Introduction to Lasers and High Power Lasers

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Outline

• Laser basics and Applications
• Oscillators, Amplifiers, CPA
• Contrast, Gain narrowing, Thermal effects
• OPCPA
• Examples of high-power lasers, cost, size
Lasers can be small

Lasers can be large
Lasers are used for Cutting and Welding

Lasers are used in Medicine
Optical Storage  
CD-player, DVD-player, etc

Fiberoptic Communication

Lasers are used in Wakefield Accelerators

From Albert et al 2014 PPCF
LASER

Light Amplification by Stimulated Emission of Radiation

Einstein, 1916
Basov and Prokhorov, 1953
Schawlow and Townes, 1958
Maiman, 1960

Spontaneous emission  Incoherent light

Stimulated emission  Coherent light
LASER
Light Amplification by Stimulated Emission of Radiation

\[ \Delta E = h \nu \]

High-Power Laser Systems

Oscillator  Amplifier  Amplifier(s)

Pump laser

Mode-locking
Short pulses
MHz rep rate

High gain
10-1000 Hz

High energy
0.01-10 Hz
Pumping for Population Inversion

Two-level system

Laser Transition

Pump Transition

At best, you get equal populations. No lasing.

Three-level system

Laser Transition

Pump Transition

Fast decay

Level empties fast!

Four-level system

Laser Transition

Pump Transition

Fast decay

Fast decay

Pumps: Flash lamps, CW or pulsed lasers, incl. laser diodes, Gas discharges and charge transfer, etc

The first laser, a 3-level ruby laser (1960)

Theodore H. "Ted" Maiman
High-power lasers

\[ P = \frac{E}{\tau} \]

Two approaches:

ICF: \( \tau \sim 1 \text{ ns}, \quad E \sim 100 \text{ kJ} \quad 100 \text{ TW} \quad \text{Few shots/day} \)

T³: \( \tau \sim 10\text{'s fs} \quad E \sim 1 \text{ J} \quad 100 \text{ TW} \quad 10 \text{ Hz} \)

Use short pulses to get high power!

Short pulses also good to drive plasma waves resonantly!

### Pulses of Light

<table>
<thead>
<tr>
<th>Time</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short pulse</td>
<td>[\text{Spectrum}]</td>
</tr>
<tr>
<td>Long pulse</td>
<td>[\text{Spectrum}]</td>
</tr>
</tbody>
</table>
**Short-Pulse Solid State Lasers**

\[ \tau_{\text{pulse}} \approx \frac{1}{\Delta v} \]

<table>
<thead>
<tr>
<th>Material</th>
<th>( \tau )</th>
<th>( \lambda_{\text{lasing}} )</th>
<th>( \tau_{\text{upper}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nd:YAG</td>
<td>~10 ps</td>
<td>1064 nm</td>
<td>230 ( \mu \text{s} )</td>
</tr>
<tr>
<td>Nd:Glass</td>
<td>~0.5 ps</td>
<td>1054 nm</td>
<td>300 ( \mu \text{s} )</td>
</tr>
<tr>
<td>Yb:Glass</td>
<td>~100 fs</td>
<td>1035 nm</td>
<td>1.4 ms</td>
</tr>
<tr>
<td>Ti:Sapphire</td>
<td>&lt;5 fs</td>
<td>700-1000 nm</td>
<td>3.2 ( \mu \text{s} )</td>
</tr>
<tr>
<td>(Ti:Al(_2)O(_3))</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Titanium Sapphire  Ti:Al\(_2\)O\(_3\)**

Upper level lifetime: 3.2 \( \mu \text{sec} \)

Laser pumping required

It can be pumped with a frequency doubled Nd laser (~532 nm).

Ti:Sapphire lases from ~700 nm to ~1000 nm.
Generating ultrashort pulses = mode-locking

Random phases of all laser modes

Locked phases of all laser modes

Irradiance vs. time

Random phases

Light bulb

Locked phases

Ultrashort pulse!!

Phase-locked modes
Group velocity dispersion (GVD) broadens ultrashort laser pulses

Different frequencies travel at different velocities in materials, causing pulses to expand to highly "chirped" (frequency-swept) pulses.

Longer wavelengths almost always travel faster than shorter ones.

Prism Pulse Compressor

The longer wavelengths traverse more glass.
High-power and high-intensity lasers

\[ P = \frac{E}{\tau} \]

Two approaches:
ICF: \( \tau \sim 1 \text{ ns} \), \( E \sim 100 \text{ kJ} \), 100 TW, Few shots/day
T³: \( \tau \sim 10\text{'s fs} \), \( E \sim 1 \text{ J} \), 100 TW, 10 Hz

\[ I = \frac{P}{A} \]

Focus diameter \( \sim 10 \mu \text{m} \) \( I \sim 10^{20} \text{ W/cm}^2 \)

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Laser focus

\[ I(r) = I(r=0)/e^2 \]

Beam waist radius \( \omega_0 \)

\[ \omega_0 = \frac{f\lambda}{\pi\omega_b} \]

Rayleigh range \( Z_R \)

\[ Z_R = \frac{\pi\omega_0^2}{\lambda} \]

