NSF ERC for EUV Science and Technology

news from the EUV ERC

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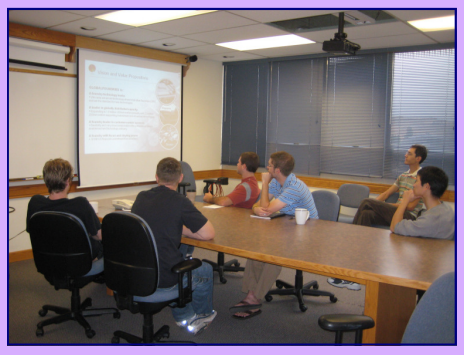
Student Leadership Council

Industry Seminars

The Student Leadership Council sponsors seminars in which members of industry give a short presentation describing their career paths and choices as well as details of their experiences in their company. Following the presentation, a student question/answer session explores a variety of topics.

This year's first seminar was given on October 6th with CU, Boulder, serving as the host university. An AV link to CSU and UC, Berkeley, supported participation by students at all three member universities.

The presenter at this seminar was Oleg Kritsun (pictured on the right) of GLOBALFOUNDRIES. The event was well attended. Oleg fielded questions from students in the conference room and through the remote connections.



Students at CSU participating in the seminar through a remote link.

The next seminar is scheduled for December 9th, 2010, at 11:00 MST. Colorado State University will host this seminar with remote participation through AV links with the University of Colorado, Boulder, and the University of California, Berkeley. The guest speaker is Richard Solarz from KLA-Tencor.

Awards and Honors

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Schawlow Prize

Henry Kapteyn and **Margaret Murnane** won the 2010 Arthur L. Schawlow Prize in Laser Science for their pioneering work in the area of the ultrafast laser science, including development of ultrafast optical and coherent soft x-ray sources. Kapteyn and Murnane also received a certificate citing their contributions to basic research that uses lasers to advance our knowledge of the fundamental properties of materials and their interaction with light

The Schawlow Prize, was endowed in 1991 by the NEC Corporation to recognize outstanding basic research that uses lasers to "advance our knowledge of the fundamental physical properties of materials and their interaction with light."

Schawlow Prize Lecture Title: "Attosecond Light and Science at the Time-scale of the Electron - Coherent X-Rays from Tabletop Ultrafast Lasers", M. Murnane, H. Kapteyn
Abstract: Using the extreme nonlinear process of high harmonic generation, light from an ultrafast laser can be coherently upshifted, generating bright ultrafast coherent beams extending into the soft and soon hard x-ray regions of the spectrum. Applications in molecular and materials dynamics, as well as nano- and attosecond science, will be discussed.

Murnane Appointed to Whitehouse Committee

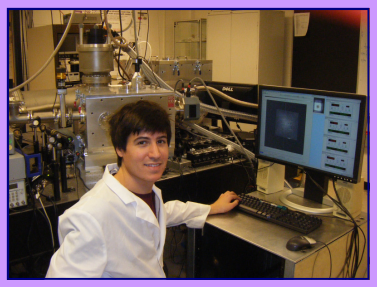
Professor Margaret Murnane, University Distinguished Professor, JILA and Departments of Physics and ECE at the University of Colorado at Boulder and the Deputy Director of the EUV ERC, has been appointed by President Barack Obama to the President's Committee on the National Medal of Science.The **National Medal of Science** is an honor bestowed by the President of the United States to individuals in science and engineering who have made important contributions to the advancement of knowledge in the fields of behavioral and social sciences, biology, chemistry, engineering, mathematics and physics. The twelve member presidential Committee on the National Medal of Science is responsible for selecting award recipients and is administered by the National Science Foundation (NSF).

View the Whitehouse announcement at http://m.whitehouse.gov/the-press-office/2010/09/17/president-obama-announces-more-key-administration-posts

Awards and Honors

XRM 2010 Conference Outstanding Student Award given to Sergio Carbajo

Sergio Carbajo, a Graduate Student in Electrical and Computer Engineering at Colorado State University in Fort Collins, Colorado, was one of three students to win the Outstanding Student Poster Award at XRM 2010 the 10th International Conference on X-Ray Microscopy held at Argonne National Laboratory in Chicago, Illinois August 15 – 20, 2010. Sergio's poster was titled, "Stop-Action Extreme Ultraviolet Imaging" and reported the first demonstration of stop-motion imaging with nanoscale spatial resolution and nanosecond temporal resolution using a compact full-field microscope based on a desktop-size l=46.9 nm extreme ultraviolet (EUV) laser. The microscope captures full-field images with a single nanosecond laser pulse and with a measured spatial resolution of 54 nm when using a 0.31 NA zone plate objective. The periodic motion of the AFM tip with a peak to peak displacement of 640 nm at a frequency of 269.8 kHz was readily captured from its synchronized single-shot images. This proof-of-principle stop-motion extreme ultraviolet imaging demonstration opens opportunities for assessing the linear and non-linear dynamics of nanoscale devices with nanometer spatial resolution and high temporal resolution.



