

# **Section 1 – Systems Vision and Value Added/Broader Impacts of the Center**

## **1.1 Systems Vision**

### **1.1.1 Introduction**

This document constitutes the seventh year annual report of the NSF Center for Extreme Ultraviolet Science and Technology (EUV ERC). It summarizes in two volumes the significant progress made in the first 6 ½ years of operation of the Center towards achieving the goals of its strategic plan, and reviews the achievements of the past year. It also discusses the long term Center vision and reviews the strategic plan for realizing that vision, with new timetables developed last year. The EUV ERC is a National Science Foundation (NSF) Engineering Research Center (ERC) that began operation in October 2003 with the goal of exploiting the advantages of coherent EUV light produced by compact sources in solving challenging technological and industrial problems. The EUV ERC is the result of the close collaboration among four core partner institutions: Colorado State University, the University of Colorado at Boulder, the University of California at Berkeley and Lawrence Berkeley National Laboratory, and a set of research and educational affiliate partners that include universities, four year colleges, and national laboratories. These Affiliate institutions include Morehouse College, Spelman College, Agnes Scott College, CSU–Pueblo, the University of the South Sewanee, Massachusetts Institute of Technology, Harvey Mudd College, University of Buenos Aires, Sofia University, the Pueblo School of Arts and Sciences, Lebedev Physical Institute, and Lawrence Livermore National Laboratory. Other partners include the NIST Boulder Laboratories, University of Delaware, Northwestern, NRC Canada, Argonne National Lab., Kaiserslautern, Kiel, University of Arizona, and BYU.

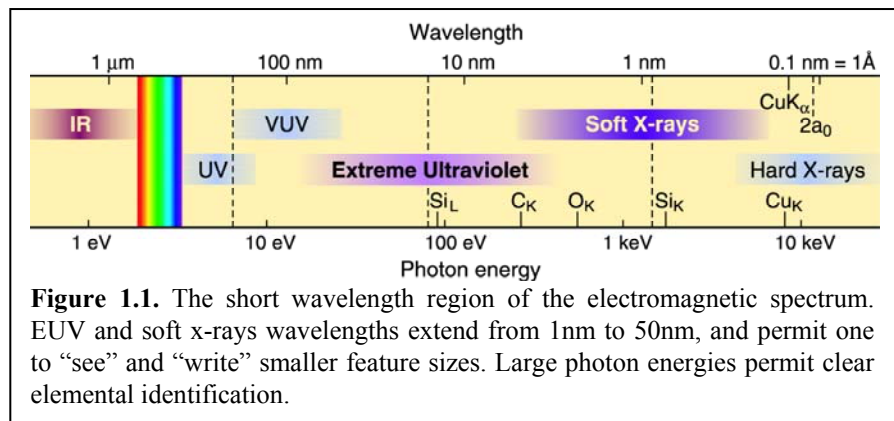
Volume I of this report describes the long term vision, mission, and the research and education strategic plans of the EUV ERC, and includes a summary of the progress to date in fulfilling the Center’s vision. The research is organized in three inter-linked thrusts designed to implement the strategic plan of the ERC, and is discussed in Volume 1 at the systems level. Volume II includes detailed project descriptions, and a list of the publications that resulted from the last 12 months of the EUV ERC. We begin this report by presenting the long term vision of the EUV ERC.

### **1.1.2 The EUV ERC Vision**

The vision of the EUV ERC is 1) to advance the technology of small-scale and cost effective coherent EUV sources; and 2) to demonstrate their utility by integrating them into testbed applications such as high-resolution imaging, materials metrology and characterization, elemental- and bio-microscopy, as well as x-ray science, ultrafast x-ray science, nanoscience and nano-fabrication. As result of the ERC effort, we expect that EUV radiation, that at the beginning of the Center was mostly limited to a handful of large national facilities, will be routinely used in a broad variety of settings, for applications such as high-resolution imaging, spectroscopy,

elemental- and bio-microscopy, and nano-fabrication. This goal will be accomplished *both* through research done at the EUV ERC, and, perhaps more importantly, by creating a workforce trained in EUV optical technologies. We have graduated a first cadre of EUV ERC “alumni,” who are starting to play a critical role in maintaining US technological competitiveness.

One of the major defining factors of modern science and technology has been the understanding and use of electromagnetic (EM) radiation. Understanding the interaction of EM radiation with matter led to the development of quantum theory, and subsequently of solid-state physics, electronics, and lasers. One region of the EM spectrum, however, had been relatively unexploited: the extreme-ultraviolet and soft x-ray range (henceforth referred to collectively as the EUV). This region of the spectrum corresponds to wavelengths 10-100 times shorter than visible light, and photon energies in the range of 10’s to 100’s of electron volts. EUV light is both useful *and* difficult to exploit for the same reason—it is ionizing radiation that interacts strongly with matter. This strong interaction with matter makes EUV light difficult to generate and limits the range of available optics, complicating optical design. Conversely, its short wavelength also makes it possible to “see” smaller features and “write” smaller patterns in applications such as microscopy and lithography. Furthermore, these wavelengths are well matched to the primary atomic resonances of most elements, making possible many element- and chemically- specific spectroscopies and spectromicroscopies. EUV wavelengths also correspond to the scale relevant to nanotechnology (~ 2-100 nm). If we are to make rapid progress in the “nano” regime, a wide variety of techniques will be needed to make it possible to observe, manipulate, and fabricate nanoscale objects. EUV light sources make possible techniques such as ultra high-resolution microscopy, imaging, lithographic patterning, and surface analysis, all of which are complimentary to other existing nanoprobe such as atomic force microscopes which promise to become important tools in the quest to develop practical nanoscale “machines.”



Compelling potential applications have led to the development of a number of large-scale synchrotron radiation sources. In this ERC, we are conducting a coordinated effort to accelerate progress in compact EUV sources and testbed applications that will lead to the widespread use of coherent EUV light in solving challenging industrial and scientific problems. The engineering systems concept permeates our entire EUV ERC because all four core institutions, together with our outreach institutions, must work as a team to bring sources and applications together to accomplish our goals.

During its first 6 ½ years the Center has made very significant progress in realizing its vision. Paragraphs A-D below summarize original goals of this program for the first five years, as envisioned at the creation of the Center in 2003. Section 1.2 gives a brief summary of the progress achieved to date.

**A. Research**

A1) Demonstration of small-scale coherent EUV sources operating in the 3 - 50 nm range that will overcome the size/cost source barriers that currently limit the widespread use of EUV radiation.

A2) Demonstration of integrated EUV testbed applications for nanoscale imaging, EUV interferometry and metrology, nanocluster spectroscopy, surface spectroscopy, and linear and nonlinear ultrafast EUV spectroscopies.

A3) Contributions to fundamental knowledge and advanced technology in areas including optics, laser science, EUV science and technology, and plasma physics.

**B. Education**

B1) Contribute to the transformation of undergraduate and graduate education by developing innovative, interdisciplinary curricula, courses, and course modules at the three universities that influence education beyond individual departments. These courses will be coordinated among the three universities and some will be available over the internet. Center wide testbed research projects will also be developed that enable a broad range of people from the core and outreach universities, as well as personnel from industry and national laboratories, to work together on a large-scale effort. Individuals including high school students and teachers, undergraduate and graduate students, post docs, scientists, professors, and visitors will be involved. This will provide a unique educational environment for the EUV ERC.

B2) Development of workshops and teaching tools for K-12 teachers and students that improve engineering and scientific literacy for both teachers and students, and that develop and nurture long-term partnerships.

B3) Training of students proficient in EUV science and technology.

**C. Technology Transfer**

C1) Providing a forum for interaction for large and small industries in a wide range of applications, exposing them to cutting edge research in EUV science and technology.

C2) Providing industry with a trained workforce in areas related to EUV science and technology.

C3) Development of collaborative projects between industry and the EUV ERC.

**D. Diversity**

D1) Demonstration of a successful strategy to attract and retain women and minority students to science and engineering. This includes students at all levels, as well as preserving diversity in the Center Management team and faculty participants.

D2) Development of an environment that ensures the success of women and minority students, and that includes role models, career planning and leadership opportunities.

D3) Development of long-term partnerships with women- and minority- serving institutions to increase the numbers of underrepresented students pursuing degrees in engineering and in science.

The logo for the EUV Engineering Research Center, featuring the letters 'EUV' in a stylized, outlined font.

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D4) Working towards changing the face of science and engineering as a whole, by developing site visits, effective mentoring techniques, lectures and seminar series, workshops, or other vehicles that will improve the climate for women and minorities in other disciplines.

## **1.2 Value Added and Broader Impacts**

### **1.2.1 Research Productivity and Quantifiable Output**

Several important breakthroughs in the development and applications of compact coherent EUV sources have occurred during the first 6 ½ years of the EUV ERC. The results have been published in peer review journals that include Science [1-60, 1-69, 1-87, 2-37, 3-1], Nature [1-23, 1-68, 2-1, 2-29, 3-9], Nature Photonics [1-19, 1-90, 2-38], Nature Physics [1-66], Physical Review Letters [1-4, 1-5, 1-6, 1-11, 1-79, 2-2, 3-2, etc.], Physical Review A [1-8, 1-14, 1-24, 1-29, 1-75, etc.], Proceedings of the National Academy of Sciences [1-80, 2-3, 2-36], Optics Letters [1-7, 1-9, 1-13, 1-25, 1-38, 1-53, 1-61, 2-7, etc.], Optics Express [1-17, 1-22, 1-27, 1-35, 1-56, 1-59, 1-83, etc.], Applied Physics Letters [1-64, 3-7, 3-8], Applied Optics [2-15], IEEE Selected Topics in Quantum Electronics [1-16, 1-70, 1-71, 2-6], Physics Today [1-78], and Review of Scientific Instruments [3-14, 3-27]. The publications of the EUV ERC reflect the strong teamwork and systems orientation of the center. Many of these papers include co-authors from two or all three of the core institutions [1-22, 1-30, 1-54, 2-36, etc.], or co-authors from core institutions and outreach institutions [2-41]. The Center research has been reported in 276 peer review journal papers (46 this past year) and 883 conference presentations and seminars (223 in the past year), with many others in press or submitted. Other forms of dissemination include invited and plenary talks, contributed conference presentations, and a number of high profile news articles..

<b>Table 1: Quantifiable Outputs</b>							
<b>Outputs</b>	<b>Early Cumulative Total [1]</b>	<b>Oct 01, 2005 - Sep 30, 2006</b>	<b>Oct 01, 2006 - Sep 30, 2007</b>	<b>Oct 01, 2007 - Sep 30, 2008</b>	<b>Oct 01, 2008 - Sep 30, 2009</b>	<b>Oct 01, 2009 - Sep 30, 2010</b>	<b>All Years</b>
<b>Publications That Result from Center Support</b>							
In Peer-Reviewed Technical Journals	17	22	36	58	46	42	221
In Peer-Reviewed Conference Proceedings	25	13	17	49	49	51	204
In Trade Journals	1	2	6	5	0	1	15
With Multiple Authors:	41	37	56	107	94	94	429
Co-authored with ERC Students	40	33	50	75	69	67	334
Co-authored with Industry	0	2	3	6	2	5	18
With Authors from Multiple Engineering Disciplines	5	3	0	8	9	4	29
With Authors from Both Engineering and non-Engineering Fields	34	31	33	38	87	67	290
with authors from multiple institutions	32	24	31	51	42	61	241
<b>Publications That Result from Associated Projects in the Strategic Plan</b>							
In Peer-Reviewed Technical Journals	9	9	13	12	8	4	55
In Peer-Reviewed Conference Proceedings	5	13	3	2	9	5	37
<b>Publications Resulting From Sponsored Projects</b>							
In Peer Reviewed Technical Journals	N/A	N/A	N/A	0	0	0	0
In Peer Reviewed Conference Proceedings	N/A	N/A	N/A	0	0	0	0
<b>Participating Industrial and Practitioner Organizations</b>							
Members [2]	14	13	14	19	18	14	92
Affiliates [2]	0	0	0	0	0	1	1
Contributing Organizations [2]	0	0	0	0	0	0	0
<b>ERC Technology Transfer</b>							
Inventions Disclosed (submitted to agencies by	0	0	7	5	2	4	18
Patent Applications Filed	1	2	0	3	1	4	11
Patents Awarded	2	0	0	0	1	3	6
Licenses Issued	0	1	0	1	0	1	3
Spin-off Companies Started	0	0	0	0	1	0	1
Estimated Number of Spin-off Company Employees	0	0	0	0	5	0	5
Building Codes Impacts	0	0	0	0	0	0	0
Technology Standards Impacts	0	0	0	0	0	0	0
New Surgical and other Medical Procedures	0	0	0	0	0	0	0
<b>Degrees to ERC Students</b>							
Bachelor's Degrees Granted	14	4	6	2	5	1	32
Master's Degrees Granted	4	2	5	4	0	1	16
Doctoral Degrees Granted	3	1	2	5	8	9	28