Spot size
Nonlinear Refractive Index

\[ n = n_0 + n_2 I \]

\[ I = I(r, t) \Rightarrow n = n(r, t) \]

\[ n(t) \Rightarrow \text{Self Phase Modulation, SPM} \]

\[ n(r) \Rightarrow \text{Self Focusing} \Rightarrow \text{DAMAGE} \]
Chirped Pulse Amplification CPA

Energy

30 fs
1 nJ

Time

300 ps

3 J
100 TW

Grating Stretcher

• **Shorter** optical path for longer wavelength
Pulse Compression by Gratings

- *Longer* optical path for longer wavelength

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Regenerative Amplifiers
Multipass Amplifiers

Lund 40 TW, 35 fs, 10 Hz, CPA Terawatt Laser
wall-plug efficiency <1%
CPA works well!

But there are some issues to pay attention to:

- Gain Narrowing
- Temporal contrast
- Thermal aberrations

Gain Narrowing (Ti:Sapp)

Factor of 2 loss in bandwidth for $10^7$ gain
10 fs oscillator is OK, but sub 30 fs at TW level is tough
Temporal Contrast of Amplified Pulses

Contrast Improvement Methods

One or several fast Pockels cells to suppress prepulses

Reduced amplifier gain to minimize ASE
High pulse energy oscillator
Preamplifier + nonlinear pulse cleaning before stretching
Double-CPA system with nonlinear pulse cleaning
OPA
**Thermal Effects in Amplifiers**

Heat deposition causes lensing and small-scale self-focusing. These thermal aberrations increase the focus spot size and reduce the intensity

\[ I_{\text{peak}} = \frac{E}{A \tau} \]

**Low Temperature Minimizes Lensing**

In sapphire, conductivity increases and \( dn/dT \) decreases as \( T \) decreases.

Cryogenic cooling results in almost no thermal lensing
OPCPA

Chirped Pulse Amplification + Optical Parametric Amplification

Basic Nonlinear Optics

\[ P = \epsilon_0 \chi \mathcal{E} + 2d \mathcal{E}^2 + 4 \chi^{(3)} \mathcal{E}^3 + \cdots \]
### Wave Mixing

\[
P = \epsilon_0 \chi \mathcal{E} + 2d \mathcal{E}^2 + 4\chi^{(3)} \mathcal{E}^3 + \cdots
\]

- Frequency Matching
- Conservation of energy
- Phase Matching
- Conservation of momentum

\[
\begin{align*}
\omega_2 & \rightarrow \omega_3 & \omega_1 + \omega_2 &= \omega_3 \\
\vec{k}_2 & \rightarrow \vec{k}_3 & \vec{k}_1 + \vec{k}_2 &= \vec{k}_3 \\
\omega_3 & \rightarrow \omega_2 & \\
\omega_1 & \rightarrow & \\
\end{align*}
\]

### Optical Parametric Amplification (OPA)

- Pump
- Seed pulse
- Non-linear crystal
- Depleted Pump
- Amplified Seed
- Filter
**OPA vs Laser**

<table>
<thead>
<tr>
<th>OPA</th>
<th>Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>No energy stored in the medium.</td>
<td>Laser integrates pump energy prior to lasing</td>
</tr>
<tr>
<td>No heat loading</td>
<td>BW given by laser transition</td>
</tr>
<tr>
<td>BW given by phase matching</td>
<td></td>
</tr>
</tbody>
</table>

**Optical Parametric Chirped Pulse Amplification**

OPCPA uses a narrow bandwidth laser to provide the energy transfer mechanism to a CPA beam.

Ross et al, Optics Communications, 144, (1997) 123
Dubietis et al, Optics Communications, 88, (1992) 437
OPCPA “Magic List” of Properties

- Very High Gains (eg $10^{12}$) - Little Material (cm’s)
- Ultra Broad Bandwidth, No gain narrowing, Short pulses
- High Energy - pump limited
- No Thermal Loading and Excellent Beam Quality
- High Efficiency
- Good Contrast (shorter ASE duration)
- Directional Gain – no transverse ASE

Disadvantages…

- Non-storage gain medium
- High efficiency only if pump duration less than few ns
- Accurate synchronization to pump pulse required
- Careful control of pump shape required for maximum bandwidth and efficiency
- Critical Phase Matching
A few examples of “compact” high-power lasers suitable for LWFA

1 PW: DRACO in Dresden, Germany and VEGA in Salamanca, Spain
~25 J in 25 fs, at 1 Hz (soon!)
1 PW: BELLA, in Berkeley, USA
40 J in 40 fs @ 1 Hz
Building etc more expensive

10 PW: Apollon at CILEX, Plateau de Saclay, France

10 PW : 150 J in 15fs at 1 shot per minute

C. Le Blanc
Roadmap & Governance

ESFRI  ELI-PP  ELI-ALPS  ELI-NP

2008  2011  2013  2017

PP  MoU  ELI-DC International Association  ELI-ERIC

Price

With buildings  ~ 800 M€

G. Korn at ELI summer school 2014
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