Kathy Hoogeboom-Pot Receives NSF Graduate Research Fellowship.

The National Science Foundation's Graduate Research Fellowship Program (GRFP) helps ensure the vitality of the human resource base of science and engineering in the United States and reinforces its diversity. The program recognizes and supports outstanding graduate students in NSF-supported science, technology, engineering, and mathematics disciplines who are pursuing research-based master's and doctoral degrees at accredited US institutions. Kathy Hoogeboom-Pot graduated from Calvin College in 2008 with a BS in Physics . Her undergraduate research included the photoassociation of laser-cooled atomic krypton, the spin periods of Trojan asteroids and the dynamics of asteroids in the main belt. She joined the KM group at CU Boulder in the summer of 2009.

Stefan Mathias Receives Marie Curie Postdoctoral Fellowship

Dr. Mathias obtained a PhD in Physics from the University of Kaiserslautern, Germany in July 2008. His focus of research are investigations of ultrafast phenomena in condensed matter. This includes the combination of ultrashort femtosecond laser systems with surface science technology in order to develop new methods for measuring ultrafast electron-lattice-spin interactions in real time with high temporal resolution. In spring 2009 Dr. Mathias spent a semester lecturing Solid State Physics and Mathematical Physics at the University Kigali Institute of Science and Technology, KIST, in Rwanda, Africa. He joined the Kapteyn-Murnane group in July 2009 and is currently working on ultrafast magnetization and condensed matter dynamics using novel X-ray pump-probe spectroscopy techniques

Susannah Brown Receives COSI-IGERT Fellowship.

Computational Optical sensing and Imaging (COSI) is an Integrative Graduate Education and Research Traineeship (IGERT) program funded by the National Science Foundation and the University of Colorado. This program educates students about computational imaging systems in order to train a future work force in this area, encourage interdisciplinary collaboration, and strengthen relationships with national labs, industry, and international colleagues. Susannah graduated from MIT in 2009 with a B.S. in physics and joined the KM group in 2010. As an undergraduate, she worked on a thermal emittance measurement system for characterization of thermal photovoltaics and photonic crystals. She is interested in developing sources for high harmonic generation and all-optical quasi phase matching.

EUV ERC Calendar

Nov 2010

IEEE Photonics Society 2010 Annual Meeting, Denver, Colorado (advance program available at http://www.photonicsconferences.org/ANNUAL2010/annual-2010-advance-program.pdf)

Multiple invited talks and demonstrations by EUV ERC Principal Investigators and graduate students including:

Monday, November 8, J. Rocca et all, 1:30 PM, Advances in Compact High Repetition Rate Soft X-Ray Lasers. 2:00 PM Invited talk, M. Murnane

Tuesday, November 9, 2:00 PM, Demonstration of 10.9 mm Table-Top Soft X-Ray Laser at 1 Hz Repetition Rate. M. Berrill, B. M. Luther, J. J. Rocca, Y. Wang, D. Alessi and D. H. Martz, et al.

Also, at 3:30 PM, M. Marconi et al, Extreme Ultraviolet Lasers Demonstrate New Nano-Patterning Schemes. 4:00 Soft X-Ray Laser Interferometry Study of Dense Plasma Jet Collimation, J. Grava et al. 4:15 Table-top Soft X-ray Laser Operating at 13.9 nm with Increased Average Power, D. H. Martz et al. 4:30 Beam Characteristics of an Injection-Seeded Solid-Target Plasma Soft X-Ray Laser, D. Alessi et al.

Thursday, November 11, 9:45 AM, Laser Based Aerial Microscope for At-Wavelength Characterization of ExtremeUltraviolet Lithography Masks,S. Carbajo et al.

Colorado Photonics Industry Association 13th Annual Focus on University Research, University of Colorado, Boulder. Featuring photonics and optics research conducted at All Colorado research universities. See http://www.coloradophotonics.org/CPIAAnnualMeetingNew.html

December 2010

National Science Foundation Engineering Research Centers Annual Meeting: December 1-3, Bethesda, Maryland.

