Compact, bright, Plasma-based EUV Lasers for Metrology


Engineering Research Center for Extreme Ultraviolet Science & Technology
Colorado State University

Work Supported by the NSF Engineering Research Centers Program and the US Department of Energy
Applications require EUV laser pulses with pulse high energy (large number of photons), high average power.

Compact atomic soft x-ray lasers

- Single shot imaging
- Nanoscale ablation
- Analytic nanoprobees
- Error-free nanopatterning

- High pulse energy (µJ-mJ)
- High monochromaticity (λ/Δλ < 10^{-4})
- High peak spectral brightness
EUV lasers can be created by electron impact excitation of highly ionized atoms in dense plasmas.

**Singly ionized** Ar ion, Kr ion lasers in the visible spectral region.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Spectral Region</th>
<th>Laser Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar+</td>
<td>EUV/SXR</td>
<td>13.2 nm</td>
</tr>
<tr>
<td>Ar</td>
<td>Visible</td>
<td>514 nm</td>
</tr>
</tbody>
</table>

**Highly ionized** (8-35 times) in the EUV/SXR spectral region.

Plasma requirements:
- $Te \sim 5 \text{ eV}$
- $Ne \sim 1 \times 10^{14} \text{ cm}^{-3}$

NexTe increases by $10^7$-$10^{10}$.

**Cd**$^{2+}$
- $Te \sim 100$-$1000 \text{ eV}$
- $Ne \sim 1 \times 10^{19}$-$1 \times 10^{21} \text{ cm}^{-3}$

$13.2 \text{ nm laser}$

$5000 \text{ eV}$

$514 \text{ nm laser}$

$35 \text{ eV}$
Assessing the wavelength extensibility of optical patterned defect inspection

Bryan M. Barnes*, Hui Zhou, Mark-Alexander Henn, Martin Y. Sohn, and Richard M. Silver

Engineering Physics Division, National Institute of Standards and Technology,
100 Bureau Drive MS 8212, Gaithersburg, MD, USA 20899-8212

ABSTRACT

Qualitative comparisons have been made in the literature between the scattering off deep-subwavelength-sized defects and the scattering off spheres in free space to illustrate the challenges of optical defect inspection with decreasing patterning sizes. The intensity scattered by such a sphere (for diameters sized well below the wavelength) is proportional to its diameter to the sixth power, but also scales inversely to the fourth power of the wavelength. This paper addresses through simulation the potential advantages of applying shorter wavelengths for improved patterned defect inspection. Rigorous finite-difference time-domain 3-D electromagnetic modeling of the scattering from patterned defect layouts has been performed at five wavelengths which span the deep ultraviolet (193 nm), the vacuum ultraviolet (157 nm and 122 nm), and the extreme ultraviolet (47 nm and 13 nm). These patterned structures and defects are based upon publicly disclosed geometrical cross-sectional information from recent manufacturing processes, which then have been scaled down to an 8 nm Si linewidth. Simulations are performed under an assumption that these wavelengths have the same source intensity, noise sources, and optical configuration, but wavelength-dependent optical constants are considered, thus yielding a more fundamental comparison of the potential gains from wavelength scaling. To make these results more practical, future work should include simulations with more process stacks and with more materials as well as the incorporation of available source strengths, known microscope configurations, and detector quantum efficiencies. In this study, a 47 nm wavelength yielded enhancements in the signal-to-noise by a factor of five compared to longer wavelengths and in the differential intensities by as much as three orders-of-magnitude compared to 13 nm, the actinic wavelength for EUV semiconductor manufacturing.
A fast current pulse compresses a plasma creating a hot and dense column with aspect ratio $L/d > 1000$

Sequence of on-axis interferograms showing rapid plasma column compression in an Ar capillary discharge
Demonstration of a discharge-pumped EUV laser: capillary discharge laser in Ne-like Ar

J.J. Rocca, V. Shlyaptsev, F.G. Tomasel, O.D. Cortázar, D. Hartshorn, and J.L.A. Chilla

Electrical Engineering Department, Colorado State University, Fort Collins, Colorado 80523
(Received 31 May 1994)

Amplification ($g_l = 7.2$) in a discharge-created discharge was used to excite plasma columns inversion in the $J = 0-1$ line of Ne-like: am divergence was measured to be $<9$ mrad.

Essentially full spatial coherence is achieved by increasing the capillary length.

Table-top laser in Ne-like Ar produces coherent average power at $\lambda=46.9$ nm similar to synchrotron beam line

Ne-like Ar Capillary discharge 46.9 nm laser
High average power: up to 3 mW
High pulse energy: 0.1 mJ - 0.8 mJ @4 Hz
Narrow spectral bandwidth: $\Delta\lambda/\lambda = 3 \times 10^{-5}$
Beam divergence: $\theta = 4.5$ mrad

CSU Capillary Discharge Laser Technology is today turn-on key

2005
• 10 microjoule /pulse
• 0.15 mW average power
• 1-12 Hz repetition rate
• Pulse duration ~1.5 ns
• $\Delta \lambda / \lambda < 1 \times 10^{-4}$

S. Heinbuch, M. Grisham, D. Martz, J.J. Rocca
Optics Express, 30, 2095, (2005)

2015
• 50 microjoule /pulse
• 0.5 mW average power
• 1-10 Hz repetition rate
• Pulse duration ~1.5 ns
• $\Delta \lambda / \lambda < 1 \times 10^{-4}$
• Jitter < 2 ns
Compact $\lambda = 46.9$ nm full field microscope