<b>Table 1: Quantifiable Outputs</b>							
<b>Outputs</b>	<b>Early Cumulative Total [1]</b>	<b>Oct 01, 2005 - Sep 30, 2006</b>	<b>Oct 01, 2006 - Sep 30, 2007</b>	<b>Oct 01, 2007 - Sep 30, 2008</b>	<b>Oct 01, 2008 - Sep 30, 2009</b>	<b>Oct 01, 2009 - Sep 30, 2010</b>	<b>All Years</b>
Industry:	4	3	2	1	2	2	14
ERC Member Firms	1	0	1	1	0	1	4
Other U.S. Firms	3	3	1	0	2	1	10
Other Foreign Firms	0	0	0	0	0	0	0
Government	1	1	2	0	0	1	5
Academic Institutions	5	0	11	8	11	8	43
Other	9	2	0	0	0	0	11
Undecided/Still Looking/Unknown	2	1	0	2	0	0	5
<b>ERC Influence on Curriculum</b>							
New courses based on ERC research that have been approved by the curriculum committee and are currently offered [4]	1	3	4	4	0	0	12
Currently offered, on-going courses with ERC	0	0	0	0	10	5	15
New Textbook Chapter Based on ERC Research	0	0	1	0	0	0	1
New Textbooks Based on ERC Research	1	0	0	0	0	0	1
Free-Standing Course Modules or Instructional CDs	33	0	0	0	0	0	33
New full degree programs based on ERC research	0	0	0	0	0	0	0
New degree minors or minor emphases based on	1	0	0	0	0	0	1
New certificate programs based on ERC research	2	0	0	0	0	0	2
<b>Active Information Dissemination/Educational Outreach</b>							
Workshops, Short Courses, and Webinars [3]	27	17	3	0	3	3	53
Number of participants that attended activity	N/A	N/A	N/A	N/A	0	250	250
Seminars, Colloquia, Invited Talks, etc.	45	66	88	116	110	164	589
ERC Sponsored Educational Outreach Events for K-	0	0	0	0	34	9	43
Number of students that attended activity	324	287	240	577	2,185	1,587	5200
Number of teachers that attended activity	0	0	0	0	283	47	330
ERC Sponsored Educational Outreach Events for Community College or Undergraduate students	0	0	0	0	6	1	7
Number of students that attended activity	0	0	0	0	17	9	26
Number of faculty that attended activity	0	0	0	0	2	1	3
<b>Personnel Exchanges</b>							
Student Internships in Industry	1	2	2	2	0	0	7
Faculty Working at Member Firm	0	0	0	0	0	0	0
Member Firm Personnel Working at ERC	0	1	0	0	0	0	1

[1] For Centers in operation for more than five years.

[2] Cumulative count of Individual Firms/Organizations may not equal the sum across all years.

[3] For years prior to 2009, the values include 'Workshops and short courses to industry' and 'Workshops and short courses to non-

[4] New courses currently offered and approved by the curriculum committee are only counted in the first year that they are offered so there is no multiple counting of these courses.



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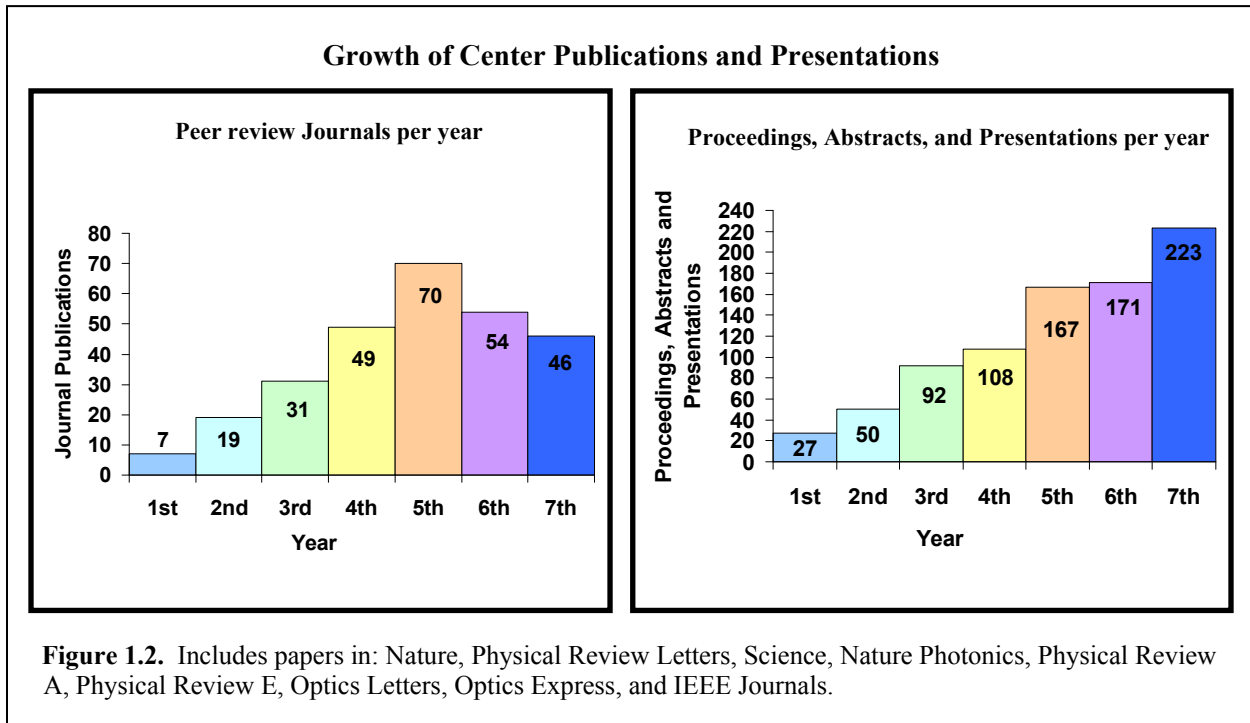
Table 1a: FY2009 Average Metrics Benchmarked Against All Active ERC's and the Center's Tech Sector					
Metric	Average All Active ERC's FY2009	Average Microelectronics Sector FY2009	Average for Class of 2003 - FY 2009	Extreme Ultraviolet Science and Technology Total	Extreme Ultraviolet Science and Technology Total
	(20 ERC's)	(7 ERC's)	(4 ERC's)	FY2009	FY2010
<b>Industrial Member Firms</b>	18	25	14	17	13 [8]
Small	38%	28%	37%	59%	54%
Medium	14%	17%	7%	6%	8%
Large	49%	55%	56%	35%	38%
<b>Non-Industry Sector Firms</b>	1	2	2	1	1
<b>Total Member Organizations</b>	19	27	16	18	14
<b>Affiliate Organizations</b>	1	1	0	0	1
<b>Contributing Organizations</b>	1	1	0	0	0
<b>Total Membership Fees Received</b>	\$				
<b>Direct Sources of Support [1]</b>	\$				
NSF	68%	69%	74%	81%	76%
Industry	7%	6%	6%	6%	5%
Other Federal	0%	1%	1%	0%	0%
Academic	21%	22%	15%	9%	11%
State	2%	1%	3%	4%	8%
Other	2%	0%	0%	0%	0%
<b>Associated Project Support</b>	\$				
<b>ERC Personnel &amp; Educational Participants[2] [3]</b>	687	747	178	225	232
Leadership Team [7]	13	13	12	12	12
Faculty [2] [4]	44	46	43	46	45
Graduate Students [2]	87	77	56	67	75
Undergraduate Students [2]	87	52	22	24	37
REU Students	11	13	9	9	14
K-12 Teachers [3]	111	294	120	292	56
K-12 Students [3]	1,437	3,123	920	2,189	1,591
Faculty that attended ERC Sponsored Educational Outreach Events [3]	2	6	3	2	4
Community College or Undergraduate students that attended ERC Sponsored Educational Outreach Events [3]	26	73	15	17	9
% Women [5] [6]	28%	26%	26%	22%	24%
% Underrepresented Racial Minorities [5] [6]	13%	13%	10%	8%	13%
% Hispanic [5] [6]	10%	13%	15%	12%	8%



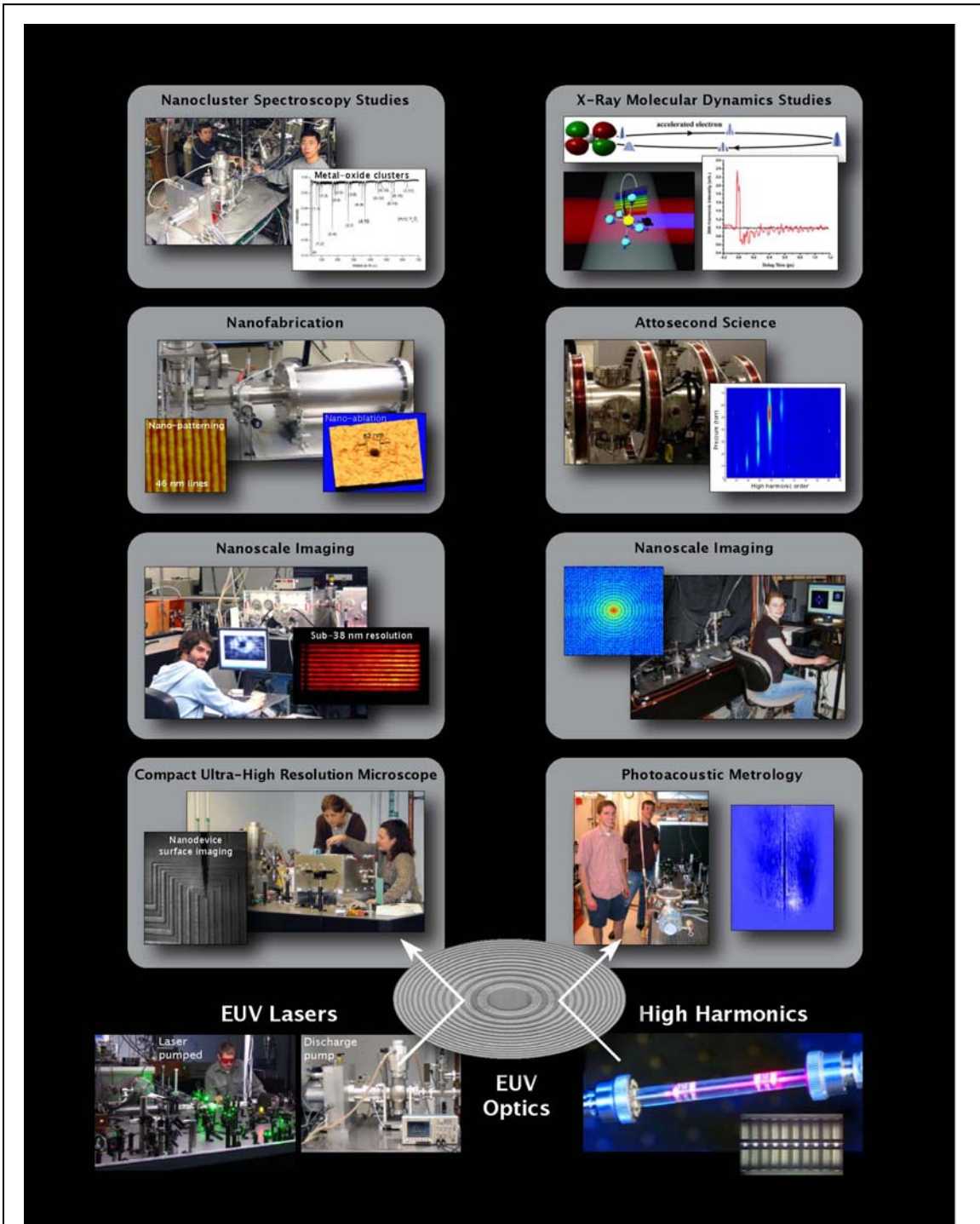
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Table 1a: FY2009 Average Metrics Benchmarked Against All Active ERC's and the Center's Tech Sector					
Metric	Average All Active ERC's FY2009	Average Microelectronics Sector FY2009	Average for Class of 2003 - FY 2009	Extreme Ultraviolet Science and Technology Total	Extreme Ultraviolet Science and Technology Total
	(20 ERC's)	(7 ERC's)	(4 ERC's)	FY2009	FY2010
<b>Publications</b>	<b>Average</b>	<b>Average</b>	<b>Average</b>	<b>Total</b>	<b>Total</b>
In Peer Reviewed Technical Journals	23	38	34	46	42
In Peer Reviewed Conference Proceedings	29	56	27	49	51
Multiple Authors: Co-Authored With ERC Students	32	57	43	69	67
Multiple Authors: Co-Authored With Industry	4	7	4	2	5
<b>Intellectual Property</b>	<b>Average</b>	<b>Average</b>	<b>Average</b>	<b>Total</b>	<b>Total</b>
Invention Disclosures	4	3	10	2	4
Patent Applications	4	2	10	1	4
Patents Awarded	2	1	8	1	3
Licenses (patents, software)	3	7	2	0	1
<b>Education and Outreach Outputs</b>	<b>Average</b>	<b>Average</b>	<b>Average</b>	<b>Total</b>	<b>Total</b>
New Courses Developed	1	1	0	0	0
Currently offered, on-going courses with ERC content	10	20	10	10	5
New Full Degree Programs	0	0	0	0	0
New degree minors or minor emphases	0	0	0	0	0
New certificate programs based on ERC research	0	0	0	0	0