Invited talk, Richard Sandberg et al, International Symposium on Ultrafast Intense Laser Science 9 (http://www.isuils.jp/) will be held during December 9th and 13th, 2010, at Hyatt Regency Maui Resort & Spa (http://maui.hyatt.com/hyatt/hotels/index.jsp) in Maui, Hawaii, US.

Invited talk, M. Murnane et al, Annual Meeting of the Australian Institute of Physics, Melbourne, Australia, December 2010.

IEEE Conference Presentations

Presentations and Demonstrations delivered at the IEEE Photonics Society 2010 Annual Meeting

Advances in Compact High Repetition Rate Soft X-Ray Lasers, J. J. Rocca, B. A. Reagan, F. J. Furch, Y. Wang, D. Alessi, D. H. Martz, B. M. Luther, M. Berrill and A. H. Curtis, Colorado State University, Fort Collins, CO, USA
We review recent progress in the development of table-top soft x-ray lasers that includes the demonstration of a gainsaturated λ= 10.9 nm laser, and the first demonstration of an all-diode-pumped soft x-ray laser.

Demonstration of 10.9 nm Table-Top Soft X-Ray Laser at 1 Hz Repetition Rate, M. Berrill, B. M. Luther, J. J. Rocca, Y. Wang, D. Alessi and D. H. Martz, Colorado State University, Fort Collins, CO, USA
We report a 10.9 nm gain-saturated tabletop soft x-ray laser operating at 1 Hz repetition rate. With average power of 1 microwatt and pulse energy up to ~ 2 microjoules this laser extends the ability to conduct table-top laser experiments to a shorter wavelength.

Extreme Ultraviolet Lasers Demonstrate New Nano-Patterning Schemes, M. C. Marconi, P. Wachulak, L. Urbanski, C. S. Menoni, J. J. Rocca, Colorado State University, Fort Collins, CO, USA, A. Isoyan, F. Jiang, Y.-C. Cheng and F. Cerrina, University of Wisconsin- Madison, Madison, WI, USA
Table-top extreme ultraviolet lasers at ⎣ =46.9 allow compact photo-lithography systems utilizing coherent imaging techniques. Interferometric lithography, holographic lithography and Talbot lithography were demonstrated with sub-100 nm resolution in compact setups.

Soft X-Ray Laser Interferometry Study of Dense Plasma Jet Collimation, J. Grava, D. P. Ryan, M. A. Purvis, J. Filevich, V. N. Shlyaptsev, Colorado State University, Fort Collins, CO, USA, S. J. Moon, J. Dunn, Lawrence Livermore National Laboratory, Livermore, CA, USA and J. J. Rocca, Colorado State University, Fort Collins, CO, USA
Soft x-ray laser interferometry and hydrodynamic simulations were used to study the increase in collimation of laboratory plasma jets created with low energy (<= 1 J) short laser pulses irradiating target of varying atomic number.

Table-top Soft X-ray Laser Operating at 13.9 nm with Increased Average Power, D. H. Martz, D. Alessi, B. M. Luther, Y. Wang, M. Berrill, D. Kemp, D. Patel, C. S. Menoni and J. J. Rocca, Colorado State University, Fort Collins, CO, USA
We have demonstrated a ⎣ =13.9 nm tabletop laser with pulse energies above 10 μJ in a laser created Ag plasma. Operation at 2.5 Hz resulted in an average power of 20 μW.

Beam Characteristics of an Injection- Seeded Solid-Target Plasma Soft X-Ray Laser, D. Alessi, M. Berrill, Y. Wang, S. Domingue, D. H. Martz, B. M. Luther, Colorado State University, Fort Collins, CO, USA, M. Limin, O. Guilbaud, A. Klisnick, Université Paris-Sud, Orsay cedex, France and J. J. Rocca, Colorado State University, Fort Collins, CO, USA
We have measured the near-field and farfield profiles (for ⎣ =13.9 nm) as well as temporal coherence (for ⎣ =18.9 nm) of injection-seeded and self-seeded solidtarget amplifiers. The measurements were compared with model simulations.