46.9 nm SXR laser

Microscope vacuum chamber

Single shot image of 50 nm nanotubes

EUV microscopes captures images of nanostructures with very high resolution

**TRANSMISSION**

NA=0.32 (M~1000)

200 nm half period diatom

5 sec exposure

50 nm carbon nanotube

Single shot, 1.5 ns exposure


**REFLECTION**

NA=0.12 and 0.19 (M~250)

5-20 sec exposures

Partially Processed semiconductor chip

Zr surface showing twin in grain

100 thick GaN nanowire between Al contacts

Movies of Nano-scale Dynamics on a Table-top

SXR laser

Sc/Si Schwarzschild Condenser

Nanoprobe

Freestanding zone plate

319 kHz

Single shot image of 50 nm nanotubes

B. Brewer et al
Optics Lett.
33,518,(2008)

Magnetic force microscope tip interaction with stray magnetic field

Effective Spring Constant

\[ k_{\text{tip}} + k_{\text{force}} \]

\[ \omega_{\text{res}}^2 = \frac{k}{m} = \frac{1}{m} \left( k - \frac{\partial F}{\partial z} \right) \]

Real time nano-scale resolution imaging by Fourier Holography

Measurements to validate a model that describes the nonlinear interaction between nanopillars

N. Monserud, M. Marconi et al. Optics Express, 22, 4161, (2014)
Applications in dense plasma diagnostics and photochemistry

Plasma Interferometry

Single photon ionization mass spectrometry


Visible laser ablation
ToF
SXR laser (ionization)
Beyond morphology: composition

Condensed phase micro- and nanostructures

Micro-organisms

M. tuberculosis bacillus

Compiled MS image of M. tuberculosis bacillus

High resolution composition maps
EUV laser ablation time-of-flight (TOF) imaging mass spectrometry

1. Focused laser ablates the material
2. Simultaneously ionizes species in the ablation plume
3. Ions are extracted into the mass spectrometer
3D imaging EUV mass spectrometry imaging nanoprobe

EUV Optics
Fresnel zone plate 0.16 NA

SXR Laser
10^{12} \text{ph/pulse}

EUV laser
- Wavelength: 46.9 nm
- Energy per pulse > 10 \mu J
- Repetition rate: 12 Hz
- Pulse duration \sim 1.5 \text{ns}

S. Heinbuch Optics Express
vol. 13, 4050 (2005)

Optics engineered by W. Chao and E. Anderson at Center of X-Ray Optics, Lawrence Berkeley Lab.

80 nm lateral resolution was measured on both inorganic and organic samples.

I. Kuznetsov et al. Nature Comm., 6, 6944,( 2015)

Depth resolution of 20 nm is achieved on organic multilayers

2D Imaging of uranium micron size particles by EUV TOF MSI reveals isotopic content

Measured: 235U/238U ratio of 0.248 (±0.0014)
Expected value is 0.2513 (±0.0003) (U200 standard)

Collaboration with Pacific Northwest Laboratory
Talbot lithography: Coherent illumination of a periodic mask prints arrays of arbitrary features error-free

M. Marconi, F. Cerrina, et al. (2009)

Proof of principle: 120 nm resolution

Error free printing

Error-Free Printing of Periodic metallic structures

Talbot Mask

Print in HSQ

Grating etched in Au 500/600 lines/spaces
Scaling to shorter wavelengths

AR (46.9 nm)
Ti
V
Cr (28.5 nm)

Neon Like

Mo (18.9)

Nickel Like

La (8.8 nm)

Saturated
Seeded
Simulation showed gain-saturated amplification at 13.2 nm in Ni-like Cd can be achieved with ~ 1 J pump.

- **Pre-pulse**: 300 mJ, 120 ps
- **Heating pulse**: 1 J, 6 ps
EUV lasers excited by rapid heating of plasmas with short laser pulses

Laser Pumping Geometry

Grazing incidence allows for efficient heating of plasma region with optimum electron density

\[ \theta = \sqrt{\frac{N_e}{N_c}} \]

High repetition rate table-top EUV lasers in transitions of Ni-like ions down to 10.9 nm

Gain saturated operation demonstrated

λ=13.2 nm microscope for at-wavelength aerial mask inspection and broad area imaging of nanostructures

- Uses output from 13.2 laser
- Captures images with large field of view with exposures of 20-90 seconds

**TRANSMISSION**
- Spatial resolution: better than 38 nm

**REFLECTION**
- Zone plate microscope for at-wavelength defect inspection
- Illumination emulates EUVL stepper
- Spatial resolution: 55 nm

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**Diagram Notes:**
- Condenser zone plate
- Objective zone plate
- EUV Laser
- Sample
- EUV-sensitive CCD
- Overhead view
- Condenser zone plate
- Off-axis objective zone plate
- Laser in
- EUVL patterned mask
- Emissive EUVL mask

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**Graph:**
- LER/CD=0.08

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**Images:**
- 50 nm dense lines
- 0.5 μm
λ = 13.2 nm resonant with Mo/Si coatings in extreme ultraviolet lithography masks

CD = 180 nm

EUV Optics from CXRO, Berkeley

F. Brizuela et al., Optics Express 18, 14467, (2010)
EUV mask inspection microscope

EUV MASK IMAGES

Spatial resolution: 55 nm half-pitch

LER< 10% CD

EUV lasers self-seeded by spontaneous emission noise have poor temporal coherence.

