Ultrafast Lasers

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Laser Principles

• **Gain Medium**
  – Crystal, gas, semiconductor, glass
  – Gain \( \geq \) loss \( \Rightarrow \) lasing

• **Resonator**
  – Cavity (minimum of two mirrors)
  – Stability (ABCD transmission matrix)

• **Loss Mechanisms**
  – Mirror reflectivity
  – Gain medium interface (Brewster’s Angle)
  – Dirt, dust, water vapor
Laser Basics

• Output Mechanism
  – Output coupler
  – Cavity dumper

• Pump Source (Electrical or Optical)
  – Supplies energy
  – Most expensive and cumbersome

• Most efficient Lasers: Semiconductor Lasers
  (~ 60% of electrical pump energy to light)

• Typical Efficiency of Lasers << 10 %
Ultrafast Laser

• **Ultra**: Going beyond others or beyond due limit: EXTREME

• **Fast**: Used to mean *nanoseconds* (back in the old days)

• Today **Ultrafast** typically implies temporal resolution < 10 *picoseconds* (10^{-11} seconds)

• **World Record**: 
  
  6 *femtoseconds* (at ~ 800 nm)

  ⇒ two optical periods

  (1 *femtosecond* = 10^{-15} seconds)
Ultrafast Laser

• “Typical” Short Pulse Lasers ~ 100 $fs$
  (relatively easy to attain)

• Optical Frequency
  – Central frequency of Ti:Sapphire laser ~ 800 nm
  – **Enormous bandwidth:**
    – $\nu_o = c/\lambda_o = 375$ THz ($>10^{12}$ Hz!)
Properties of Short Pulse

• For a delta function \( \delta(t) \)

\[
\mathcal{F}\{ \delta(t) \} = 1
\]

(\( \mathcal{F} \) - Fourier Transform)

• Infinitely narrow in time

\[ \Rightarrow \text{Infinitely broad in frequency domain} \]

• Shorter pulses

\[ \Rightarrow \text{Larger bandwidth required} \]
Real World Pulses

\[ \Delta \tau_p \Delta \nu = Const = 0.44 \]

\[ \nu = \frac{c}{\lambda} \]

\[ \Delta \nu = \frac{c}{\lambda} \frac{\Delta \lambda}{\lambda} = \nu_o \frac{\Delta \lambda}{\lambda} = 9.4 \, THz = 1.9 \, million \, video \, channels \]
Gain Medium: Einsteins $A$ & $B$ Coefficients

- $A_{21}$: Spontaneous Emission
- $B_{12}$: Absorption
- $B_{21}$: Stimulated Emission

Material: $I_v(0)$ to $I_v(z)$
Gain Medium: Einsteins A & B Coefficients

\[ I_v(z) = I_v(0) \cdot e^{\gamma_0(v) \cdot z} \]
\[ \gamma_0(v) = \sigma(v) \cdot \left[ N_2 - \frac{g_2}{g_1} \cdot N_1 \right] \]
\[ \sigma(v) = A_{21} \cdot \frac{\lambda^2}{8\pi n^2} \cdot g(v) \]

\( N_2 > \frac{g_2}{g_1} \cdot N_1 \)

\( \sigma(v) \): Stimulated Emission cross section

\( g(v) \): Lineshape Function (width of transm. Spectrum)
Laser Oscillation

\[ \gamma_0(v) = A_{21} \cdot \frac{\lambda^2}{8\pi n^2} \cdot g(v) \cdot \left[ N_2 - \frac{g_2}{g_1} \cdot N_1 \right] \]

\[ I_v(z) = I_v(0) \cdot e^{\gamma_0(v) \cdot z} \]

For amplification we need to have Gain.
Laser Oscillation

\[ \text{Loss} = R_1 \cdot R_2 \quad \text{Gain} = G_0^2(\nu) = \left(e^{\gamma_0(\nu)l}\right)^2 = e^{2\gamma_0(\nu)l} \]

Here

\[ \gamma_0(\nu) \geq \frac{1}{2l} \cdot \ln \left[ \frac{1}{R_1 R_2} \right] = \alpha_0 \]

Gain/Length \quad Loss/Length

\[ \gamma_0(\nu) \quad \alpha_0 \]

Possible Oscillation

Lasing takes place at longitudinal mode with highest gain to loss rate.