Soft X-Ray Laser Interferometry Study of Dense Plasma Jet Collimation, J. Grava, D. P. Ryan, M. A. Purvis, J. Filevich, V. N. Shlyaptsev, Colorado State University, Fort Collins, CO, USA, S. J. Moon, J. Dunn, Lawrence Livermore National Laboratory, Livermore, CA, USA and J. J. Rocca, Colorado State University, Fort Collins, CO, USA
Soft x-ray laser interferometry and hydrodynamic simulations were used to study the increase in collimation of laboratory plasma jets created with low energy (<= 1 J) short laser pulses irradiating target of varying atomic number.

Laser Based Aerial Microscope for At-Wavelength Characterization of ExtremeUltraviolet Lithography Masks, S. Carbajo, F. Brizuela, D. H. Martz, D. Alessi, Y. Wang, M. C. Marconi, J. J. Rocca, C. S. Menoni, Colorado State University, Fort Collins, CO, USA, A. Sakdinawat, E. H. Anderson, K. A. Goldberg, D. Attwood, Lawrence Berkeley National Laboratory, Berkeley, CA, USA and B. La Fontaine, GLOBALFOUNDRIES, Sunnyvale, CA, USA
We have developed a compact aerial full field microscope based on a table-top 13.2 nm wavelength extreme ultraviolet laser and diffractive optics to characterize the printing performance of EUV lithographic masks.

Beam Characteristics of an Injection-Seeded Solid-Target Plasma Soft X-Ray Laser, D. Alessi, M. Berrill, Y. Wang, S. Domingue, D. H. Martz, B. M. Luther, Colorado State University, Fort Collins, CO, USA, M. Limin, O. Guilbaud, A. Klisnick, Université Paris-Sud, Orsay cedex, France and J. J. Rocca, Colorado State University, Fort Collins, CO, USA
We have measured the near-field and farfield profiles (for ⎣ =13.9 nm) as well as temporal coherence (for ⎣ =18.9 nm) of injection-seeded and self-seeded solidtarget amplifiers. The measurements were compared with model simulations.

Table-top Soft X-ray Laser Operating at 13.9 nm with Increased Average Power,
D. H. Martz, D. Alessi, B. M. Luther, Y. Wang, M. Berrill, D. Kemp, D. Patel, C. S. Menoni and J. J. Rocca, Colorado State University, Fort Collins, CO, USA
We have demonstrated a ⎣ =13.9 nm tabletop laser with pulse energies above 10 μJ in a laser created Ag plasma. Operation at 2.5 Hz resulted in an average power of 20 μW.

Looking Ahead to 2011 Mark your Calendars

IAB Meeting in San Jose, February 28th, 2011, 7:30-11:30 Breakfast, Presentations and Dialog

This meeting coincides with the SPIE Advanced Lithography meeting, February 28th through March 4th. The meeting provides a significant opportunity for IAB members to receive updates on the latest advances in Center research. It also is a primary forum in which members of the IAB can provide guidance and feedback. We look forward to seeing you there.

EUV ERC Annual Retreat, The IAB is Invited January 13th and 14th, Fort Collins, Colorado

- Principal Investigator Presentations
- Student Research Presentations
- Student Poster Sessions
- Lab Tours

NSF Site Visit for 2011, May 18th and 19th Lawrence Berkeley National Labs, Berkeley, California

The 2010 NSF Site Visit's success was a direct result of the generous attendance and support by members of the IAB. Your support at this critical meeting was significantly important. In 2011, the EUV ERC will once again be expected to demonstrate a strong industry program. Your attendance again this year will be very important to enabling the final two years of this NSF program. Please mark your calendars.

Please join us in welcoming IBM to the Industrial Advisory Board!

IBM has been a long-time supporter of the EUV ERC. As of October 1st, IBM joined the Industrial Advisory Board as a Corporate Member as defined in the new bylaws.

If you have further interest in any of these topics, please contact Robert.Bower@colostate.edu

Publications

Three-dimensional structure determination from a single view
Kevin S. Raines, Sara Salha, Richard L. Sandberg, Huaidong Jiang, Jose A Rodriguez, Henry C. Kapteyn, Jincheng Du and Jianwei Miao, *Nature **463**, 214 (2010)*
The ability to determine the structure of matter in three dimensions has profoundly advanced our understanding of nature. Traditionally, the most widely used schemes for three-dimensional (3D) structure determination of an object are implemented by acquiring multiple measurements over various sample orientations, as in the case of crystallography and tomography1,2, or by scanning a series of thin sections through the sample, as in confocal microscopy3. Here we present a 3D imaging modality, termed ankylography (derived from the Greek words ankylos meaning 'curved' and graphein meaning 'writing'), which under certain circumstances enables complete 3D structure determination from a single exposure using a monochromatic incident beam. We demonstrate that when the diffraction pattern of a finite object is sampled at a sufficiently fine scale on the Ewald sphere, the 3D structure of the object is in principle determined by the 2D spherical pattern. We confirm the theoretical analysis by performing 3D numerical reconstructions of a sodium silicate glass structure at 2A ° resolution, and a single poliovirus at 2–3nm resolution, from 2D spherical diffraction patterns alone. Using diffraction data from a soft X-ray laser, we also provide a preliminary demonstration that ankylography is experimentally feasible by obtaining a 3D image of a test object from a single 2D diffraction pattern. With further development, this approach of obtaining complete 3D structure information from a single view could find broad applications in the physical and life sciences.