**Self-seeded**

EUV Amplifier

Spontaneous emission

**Injection-seeded**

EUV Amplifier

Coherent seed

Seed pulses can be greatly amplified preserving or even improving their properties.
Injection-seeding SXR Lasers have full phase-coherence and shorter pulsewidth.

**Ag plasma amplifier**

**Amplified single harmonic**

**Seed pulses**

**Ag target**

Full spatial coherence

Full temporal coherence

Shorter pulsewidth

\(1.13 \pm 0.47\) ps

High repetition rate, diode-pumped table-top soft x-ray lasers

**Laser Diode Pumping Advantages**

- Highly efficient
  - >50% Electrical efficiency
- Narrow bandwidth
  - Efficiently pump a single transition
- Directional
  - End-pumping
- Very high average power
  - Allow high repetition rate
- Compact

**Yb$^{+3}$ Lasers**

\[
\begin{align*}
2F_{5/2} & \quad \text{Pump} \quad 940 \text{ nm} \\
2F_{7/2} & \quad \text{Laser} \quad 1030 \text{ nm}
\end{align*}
\]

- Absorption bands at InGaAs wavelengths
- Small quantum defect (<10%)
- Long lifetime for high energy storage
Beyond 100 Hz Repetition Rate: 500 Hz Compact High Energy, High Power Pump Laser

Demonstration of bright 18.9 nm laser at 100 Hz repetition rate

$\lambda = 18.9 \text{ nm}$ Laser Average Power: 0.2 mW

$\mu = 1.5 \mu J, \, \sigma = 11.5\%$

\( \lambda = 18.9 \text{ nm} \): \( 10^5 \) Consecutive EUV Laser Shots at 100 Hz repetition rate

\[ \lambda = 1.03 \mu \text{m}, \ 1J, \ 5 \text{ ps} \]

Extending diode-pumped lasers to $\lambda = 10.9$ nm

Ni-like ions

<table>
<thead>
<tr>
<th>Element</th>
<th>Z</th>
<th>Atomic Mass</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>39</td>
<td>88.912</td>
<td></td>
</tr>
<tr>
<td>Zr</td>
<td>40</td>
<td>91.224</td>
<td></td>
</tr>
<tr>
<td>Nb</td>
<td>41</td>
<td>92.906</td>
<td></td>
</tr>
<tr>
<td>Mo</td>
<td>42</td>
<td>95.940</td>
<td>10.9</td>
</tr>
<tr>
<td>Tc</td>
<td>43</td>
<td>99.822</td>
<td></td>
</tr>
<tr>
<td>Ru</td>
<td>44</td>
<td>100.905</td>
<td></td>
</tr>
<tr>
<td>Rh</td>
<td>45</td>
<td>102.905</td>
<td></td>
</tr>
<tr>
<td>Pd</td>
<td>46</td>
<td>106.420</td>
<td></td>
</tr>
<tr>
<td>Ag</td>
<td>47</td>
<td>107.870</td>
<td>18.9</td>
</tr>
<tr>
<td>Cd</td>
<td>48</td>
<td>112.411</td>
<td></td>
</tr>
<tr>
<td>In</td>
<td>49</td>
<td>114.820</td>
<td>13.9</td>
</tr>
<tr>
<td>Sn</td>
<td>50</td>
<td>118.710</td>
<td></td>
</tr>
<tr>
<td>Sb</td>
<td>51</td>
<td>121.760</td>
<td></td>
</tr>
<tr>
<td>Te</td>
<td>52</td>
<td>127.600</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>53</td>
<td>128.000</td>
<td></td>
</tr>
<tr>
<td>Xe</td>
<td>54</td>
<td>131.300</td>
<td></td>
</tr>
</tbody>
</table>

- 0.2 mW at $\lambda = 18.9$ nm
- 0.1 mW at $\lambda = 13.9$ nm
Extension of gain-saturated table-top SXRL to sub-10 nm wavelengths using lanthanide ions.
Gain-saturated sub-10 nm table-top lasers

1 Pre-pulse 185 ps

2 7.1 J, 0.7 ps

3 Grazing incidence
Vertical focus

4 Traveling wave

Target
Reflection echelon
Horizontal focus

4d $^1S_0$
4p $^1P_1$

7.36 nm laser
Ionized 34 times

Transient excitation

Pre-pulse

Sm$^{34}$
Lasing in transitions down to 7.36 nm
Nickel-like lanthanide ions $4d^1S_0 - 4p^1P_1$

D. Alessi et al. Phys. Rev. X, 1, 021023
Extension of gain-saturated table-top SXRL to sub-7 nm wavelengths using lanthanide ions

<table>
<thead>
<tr>
<th>Ion Charge (Z)</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar (46.9 nm)</td>
<td>Neon Like</td>
</tr>
<tr>
<td>Ti</td>
<td>28.5 nm</td>
</tr>
<tr>
<td>Cr (28.5 nm)</td>
<td></td>
</tr>
<tr>
<td>Mo (18.9)</td>
<td>Nickel Like</td>
</tr>
<tr>
<td>Ru</td>
<td></td>
</tr>
<tr>
<td>Pd</td>
<td></td>
</tr>
<tr>
<td>Ag</td>
<td></td>
</tr>
<tr>
<td>Cd</td>
<td></td>
</tr>
<tr>
<td>Sn</td>
<td></td>
</tr>
<tr>
<td>Sb</td>
<td></td>
</tr>
<tr>
<td>Te (10.9 nm)</td>
<td></td>
</tr>
<tr>
<td>La (8.8 nm)</td>
<td></td>
</tr>
</tbody>
</table>
| Ce, Pr, Nd, Sm, Gd, Tb, Dy (5.85 nm) | Seeded
|                 |                 |
Gain saturation in Ni-like Gd at 6.86 nm