- [1] Includes new support (unrestricted cash, restricted cash, and in-kind donations) from table 9 only. Residual funds carried over from previous years are not included in benchmarking figures.
- [2] Includes total ERC Personnel from table 7.
- [3] Includes participant values from Table 1 Quantifiable Outputs.
- [4] Includes Directors, Education Program Leaders, Thrust Leaders, Senior Faculty, Junior Faculty, and Visiting Faculty from table 7.
- [5] These data do not include K-12 Student or Teacher Participants in the percentage calculations. Demographic data are not collected for K-12 Student or Teacher Participants. We only collect the total number of K-12 Student and Teacher Participants.
- [6] The percentage calculations are based on the following categories of Personnel only:  
Faculty, Graduate Students, Undergraduate Students, REU Students, Directors, Thrust Leaders, Research Thrust Management & Strategic Planning, Administrative Director, and Industrial Liasion Officer.
- [7] Includes Directors, Thrust Leaders, Education Program Leaders, Research Thrust Management & Strategic Planning, Administrative Director, and Industrial Liasion Officer.
- [8] **Does not include industry consortium (Sematech), nor industry member ASML who is in the process of payment at the publication of this report. Our total membership with these two is 15.**
- [9] **Does not include membership fees from Sematech (\$15K), nor funds committed but not yet received at the time of this report, nor in-kind fees. As discussed elsewhere in this report, total committed fees including cash and in-kind is \$257,500.**



In particular during years 3 through 6 of the EUV ERC, advances that combined the strengths of two or more groups have been very exciting. In EUV source development, high harmonic generation has been demonstrated in a capillary discharge plasma, to generate a new type of hybrid EUV source that overcomes one of the main limitations to efficient generation of coherent short wavelength light, by reducing energy loss of the driving laser due to ionization-induced refraction. The use of such engineered plasmas has important consequences for the future, and should enable efficient harmonic generation at keV photon energies and higher. Other advances combine the nanofabrication ability of the UC - Berkeley team with compact EUV laser sources, to demonstrate the highest resolution zone plate imaging and lensless diffractive imaging using any type of compact EUV source. Strong teamwork among all the Center partner institutions has resulted in the successful completion of several application test-beds. Figure 1.3 illustrates how the new compact coherent EUV sources developed at the EUV ERC have been combined with EUV optics technology to enable the successful realization of several applications testbeds in imaging, spectroscopy, materials modifications, and nanopatterning. The major achievements in the each of the three Center thrusts for the first 6 ½ years are summarized below, while achievements of the past year are summarized below in Table 1.1. The progress achieved continues to meet the research milestones in the Center strategic plan.



**Figure 1.3.** Illustration of how the new compact coherent EUV sources developed at the EUV ERC in combination with EUV optics are impacting applications test beds.



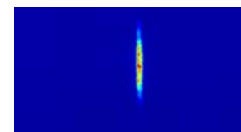
## Thrust 1

Several important advances were achieved in the development of compact coherent EUV sources during the first 6 ½ years of the EUV ERC. This research thrust constitutes the backbone of the Center’s Research Strategic Plan, because compact EUV sources are indispensable tools for the majority of the proposed industrial and scientific testbeds. Significant advances include:

- 1. Demonstration of the first all-diode-pumped EUV laser.** [F. Furch et al. Optics Letters, **34**, 3352, (2009)]

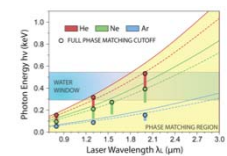


- 2. Demonstration of a gain-saturated table-top EUV laser at 10.9 nm.** [D. Alessi et al, Optics Letters, (2010)]

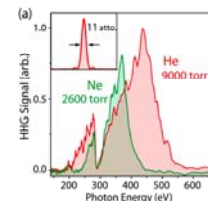


- 3. Demonstration of 13.9nm table-top EUV laser with 20 microwatt average power.** [ D.Martz et al, submitted (2010)]

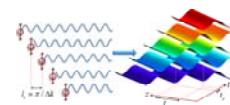
- 4. Demonstration of full phase matching spanning the water window (to 530 eV) using a compact source for the first time** [M. Chen, submitted (2010)]



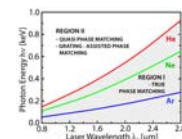
- 5. Generation of broad coherent bandwidths in the soft x-ray region supporting 10 attosecond pulse generation for the first time** [M. Chen, submitted (2010)]



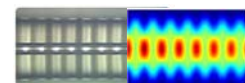
- 6. Development of a new spatio-temporal quasi phase matching scheme that allows spectral tuning of low-order harmonics** [A. Bahabad, submitted (2010)]



- 7. Experimental demonstration of full phase matching extending into the water window for the first time at 330 eV, using mi-infrared driving lasers.** [T. Popmintchev et al, Optics Letters **33**, 2128, (2008); T. Popmintchev et al., PNAS **106**, 10516 (2009).]

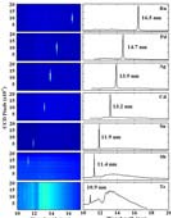


- 8. Demonstration of partial phase matching in the water window at 4 nm for the first time** (collaboration between CU and UC – Berkeley). [E. Gibson et al., Science **302**, 95, (2008); A. Paul et al., Nature **421**, 51, (2003); A. Paul et al., IEEE J. Quant. Electronics **42**, 14, (2006); E. Gibson et al., IEEE J. Quant. Electronics **10**, 1339, (2004)]

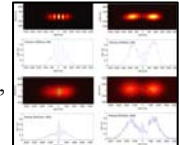




9. **Demonstration of the first high repetition rate table-top lasers with wavelengths as short as 10.9 nm** and gain-saturated output at wavelength as short as 13.2 nm. These lasers developed at CSU are the first short wavelength, highest average power compact EUV lasers demonstrated. [Y. Wang et al., *Physical Review A* **72**, 053807, (2005); D. Alessi et al., *Optics Express* **13**, 4050, (2008); M. Larotonda et al., *IEEE J. Quant. Electronics* **10**, 1363, (2005); B. Luther et al., *IEEE J. Quant. Electronics* **42**, 4, (2006); B. Luther et al., *Optics Letters* **30**, 165, (2005)]



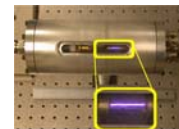
10. **Demonstration of fully coherent beams at 13 nm** by high harmonic generation (collaboration between CU, UC - Berkeley and CSU). [X. Zhang et al., *Optics Letters* **29**, 1357, (2004)]



11. **Demonstration of a desk-top size EUV laser** operating a 46.9 nm pumped by a discharge at 12 Hz repetition rate (the highest repetition rate and smallest size of any EUV laser to date). [S. Heinbuch et al., *Optics Express* **13**, 4050, (2005)]

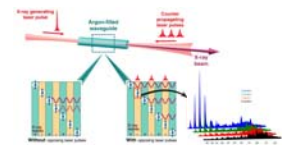


12. **First demonstration of high harmonic generation in a discharge-created plasma**, that significantly reduces loss associated with laser induced ionization and refraction. (Collaboration between CU and CSU). [D. Gaudiosi et al., *Physical Review Letters* **96**, 203001, (2006); B. Reagan et al., *Physical Review A* **76**, 013816, (2007)]

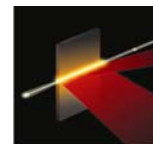


13. **Demonstration of high harmonic generation from ions**, at photon energies greater than a factor of two higher than has been observed previously, in neon, argon, krypton and xenon (collaboration between CU and CSU). [D. Gaudiosi et al., *Physical Review Letters* **96**, 203001, (2006); B. Reagan et al., *Physical Review A* **76**, 013816, (2007); E. Gibson et al., *Physical Review Letters* **92**, 033001, (2004)]

14. **Demonstration of a new scheme for all-optical quasi phase matching**, that increases the high harmonic yield at 70eV – 150 eV by > two orders of magnitude over and above what can otherwise be obtained. [O. Cohen et al., *Physical Review Letters* **99**, 053902, (2007); A. Lytle et al., *Optics Letters* **33**, 174, (2008); X. Zhang et al., *Nature Physics* **3**, 270, (2007); O. Cohen et al., *Physical review Letters* **98**, 043903, (2007); Z. Xiaoshi et al., *New Journal of Physics* **10**, 025021 (2008); A. Lytle et al., *Physical Review Letters* **98**, 123904, (2007); H. Kapteyn et al., *Science* **317**, 775, (2007)]



15. **First demonstration of an essentially fully coherent gain-saturated EUV laser amplifier by injection seeding of a dense plasma-created ablating of a solid target.** [Y. Wang et al., *Physical Review Letters* **97**, 123901, (2006)]



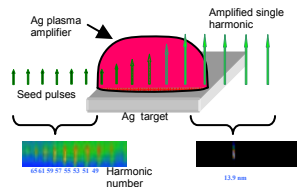
16. **Demonstration of a new regime of harmonic generation**, where isolated, sub-optical cycle EUV pulses are generated that are insensitive to the value of the carrier-envelope phase of the laser. This approach allows for selective control of the EUV energy and bandwidth. [I. Thomann et al., submitted, (2008); A. Sandhu et al., *Physical Review A* **74**, 061803, (2006)]



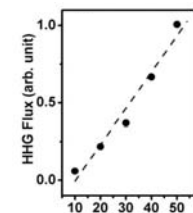
17. **Complete characterization of a complex attosecond light field for the first time**, by determining both the amplitude and phase. [I. Thomann et al., Phys. Rev. A **78**, 011806 (2008).]

18. **Theoretical new scheme with the potential for phase matched high harmonic generation at keV photon energies**. This will require the use of a hybrid discharge/harmonic source. [O. Cohen et al., Physical Review Letters **99**, 053902, (2007); O. Cohen et al., Physical review Letters **98**, 043903, (2007)]

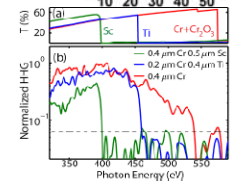
19. **First demonstration of phase coherent EUV lasers in the 13 nm spectral region**. Obtained by injection seeding of Ni-like Ag and Ni-like Cd plasma amplifications. [Y. Wang et al., Nature Photonics **2**, 94, (2008) ; F. Pedaci et al., Optics Letters **33**, 491, (2008)]



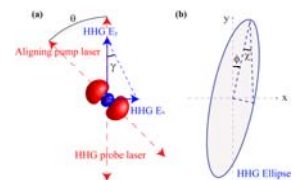
20. **Demonstration of a spatially coherent, phase matched, high harmonic EUV light source at 50 kHz**. [M. Chen et al., Optics Express **17**, 17376 (2009)]



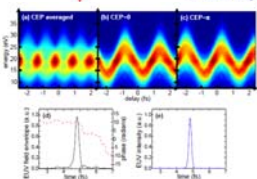
21. **Generation of > 500 eV photons from multiply-ionized Argon ions for the first time**. [P. Arpin et al., Physical Review Letters **103**, 143901 (2009)]



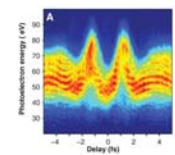
22. **Observation of elliptically polarized high harmonic emission from molecules driven by linearly polarized laser light**. [X. Zhou et al., Physical Review Letters **102**, 073902 (2009)]



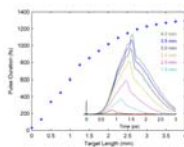
23. **Generation of isolated attosecond pulses, with a duration of ~200 attoseconds, using CEP unstabilized 15 fs multi-cycle driving pulses for the first time**. This is a far simpler approach than has been implemented to date. [I. Thomann et al. Optics Express **17**, 4611 (2009)]



24. **Measured 80 asec EUV pulses with novel multilayer optics developed at UC – Berkeley achieving the shortest pulse known to date**. [E. Goulielmakis et al., Science **20**,1614 (2008)].