Mask roughness and its implications for LER at the 22- and 16-nm nodes , Patrick P. Naulleau, Simi A. George, Brittany M. McClinton, Proc. SPIE **7636**, 76362H-1 (2010).
Line-edge roughness (LER) remains the most significant challenge facing the development of extreme ultraviolet (EUV) resist. The mask, however, has been found to be a significant contributor to image-plane LER. This has long been expected based on modeling and has more recently been demonstrated experimentally. Problems arise from both maskabsorber LER as well as mask multilayer roughness leading to random phase variations in the reflected beam and consequently speckle. Understanding the implications this has on mask requirements for the 22-nm half pitch node and below is crucial. Modeling results indicate a replicated surface roughness (RSR) specification of 50 pm and a ruthenium capping layer roughness specification of 440 pm. Moreover, modeling indicates that it is crucial to achieve the current ITRS specifications for mask absorber LER which is significantly smaller than current capabilities.

Experimental and theoretical studies of reactions of neutral vanadium and tantalum oxide clusters with NO and NH3 S. Heinbuch,2,3 F. Dong,1,2 J. J. Rocca,2,3 and E. R. Bernstein1,2,a1*Department of Chemistry, Colorado State University, Fort Collins, Colorado 80523, USA,2NSF ERC for Extreme Ultraviolet Science and Technology, Colorado State University, Fort Collins, olorado 80523, USA* 3*Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, Colorado 80523, USA.*
Reactions of neutral vanadium and tantalum oxide clusters with NO, NH3, and an NO/NH3 mixture in a fast flow reactor are investigated by time of flight mass spectrometry and density functional theory DFT calculations. Single photon ionization through a 46.9 nm 26.5 eV extreme ultravioletEUV laser is employed to detect both neutral cluster distributions and reaction products. Association products VO3NO and V2O5NO are detected for V*m*O*n* clusters reacting with pure NO, and reaction products, TaO3,4NO1,2, Ta2O5NO, Ta2O6NO1–3, and Ta3O8NO1,2 are generated for Ta*m*O*n* clusters reacting with NO. In both instances, oxygen-rich clusters are the active metal oxide species for the reaction M*m*O*n*+NO→M*m*O*n*NO*x*. Both V*m*O*n* and Ta*m*O*n* cluster systems are very active with NH3. The main products of the reactions with NH3 result from the adsorption of one or two NH3 molecules on the respective clusters. A gas mixture of NO:NH3 9:1 is also added into the fast flow reactor: the V*m*O*n* cluster system forms stable, observable clusters with only NH3 and no V*m*O*n*NO*x*NH3*y* species are detected; the Ta*m*O*n* cluster system forms stable, observable mixed clusters, Ta*m*O*n*NO*x*NH3*y*, as well as Ta*m*O*n*NO*x* and Ta*m*O*n*NH3*y* individual clusters, under similar conditions. The mechanisms for the reactions of neutral V*m*O*n* and Ta*m*O*n* clusters with NO/NH3 are explored via DFT calculations. Ta*m*O*n* clusters form stable complexes based on the coadsorption of NO and NH3. V*m*O*n* clusters form weakly bound complexes following the reaction pathway toward end products N2+H2O without barrier. The calculations give an interpretation of the experimental data that is consistent with the condensed phase reactivity of V*m*O*n* catalyst and suggest the formation of intermediates in the catalytic chemistry. © *2010*
American Institute of Physics. doi:10.1063/1.3497652