Energy on target = 14 J, pre-pulse width = 185 ps, short pulse width = 0.7 ps, 40% in pre-pulse

g_0 = 23.6 cm^{-1}
G_0 \times L = 16.2
Laser amplification down to 5.8 nm (Ni-like Dy)
Acknowledgements

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Mario Marconi

Andrew Duffin (Pacific Northwest Laboratory)
Elliot Bernstein (CSU Chemistry Department)
Zone plates: Weilun Chao, Patrick Naulleau (Lawrence Berkeley National Laboratory)

Funding: National Science Foundation and US Department
Demonstration of gain saturation in the 7.3 nm line of Ni-like Sm

Energy on target = 11.4 J, pre-pulse width= 185 ps, short pulse width= 0.7 ps, 30% pre-pulse
Frequency multiplication of periodic patterns by fractional Talbot lithography

Frequency multiplication factors up to 5X were demonstrated

(a)  

(b)  

(c)  

(d)
λ = 18.9nm Laser operating at 400 Hz

400 Hz repetition rate
Raw EUV photodiode output of first 400 shots (1 second).

Single shot EUV spectrum showing 18.9nm Laser at 400 Hz repetition rate

Recent research has shrunk capillary discharge SXRL to desk-top size

Smallest SXRL laser, $\lambda = 46.9$ nm

12 Hz repetition rate, 0.15 mW average power

- 10 microjoule/pulse
- 0.15 mW average power
- 1-12 Hz repetition rate
- Pulse duration $\sim 1.5$ ns
- $\Delta \lambda / \lambda < 1 \times 10^{-4}$

S. Heinbuch, M. Grisham, D. Martz, J.J. Rocca
Optics Express, 30, 2095, (2005)
ASE-Mitigated, Thick Disk Active Mirrors

Cryo Cooling Through Back Face

Absorbing Cladding
Undoped Anti-ASE Cap
Yb:YAG
HR Coated
AR Coated

Cross Section

Temp. (K)
83.4
81.8
80.2
78.6
77.0

Thermally-efficient, ASE-Mitigated, Composite Yb:YAG Disk Amplifiers

Dual Disk Amplifier Heads: Modular and Scalable
Molecular sensitivity to aminoacid Alanine of 0.01 amol is 40× that of SIMS TOF

10 keV Bi⁺ at 45° into C

<table>
<thead>
<tr>
<th>ALANINE</th>
<th>SXR TOF (First results)</th>
<th>SIMS TOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area probed (µm²)</td>
<td>4.5 x 10⁻²</td>
<td>2.25 x 10^4</td>
</tr>
<tr>
<td>Depth probed (µm)</td>
<td>3.5 x 10⁻³</td>
<td>2 x 10⁻³</td>
</tr>
<tr>
<td>Volume probed (aL)</td>
<td>0.05</td>
<td>4.5 x 10⁴</td>
</tr>
<tr>
<td>Sensitivity (amol)</td>
<td>0.01</td>
<td>0.4</td>
</tr>
<tr>
<td>Ion yield, normalized to probed volume (L⁻¹)</td>
<td>4 x 10¹⁴</td>
<td>8.5 x 10¹⁰</td>
</tr>
<tr>
<td>Level of fragmentation</td>
<td>1.1</td>
<td>1</td>
</tr>
</tbody>
</table>

Electron impact excitation of 6.86 nm Gd laser requires plasma with high electron temperature

Previous work achieved unsaturated lasing at 6.86 nm in Ni-like Gd

• Daido et al. using 250 J of laser pump energy (Phys. Rev. Lett. 75 1074, 1995)
Compact plasma-based soft x-ray lasers can be installed at the application’s site

- **Laser Pumped SXRL**
  - $\lambda = 8.8 - 32.6$ nm

- **Discharge Pumped SXRL**
  - $\lambda = 46.9$ nm

- Nanomachining
- Plasma diagnostics
- Microscopy
- 100 nm lines
- Nanoablation
- 82 nm holes
- 58 nm pillars

- 0 ns Interferometry
- Chemical spectroscopies
- Nanopatterning

- High pulse energy ($\mu$J-mJ)
- High monochromaticity ($\lambda/\Delta\lambda < 10^{-4}$)
- High peak spectral brightness
Optimum grazing incidence angle increases linearly with Z

Measurement is indicative of the electron density where maximum gain occurs

Experimentally determined optimum angles up to Dy (Z=66)

\[ \text{Mo (Z=42)} \quad \text{Ne} = 1.5 \times 10^{20} \text{ cm}^{-3} \]

\[ \text{Dy (Z=66)} \quad \text{Ne} = 7.5 \times 10^{20} \text{ cm}^{-3} \]
Plasma formation controlled pre-pulse duration, delay, is critical for large Sm gain.
Capillary plasma columns generate gain-saturated soft X-ray amplification in Ar$^{+8}$

Exponential amplification in Ar$^{+8}$ 3p$^1S_0$-3s$^1P_1$ line at 46.9 nm

3-4 mm Capillary diameter, 25-40 kA, >30 ns rise time
Electron Temperature: 60-100 eV, Electron Density: 0.2-1.0×10$^{19}$ cm$^{-3}$

*Math. Rev. Lett. 73 2192 (1994)*
UV PI on Uranium (~1%) filter glass shows higher SUE

- 6.19 eV – 1st ionization potential of U

![Diagram showing UV PI on Uranium filter glass]