\[ \Rightarrow \text{CW Operation} \]
Mode Locking

\[ \Delta \nu \sim \frac{1}{2\pi \Delta t_p} \]

For a simple Laser: \( \tau_{RT} - \frac{c}{2d} = FSR \)

Suppose \( \Delta t_p = 6 \text{ fs} \), \( \lambda_0 = 600 \text{ nm} \) (\( \nu_0 = 5 \times 10^{14} \text{ Hz} \))

\[ \Rightarrow \Delta \nu \sim 2.65 \times 10^{13} \text{ Hz} \]

\[ \Delta \nu \sim 5\% \text{ of the entire region} \]

\[ \Rightarrow \text{pulse is 1.8 } \mu \text{m long } \Rightarrow 3 \text{ optical wavelength} \]

or 6 optical cycles in entire pulse
Mode Locking
Typical Energy-level Arrangements

- **Traditional solid-state lasers**
  - Initial Upper
  - Rapid decay
  - Pump
  - Laser
  - Lower

- **Gas Lasers**
  - Initial Upper Laser
  - Lower
  - Ground
  - Rapid decay

- **Solid-state and Dye Lasers**
  - Initial Upper Laser
  - Lower Ground
  - Rapid decay
Kerr Lens Modelocking

![Diagram of Kerr Lens Modelocking]

- **CW Argon-ion laser**
- **Output coupler**
- **Adjustable slit**
- **B.R.F**
- **M<sub>2</sub>**
- **L**
- **Ti:Al<sub>2</sub>O<sub>3</sub>**
- **M<sub>3</sub>**
- **P<sub>1</sub>**
- **P<sub>2</sub>**
- **M<sub>4</sub>**
Typical Alexandrite Laser Properties

- Laser Wavelengths: 700 - 820 nm
- Upper Laser Level Lifetime: 260 microsec at 298K
- Inversion Density: $6 \times 10^{24}/m^3$
- Small Signal Gain Coefficient: 4 - 20/m
- Laser Gain Medium Length: 0.12m
- Single Pass Gain: 1.6 - 11
- Pumping Method: optical (flashlamp or laser)
- Pumping Bands: 380 - 630 nm, with peaks at 410 and 590 nm
- Output Power: up to 1.2J/pulse
- Mode: single-mode or multi-mode
## Typical Titanium Sapphire Laser Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Wavelengths</td>
<td>660 - 1180nm</td>
</tr>
<tr>
<td>Upper Laser Level Lifetime</td>
<td>3.8 µs</td>
</tr>
<tr>
<td>Small Signal Gain Coefficient</td>
<td>20 /m</td>
</tr>
<tr>
<td>Laser Gain Medium Length</td>
<td>0.1m</td>
</tr>
<tr>
<td>Single Pass Gain</td>
<td>7 - 10</td>
</tr>
<tr>
<td>Pumping Method</td>
<td>optical (flashlamp or laser)</td>
</tr>
<tr>
<td>Pumping Bands</td>
<td>380 - 620nm</td>
</tr>
<tr>
<td>Output Power</td>
<td>up to 50W (cw), $10^{12}$ W for 100 fs pulse</td>
</tr>
<tr>
<td>Mode</td>
<td>single-mode or multi-mode</td>
</tr>
</tbody>
</table>
## Chromium - LiSAF and Chromium - LiCaF

<table>
<thead>
<tr>
<th>Parameters</th>
<th>LiSAF</th>
<th>LiCaF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Wavelengths</td>
<td>780-1010nm</td>
<td>720-840nm</td>
</tr>
<tr>
<td>Upper Laser Level Lifetime</td>
<td>$67 \times 10^{-6}$s</td>
<td>$170 \times 10^{-6}$s</td>
</tr>
<tr>
<td>Small Signal Gain coefficient</td>
<td>16/m</td>
<td>9/m</td>
</tr>
<tr>
<td>Single Pass Gain</td>
<td>up to 10</td>
<td>up to 4</td>
</tr>
<tr>
<td>Pumping Method</td>
<td>optical</td>
<td>optical</td>
</tr>
<tr>
<td>Pumping Bands</td>
<td>peak at 620nm, peak at 420nm, peak at 280nm</td>
<td></td>
</tr>
<tr>
<td>Output Power</td>
<td>up to 10MW pulses of 10ns duration</td>
<td></td>
</tr>
<tr>
<td>Mode</td>
<td>Single or multi-mode</td>
<td></td>
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