Examples of Specific Laser Systems

- **Gas Lasers**
  - CO$_2$  200+ kW

- **Solid-State Lasers**
  - Nd:YAG  (15 kW)

- **Fiber Lasers**
  - Yb$^{3+}$ (5+ kW)

- **Dye Lasers**

- **Chemical Lasers**
  - COIL  (7+kW),  MIRACL (>1 MW !!)

- **Semiconductor Lasers**
6.5 Active media and spectral ranges

Ultraviolet

Visible

dye lasers

excimer lasers

semiconductor lasers

solid-state lasers

Infrared

molecular gas lasers

atomic gas lasers

wavelength

100 nm

500 nm

1 μm

10 μm
electronic transitions

vibrational transitions

rotational transitions

emission

VIS, UV

NIR, IR

FIR
Typical laser efficiencies $\eta$:

\[ \eta = \frac{\text{output power}}{\text{electrical input power}} \]

- Argon - ion < 0.1%
- CO$_2$ laser < 20%
- Excimer < 20%
- GaAlAs (diode laser) < 40%
- HeNe < 0.1%
- Nd:YAG < 10%
The excitation mechanism in most gas lasers is via *electric discharge*
The first Gas Laser: He-Ne

Ali Javan, et al. (Bell Labs, 1962)

- The second working LASER system to be demonstrated.
- The first gas LASER to be produced.
- The first LASER to produce a continuous output beam.
- The active laser medium is a gaseous mixture of He & Ne atoms, in a roughly 10:1 proportion.
- The gas is enclosed in a cylindrical quartz DISCHARGE tube.
## Comparison of Gas Lasers

<table>
<thead>
<tr>
<th>Laser Type</th>
<th>Linear Power Density W/m</th>
<th>Maximum Power W</th>
<th>Power Efficiency percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>He-Ne</td>
<td>0.1</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Argon</td>
<td>1-10</td>
<td>50</td>
<td>0.1</td>
</tr>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>60-80</td>
<td>&gt;10&lt;sup&gt;4&lt;/sup&gt;</td>
<td>15-20</td>
</tr>
</tbody>
</table>
CO₂ Lasers (9-11 micron)

Applications (*pealing peanuts to star wars*)

- Industrial (cutting, welding, material processing)
- Military (range finding, targeting, remote sensing, sensor blinding, destroying ...)
- Medical (cutting, skin resurfacing)
- ...
Transitions are between molecular vibrational-rotational levels.

Modes of vibrations:
- Symmetric stretch
- Asymmetric stretch
- Bending mode
Simple Harmonic Oscillator (Quantum Mechanics):

\[ E(n_1, n_2, n_3) = h\nu_1 (n_1 + 1/2) + h\nu_2 (n_2 + 1/2) + h\nu_3 (n_3 + 1/2) \]
CO₂ Laser Transitions

Tuning:

P- branch
J \rightarrow J-1

R- branch
J \rightarrow J+1

P(50)
P(20)R(17)P(19)

λ(µm)

λ=9-11(µm)

diffraction grating

CO₂:N₂:He

H.V.
Effect of Gas Mixtures: \( \text{CO}_2 + \text{N}_2 + \text{He} \)

- Nitrogen helps populating the upper laser level in a discharge
- Helium helps to depopulate the lower laser level by collisions

Other possible additions to the gas mixture: CO, \( \text{H}_2 \)
<table>
<thead>
<tr>
<th>CO₂</th>
<th>N₂</th>
<th>He</th>
<th>Laser Power Rating W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>17</td>
<td>20</td>
</tr>
<tr>
<td>1</td>
<td>1.5</td>
<td>9.3</td>
<td>50</td>
</tr>
<tr>
<td>1</td>
<td>1.5</td>
<td>9.3</td>
<td>100</td>
</tr>
<tr>
<td>1</td>
<td>1.35</td>
<td>12.5</td>
<td>275</td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td>23</td>
<td>375</td>
</tr>
<tr>
<td>1</td>
<td>6.7</td>
<td>30</td>
<td>525</td>
</tr>
<tr>
<td>1</td>
<td>2.3</td>
<td>17</td>
<td>1000</td>
</tr>
</tbody>
</table>
11.3 Gas Discharge Phenomena

- Electrons emitted from cathode get accelerated by the electric field
- The energetic electrons excite the vibrational modes of the gas molecule via inelastic collisions

Example:
L=1 meter and P=25 torr
Need \( V=25 \text{ kV} \) for optimum operation
11.4 Specific Types of CO\textsubscript{2} Lasers

High Power CW Operation

- **DC-Discharge**
  - Longitudinal discharge (High Voltage: 10-100 kV)
  - Pressure: 10-100 torr
  - Multistage discharge tubes can be used to produce kilowatts of output power

- **RF-Discharge**
  - In practice waveguides are used.
  - High discharge stability, high pulsing frequency (up to 100 kHz)
  - Expensive RF generator and requires EMI shielding