- 26.4 eV SPI

- Post-ionization: 3.5eV
High interest in intense Coherent SXR light

FLASH: 4.1 - 47 nm (fundamental)
Pulse energy = 10 - 100 μJ

LCLS: 2.2 - 0.12 nm

Si melting
M.Beyer et al. PNAC, (2010)

Sequential nano-scale imaging

Photoinization of solids

0.014% sample utilization efficiency (SUE) of trace elements is similar to SIMS TOF

- 500 ppm of Uranium in NIST 611 glass
- 1200 shots → 10×10×0.3 µm crater

*T. Green et al., J. of Analytical Atomic Spectrometry, 32, 1092, (2017)*
SXRL Ablation Mass Spectrometry Imaging Nanoprobe

3-D maps of materials composition with nanometer resolution

Applications in dense plasma diagnostics and photochemistry

Plasma Interferometry

Single photon ionization mass spectrometry
Scaling to shorter wavelengths requires hotter-denser plasmas.
Soft X-ray lasers excited by rapid heating of plasmas with short laser pulses

Grazing incidence allows for efficient heating of plasma region with optimum electron density

\[ \theta = \sqrt{\frac{N_e}{N_c}} \]

Simulation showed gain-saturated amplification at 13.2 nm in Ni-like Cd can be achieved with ~1 J pump.

Pre-pulse: 300 mJ, 120 ps

Heating pulse: 1 J, 6 ps

Mean ion Charge
Gain (cm⁻¹)

Electron Temperature (eV)

Mean ion Charge

Gain (cm⁻¹)
Lasers pumped by a 5-10 Hz ~ 1 J Short Pulse Table-top Ti: Sapphire System
High repetition rate table-top SXRL in transitions of Ni-like ions down to 10.9 nm

Gain saturated operation demonstrated

\[ \lambda = 13.9 \text{ nm} \quad (4d \rightarrow 4p) \]


SXR lasers self-seeded by spontaneous emission noise have poor temporal coherence.

**Self-seeded**

EUV Amplifier

Spontaneous emission

**Injection-seeded**

EUV Amplifier

Coherent seed

Seed pulses can be greatly amplified preserving or even improving their properties.
Injection-seeding SXR Lasers have full phase-coherence and shorter pulsewidth.

- Full spatial coherence
- Full temporal coherence
- Shorter pulsewidth $(1.13 \pm 0.47) \text{ps}$

Seed pulses

Ag plasma amplifier

Amplified single harmonic

Ag target

65 61 59 57 55 53 51 49

13.9 nm

13.2 nm laser-based microscope for defect inspection in EUV lithography masks

\[ \lambda = 13.2 \text{ nm} \text{ resonant with Mo/Si coatings in extreme ultraviolet lithography masks} \]

EUV Optics from CXRO, Berkeley

F. Brizuela et al., Optics Express 18, 14467, (2010)
Extension of gain-saturated table-top SXRL to sub-10 nm wavelengths using lanthanide ions
Electron impact excitation of 8.8 nm La laser requires plasma with high electron temperature

Ionized 29 times

$4d^1S_0$ > 12,700 eV above Atom ground state

Previous work achieved unsaturated lasing at 8.8 nm in Ni-like La

- Daido et al. using 520 J of laser pump energy (Optics Lett. 21, 958, 1996)
Simulation for 8.8 nm table-top Laser in Ni-like La predicts < 7 J pump energy needed for gain saturation

Simulation by Mark Berrill
Average Energy Pre-compression = 13 J
Std div. = 1.5 %
High energy pump laser for Ti:Sapphire: 35 J at 527 nm
Gain-saturated sub-10 nm table-top lasers

Pre-pulse 210 ps

Gain duration < 5ps

Gain (cm\(^{-1}\))

Reflection echelon

Horizontal focus

Vertical focus

4.5 J, 2 ps
Demonstration of Gain-saturated table-top laser at 8.8 nm at 1 Hz repetition rate

Ni-like Lanthanum 4d¹S₀⁻ 4p¹P₁

Pulse energy up to ~ 2.7 µJ

7.5 J Total Pump Energy

Near field beam profile measurement

1 Hz $\lambda = 8.8$ nm laser output intensity exceeds computed saturation intensity by an order of magnitude.

SXRL Fluence: $0.6 \text{ J cm}^{-2}$
Experiment: $I \sim 2.4 \times 10^{11} \text{ W cm}^{-2}$
Computed $I_{\text{sat}}: \sim 3 \times 10^{10} \text{ W cm}^{-2}$

$D. \text{ Alessi et al. Phys. Rev. X, 1, 021023 (2011)}$
Lasing in transitions down to 7.36 nm
Nickel-like lanthanide ions $4d^1S_0 - 4p^1P_1$

Gain-saturated table-top SXRLs cover 8.8 nm - 47 nm wavelength region

The Next Generation: Increasing the repetition rate of Table-Top Soft X-Ray Lasers to 100 Hz


13.9 nm laser

Ag⁺¹⁹
Directly diode-pumped Yb CPA laser increases repetition rate and average power

**Laser Diode Pumping Advantages**

- Highly efficient
  - >50% Electrical efficiency
- Narrow bandwidth
  - Efficiently pump a single transition
- Directional
  - End-pumping
- Very high average power
  - Allow high repetition rate
- Compact

