g. magnesium are subject to bending, cracks appear, that can lead to rupture. The reason for this is, that the elongation of the outer fibres becomes stronger than the ductility, the elongation at rupture. Since the latter rises by more than 200% at slightly elevated temperatures of a few hundred centigrades and deformations

take place only in the near vicinity of the bending edge, selective heating along the latter with diode lasers arranged one besides the other can solve the problem of bending brittle materials.

The technical realization has been carried out together with the company Trumpf Maschinen Austria with the help of diode laser arrays mounted on so called microchannel coolers, where a light emitting edge with a length of 10 mm generates 200 W. Arranging 8 of these devices shoulder to shoulder allows to heat 100 mm of the bending edge, thus allowing to energize a bending die with 100 mm length (see Fig.1). Combination of several similar dies allows bending of arbitrary length. Bending experiments with 5 laser energized dies covering a bending length of 500 mm with Magnesium, Titanium and high strength Aluminium yielded perfect results.

[57] Time-resolved White-light Interferometry for Ultrafast Metrology

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Topics

Ultrafast Metrology, High Power Lasers Application and Diagnostics, Physics of Laser Matter Interactions

Abstract: The material modification in the volume of transparent dielectrics using tightly focused fs-laser radiation is an important topic for many research groups all over the world. A wide range of applications like the writing of waveguides, micro-structuring by material modification and subsequent etching, or the micro-welding of glass is based on the localized melting and quenching in a different state.

Time-resolved white-light interferometry is adopted for the measurement of the optical phase changes in processed materials. A modified Mach-Zehnder interferometer setup combined with microscope objectives is used. The white light is generated by focusing ultrafast laser radiation (t_p=80 fs) in a sapphire crystal using a micro-lense array to minimize temporal and spatial fluctuations in the white-light continuum. Lateral and coaxial pump-probe measurements of the phase changes during material processing are performed using one or two coupled ultrafast laser sources at different repetition rates (f_{rep}=1kHz-1MHz) or by adopting single pulses. The temporal delay between the pump and the probe can be adjusted in the range $\tau \leq 1.8\ \mu s$ in dependence on the repetition rate of the pump radiation.

The optical phase shift and therefore the refractive index of the material is calculated from the interference images. The knowledge of the refractive index during the modification process with a temporal resolution in the ps-range and a spatial resolution of several microns leads to a better understanding of the initial processes for the permanent material modifications. For example the temperature is calculated from the refractive index of glass, and the heat accumulation effect in dependency of the repetition rate is observed.

[120] Laser Shock Processing of Metallic Materials

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A revew of the physical and technological issues of LSP, including laser-plasma interaction in the ns, GW/cm^2 regime; equation of state for plasma and for compressed matter; numerical simulation methods for the coupled plasma-thermomechanic analysis; experimental assessment of plasma expansion and compression dynamics; practical implementation of the technique: different approaches; open questions for the better knowledge and control of the process could be treated.

Appendix C: Program Committee, HPLA 2010

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Michel Autric	Université de la Méditerranée	France
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Willy Bohn	DLR Stuttgart	Germany
Boris Chichkov	Laser Zentrum Hannover	Germany
Richard Haglund	Vanderbilt University	USA
Victor Hasson	Trex Enterprises	USA
David Hostutler	Air Force Research Laboratory	USA
Andrei Ionin	P. N. Lebedev Physical Institute	Russia
Michael Lander	General Dynamics Information Technologies	USA
Willaim P. Latham	AFRL Kirtland AFB	USA
Thomas Lippert	Paul Scherrer Institut	Switzerland
Boris Luk'yanchuk	Data Storage Inst., ASTAR	Singapore
Max Michaelis	University of Natal, Durban	South Africa
Minoru Obara	Keio University	Japan
Dennis Paisley	Los Alamos National Laboratory	USA
Baerbel Rethfeld	Technische Universität Kaiserslautern	Germany
Klaus Sokolowski-Tinten	Universität Jena	Germany
Takashi Yabe	Tokyo Institute of Technology	Japan

Appendix D: HPLA 2010 Sessions and Session Heads

Session	Title	Session Head	Institution
1	Introductory Remarks	Claude Phipps	Photonic Associates
2	Laser-matter interaction physics and modeling I	Thomas Dickinson	Washington State University
3	Laser-matter interaction physics and modeling II	Wayne Hess	Pacific Northwest National Laboratory
4	Short pulse laser-matter interactions I	Pete Latham	AFRL Kirtland
5	Short pulse laser-matter interactions II	Richard Haglund	Vanderbilt University
6	Nano-processing and engineering of materials	Thomas Dickinson	Washington State University
7	Laser Propulsion	Andrei Ionin	P.N. Lebedev Physical Institute
8	Plume Dynamics	James Lunney	
9	Alkali halide, other optically pumped lasers and oxygen-iodine lasers	David Hostutler	AFRL Kirtland
10	Space Applications	Jørgen Schou	Technical University of Denmark
11	PLD, MAPLE and processing of advanced materials	Minoru Obara	Keio University
12	Advanced applications and diagnostics	Michael Lander	General Dynamics Information Technologies
13	Monday evening poster session	David Hostutler	AFRL Kirtland
14	Tuesday evening poster session	David Hostutler	AFRL Kirtland