Control of Electron Localization in Deuterium Molecular Ions Using an Attosecond Pulse Train and a Many-Cycle Infrared Pulse, K. P. Singh, F. He, P. Ranitovic, W. Cao, S. De, D. Ray, S. Chen, U. Thumm, A. Becker, M. M. Murnane, H. C. Kapteyn, I. V. Litvinyuk, and C. L. Cocke, *Physical Review Letters **104**, 023001 (2010)*
We demonstrate an experimental control of electron localization in deuterium molecular ions created and dissociated by the combined action of an attosecond pulse train and a many-cycle infrared (IR) pulse. The attosecond pulse train is synthesized using both even and odd high order harmonics of the driving IR frequency so that it can strobe the IR field once per IR cycle. An asymmetric ejection of the deuterium ions oscillates with the full IR period when the APT-IR time-delay is scanned. The observed control is due to the creation of a coherent superposition of 1s and 2p states via interference between one-photon and two-photon dissociation channels.

Publications

If you have further interest in any of these topics, please contact Robert.Bower@colostate.edu

IR-Assisted Ionization of Helium by Attosecond XUV Radiation
P. Ranitovic, Xiao-Min Tong, B. Gramkow, S. De, B. DePaola, K.P. Singh, W. Caol, M. Magrakvelidze, D. Ray, I. Bocharova, H. Mashiko, A. Sandhu, E. Gagnon, M. M. Murnane, H. C. Kapteyn, I. Litvinyuk and C.L. Cocke, *New Journal of Physics* ***12****, 013008 (2010)*
Abstract. Attosecond science has opened up the possibility of manipulating electrons on their fundamental timescales. Here, we use both theory and experiment to investigate ionization dynamics in helium on the attosecond timescale by simultaneously irradiating the atom with a soft x-ray attosecond pulse train (APT) and an ultrafast laser pulse. Because the APT has resolution in both energy and time, we observe processes that could not be observed without resolution in both domains simultaneously.We show that resonant absorption is important in the excitation of helium and that small changes in energies of harmonics that comprise the APT can result in large changes in the ionization process.With the help of theory, ionization pathways for the infrared-assisted excitation and ionization of helium by extreme ultraviolet (XUV) attosecond pulses have been identified and simple model interpretations have been developed that should be of general applicability to more complex systems (Zewail A 2000 *J. Phys. Chem.*A **104** 5660–94).

Extreme Ultraviolet Laser-based Table-Top Aerial Image Metrology of Lithographic Masks
Fernando Brizuela,1,2* Sergio Carbajo,1,2 Anne Sakdinawat,1,3 David Alessi,1,2 Dale Martz,1,2 Yong Wang,1,2 Bradley Luther,1,2 Kenneth A. Goldberg,3 Iacopo Mochi,3 David T. Attwood,1,3 Bruno La Fontaine,4 Jorge J. Rocca,1,2 and Carmen S. Menoni1,2 *1National Science Foundation Engineering Research Center for Extreme Ultraviolet Science and Technology 2Electrical and Computer Engineering, Colorado State University, Fort Collins, CO 80526, USA 3Center for X-Ray Optics, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA 4GLOBALFOUNDRIES, 1050 E. Arques Avenue, Sunnyvale, CA, 94085, USA*
Abstract: We have realized the first demonstration of a table-top aerial imaging metrology system (AIMS) capable of characterizing pattern and defect printability in extreme ultraviolet lithography masks. The microscope combines the output of a 13.2 nm wavelength, table-top, plasma-based, EUV laser with zone plate optics to mimic the imaging conditions of an EUV lithographic stepper. We have characterized the illumination of the system and performed line-edge roughness measurements on an EUVL mask. The results open a path for the development of a compact AIMS tool for high-volume manufacturing.

Photonics at the Time-scale of the Electron - Bright Coherent X-Rays from Tabletop Ultrafast Lasers, T. Popmintchev, M.M. Murnane and H.C. Kapteyn
Invited review paper, to be published in Nature Photonics, (2010)

Mask roughness induced LER: a rule-of-thumb, B. McClinton and P. Naulleau , J. Micro/Nanolith. MEMS MOEMS JM3, *to be published*, (2010).
Much work has already been done on how both the resist and line-edge roughness (LER) on the mask affect the final printed LER. What is poorly understood, however, is the extent to which system-level effects such as mask surface roughness, illumination conditions, and defocus couple to speckle at the image plane, and currently factor into LER limits. Here, we propose a "rule-of-thumb" simplified solution that provides a fast and powerful method to obtain mask roughness induced LER. We present modeling data on an older generation mask with a roughness of 230 pm as well as the ultimate target roughness of 50 pm. Moreover, we consider feature sizes of 50 nm and 22 nm, and show that as a function of correlation length, the LER peaks at the condition that the correlation length is approximately equal to the resolution of the imaging optic.