**Yb³⁺ Lasers**

- Absorption bands at InGaAs wavelengths
- Very low quantum defect (<10%)
- Long lifetime for high energy storage

\[ \text{Pump } 940 \text{ nm} \]
\[ \text{Laser } 1030 \text{ nm} \]
Thermal and gain properties of Yb:YAG are dramatically improved at cryogenic temperature

<table>
<thead>
<tr>
<th>Yb:YAG at room and cryogenic temperature</th>
<th>300 K</th>
<th>77 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity (W/mK)</td>
<td>10</td>
<td>90</td>
</tr>
<tr>
<td>Thermo-optic coefficient ($10^{-6}$/K)</td>
<td>7.8</td>
<td>0.9</td>
</tr>
<tr>
<td>Expansion coefficient ($10^{-6}$/K)</td>
<td>6.14</td>
<td>1.95</td>
</tr>
<tr>
<td>Saturation fluence (J/cm$^2$)</td>
<td>9.2</td>
<td>1.7</td>
</tr>
</tbody>
</table>

G. A. Slack and D. W. Oliver; Phys. Rev. B4; 592-609 (1971)

Other recent cryogenic diode-pumped CPA work:
Compact high power diode-pumped CPA laser driver for 100 Hz table-top SXRL

Yb:KYW Oscillator → Pulse Stretcher → Yb:YAG Amplifier 1 → Cryo Yb:YAG Amplifier 2

Line Focusing Optics → 1 J, 5 ps

Grating Pulse Compressor → 1.5 J

Cryo Yb:YAG Amplifier 3 → 140 mJ

Target Chamber → 18.9 nm Soft X-ray Laser
2nd stage cryo-cooled Yb:YAG amplifier

140 mJ, 100 Hz, amplifier operation demonstrated

100 Hz repetition rate 1.5 Joule diode-pumped cryo-cooled Yb:YAG amplifier

Uncompressed pulses

M² of amplified pulses

2nd order autocorrelation of compressed 1 J pulses

1 J, 5 ps pulses at 100 Hz repetition rate
Soft X-Ray laser employs ns ASE pedestal followed by ps pump pulse from same CPA diode-pumped laser

Delay

Intensity

Compressed Heating Pulse

Adjustable ASE Pedestal (~ 2.5 ns)

Cylindrical Mirror

Cylindrical Lens

From Compressor

100 Hz Operation
Gain-Saturated 18.9nm Laser Operation at 100 Hz repetition rate

Pump: 970 mJ on target

GL = 16.8

g₀ = 43 cm⁻¹

100 Hz, 18.9 nm laser

940 mJ on target moved at 200 um/s, (2um/shot)

Mean Energy = 1.46 μJ, σ = 11%

0.15 mW average power

( Fermi FEL 20-65 nm: 30-60 uJ x 10 Hz = 0.3-0.6 mW Luca Giannessi ICXRL)
Helicoidal targets developed to allow continuous operation at 100 Hz repetition rate

Slab targets for parameterization of the soft x-ray laser

Demonstration of all-diode-pumped laser at 13.9nm in Ni-like silver plasma

Single-shot spectrum of Ag plasma, 950 mJ pulse energy on target Driver laser operating at 50 Hz repetition rate.

Summary

• Gain-saturated table-top SXRLs reach $\lambda = 8.85$ nm. Amplification observed down to $\lambda = 7.3$ nm.

• Compact diode-pumped soft x-ray laser operating at record 100 Hz rep. rate produces 0.15 mW average power on a table-top.

Work Supported by the NSF Engineering Research Centers Program and the US Department of Energy.
Acknowledgement
New Facilities are allowing to expand optical drivers for secondary radiation generation

Advanced Beam Laboratory

Diode Pumped Ti:Sa CPA

Diode Pumped Yb:YAG CPA
Photonics at extreme ultraviolet and soft x-ray wavelengths on a table-top

Carmen S. Menoni
Center for Extreme Ultraviolet Science and Technology
Department of Electrical & Computer Engineering
Department of Chemistry

IEEE Distinguished Lecture

Imaging of nanostructures

Movies at the nanoscale

Molecular Imaging
EUV/SXR sources are paving the way to scientific research and technological innovation

PHOTON FACTORIES

Synchrotron Light Source

Free Electron Laser

FERMI@elettra FEL1

COMPACT SOURCES

Incoherent sources

High Harmonic Generation

Lasers

http://www.ino.it

Soft X-Ray Plasma Amplifier
Compact plasma-based soft x-ray lasers can be installed at the application’s site.

- Discharge Pumped SXRL $\lambda=46.9$ nm
- Laser Pumped SXRL $\lambda=8.8–32.6$ nm

- High pulse energy ($\mu$J-mJ)
- High monochromaticity ($\lambda/\Delta\lambda < 10^{-4}$)
- High peak spectral brightness

- Nanopatterning
- Analytic nanoprobe

- 82 nm holes
- 100 nm lines
- 2 $\mu$m

- Interferometry
- Nano-ablation
- Nano-machining
New Facilities are allowing to expand optical drivers for secondary radiation generation

Advanced Beam Laboratory

Diode Pumped Ti:Sa CPA

Diode Pumped Yb:YAG CPA
Gain-saturated table-top SXRLs cover 8.8 nm - 47 nm wavelength region - Pump: CPA Ti:Sapphire

J.J. Rocca laser team

SXRL microscopes are critical photonic technologies for imaging nanostructures and surfaces

**Transmission**

\[ \lambda = 46.9 \text{ nm, } 13.9 \text{ nm} \]