25. **First demonstration of a ~1 ps EUV laser pulses from a table-top plasma amplifier**. These are the shortest laser pulses achieved to date from a table-top EUV laser source. [Y. Wang et al., Phys. Rev. A **79**, 023810, (2009)].



26. **Developed multilayer "quarter" wave plate mirrors to convert linearly polarized HHG pulses to circularly polarized fsec pulses**.

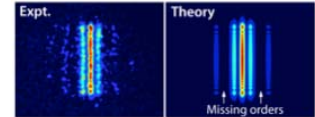


The combination of compact EUV sources and optics is enabling testbeds with unique capabilities. These advances have enabled the development of the nano-scale imaging, EUV patterning, and EUV spectroscopy testbeds described latter in this volume and in the Project Summaries in Volume II. The advances in EUV source testbeds will also eventually lead to compact microscopy testbeds for bio-imaging.

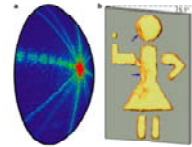
**Thrust 2**

Very significant progress was also achieved in soft x-ray imaging, EUV patterning, and microscopy:

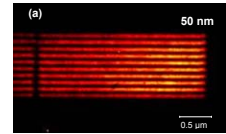
- 1. Demonstration of spatially coherent light in the water window using a compact source for the first time** [M. Chen, submitted (2010)]



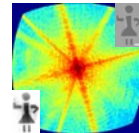
- 2. 3D structural determination from a single view** [K. Raines et al., Nature 463, 214 (2010)]



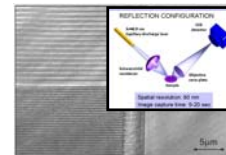
- 3. Table-top EUV Zone Plate microscopy with 38 nm spatial resolution using a newly developed high repetition rate 13.2 nm laser and zone plate optics** (collaboration between CSU and UC – Berkeley). The wavelength of operation falls within the bandwidth of Mo/Si mirrors for EUV lithography, opening up a pathway to table-top at-wavelength metrologies for defect inspection. [F. Brizuela et al., Optics Express 30, 2095, (2005)]



- 4. Table-top lensless coherent imaging using small-scale coherent EUV sources was demonstrated for the first time**, achieving a record resolution of 70 nm. This advance used both high harmonic EUV sources and a compact EUV laser. (Collaboration between CU, CSU, UCLA and UC – Berkeley). This result may be of interest for defect inspection) [R. Sandberg et al., Proc. Of the National Academy of Science 105, 24, (2008); R. Sandberg et al., Physical Review Letters 99, 098103, (2007)]



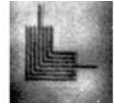
- 5. A compact EUV microscope capable of operation in the reflection mode for the inspection of surfaces and nanostructures** was also developed using the combination of a 46.9 nm capillary discharge laser, reflective optics and diffractive optics (collaboration between CSU, UC - Berkeley and the Lebedev Physical Institute). In the last year the resolution of this microscope was improved to 54 nm.[G. Vaschenko et al., Optics Letters 30, 2095, (2005), F. Brizuela et al., Optics Express 30, 2095, (2005)]



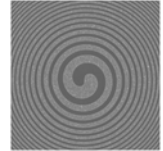
- 6. Demonstration of ultrafast EUV holographic imaging** for the first time (collaboration with MIT). [R.I. Tobey et al., Optics Express 32, 286, (2007)]



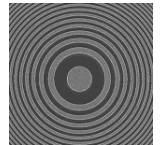
7. **Demonstration of a table-top 13.2 nm reflection microscope for actinic mask characterization using EUV laser illumination with a resolution of 55nm** (Collaboration between CSU and UC – Berkeley). [F. Brizuela et al., Optics Letters **34**, 271, (2009)]



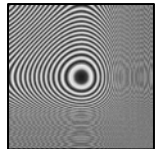
8. **First demonstration of phase contrast imaging with a spiral zone plate** confirming formation of x-ray optical vortices using diffractive optics. [A. Sakdinawat and Y. Liu, Optics Letters **32**, 2635 (2007)]



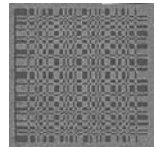
9. **X-ray Zernike phase contrast imaging using the Zernike zone plate**, a single diffractive optical element. [A. Sakdinawat and Y. Liu, Optics Express (2008)]



10. **Extended depth of field imaging using wavefront coded zone plates** demonstrated for 40 nm features. [A. Sakdinawat, et. al., in preparation ]



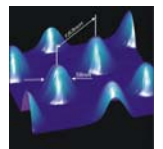
11. **Massively parallel x-ray holography using uniformly redundant arrays increases resolution capability for holographic imaging** (collaboration with ALS). [S. Marchesini, et. al. Nature Photonics (2008)]



12. **EUV holograms with 50 nm resolution using a table-top 46.9 nm EUV laser.** [P Wachulak et al., Optics Express **14**, 9636, (2006)]

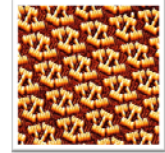
13. **Synchrotron radiation based EUV interferometry was advanced to the wave front analysis of a 0.3 NA multilayer coated optics**, a factor of three increases in NA with respect to previous experiments. EUV static exposures were printed with 25 nm features for the first time. [K. Goldberg et al., SPIE **5374**, 64, (2004)]

14. **Patterning of gratings with periods as small as 55 nm using a 46.9 nm EUV laser.** Printing arrays of nanostructures with features as small as 56 nm. [P. Wachulak et al., Journal of the Optical Society of America B **25**, B20, (2008); P. Wachulak et al., Journal of the Optical Society of America B **25**, B104, (2008); P. Wachulak et al., Opto-Electronics Review **16**, 144, (2008); P. Wachulak et al., Optical Society of America B **25**, 1811, (2008); P. Wachulak et al., Optics Express **15**, 10622, (2007); P. Wachulak et al., Optics Express **15**, 3465, (2007); M. Capeluto et al., Microelectronic Engineering **84**, 721, (2007); P. Wachulak et al., Optics Express **14**, 9636, (2006); M. Capeluto et al., IEEE Transactions on Nanotechnology **5**, 3, (2006)]





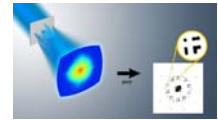
15. **Phase contrast images were obtained for the first time with a new “XOR” soft x-ray microscope objective that combines both a zone plate and a grating in a single element.** The experiments were performed near the Fe-L3 and L2 absorption images of magnetic nanostructures.



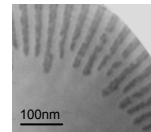
16. **Printing of arrays of arbitrarily shaped nano-patterns by Talbot imaging using a table-top laser illumination** [ F. Cerrina et al., submitted (2009)]

17. **Holographic printing of arbitrary nano-patterns using table-top EUV laser illumination.**

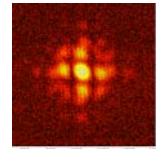
18. **Demonstration of lensless imaging using 30 nm wavelength high harmonic sources with resolutions of 50 nm.** This improved the image resolution achieved using HHG by a factor of 2. [R. Sandberg et al., Optics Letters **34**, 1618 (2009); Murnane and Miao, Nature **460**, 1088 (2009)]



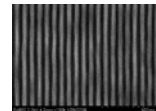
19. **Zone plate microscopy using synchrotron radiation was advanced from a spatial resolution of 15 nm in 2005 to a record resolution of 12 nm.** [W. Chao et al., Journal of Vacuum Science Technology B **21**, (2003); W. Chao et al., Nature **435**, 1210, (2005); W. Chao et al., (manuscript in preparation)]



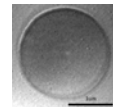
20. **Demonstration of lensless imaging using 13 nm wavelength high harmonic sources for the first time,** with resolutions of 90 nm. [D. Raymondson et al. submitted (2010)]



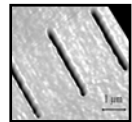
21. **22 nm printed lines and spaces (dense) for EUV lithography at 13.5 nm wavelength.** EUV chemically amplified photoresist is now probing the 20 nm barrier with doses of 15 mJ/cm<sup>2</sup> [P. Naulleau, C. Anderson, SPIE Advanced Lithography 2009]



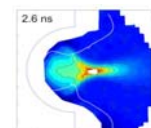
22. **Direct x-ray imaging of vortex dynamics in magnetic nanostructures at the Fe L3 edge.** Gyrotropic resonant motion of the magnetic vortex core has been observed with 300ps time steps. [B.L. Mesler, M.-Y. Im, P. Fischer, MRS Spring Meeting Poster, San Francisco, (2009)]



23. **Demonstration of nano-machining with a focus EUL laser (200 nm grooves)** (Collaboration between CSU and UC – Berkeley). [H. Bravo, CLEO, (2009)]



24. **Demonstration of dense plasma interferometry using a table-top laser** (Collaboration between CSU and Lawrence Livermore National Laboratory). [J. Filevich et al., Applied Optics **43**, 3938, (2004); J. Filevich et al., Physical Review Letters **94**, 035005, (2005); J. Filevich et al., J. Quant. Spec. and Rad. Trans. **99**, 165, (2006); J. Filevich et al., Physical Review E **74**, 016404, (2006); J. Filevich et al., Laser Particle Beams **25**, 47, (2007)]

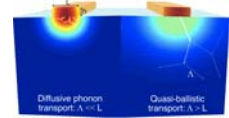




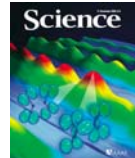
**Thrust 3**

Very significant progress was also achieved in linear and nonlinear spectroscopies using compact sources:

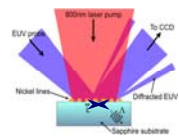
1. **Measurement of quasi-ballistic heat transport at nanoscale interfaces for the first time, using ultrafast coherent EUV beams** (collaboration between CU, UC – Berkeley and MIT). [M. Siemens et al, Nature Materials 9, 26 (2010).



2. **Probing of coupled electron and nuclear dynamics in polyatomic molecules using coherent electrons and x-rays.** This work was featured on the cover of Science. [W. Li et al., Science 322, 1207, (2008)]



3. **A very-sensitive testbed for probing of acoustic dispersion and surface deformation was developed using EUV light for the first time.** This testbed is several orders of magnitude more sensitive than the equivalent optical probe. Photo-thermal and photo-acoustic transients and acoustic dispersion on nanoscale dimensions were probed with EUV light using a high harmonic source. This work is now being extended to study heat transport in devices on nanoscale dimensions below 200nm (collaboration with MIT). [R. Tobey et al., Applied Physics Letters 89, 091108, (2006); R. Tobey et al., Applied Physics Letters 85, 564, (2004); M. Siemens et al., Applied Physics Letters 94, 093103 (2009)]

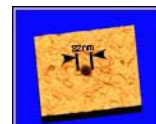


4. **Spectroscopy of metal-oxide nanoclusters was successfully demonstrated using a desk-top sized EUV laser as a single photon ionization source.** [S. Heinbuch et al., Optics Express 13, 4050, (2005); F. Dong et al., Journal of Chemical Physics 124, 224319, (2006); F. Dong et al., Journal of Chemical Physics 125, 154317, (2006); S. Heinbuch et al., Journal of Chemical Physics 125, 154316, (2006); F. Dong et al., Journal of Chemical Physics 125, 164318, (2006); S. Heinbuch et al., Journal of Chemical Physics 126, 244301 (2007); F. Dong et al., Journal of the American Chemical Society 130, 1932, (2008); S.-G. He et al., Journal of Physical Chemistry A 112, 11067, (2008); F. Dong et al., J. Am. Chem. Soc. 131, 1057, (2009)]

5. **First study of chemical reactions of industrial importance using of desk-top size capillary discharge EUV laser as single photon ionization source of nanoclusters.** [F. Dong et al., Journal of the American Chemical Society 130, 1932, (2008); S.-G. He et al., Journal of Physical Chemistry A 112, 11067, (2008).]

