Chapter 7

EXTREME ULTRAVIOLET AND SOFT X-RAY LASERS

\[
\frac{I}{I_0} = e^{GL} \quad (7.2)
\]

\[
G = n_w \sigma_{stim} F \quad (7.4)
\]

\[
\sigma_{stim} = \frac{\pi \lambda r_e}{(\Delta \lambda / \lambda)} \left( \frac{g_l}{g_u} \right) f_{lu} \quad (7.18)
\]

\[
\frac{P}{A} = \frac{16\pi^2 c^2 \hbar (\Delta \lambda / \lambda) GL}{\lambda^4} \quad (7.22)
\]
The Processes of Absorption, Spontaneous Emission, and Stimulated Emission

Absorption

Spontaneous emission

Stimulated emission
The Lasing Process Begins with Amplified Spontaneous Emission (ASE)

- Spontaneous emission
  - both directions equally likely

Gain medium of inverted population density
Equilibrium and Non-Equilibrium Energy Distribution

Equilibrium energy distribution

Non-equilibrium inverted energy distribution

Energy level
Population density

Lasing requires an inverted population density (more atoms in the upper state than in the lower state.)
Three-level Lasing Between an Upper State $u$ and a Lower State $\ell$

- **Pump**
- Long lived state
- Fast radiative decay

$\lambda$

$u$

$\ell$

$g$
Radiative Decay Involves An Atom Oscillating Between Two Stationary States at the Frequency $\omega_{if} = (E_i - E_f) / \hbar$
EUV/SXR Lasers are High Gain With Minimal Cavity Optics

Visible Light Laser

EUV/Soft X-ray Laser

Refractive index of an electron plasma:

\[ \frac{\Delta \lambda}{\lambda} \approx 10^{-6} \]

Spatial and temporal coherence addressed in chapter 8.
Early Successes With Lasing in the 4-46 nm Wavelength Region

- Recombination lasing in rapidly cooled H-like carbon
- Collisionally pumped lasing in Ne-like Se
- Extension to shorter wavelengths with collisionally pumped Ni-like Ta, W, . . .
- Saturation of Ni-like Ag, In, Sn, Sm, . . . with refraction compensated plasmas

More recently:

- Table-top lasing in the EUV with high spatial coherence and mW average power
- Compact lasing with $f_{\text{sec}}$ transient gain techniques
Stimulated $n = 3$ to $n = 2$ Emission for a Hydrogen-Like Ion

$n = \infty$
$n = 4$
$n = 3$
$n = 2$
$n = 1$

\[ \hbar \omega = (13.606 \text{ eV}) Z^2 \left( \frac{1}{n_f^2} - \frac{1}{n_i^2} \right) \quad (7.1) \]

Binding energy
### Transitions in Single Electron, Hydrogen-Like Carbon Ions \((Z = 6)\)

\[
\hbar \omega = (13.606 \text{ eV}) \, Z^2 \left( \frac{1}{n_f^2} - \frac{1}{n_i^2} \right)
\]

\[(7.1)\]

<table>
<thead>
<tr>
<th>Transition (u-l)</th>
<th>Photon energy (\hbar \omega (\text{eV}))</th>
<th>Wavelength (\lambda ) (nm)</th>
<th>Oscillator strength (f_{lu})</th>
<th>Lifetime (\tau = 1/A_{ul}) (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2p–1s</td>
<td>367.0</td>
<td>3.378</td>
<td>0.4162</td>
<td>1.2</td>
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<tr>
<td>3p–1s</td>
<td>435.0</td>
<td>3.350</td>
<td>0.0791</td>
<td></td>
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<tr>
<td>4p–1s</td>
<td>458.7</td>
<td>2.703</td>
<td>0.0290</td>
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<tr>
<td>3p–2s</td>
<td>68.03</td>
<td>18.22</td>
<td>0.435</td>
<td>4.1</td>
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<tr>
<td>3s–2p</td>
<td>68.03</td>
<td>18.22</td>
<td>0.0136</td>
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<tr>
<td>3d–2p</td>
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<td>18.22</td>
<td>0.696</td>
<td>12.0</td>
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<tr>
<td>4p–2s</td>
<td>91.84</td>
<td>13.50</td>
<td>0.103</td>
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<td>0.0030</td>
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<td>13.50</td>
<td>0.122</td>
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<tr>
<td>4p–3s</td>
<td>23.81</td>
<td>52.07</td>
<td>0.485</td>
<td></td>
</tr>
</tbody>
</table>

- \(\hbar \omega \propto Z^2\)
- \(\tau \propto \tau_H/Z^4\)
Recombination Lasing With H-like Carbon Ions

Expanding carbon plasma of length $L$

Carbon disk target

EUV

10.6 m laser-heating pulse

Magnet coils

Co$_2$ laser: $10.6 \mu$m, $5 \times 10^{12}$ W/cm$^2$, 70 ns

Ionization of C$^{+5} = 490$ eV

Plasma: $\kappa T = 100$-200 eV, $5 \times 10^{18}$ e/cm$^3$

Recombination of C$^{+6}$ and e$^-$ cascading down excitation states (n)