- 46.9 nm Laser
- Schwarzschild condenser
- Sample
- Objective zp
- to CCD

38 nm spatial resolution @ 13.9 nm

*G. Vaschenko et al, Opt.Lett 2006*

**Single shot Imaging of nanostructures**

50 nm Carbon Nanotubes

Spatial resolution: 50 nm

*C. Brewer et al, Opt.Lett 2008*

**Time resolved Imaging**

Frames from a SXR motion picture

*S. Carbajo et al, Opt. Lett. 2012*

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**Reflection**

\[ \lambda = 46.9 \text{ nm, } 13.2 \text{ nm} \]

- 13.2 nm Laser
- EUVL Mask
- Off-axis zp
- Condenser zp
- to CCD
- Mo/Si Mirror

Aerial inspection of EUVL masks (\( \lambda = 13.2 \text{ nm} \))

Compact $\lambda = 46.9$ nm full field microscope

**Laser Output Characteristics:**
- Output Energy: $> 10 \, \mu J/pulse$
- Repetition rate: up to 12 Hz
- Pulse duration: $\sim 1.5$ ns
- Bandwidth: $\Delta \lambda / \lambda < 1 \times 10^{-4}$
- Tailored spatial coherence

**Sc/Si multilayer coated Schwarzschild condenser**
- Throughput: 13%
- NA = 0.18, working distance: 60 mm

**Freestanding Fresnel zone plate objective**
- NA, $\Delta r$, f
- 0.32, 70 nm, 0.75 mm
- 0.19, 120 nm, 1.28 mm
- 0.12, 200 nm, 2.13 mm

**Capillary discharge pumped**
- $\lambda = 46.9$ nm laser

**Vacuum chamber**
- EUV-sensitive CCD connected to computer

**Power supply and gas handling controls**

**Courtney Brewer**

7/15/2018
EUV/SXR microscope captures images of nanostructures with very high resolution

**TRANSMISSION**

NA = 0.32 (M~1000)
200 nm half period diatom

![Image of 200 nm half period diatom](image1)

5 sec exposure

50 nm carbon nanotube

![Image of 50 nm carbon nanotube](image2)

Single shot, 1.5 ns exposure


**REFLECTION**

NA = 0.12 and 0.19 (M~250)
5-20 sec exposures

![Image of partially processed semiconductor chip](image3)

Partially Processed semiconductor chip

100 nm and 200 nm lines

![Image of 100 thick GaN nanowire between Al contacts](image4)

100 thick GaN nanowire between Al contacts

Single-shot sequential imaging
Motion picture of nanoscale dynamics

Laser Output at 46.9 nm
Energy > 10 µJ/pulse
(2.4 $10^{12}$ ph/pulse)
Pulse duration ~1 ns

- Test object: Oscillating cantilever driven by periodic voltage signal
- Single shot images were acquired to map oscillation over an entire period
Visualizing magnetic nanoscale dynamics

- Variations of 30 nm in the amplitude of the oscillation detected.
- Model predicts change in the restoring force of the tip and associated amplitude changes that agree with experiment.
SXRL laser holography captures images with a single laser flash

IN LINE HOLOGRAPHY

Hologram

Reconstructed image

50 nm spatial resolution


SINGLE SHOT EUV FOURIER HOLOGRAPHY CAPTURES MOTION OF NANOPILLARS

80 nm spatial resolution


Marconici’s group
EUV/SXR interference contrast imaging

\[ \lambda = 46.9 \text{ nm} \]
SXRL
LC: 700 \( \mu \text{m} \)
TC: 90\% of beam diameter
Pulse energy: 0.1 mJ

Object: Si elbow test pattern onto Si3N4 window– 30\% absorption contrast @ \( \lambda = 46.9 \text{ nm} \)

Image plane hologram

Full field images of a 230 nm dense line elbow pattern with 600x magnification

Phase difference of \((2.3\pm0.3)\) rad corresponds to \((100\pm15)\) nm thick Si
\( \lambda = 13.2 \text{ nm} \) microscope for EUVL mask inspection illumination emulates EUVL stepper

\( \lambda = 13.2 \text{ nm laser} \)
Rep. Rate = 5 Hz
Average Power \(~2\ \mu\text{W}\
\( \Delta \lambda / \lambda < 10^{-4} \)
Nanoscale Molecular imaging by SXR laser ablation mass spectrometry

Mass Spectrometry Imaging (MSI) allows for identification of and mapping of the spatial distribution of elemental and molecular components in solid samples.

CHALLENGES IN MSI of bio/organic samples to reach nanoscale resolution are:
- Reduction of ion yield when probing nanoscale volumes
- Molecular fragmentation

SXR laser ablation spot size: 100x100x50 nm³

10 μm diameter – 2D matrix assisted laser desorption MSI

Compiled MS image of *M. tuberculosis* bacillus

High resolution composition maps
Laser pulses are focused onto specimen:
- Wavelength: 46.9 nm
- Pulse duration: 1.5 ns
- Pulse energy: 0.01 mJ

The focused laser ablates the material and simultaneously ionizes the fragments in the ablation plume.

Ions are extracted into the Time of Flight mass spectrometer.
Profile of a crater with a volume of 1 aL ablated in PMMA with a single shot. The crater’s profile shows no sign of thermal damage.