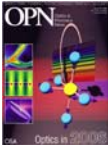

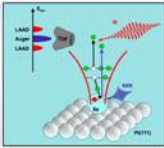
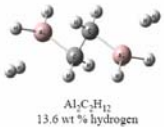
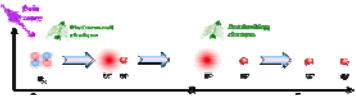
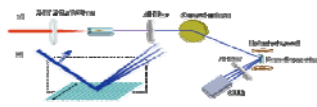
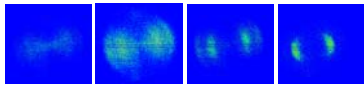
6. **First demonstration of spectroscopic identification of material ablated using a focused EUV laser** (collaboration between CSU, UC – Berkeley and JMAR). This industrial project is aimed at the development of a new set of analytical tools for nanotechnology. [M Berrill et al., Journal of the Optical Society of America B 25, B32, (2008)]

7. **Demonstration of ablation of 82 nm holes for LIBS nanoprobe.** [G. Vaschenko et al., Optics Letters 31, 1214, (2006)]



8. **Photoemission spectroscopy of novel electronic materials was demonstrated with higher resolution using a compact high harmonic source** (collaboration with CU physics). [J. Koralek et al., Physical Review Letters 96, 017005, (2006); J. Koralek et al., Review of Scientific Instruments 78, 053905, (2007)]



9. **Use of attosecond electron recollisions during the process of high harmonic generation to probe molecular structure and dynamics.** Observation of phase shifts in harmonic emission due to the structure of the molecule for the first time. [X. Zhou et al., Physical Review Letters **100**, 073902, (2008); N. Wagner et al., Physical Review A (2008)]
 
10. **Use of ultrafast x-rays to initiate and study ultrafast radiation femtochemistry for the first time** (collaboration with Kansas State). [E. Gagnon et al., Science **317**, 1374, (2007)]
 
11. **Measurement of the orientation dependence of single photon ionization of a molecule for the first time.** [I. Thomann, J Physical Chemistry A **112**, 9382 (2008)]
12. **Laser-assisted photoemission was observed from a surface for the first time.** This work has important implications for observing attosecond dynamics in solids. To date, such dynamics have been observed only in gas phase (collaboration with Kaiserslautern). [L. Miaja-Avila et al., Physical Review Letters **97**, 113604, (2006); G. Saathoff et al., Physical Review A **77**, 022903, (2008)]
 
13. **Measurement of charge transfer processes between an adsorbate and surface in real time for the first time.** This measurement was made on Pt, which is an important catalytic surface. [L. Miaja-Avila et al., Physical Review Letters **101**, 046101 (2008)]
14. **Identification of high hydrogen storage capacity materials using single photon ionization mass spectroscopy using a desk-top size EUV laser.** [F. Dong et al., submitted Journal of the American Chemical Society]
 
15. **Measurement of the highest frequency (50 GHz) surface acoustic wave propagation in nanostructures using ultrafast HHG beams.** [M. Siemens et al. Applied Physics Letters **94**, 093103, (2009)]
16. **Observation of the birth of a highly excited Feshbach resonant state in soft x-ray induced molecular dissociation.** [A. Sandhu et al., Science **322**, 1081 (2008)]
 
17. **First characterization of element-specific dynamics in magnetic materials** [Physical Review Letters **103**, 257402 (2009)]
 
18. **First real time imaging of electron orbitals as a molecule dissociates.** [W. Li et al. submitted (2010)]
 



19. **Development of a femtosecond transient absorption apparatus for molecular dynamics**
  - \* Orbital alignment of Xe high field ionization probed by EUV high order harmonics.
  - \* Wave packet observed in methyl iodide via EUV core level absorption.[Z.-H. Loh, et al., Phys. Rev. Lett. **98**, 143601 (2007)]
20. **Electromagnetically induced transparency principle demonstrated in EUV transitions in He** [Z.-H. Loh, et al., Chem. Phys. **350**, 7 (2008)]

Work on associated Center projects, several of them conducted in collaboration with the Center research affiliate institutions, has also produced significant results. New results were obtained in picosecond resolution soft x-ray laser interferometry of dense plasmas, in collaboration with researchers at Lawrence Livermore National Laboratory [2-15 and 2-18]. We have also collaborated in nanopatterning with the University of Wisconsin [1-37], Morehouse College [2-41], and University of Buenos Aires [1-36], in observing the coupled motions of electrons and atoms in real time for the first time with NRC Canada [3-23], in using compact EUV sources to observe element-specific dynamics in magnetic materials for the first time with NIST and Kaiserslautern [3-13], in understanding x-ray driven molecular explosions with Argonne National Lab [3-28], in monitoring fast electron transfers between catalytic surfaces and adsorbates with Kaiserslautern [3-21], in EUV laser imaging with Krakow Institute, the Lebedev Institute [1-30], and the Institute of Physics, Czech Academy of Sciences [3-46] and in EUV laser pulse width characterization with Kansas State University [3-1]. Aside from the development of models at the Center core institutions, we have maintained very successful collaborations in the modeling of EUV lasers, high harmonic sources and plasmas with the University of Sophia and the UC - Davis. In addition we are working in two associated projects, both funded by NIH, to build soft x-ray microscopes for biological applications, in one case a compact microscope with a corporate partner Energetiq, in the other a microscope capable of tomographic imaging with several minutes exposures at a synchrotron facility.



**Table 1.1 Summary of 2009-2010 Most Significant Research Accomplishments**

1. Demonstrated the first all-diode-pumped EUV laser.
2. Extended gain-saturated table-top EUV lasers to 10.9 nm
3. Increased the average power of 13.9 nm EUV lasers to 20 microwatts.
4. Characterized the temporal coherence of injection-seeded EUV lasers, confirming these lasers have full phase coherence.
5. Development of a 2-dimensional plasma modeling code to assist in the development of compact EUV lasers
6. First demonstration of full phase matching of high harmonic generation spanning the water window region of the spectrum, to 530eV.
7. First demonstration of spatial coherence in the water window region of the spectrum.
8. First generation of 10 attosecond pulses, using ultra broadband phase matching in the soft x-ray region.
9. Demonstration that >500 eV harmonics can be generated from multiply-ionized argon for the first time.
10. Spatially coherent, phase matched, high-order harmonic EUV light source at 50 kHz
11. Quasi phase matching of momentum and energy in nonlinear optical processes
12. Demonstrated aerial imaging of EUV lithography masks with a table-top microscope based on a table-top 13.2 nm EUV laser. The imaging allowed for the measurement of line edge roughness.
13. Demonstration that 3D information can be recovered from a single 2D diffraction pattern using high numerical aperture lensless imaging.
14. First characterization of element-specific dynamics in magnetic materials
15. Direct observation of the transition from molecules to atoms
16. Measurement of quasi-ballistic heat transport across nanoscale interfaces using ultrafast coherent soft x-ray
17. Soft x-ray microscopy with zone plates resolved to 12 nm
18. EUV patterning to 18 nm half-period with good sensitivity and LER
19. Optimized second order zone plates for high resolution zone plate imaging
20. New magnetic materials for soft x-ray microscopy using a novel micro-etching process
21. New simulation program for partially coherent imaging in soft x-ray microscopy
22. Fabrication of a multilayer based attosecond EUV beamsplitter and interferometer
23. Design completed of a very narrow band dispersion-free, multilayer mirror monochromator for  $\lambda/\Delta\lambda \approx 200$
24. EUV mask defect inspection tool demonstrates 70 nm (18 nm at the wafer) spatial resolution using synchrotron radiation
25. Identified new high hydrogen storage capacity materials using EUV laser-based single photon ionization mass spectrometer.

## 1.2.2 Education and Outreach

The Center has implemented an Education and Outreach plan that is designed to have an important, broad impact on society with activities that involve the science and engineering of optics, light and lasers at all levels. The plan is run by the Education Director, Dr. Kaarin Goncz, who has a multidisciplinary history involving engineering and education



The strategies by which the EUV ERC has pursued the goals of its plan include: reaching a diverse population of students and teachers by nurturing long term partnerships with four year College partners and established outreach programs, which we can enhance and complement, and assessing the success of our programs through feedback from participants, and tracking the career path of students

The plan is currently composed of a coordinated series of programs that are designed to impact students at all levels from K-12 to undergraduate and graduate. These programs are described in detail in the Education and Diversity sections of this report. Significant progress has been accomplished the past 6 ½ years in achieving the education and diversity goals of the Center. These achievements include:

### **Expanded K-12 student & teacher impact**

- *Exposed 4889 K-12 students (2789 students directly impacted by the Center and 2100 by the partner programs) and 621 teachers to the science and engineering of optics, light and lasers through the presentation of hands-on workshops. This feat has been facilitated by the Center's collaboration with partner outreach programs as well as our increased interaction with local school districts.*
- *Provided over 100 Optics Kits to teachers and other outreach organizations that specialize in delivering workshops. Improved the teaching of the science and engineering of optics, light and lasers by continuing to develop new kits based on feedback from field work by the Education Director and RETs.*
- *Presented university level lab experience to 153 high school students by having them participate in the "Optics After School" Workshop. Thirteen high school students contributed to Center research projects during the summer and all of the high school students that are now enrolled in college are pursuing STEM degrees.*
- *Completed the third year of our RET program. Thirteen teachers have participated.*
- *Established close collaboration between the Center and School Districts by 1) Recruiting RETs from the same school; 2) Offering workshops in RET alumni schools; 3) Collaborating with University sponsored K-12 recruitment programs, such as the Alliance Program at CSU, to increase our impact on URM from "feeder" schools.*

### **Enhanced research experiences for undergraduate students.**

- *Provided research experience for 140 undergraduates from 28 different institutions. Of these students, 53% are from under-represented groups (36% URM and 28% women). Sixty two percent of our undergraduates that have graduated are now enrolled in graduate school pursuing STEM degrees and 29 percent are in industry.*
- *Established vibrant collaborations with Colleges that serve underrepresented minorities (Morehouse, Spelman, Agnes Scott) by providing undergraduate research opportunities for these students both at their home institutes and at the Center. A total of 28 undergraduate students from these institutes have participated in Center Research.*

### **Broaden graduate student training**

- *Mentored 84 graduate students through their career in a highly multi-disciplinary, multi-institution environment.*



- *Celebrated the accomplishments of 50 EUV students who distinguished themselves through awards they have received for their EUV research work from the professional societies, industry associations, government agencies and the universities. Fourteen students have won more than one award.*
- *Provided opportunities for over 40% of the Center graduate students to conduct education outreach activities*
- *Developed and taught courses in EUV and 14 courses in related subjects. Two on-line courses have been accessed by thousands of students all over the world.*

### **1.2.3 Industrial Collaboration**

The EUV ERC has an active interaction with a wide variety of industrial participants. The EUV ERC has a strategy for involvement that emphasizes the quality of the interaction by closely collaborating with the industrial members in the research, education, and technology transfer aspects of the Center.

The Center impacts industry thought different avenues. These include the unique training of a workforce with proficiency in EUV and systems engineering experience, the creation of new knowledge, methodologies and equipment that can assist industry in overcoming the challenges and barriers making new manufacturing technologies a reality (as is the case of EUV lithography), and the demonstration of new devices, scientific equipment, and techniques resulting in new commercial products. Several companies have contracts for associated projects with core institutions for Center related EUV research, a key component of the total support for the overall research activities of the Center. Center students have participated in summer internships, as well as in projects that are either directly sponsored by industry or that have industrial interest. Technology transfer at the EUV ERC is an active area that takes multiple forms, ranging from frequent consultations by industry to licensing of Center technology. The contributions that the Center is making through each of these avenues are summarized in the Industry section of this report.

Accomplishments to date include:

- Fourteen companies are members of the Center after the EUV ERC changed the membership fee structure in October 2009 to increase the amount of cash support contributed by industry. The companies represent small, medium and large companies, in the fields of lasers, optics, instrument and metrology instrumentation suppliers, aerospace, as well as larger semiconductor companies and consortia
- Expanding industrial membership, that now also includes representatives from the aerospace.
- Numerous industrial collaborations include the development of new products (e.g. EUV sources, microscopes, lasers and laser components), the development of new fabrication methodologies, the development of new metrology techniques for the evaluation of critical components in industrial manufacturing processes (e.g. evaluation of lithographic resists, mask inspection techniques, nanopatterning methods), and the metrology of components using the Center's unique facilities (evaluation of debris, EUV filter and mirror characteristics, detector calibration)
- New commercial products on the market (coherent EUV sources, laser components) or under development (nanopatterning products, microscopes)



- The hiring of numerous ERC students and post doctoral fellows that have made key contributions to industry. Examples of the unique expertise of EUV ERC graduates that have immediately impacted industry include Georgiy Vaschenko at Cymer, and Dr. Xiaoshi Zhang, who commercialized a new laser (Wyvern) and compact EUV source (XUUS) at KMLabs.
- Continued receipt of industrial support for Center associate projects.