Ultrafast Lasers Yield X-rays
I. McKinnie, H. Kapteyn, *Nature Photonics* ***4****, 149 (2010)*
Table-top sources that generate both extreme ultraviolet light and soft X-rays through high-harmonic generation of ultrafast infrared laser pulses look set to perform tasks previously accessible using only large-scale synchrotrons.

Bright, Coherent, Ultrafast Soft X-Ray Harmonics Spanning the Water Window from a Tabletop Source
M.C. Chen, P. Arpin, T. Pomintchev, M. Gerrity, B. Zhang, M. Seaberg, M.M. Murnane and H.C. Kapteyn*To be published in Physical Review Letters (2010)*
We demonstrate fully phase matched high-order harmonic generation with emission spanning the water window spectral region important for bio- and nano-imaging and a breadth of materials and molecular dynamics studies. We also generate the broadest bright coherent bandwidth (~300eV) to date obtained from any light source, small or large. The harmonic photon flux at 0.5 keV is 10^3 higher than demonstrated previously, making it possible for the first time to demonstrate spatial coherence in the water window. The continuum emission is consistent with a single attosecond burst, that extends bright attosecond pulses into the soft x-ray region.

Publications

If you have further interest in any of these topics, please contact Robert.Bower@colostate.edu

Measurement of Quasi-ballistic Heat Transport Across Nanoscale Interfaces Using Ultrafast Coherent Soft X-ray Beams, Mark Siemens, Qing Li, Ronggui Yang, Keith Nelson, Erik Anderson, Margaret Murnane and Henry Kapteyn, *Nature Materials **9**, 26 (2010)*
Fourier theory of thermal transport considers heat transport as a diffusive process where energy flow is driven by a temperature gradient. However, this is not valid at length scales smaller than the mean free path for the energy carriers in a material, which can be hundreds of nanometres in crystalline materials at room temperature. In this case, heat flow will become 'ballistic'—driven by direct point-to-point transport of energy quanta1. Past experiments have demonstrated sizedependent ballistic thermal transport through nanostructures such as thin films, superlattices, nanowires and carbon nanotubes. The Fourier law should also break down in the case of heat dissipation from a nanoscale heat source into the bulk. However, despite considerable theoretical discussion and direct application to thermal management in nanoelectronics, nano-enabled energy systems9,10 and nanomedicine11, this non-Fourier heat dissipation has not been experimentally observed so far. Here, we report the first observation and quantitative measurements of this transition from diffusive to ballistic thermal transport from a nanoscale hotspot, finding a significant (as much as three times) decrease in energy transport away from the nanoscale heat source compared with Fourier-law predictions.

Movies at the nanoscale using extreme ultraviolet laser light
S. Carbajo1,2†, F. Brizuela1,2, A. Sakdinawat1,4, Y. Liu1,4, W. Chao1,3, E.H. Anderson1,3, A. V. Vinogradov5, I. A. Artioukov5, D.T. Attwood1,4, M. C. Marconi1,2, J.J. Rocca1,2, and C.S. Menoni1, *NSF ERC for Extreme Ultraviolet Science and Technology Electrical and Computer Engineering, Colorado State University, Fort Collins, USA 3Center for X-ray Optics, Lawrence Berkeley National Laboratory, Berkeley, USA 4ECE Department, University of California, Berkeley, USA P. N. Lebedev Physical Institute, Moscow, Russia*
Abstract: We report on the first demonstration of stop-motion imaging with ~50 nm spatial resolution using an extreme ultraviolet laser. Images of an AFM tip resonating at ~270 kHz were acquired with 1 ns temporal resolution.
OCIS codes: (110.0110); (180.0180); (120.0120)

Quasi Phase Matching of Momentum and Energy in Nonlinear Optical Processes
Alon Bahabad, Margaret. M. Murnane and Henry C. Kapteyn, *Nature Photonics **4**, 570 (2010)*
Quasi-phase-matching is an important technique in nonlinear optics and is in widespread use. It not only makes efficient frequency conversion possible, but also enables diverse applications such as beam and pulse shaping, multi-harmonic generation, high harmonic generation, all-optical processing and the generation of entangled photons. However, since its introduction in the early 1960s at the dawn of nonlinear optics, quasi-phase-matching has always been considered a technique in which a purely spatial modulation mitigates the momentum mismatch that dispersion imposes on the interacting photons. Here, we present an important and fundamental generalization of quasi-phase-matching in which spatiotemporal nonlinear optical diffraction allows for correction of both momentum and energy mismatch. This concept provides a powerful tool for manipulating light through nonlinear interactions, and suggests unique applications. Recent experiments provide evidence for the feasibility and importance of spatiotemporal quasi-phase-matching.