- **Exceptional lateral resolution**: $\lambda = 46.9$ nm light can be focused to $\sim 100$ nm spots [G. Vaschenko et al, Opt. Lett. Vol. 31, 3615-3617]
- **Exceptional depth resolution**: $\lambda = 46.9$ nm light is strongly absorbed in most materials
- **EUV photons break bonds in organic materials** [L. Juha et al, APL, Vol. 89, 034109, 3009]

EUV laser ablation and plasma generation
- Plasma is transparent to EUV photons
- Electron heating by inverse bremsstrahlung is negligible
- EUV photons absorbed by photoionization have sufficient energy to single photon-ionize any atom or molecule

Profile of a crater with a volume of 1 aL ablated in PMMA with a single shot. The crater’s profile shows no sign of thermal damage.
3D imaging EUV mass spectrometry imaging nanoprobe

EUV Optics
Fresnel zone plate 0.16 NA

EUV laser
- Wavelength: 46.9 nm
- Energy per pulse > 10 µJ
- Repetition rate: 12 Hz
- Pulse duration ~1.5 ns

SXR Laser
$10^{12}$ ph/pulse

Interaction Chamber
Time of Flight MS
Optical Microscope

S. Heinbuch Optics Express
vol. 13, 4050 (2005)

Optics engineered by
W. Chao and E. Anderson at
Center of X-Ray Optics,
Lawrence Berkeley Lab.

E.H. Anderson, IEEE J. Quantum
Electronics, vol.42, 27, 2006
Results:
Molecular imaging of inorganic samples (negative mode extraction)

Mass spectrum of SiO2

![Mass spectrum of SiO2](image_url)
Results:
Depth profiling in organic samples with resolution ~ 20 nm

Sample
100 nm
100 nm
60 nm

SXRL

Mass spectrum showing parent ions of Alanine and Nile Red

Alanine

Nile Red

[\text{M+H}]^*
Results:

2D imaging with 70 nm lateral resolution

2D ion image plotting content of resist determined from the intensity average of 4 peaks in the 70-120 m/z range

AFM image of ablated region

Trench

ITO

Edge profile from AFM

pixel width

80%

70 nm

20%
Results:

3D composition mapping of a single *M. Smegnatis* bacterium

Iso-lines of two significant lipid fragments

Voxel size: 0.3×0.3×0.08 µm³

*I. Kuznetsov, et al, to be published in Nat. Comm. 2015*
Comparison of EUV TOF with leading molecular mass spectrometry methods UV LDI TOF and SIMS TOF

Mass spectra of alanine

- Strong absorption
- High 3D localization
- Efficient photo-ionization
- **Sensitivity:** 0.01 amol
- Fragmentation: 1.1

- Negligible absorption
- Absence of ionization
- (Requires Matrix)

- Ion collision process
- **Sensitivity:** 0.4 amol
- Fragmentation: 1
SXR Coherent lithography prints arbitrary motifs defect free

- NON-CONTACT
- LENSLESS LITHOGRAPHY
- SHORT EXPOSURES, 20-50 LASER SHOTS
- PRINTS PATTERNS DEFECT FREE OVER AREAS 0.5X0.5 mm²

Error-Free Printing of Periodic metallic structures

Talbot Mask

Print in HSQ

Grating etched in Au 500/600 lines/spaces
Smaller Features: Fractional Talbot EUV Lithography

Periodic masks produce images with higher frequency in positions that are a fraction of the Talbot distance.
Frequency multiplication of periodic patterns by fractional Talbot lithography

Frequency multiplication factors up to 5X were demonstrated.

AFM measurements for the lithography results, showing (a) $M_{sf} = 1$, (b) $M_{sf} = 2$, (c) $M_{sf} = 3$, and (d) $M_{sf} = 5$ from the parent mask of 3 µm pitch. Overlayed red curves show corresponding AFM cross-sections. The height of the PMMA structures (a-d) was ~ 80 nm.

Fractional Talbot lithography with extreme ultraviolet light

Hyun-su Kim, Wei Li, Serhiy Danylyuk, William S. Brocklesby, Mario C. Marconi, and Larissa Juschkin

Optics Letters, Doc. ID 224904
Double exposure and stitching prints 40 nm lines over millimeter square areas

Smallest lines printed

40 nm / 110 nm lines / Spaces

Coherent Printing with 100 Hz, 18.9 nm laser

400 nm lines

1 Minute Exposure, 0.5 mm² Patterned Area

Potential to print 10 nm lines

Non contact printing method is well suited for studies of EUV resist response

L. Urbanski et al
Thanks to Collaborators

Microscopy Team
J. Nedjl, S. Carbajo, I. Howlett, N. Monserut, E. Malm, M.C. Marconi and K. Buchanan (CSU) (recent work)

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Mass spectrometry imaging team

Nanopatterning Team
W. Li, L. Urbanski, M.C. Marconi

Laser Engineering Team

Optics Engineering Teams
W. Chao, E. H. Anderson, K. Goldberg, P. Naulleau

Center for X-Ray Optics, Lawrence Berkeley Lab
A. Vinogradov, I. Artioukov

Levedev Physical Institute, Russia
AIR Research Alliance project “Development of Key Technology for next generation projection lithography of integrated circuits at 6.X nm wavelengths”

Collaboration between EUV ERC and Cymer

Funded by NSF and Cymer
BRIGHT SXR LASERS ENABLE NOVEL TOOLS FOR NANOSCIENCE AND NANOTECHNOLOGY ON A TABLE TOP

Imaging of nanostructures

Movies of nanoscale interactions

3D Molecular Imaging

TODAY

FUTURE

MICROSCOPY

3D MOLECULAR IMAGING
Rocky Mountain National Park

FALL

Sky Colorado - WINTER

Thank you!

Horsetooth Park, Fort Collins - SUMMER

INTERNATIONAL YEAR OF LIGHT 2015