### **1.2.4 Team and Diversity**

The EUV ERC exceeds national engineering-wide averages for participation of women and underrepresented minorities at almost every level, as shown by the statistics presented in Section 5 of this report. The EUV ERC is actively trying to recruit underrepresented students into our research opportunities. Our leadership team includes 4 women and 3 Hispanics among its members, thus providing a supportive environment for students from these backgrounds.

#### **Highlights of results of the success of our program in increasing diversity:**

- 80% of the K-12 RET associated schools have URM group populations that are greater than or similar to the National Average.
- 53% of the 140 EUV ERC undergraduate research students have been from gender, ethnic and racial populations that are underrepresented in engineering. 62% of these URM students are now in graduate school.
- The percentage of Hispanics in the ERC EUV in all roles (Leadership, Faculty, Doctoral & Undergraduate students) is higher than both the National Engineering Average and all other ERCs.
- Engaged 28 URM students from our partner Colleges in Center research. 58% of them are now in graduate school in STEM disciplines. Successfully applied for and received fellowships every year for URM undergraduate research students from minority serving programs such as AGEP and LSAMP

### **1.2.5 Honors and Awards**

An indicator of the recognition that Center faculty and students are receiving for their work is the honors and awards that they have received in the past year of the EUV ERC. These include national honors, as well as, in the case of undergraduate students, recognition at the local level:

In the past year:

- CU Professors Margaret Murnane and Henry Kapteyn shared the 2010 Schawlow Prize in Laser Science from the American Physical Society, and the 2010 R. W. Wood Prize from the Optical Society of America.
- CSU Professor Carmen Menoni was elected Fellow of *the Institute of Electrical and Electronics Engineers*, and was named Editor in Chief of the IEEE Photonics Journal.



- In Section 3 of this report we list 49 students who received awards from professional societies or universities, several in 2009. The latter include the Eugene P. Wigner Post-Doctoral Fellowship from Oak Ridge National Laboratory to CSU student Mark Berrill, the Los Alamos National Laboratory Director's Fellowship to Richard Sandberg from CU, an NRC Postdoctoral Fellowship to Mark Siemens from CU, a Marie Curie Postdoctoral Fellowship to Stefan Mathias (Stefan did part of his Ph.D. thesis at JILA), the best paper in the field of AFM Metrology to CU student Daisy Raymondson, the best poster award from the Colorado Photonics Industry Association to CSU student Lukaskz Urbanski, a DAAD Postdoctoral Fellowship of the German Science Foundation to Isabell Thoman, an SPIE Scholarship to CSU undergraduate and Center REU Mark Woolston, NSF IGERT Fellowships to CU students Matt Seaberg and Paul Arpin, the Outstanding paper award from the APS four corners meeting to CU graduate student Qing Li, and an Investigator Award from the Basque Government to CSU graduate student Sergio Carbajo.
- Center Research was highlighted at a press conference and special symposium at the 2010 AAAS Annual Meeting in San Diego, to celebrate the 50<sup>th</sup> Anniversary of the Laser.



## 1.3 Nuggets of Significant Achievement and Impact

### 1.3.1 Learning

#### 1) NSF EUV Center students are honored by multiple awards during 2009, totaling 50 awards since the ERC launched

During 2009-2010, students from the NSF Center for Extreme Ultraviolet Science and Technology have continued to receive numerous awards from professional organization, industry associations, academia, and government sponsored organizations in recognition of their research achievements. Since the EUV Center was founded graduate and undergraduate Center students have been honored by 50 awards. In the past year these include the Eugene P. Wigner Post-Doctoral Fellowship from Oak Ridge National Laboratory to graduate student Mark Berrill, the Los Alamos National Laboratory Director’s Postdoctoral Fellowship to Richard Sandberg, an NRC Postdoctoral Fellowship to Mark Siemens, the best paper in the field of AFM Metrology to graduate student Daisy Raymondson, the best poster award from the Colorado Photonics Industry Association to Lukaskz Urbanski, a DAAD Postdoctoral Fellowship of the German Science Foundation to Isabell Thoman, a Marie Curie Postdoctoral Fellowship from the EU to Stefan Mathias, an SPIE Scholarship to undergraduate and Center REU Mark Woolston, NSF IGERT Fellowships to Matt Seaberg and Paul Arpin, the Outstanding Paper Award from the APS four corners meeting to graduate student Qing Li, and an Investigator Award from the Basque Government to graduate student Sergio Carbajo.



*Lukaskz Urbanski.  
Colorado Photonics  
Industry Best Poster  
Award*

*Daisy Raymondson SPIE  
Lithography best paper  
award*

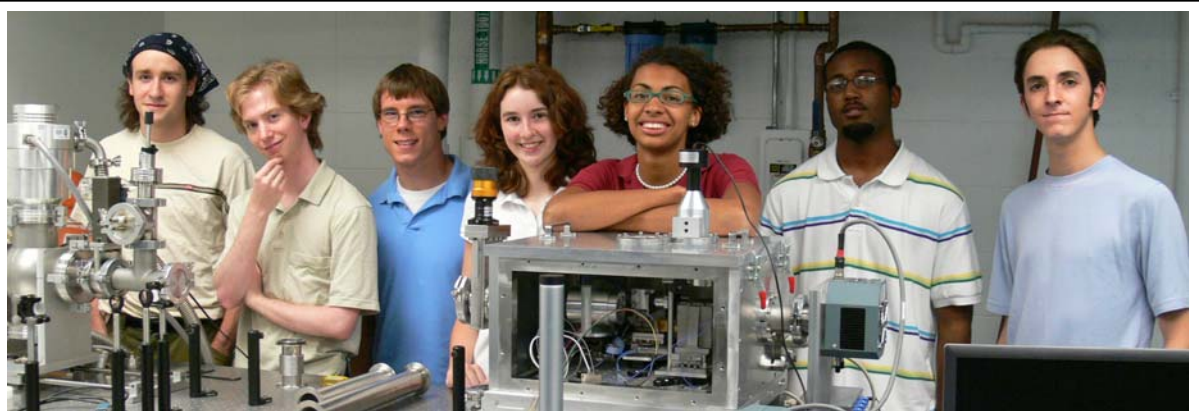
*Qing Li Outstanding  
Paper Award APS Four  
Corners Meeting*

*Mark Woolston  
receiving award from  
SPIE President*



## **2) 140 undergraduate students experienced the excitement of developing advanced engineered systems based on extreme ultraviolet light**

The NSF Center for Extreme Ultraviolet Science and Technology, now in its seventh year, has offered research experiences on laser and engineered optical systems to a diverse group of 48 undergraduate students. For ten weeks during the summer, students from across the country collaborated with EUV Center faculty, graduate students and postdocs on research projects that utilized coherent extreme ultraviolet light in applications that included ultra-high resolution microscopy and the characterization of materials. A total of 92 students also participated in year-round research experiences designed to be a key part of their education in becoming creative engineers and scientists. Participants experienced the excitement of cutting-edge research with state-of-the-art equipment in collaboration with Center researchers and enjoyed the collaborative environment of an integrated group effort. A majority of the participants have credited the research experiences for undergraduates program with motivating them to pursue graduate studies. Many of them are now enrolled in graduate degree programs at the Center's core universities.



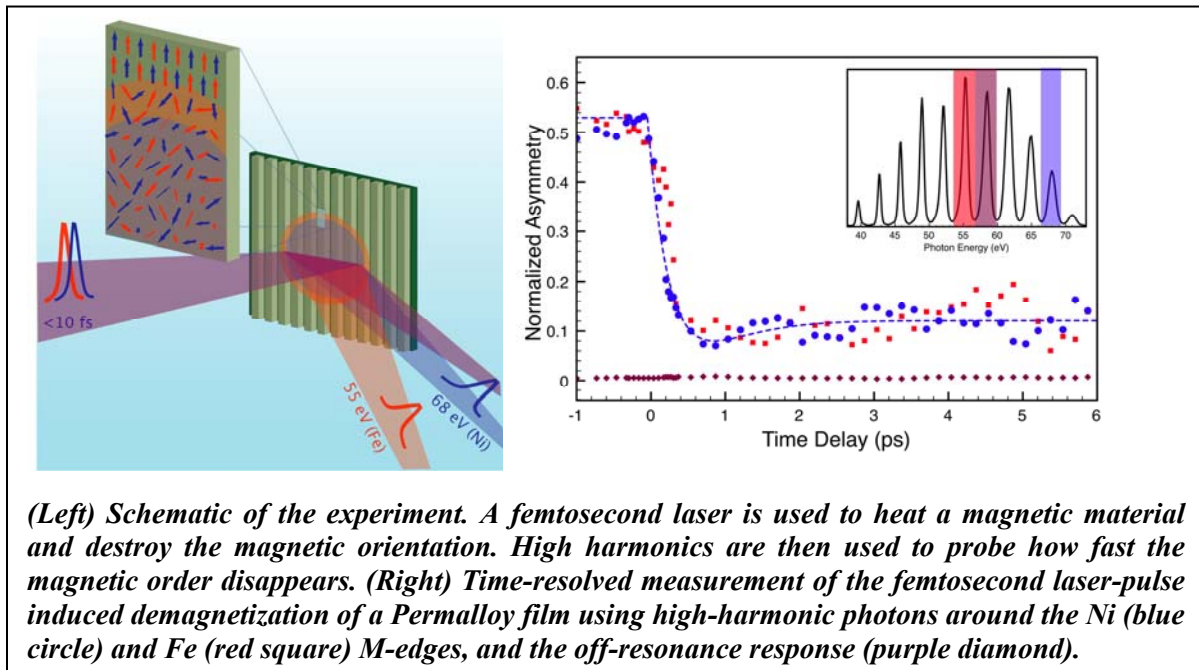
*Several of the undergraduate students who conducted research at the NSF Center for Extreme Ultraviolet Science and Technology.*



### 3) Dr. Stefan Mathias wins Marie Curie Postdoctoral Fellowship of €121K

Dr. Stefan Mathias was recently awarded a prestigious Marie Curie Postdoctoral Fellowship of €121,000 for 2 years to pursue collaborative research between the EUV ERC and the University of Kaiserslautern in Germany. Between his Ph.D. and postdoctoral fellowship, Stefan spent time teaching in Africa (Rwanda). Stefan had also performed his Ph.D. in collaboration with the EUV ERC. The Marie Curie Fellowship provides a generous stipend as well as research and travel funds, and will allow Stefan to divide his time between Colorado and Germany. His research is focusing on understanding how fast a magnet material can switch its magnetic orientation, which is important for utilizing magnetism at the nanoscale level. It is also essential for information storage since writing speed in data storage devices increases as the switching time for a single bit decreases.

In recent work (Physical Review Letters **103**, 257402 (2009)), Stefan and EUV ERC graduate students and collaborators used ultrafast soft x-rays to probe how fast the magnetic orientation in a compound material is destroyed. Past work used either ultrafast lasers or x-rays from large synchrotron facilities to follow magnetic reorientation in a material. However, ultrafast lasers in the visible region are sensitive only to the bulk response of a material, while x-ray bursts from synchrotron facilities are simply too slow ( $> 100$  femtoseconds) to follow the fastest change of a magnetic signal - which can be in the few femtosecond range or even faster. To overcome these limitations, the team used ultrafast high harmonic beams that spanned all the elemental absorption edges of the magnetic material. This allowed them to follow the magnetic behaviour of each element separately for the first time. In the future this approach can be used to uncover how magnets work at the nanoscale level, both in space and time with elemental specificity, to understand for example what are the limiting properties of materials that determine the writing speed in magnetic data storage.