Axial spectrum

C$^5$ 18.2 nm

(3 $\rightarrow$ 2)

O$^{+5}$ 17.3 nm

C$^4$ 18.6 nm

Transverse spectrum

O$^{+5}$ 17.3 nm

C$^5$ 18.2 nm

C$^{+4}$ 18.6 nm

Channel (pixel)

$0$ $1000$

$500$

$18.2$ nm

$18.6$ nm

$17.3$ nm

$15.0$ nm

L/$r \sim 10^{-2}$

$r \sim \frac{1}{2}$ mm

Courtesy of S. Suckewer et al. (1985) Princeton University
Laser Produced Plasma for Ne-like Lasing in Selenium (Z = 34)

- Double-sided irradiation of a thin Se foil
- 2.4 TW, $2\omega$, 450 ps, $7 \times 10^{13}$ W/cm$^2$
- 200 $\mu$m $\times$ 1.1 cm focal spot
- About 20% ions Ne-like
- Ionization of Fl-like Se$^{+23}$ is 1036 eV (Ne-like is 2540 eV)

Two time-gated spectrometers

High power 0.527 m laser light

(\lambda/\Delta\lambda \sim 2,000; \Delta\tau \sim 0.5 \text{ ns})

Ne-like selenium ions in a laser-produced plasma

(\lambda/\Delta\lambda \sim 200; \Delta\tau \sim 20 \text{ ps})

Alignment mirror

Time-resolved transmission grating spectrometer

Courtesy of D. Matthews et al. (1985)
Lawrence Livermore National Laboratory
Exponential Gain Observed
With Increasing Plasma Length

- Gain in axial direction only
- Use of on and off-axis time gated spectrometers
- $3p \rightarrow 3s$ lasing at 20.64 nm and 20.98 nm in Ne-like Se$^{+24}$

Courtesy of D. Matthews et al. (LLNL)
Population Inversion in Neon-like Selenium

- Laser produced plasma conditions optimized for dominant Ne-like ionization stage
- Collisionally pumped to a 3p excited state
- Fast radiative depopulation of the lower 3s state
- \( 3p \rightarrow 3s \) lasing at 20.64 nm and 20.98 nm based on selective depopulation

Simplified Energy Level Diagram for Se\(^{+24}\)

Lasing transitions

- \( 1s^22s^22p^53p \) (J = 2)
- \( 1s^22s^22p^53s \) (J = 1)
- \( 1s^22s^22p^6 \)

Fast radiative decay

Electron collisional excitation (~1.5 keV)

20.98 nm (59.10 eV)

20.64 nm (60.07 eV)

Courtesy of M. Rosen et al. (1985), LLNL.
Extension to Nickel-like Ions Permits Lasing at Shorter Wavelengths Without the Need for Higher Electron Temperature

Lasing in Ni-like Ta$^{+45}$

- Ni-like Ta ($Z = 73$, 28 e${}^-$, +45)
- 1s$^2$2s$^2$2p$^6$3s$^2$3p$^6$3d$^{10}$ ground state (28 e${}^-$)

![Diagram showing lasing transition at 4.483 nm, electron collisional excitation, and intensity vs. wavelength graph.

- Lasing transition at 4.483 nm (276 eV)
- Electron collisional excitation (~1.1 keV)
- Fast radiative decay
- 3d$^9$4d (J = 0)
- 3d$^9$4p (J = 1)
- 3d$^{10}$ ground state (J = 0)

1.7 cm Ta foil
2.5 cm Ta foil

Courtesy of B. MacGowen et al. (1987), LLNL.
Nickel-like Lasing Across the K-edge of Neutral Carbon

4d → 4p lasing

- W at 4.318 nm
- Ta at 4.483 nm
- C-K at 4.36 nm

The water window is defined by the K-absorption edges of neutral carbon and oxygen.

Courtesy of B. MacGowen et al. (1987), LLNL.
For $\omega > \omega_p$ there is a real propagating wave with phase velocity

$$v_\phi = \frac{\omega}{k} = \frac{c}{\sqrt{1 - \omega_p^2/\omega^2}} = \frac{c}{\sqrt{1 - n_e/n_c}}$$  \hspace{1cm} (6.113a)$$

The refractive index of the plasma is

$$n = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}$$  \hspace{1cm} (6.114a)$$

or equivalently

$$n = \sqrt{1 - \frac{n_e}{n_c}}$$  \hspace{1cm} (6.114b)$$
Refraction Compensating Double-Targets Used to Achieve Saturation of Lasing at 13.99 nm in Ni-like Ag

- Prepulse allows plasma expansion, decreases transverse electron density gradients and increases plasma volume.
- Double targets permit refraction compensation (opposite turning angles) and double the gain length.
- Time delay of one target irradiation enhances gain in one direction.
- Saturated $4d \rightarrow 4p$ lasing at 13.99 nm in Ni-like Ag$^{+19}$ ($Z = 47$, 28e$^-$)