Improved beam characteristics of solid-target soft x-ray laser amplifiers by injection-seeding with high harmonics
M. Berrill1,2, D. Alessi1,2, Y. Wang1,2, S.R. Domingue1,2, D.H. Martz1,2, B. M. Luther1,2, Y.Liu1,3, and J.J. Rocca1,2,4 1. National Science Foundation ERC for Extreme Ultraviolet Science and Technology 2. Electrical and Computer Engineering Department, Colorado State University, Fort Collins, CO 80523 3. University of California at Berkeley, and Center for X-ray Optics, Lawrence Berkeley National Laboratory, Berkeley, CA 94720 4. Physics Department, Colorado State University, Fort Collins, CO 80523
Injection-seeding of solid-target soft x-ray laser amplifiers with high harmonic pulses is shown to dramatically improve the far-field laser beam profile and reduce the beam divergence. Measurements and 2-dimensional simulations for a 13.9 nm nickel-like Ag amplifier show that the amplified beam divergence depends strongly on the seed, and can therefore be controlled by selecting the divergence of the seed. The near-field beam size of both the seeded and unseeded lasers is shown to be determined by the size of the gain region and the divergence of the amplified beams.

Sawtooth Grating-assisted Phase-matching
P. Sidorenko, M. Kozlov, A. Bahabad, T. Popmintchev, M.M. Murnane, H.C. Kapteyn and O. Cohen *To be published in Optics Express, (2010)*
We show that a sawtooth phase-modulation is the optimal profile for grating assisted phase matching (GAPM). Perfect (sharp) sawtooth modulation fully corrects the phase-mismatch, exhibiting conversion equal to conventional phase matching, while smoothened, approximate sawtooth structures are more efficient than sinusoidal or square GAPM modulations that were previously studied. As an example, we demonstrate numerically optically-induced sawtooth GAPM for high harmonic generation. Sawtooth GAPM is the most efficient method for increasing the conversion efficiency of high harmonic generation through quasi-phase-matching, with an ultimate efficiency that closely matches the ideal phase-matching case

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EUV ERC
Enabling The Future

Graduating

Herman Bravo

Herman first worked at the Engineering Research Center as an intern in the Summer of 2004. His work continued at the EUV ERC from September 2006 through May of 2009. During that time, his activities included scientific and engineering applications of EUV systems, nanometer scale ablation, the machining of 200 nm wide features in thin films, design and development of EUV laser induced breakdown mass spectrometer and the application of these systems in identification of material properties in semiconductor chip samples. Herman expects to graduate with a M.S. in Mechanical Engineering in the near future.

Thesis: "Nanometer scale ablation and patterning with EUV light"

Resumes can be found at
http://www.engr.colostate.edu/euverc/industry/resumes.shtml

JILA Expansion to enable new research labs for the EUV ERC

As stated in the 2010 Annual Report, "a new building is being planned for the JILA Institute in which the CU branch of the EUV ERC resides, providing the CU branch of the center with access to new space as it continues to grow." Construction began over the summer on the new tower pictured below. With the new facilities and an NSF MRI grant, the labs will build new laser systems to further the Center's mission.

Attendees to the NSF Site Visit last May, taking tours of the EUV ERC labs, entered the JILA building at the southern patio entrance, now the excavation site.

The Extreme Ultraviolet (EUV) Engineering Research Center is one of 15 centers established in the United States through the National Science Foundation and supplemented by industry funding. Colorado State University (CSU) is the host institution with partner sites at the University of Colorado (CU), UC Berkeley and Lawrence Berkeley National Laboratory. The Center research mission is the development of compact coherent EUV sources and EUV-engineered systems that provide solutions to challenging scientific and industrial problems, including the development of new tools for nanotechnology and nanoscience. The Center has an important educational mission providing a unique environment for the training of students, young engineers and scientists. An Industry Advisory Board (IAB) with members, ranging from large - to small- capitalized companies, spanning instrumentation, semiconductor, lasers and optics, nanotechnology and the biological and chemical sciences actively participate in early access to technologies, joint research projects, directed research projects and the hiring of the some of the best students in the world in these areas.

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