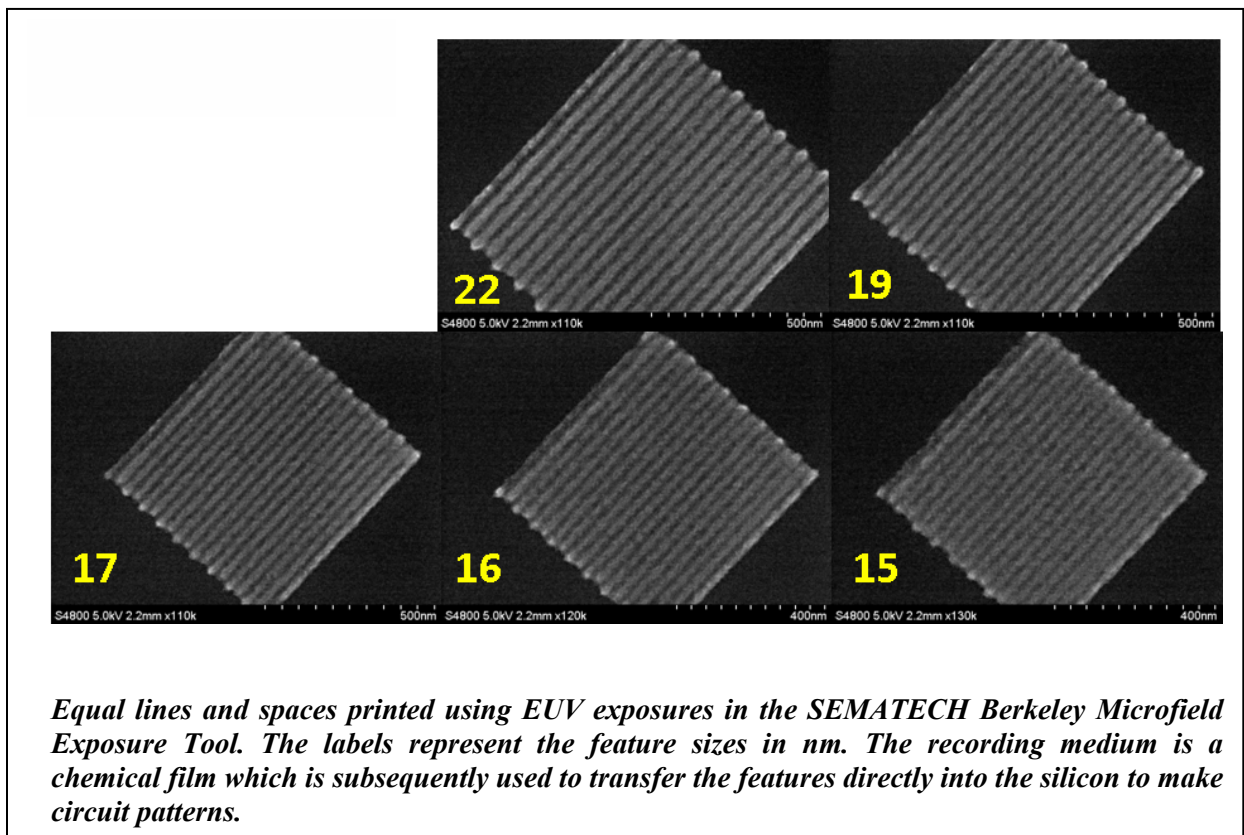


### **1.3.2 Research Infrastructure**

#### **1) Writing the finest patterns**

Optical lithography is the process by which circuit features are etched into silicon to make computer chips. Improved computer chip performance comes by printing smaller and smaller circuits. The limiting factor in the size of the circuits one can print is the wavelength of light used. To push circuit sizes to the sub 20-nm regime, lithography systems of the future will employ extreme ultraviolet (EUV) wavelengths (13.5 nm). The SEMATECH Berkeley Microfield Exposure Tool at Lawrence Berkeley National Laboratory provides a platform for advanced learning in this area. One of the key current limitations of this technology is the availability of materials capable of transferring the high resolution image produced by the lithography tool into the silicon. These materials, called photoresists, are akin to photographic film. Recently, a breakthrough in the resolving capabilities of EUV photoresists has led to patterning in the 18 nm regime and below.

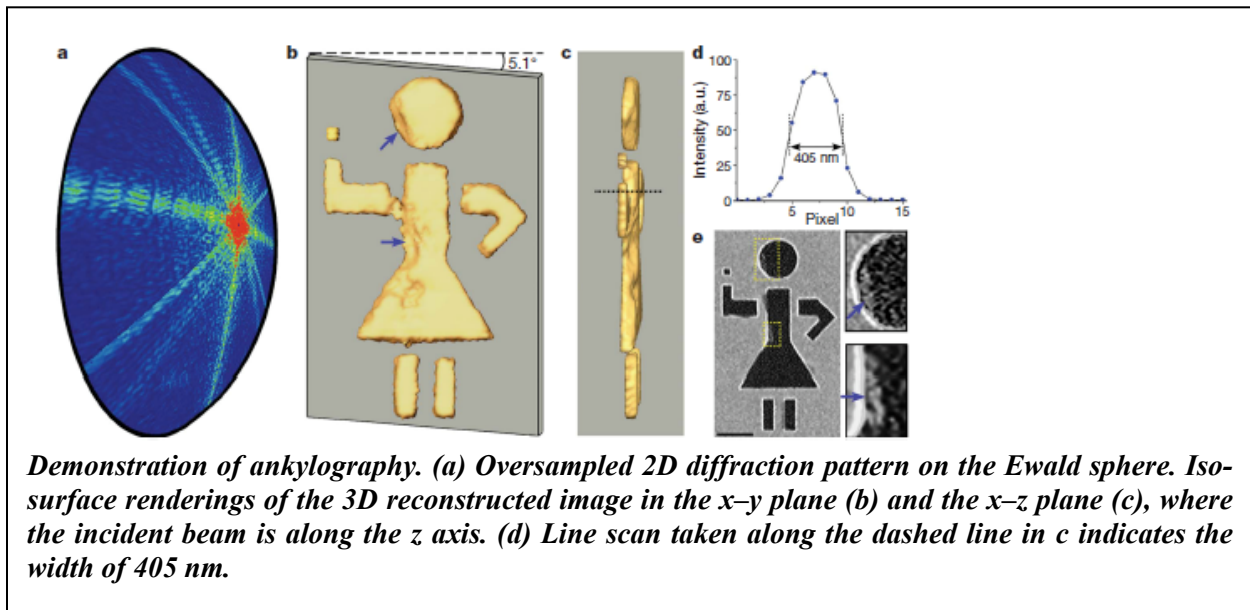
The figure below shows an example of printing results in this newly developed material provided by Inpria Corporation. The labels correspond to the printed feature sizes in nanometers. The results were obtained on the SEMATECH Berkeley exposure tool using unique illumination settings enabling resolution to the 15-nm level and below.





## 2) Ankylography - Three-dimensional structure determination from a single view

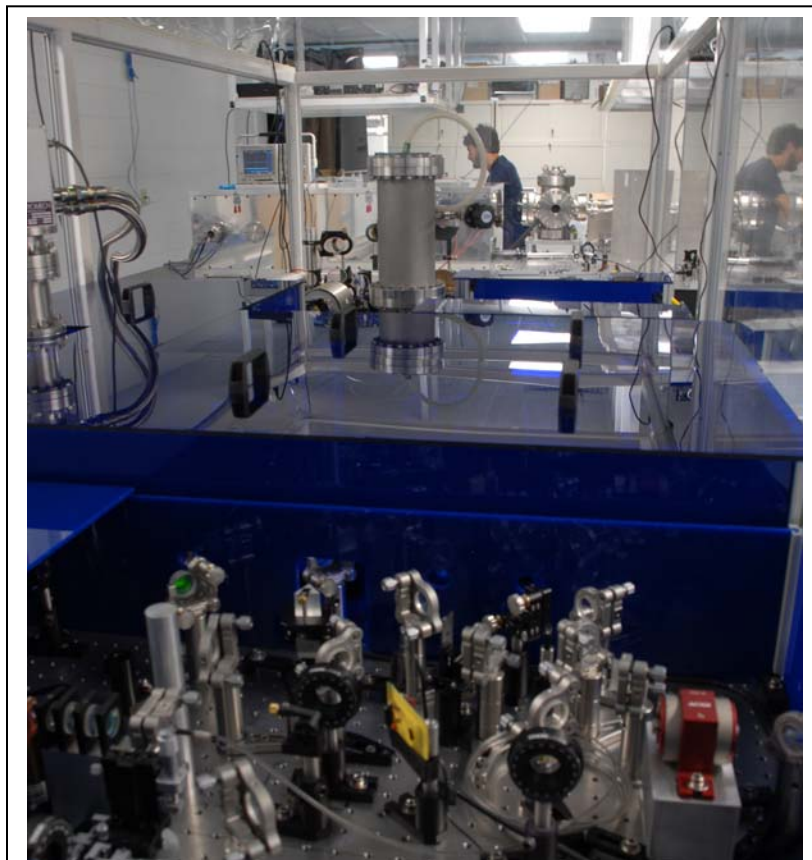
The ability to determine the structure of matter in three dimensions has profoundly advanced our understanding of nature. Traditionally, the most widely used schemes for 3D structure determination of an object are implemented by acquiring multiple measurements over various sample orientations, as in the case of crystallography and tomography, or by scanning a series of thin sections through the sample, as in confocal microscopy. In recent work in collaboration with Professor John Miao's group at UCLA (Nature **463**, 214 (2010)), the Center demonstrated a new 3D imaging modality, termed ankylography (derived from the Greek words ankylos meaning 'curved' and graphein meaning 'writing'), which enables complete 3D structure determination from a 2D image. We demonstrated that when the diffraction (scatter) pattern of a finite object is sampled at a sufficiently fine scale on a detector, the 3D structure of the object is determined by the 2D spherical pattern. In essence, by placing an object very close to the detector, light is scattered from the sides of the object and reaches the detector. This depth information can then be retrieved using a sophisticated computer algorithm. This approach of obtaining complete 3D structure information from a single view is anticipated to find broad applications in the physical, nano and life sciences and technologies.





### **3) Compact EUV laser pumped by diode lasers**

Compact high average power sources of coherent EUV light will enable new industrial metrologies and science experiments on a table-top. The shortest wavelength table-top EUV lasers demonstrated to date are based on the excitation of plasmas by optical lasers driven by light emitted by flash-lamps. Flash-lamp laser systems are inefficient and large in size. Also, the excess heat generated by flash-lamp pumping limits the maximum repetition rate at which these lasers can operate. This in turn limits the EUV laser average power that can be obtained. The same diode-laser technology that makes possible the laser pointer opens the possibility to develop a new generation of more compact, higher repetition rate EUV lasers for applications. The much higher pumping efficiency that results from pumping small quantum-defect laser materials with a narrow bandwidth diode-laser source of the optimum wavelength will allow for EUV laser operation at significantly increased repetition rates. Work conducted at Colorado State University as part of the research program of the NSF Center for Extreme Ultraviolet Science and Technology has resulted in the demonstration of the first EUV laser fully pumped by diode-lasers. Lasing was achieved at  $\lambda = 18.9$  nm by heating a plasma created by ablating a solid molybdenum target with picosecond duration laser pulses from an all-diode-pumped system. This new technology promises to enable a new set of diverse applications of intense coherent EUV light.



*Compact Extreme Ultraviolet fully pumped by efficient laser diodes.*

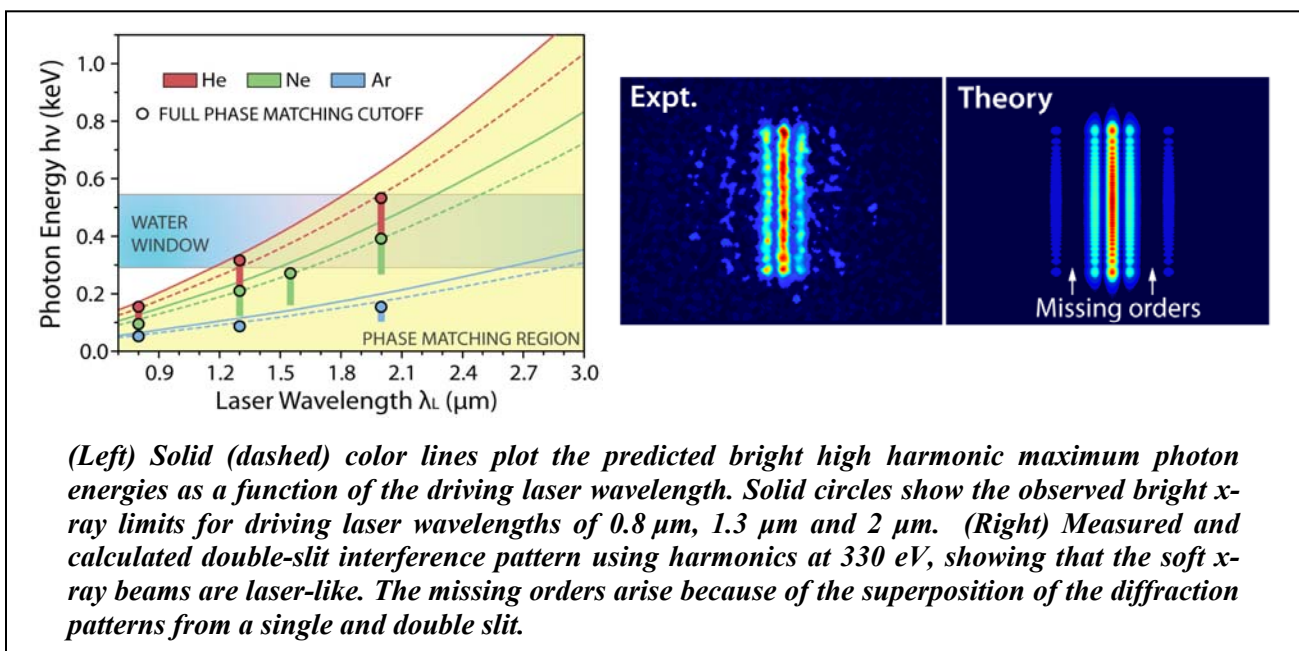


### 1.3.3 Discovery

#### 1) Bright, coherent, ultrafast soft x-ray harmonics spanning the water window from a table-top source

Nonlinear optics has revolutionized laser science by making it possible to efficiently convert laser light from one wavelength into another. Using the extreme nonlinear-optical process of high harmonic generation, light from an ultrafast laser can be coherently upshifted, resulting in a useful, tabletop, laser-like coherent light source in the extreme ultraviolet region of the spectrum. However, generating bright beams at higher, soft x-ray photon energies had been impossible to date because of the inability to make the process efficient. Recent results from the EUV ERC (PNAS **106**, 10516 (2009)) demonstrated a new regime of high-harmonic generation by using mid-infrared driving lasers and a high-pressure gas medium. In 2010, this scheme has succeeded in creating a bright and useful water window source around 200 - 500 eV that for the first time emits laser-like beams (invited talks at CLEO conference, submitted for publication). This energy range is significant for applications in materials and biological microscopies, nanoscience and nanotechnology, and a wide range of dynamics studies.