Nd laser: 1.05 µm, $2 \times 10^{13}$ W/cm$^2$, 75 ps
Target: Ag stripes, 200 µm $\times$ 25 mm
Plasma: 700 eV, $6 \times 10^{20}$ e/cm$^3$
  $43 \times 57$ µm, $1.5 \times 3.5$ mr

Courtesy of J. Zhang et al. (1997)
Rutherford Appleton Laboratory
Saturation of Nickel-like Lasing in Ag, In, Sn, and Sm

Refraction compensating double targets

Ni-like Ag
4d → 4p
13.99 nm

Ni-like Ag
13.99 nm

Ni-like In
12.59 nm

Ni-like Sn
11.98 nm

Ni-like Sm
7.355 nm

Figure 1:
- Ni-like Ag: G = 8/cm
- Ni-like In: G = 8.8/cm
- Ni-like Sn: G = 12.5/cm
- Ni-like Sm: G = 9.5/cm

Note: Wavelengths quoted are calculated by J. Scofield and B. MacGowan.

Courtesy of J. Zhang et al. (1977)
Appleton Rutherford Laboratory

Courtesy of J.Y. Lin et al. (1999)
Appleton Rutherford Laboratory

Professor David Attwood
AST 210/EECS 213
Univ. California, Berkeley
High Average Power, High Spatial Coherence Table-Top Laser at 46.86 nm

- Discharge plasma
- Fast, high current pulse compresses \((J \times B)\) and heats plasma
- 70 eV, \(5 \times 10^{18}\) e/cm\(^3\)
  - 300 \(\mu m\) \(\times\) 36 cm long (1:1000)
- Ne-like \(\text{Ar}^{+8}\), 3p \(\rightarrow\) 3s at 46.86 nm
- \(\overline{P} = 3.5\) mW, spatially coherent

Courtesy of J. Rocca (1995), Colorado State University
Spatial Coherence of 46.86 nm Laser

Courtesy of Y. Liu, UC Berkeley, and J. Rocca, Colorado State University (2001)
Scaling to 13 nm Requires Excitation of Ni-Like Cd Ions (Cd + 20)
Generation of laser radiation at 13 nm requires significantly hotter and denser plasma columns.
Pumping configurations for collisional EUV lasers in laser-created plasmas: Grazing incidence increases energy deposition efficiency*

- Two pulse sequence at normal incidence

- Grazing incidence


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

Courtesy of J. Rocca Colo. State U.
5-10 Hz Pump laser: 1 J Short Pulse Table-top Ti: Sapphire System

Courtesy of J. Rocca, Colo. State U.
Configuration for 30 μm wide short pulse line focus at 14 to 26 degrees grazing incidence

Line Focus

- Pre-pulse: 30μm FWHM,
- Short-pulse: 30μm FWHM,

Courtesy of J. Rocca, Colo. State U.
Simulation predicts high gain at 18.9 nm in Ni-like Mo, $g \sim 100 \text{ cm}^{-1}$ (Mark Berrill, CSU)

Pre-pulse: 330 mJ, 120 ps  Heating pulse: 800 mJ, 8 ps heating pulse

Courtesy of J. Rocca, Colo. State U.
Saturated 18.9 nm Ni-like Molybdenum Laser

**Long pulse: 340 mJ - Short pulse: 1 J**

Fit with the expression from Tallents et. al. 8th Int. Conf. XRL, AIP Vol. 641, 2002.

\[
GL + 2 \frac{I_{av}}{I_s} = g_0 L
\]

\[
I_{av} = I_0 \left[ \exp(GL) - 1 \right]^{3/2} / \left[ GL \exp(GL) \right]^{1/2}
\]

g_o = 65 \text{ cm}^{-1}

gxI=15.3

wavelength (nm)

Courtesy of J. Rocca, Colo. State U.
Lasing observed at wavelengths as short as 10.9 nm

Gain saturated operation demonstrated

 Courtesy of J. Rocca Colo. State U.
Saturated laser operation at 13.9 nm in Nickel-like Ag

1 J short (8 ps) pulse excitation

$g_0 = 67 \text{ cm}^{-1}$; $g_{xl} = 16.8$

$\lambda = 13.9 \text{ nm}$ (4d $\rightarrow$ 4p)

850 nJ/shot

Courtesy of J. Rocca, Colo. State U.
Gain-saturated Ni-like 13.2 nm Ni-like Cd laser

1 J short pulse – 23 degrees grazing incidence angle

Courtesy of J. Rocca, Colo. State U.
A Ni-like Cd at 13.2 nm provides a closer laser wavelength match to Mo/Si lithography mirrors.

At the wavelength of the Ni-like Cd laser the reflectivity of Mo-Si mirrors centered at $\lambda=13.5$ nm is ~ 55%.

![Graph showing reflectivity vs. wavelength with peaks at 13.2 nm and 13.9 nm.](image)

Courtesy of J. Rocca, Colo. State U.
The new compact EUV lasers are enabling application testbeds

Example: 13.9 nm Table-top EUV microscope with resolution better than 50 nm

From 13.9 nm laser

100 nm lines, exposure time: 20 seconds.

Grad. Student
Fernando Brizuela

Courtesy of J. Rocca, Colo. State U.