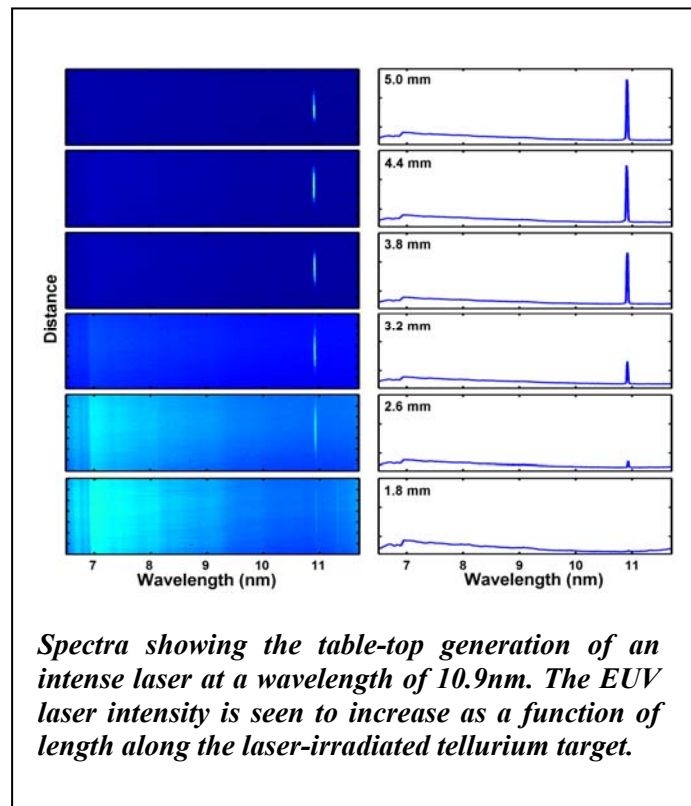
This laser-driven soft x-ray source can be thought of as the coherent version of the x-ray tube. In an x-ray tube, electrons are accelerated by a strong electric field and hit a target at random times, essentially making an x-ray flashlight beam. However, when controlled by a laser, the electrons all collide with ions at the same time, creating a directed beam in an instant – actually in 10 attoseconds, making this the fastest strobe light in existence. Moreover, x-rays have the advantage of being able to penetrate thick samples, and image with elemental and chemical specificity. These ultrafast bursts of x-rays can be used to capture function in molecules, or visualize nanoscale systems relevant to magnetic storage, lithography, spintronics, nanoscience, nanofabrication, energy harvesting, thermal management, cellular imaging and a host of other applications across a broad range of science and technology. In the future, this technology may even lead to sharper medical x-ray imaging.





## 2) Table-top lasers that emit bright beams at shorter wavelengths

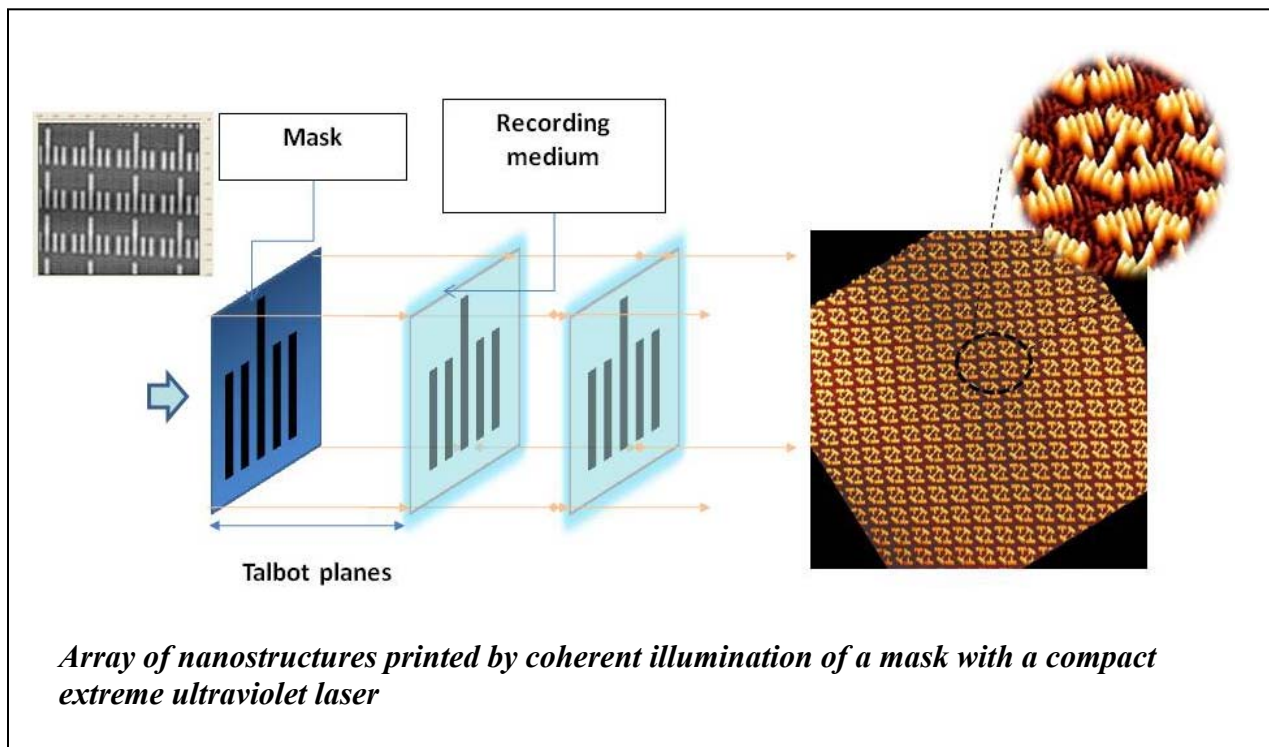
The first demonstration of the laser 50 years ago and the subsequent advances in laser technology have produced bright beams of visible light that have a broad impact in society. One of the goals in laser development has been to extend their range to shorter wavelengths. Of particular interest is the demonstration of compact table-top size lasers that operate in the extreme ultraviolet (EUV) and soft x-ray regions of the electromagnetic spectrum, which nanometer wavelengths match the dimensions of interest to nanotechnology and nanoscience. Until recently, the shortest wavelength table-top EUV laser with sufficient average power for applications has been 13.2 nm. Weak amplification had been observed at wavelengths as short as 10.9 nm line by irradiation a tellurium target with an intense optical laser, but the laser output obtained at this wavelength was weak and insufficient for applications. Recent work conducted at Colorado State University as part of the research program of the NSF Center for Extreme Ultraviolet Science and Technology has made use of a newly developed high energy optical laser to dramatically increase the output of this 10.9 nm EUV laser to the level necessary to enable applications. This was achieved by engineering the laser to reach the gain-saturated regime in which laser amplification is most efficient. This new short wavelength laser will allow the implementation of higher resolution table-top microscopes and other nano-scale applications.

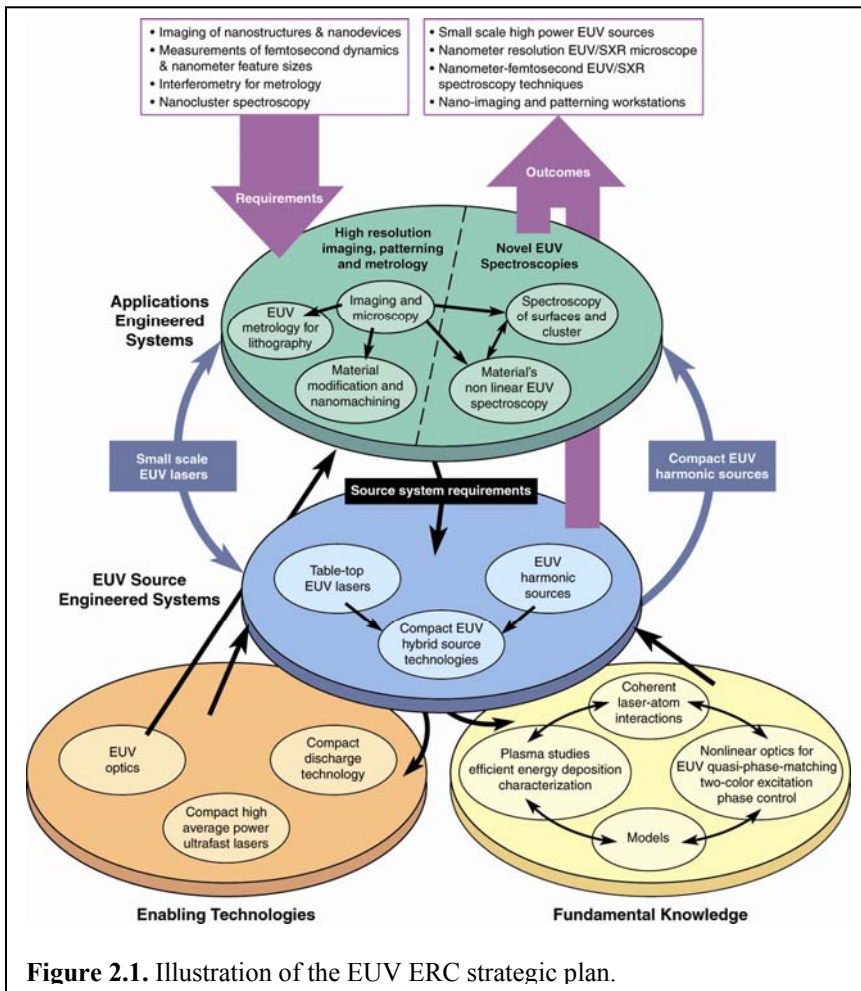




### 3) Printing nanostructures on a table-top

The ability to conveniently print nano-scale structures is key to advances in nanotechnology and nanoscience. Work conducted at the NSF Center for Extreme Ultraviolet Science and Technology demonstrated that arrays of arbitrary patterns can be written with a compact table-top set-up that combines the coherent light emitted by newly developed extreme ultraviolet lasers with a phenomenon discovered more than 100 year ago, the Talbot self-imaging effect. This approach is based on the self imaging process by which a periodic structure illuminated by a coherent light beam is reproduced at certain planes located at distances equal to multiples of a defined distance known as the Talbot distance. The self images produced at these locations are the product of the collective contribution of the diffraction of the individual cells in the mask. Because these unit cells (or tiles) are replicated many times in the plane of the mask, any defect in any of the unitary cells is averaged over the very large numbers of tiles in the mask, consequently generating a virtually defect-free image on a photoresist placed on the Talbot planes. Because the wavelength of extreme ultraviolet light has nano-scale dimensions, it allows taking advantage of the Talbot self-imaging effect to print arrays of structures of nano-scale dimensions. The key enabling tool that makes possible the demonstration of this new nano-patterning technique is the extremely compact capillary discharge laser technology developed at the Center, that allows illumination of the mask with a high flux of highly coherent 46.9 nm extreme ultraviolet light. This new method can take advantage of shorter wavelength table-top lasers to potentially print with a table-top setup structures with features of 10 nm dimension.





**Figure 2.1.** Illustration of the EUV ERC strategic plan.