0.2 W/cm in a waveguide laser
### Operating Parameters of Commercial Class I CO₂ Lasers.

<table>
<thead>
<tr>
<th>Active Length meters</th>
<th>Output Power watts</th>
<th>Gas Mixture CO₂:N₂:He</th>
<th>Gas Flow Rate liters/min</th>
<th>Power/ Length W/m</th>
<th>Water Flow Rate liters/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>1:1.5:9.3</td>
<td>1.15</td>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>1:1.5:9.3</td>
<td>1.15</td>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>275</td>
<td>2:1.35:9.3</td>
<td>4.01</td>
<td>55</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>375</td>
<td>1:8:23</td>
<td>4.26</td>
<td>62.5</td>
<td>10</td>
</tr>
<tr>
<td>9</td>
<td>525</td>
<td>1:6.7:30</td>
<td>4.23</td>
<td>58.3</td>
<td>10</td>
</tr>
<tr>
<td>18</td>
<td>1000</td>
<td>1:2.35:17</td>
<td>14.35</td>
<td>55.6</td>
<td>15</td>
</tr>
</tbody>
</table>
Laser Hardened Materials Evaluation Laboratory (LHMEL)
WP-AFB, Dayton, OHIO

Electric Discharge Coaxial Laser (EDCL)
Gas-Dynamic Lasers

Basov & Oraevskii (1963)

Principle: Population inversion by rapid expansion (supersonic flow) of a super-heated gas

\[ \text{CO}_2 + \text{N}_2 + \text{H}_2 \]

\[ T = 1000-3000 \text{ K} \]

\[ P = 1-20 \text{ atm.} \]

\[ v = 10^5 \text{ cm/sec.} \]

Inversion region

\[ \text{cw powers up to 1 MW have been obtained from gas-dynamic CO}_2 \text{ lasers !!} \]
Gas-Dynamic Lasers

Large scale 135 Kilowatt gasdynamic laser at Avco Everett Research Lab.

HELEX

High Energy Laser Experimental
Germany, 1970’s

$C_2N_2$ or CO
Most Common: Transversely Excited Atmospheric (TEA) CO₂ Lasers

- Flowing or sealed systems
- Pulsewidths from 50 ns to 300 ns
- Repetition rates: 1 Hz to 1 kHz.
- Pulse energy: 50 mJ to 10 J (amplified)
Example

Capacitor bank
Terra Watts Pulsed CO\textsubscript{2} Lasers
Picosecond TW CO\textsubscript{2} Laser at BNL

Section 11.4  p.9

[Diagram of the laser system with labeled components: TEA Oscillator, Slicer, Exit Pockels \(\lambda/4\) Cell, Multi-isotope 5 atm 1-liter Regenerative Preamplifier, Entrance Pockels \(\lambda/4\) Cell, MW, GW, Saturable Absorber, Plasma Shutter, TW.]

10 atm, 10 liter, 10 cm aperture Amplifier
Excimer lasers: applications in lithography and eye surgery

molecules exist only in the excited state

\[
\begin{align*}
\text{XeCl} & \quad 308 \text{ nm} \\
\text{KrF} & \quad 248 \text{ nm} \\
\text{ArF} & \quad 193 \text{ nm} \\
\text{F}_2 & \quad 156 \text{ nm}
\end{align*}
\]

![Diagram showing excitation and emission processes in excimer lasers.](image-url)
The lasing atoms are fixed in a solid (crystal, glass). Solid-state lasers can operate in continuous (cw) or various pulsed modes.

Examples:

(a) Nd:YAG (yttrium aluminum garnett crystal doped with Nd atoms)
\[ \lambda = 1.064 \, \mu m, \ 1.331 \, \mu m \]

(b) Nd:glass (glass doped with Nd:atoms)
\[ \lambda = 1.062 \, \mu m \text{ (silicate glass)} \]
\[ \lambda = 1.080 \, \mu m \text{ (fused silica)} \]

(c) Ti:sapphire \[ \lambda = 0.7 - 1.1 \, \mu m \]

(d) Hm:YAG (holmium atoms doped into a YAG crystal)
\[ \lambda = 2.1 \, \mu m \]

(e) color centers (intentionally created defects in a crystal)
\[ \lambda = 1.5 - 3.5 \, \mu m \text{ (in different hosts)} \]
The 4f-4f transitions in Rare-Earths Ions:

Yb \rightarrow (\text{Xe})4f^{13}6s^2

Yb^{3+} = (\text{Xe})4f^{12}

[Xe]4f^{13} 

\text{Energy}

\text{Orbital Radius}

\text{Crystal Field}

SO_3

O, O_{hy}, T_d

all other

\text{Spin Orbit Coupling}

^{2}F_{5/2} 

^{2}F_{7/2} 

^{2}F_{9/2}
### SSL: much smaller cross sections

### SSL: much longer lifetimes

### SSL: much higher saturation intensities

### SSL: much smaller quantum defect

### SSL: much(!) wider gain spectra

### SSL: atom lifetime $\gg$ cavity lifetime

### SSL: much higher number densities

<table>
<thead>
<tr>
<th></th>
<th>He-Ne</th>
<th>Nd:YAG</th>
<th>Ti:Al$_2$O$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>633 nm</td>
<td>1064 nm</td>
<td>700 - 1000 nm</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>$3 \times 10^{-13}$ cm$^{-2}$</td>
<td>$4 \times 10^{-19}$ cm$^{-2}$</td>
<td>$4 \times 10^{-19}$ cm$^{-2}$</td>
</tr>
<tr>
<td>$\tau_2/\tau_1$</td>
<td>60 ns/10 ns</td>
<td>250 $\mu$s/$\sim$30 ns</td>
<td>3.2 $\mu$s/fast</td>
</tr>
<tr>
<td>$I_{\text{sat}}$</td>
<td>2 W/cm$^2$</td>
<td>2 kW/cm$^2$</td>
<td>200 kW/cm$^2$</td>
</tr>
<tr>
<td>$E_{\text{laser}}/E_{\text{pump}}$</td>
<td>$\frac{2 \text{ eV}}{20 \text{ eV}}$</td>
<td>$\frac{1.2 \text{ eV}}{1.5 \text{ eV}}$</td>
<td>$\frac{1.6 \text{ eV}}{2.3 \text{ eV}}$</td>
</tr>
<tr>
<td>$\Delta \omega$</td>
<td>$2\pi \times 1.5$ GHz</td>
<td>$2\pi \times 200$ GHz</td>
<td>$2\pi \times 100$ THz</td>
</tr>
<tr>
<td>$\tau_c$</td>
<td>200 ns</td>
<td>5 – 100 ns</td>
<td>5 – 100 ns</td>
</tr>
<tr>
<td>$N$</td>
<td>1 torr</td>
<td>1 at.%</td>
<td>0.5 wt.%</td>
</tr>
<tr>
<td></td>
<td>$3 \times 10^{16}$ cm$^{-3}$</td>
<td>$1.4 \times 10^{20}$ cm$^{-3}$</td>
<td>$1.7 \times 10^{20}$ cm$^{-3}$</td>
</tr>
</tbody>
</table>
10.2 Layout of a solid-state laser

- **Laser rod**: Solid host material doped with the atoms of the active medium.
- **End mirror**
- **Lamp pump**: (flashlamp, arclamp, laser diodes)
- **Outcoupler**
- **Laser head** (reflective walls to concentrate the pump light)
- **Power supply**
- **Coolant in**
- **Coolant out**
- **Dual elliptical reflector**
- **Lamps**
- **Laser rod**
Maiman’s Ruby Laser
The most common solid-state laser is based on Nd atoms as dopands.

By changing the host material the laser wavelength and the thermal properties can be changed.

**Energy diagram of Nd:**

- Absorption bands
- Energy is transferred to the crystal (heating)
- Lasing

**Output (Nd:YAG):**
- **cw:** ≤ 1000 W
- **pulsed:** pulse energy ≤ 1 Joule
- **Q-switched:** 10 ns pulse duration
- **modelocked:** 100 ps pulse duration
Green Laser Pointer: a frequency doubled diode-pumped Nd:YVO$_4$ Laser!!
Titanium doped sapphire (Ti:Al₂O₃) laser

The jewel of ultrafast lasers!!

Figure 1
Historical Progress in Ultrashort Pulses

ADVANCES IN SHORT PULSE GENERATION

Pulsewidth (sec)

\[10^{-11}, 10^{-12}, 10^{-13}, 10^{-14}\]

Year


Nd:glass, Nd:YAG, Nd:YLF, Dye, S-P Dye, Diode, CW Dye, Color Center, CPM Dye, Cr:YAG, Cr:LiS(C)AF, Er:fiber (telecom), Cr:forsterite, Nd:forsterite, Ti:sapphire

w/Amplification & Compression (Low Rep. Rate)

Courtesy of E.P. Ippen
11. Fiber lasers

11.1 Introduction

Light can be guided (confined) in the core of optical fibers over great distances. This allows for large interaction lengths of light with an active medium that is doped into the fiber core.

Condition: $n_2 > n_1$

L ... $10^3$ km

Realizing large gain

Laser with resonator (many passes through the active medium)

Lens duct (unfolded resonator)

Fiber laser
11.2 Example: erbium-doped glass fibers

The wavelength of about 1550 nm is particularly interesting for applications in telecommunication.
Growth of Yb:HPFL SM
(near diffraction limited)

Power (W)

Year


3 10 20 35 50 100 500 1000 2000 3000 5000

10kW in 2010!
IPG Fiber Lasers

A single module can supply:
- 250, 400, 800, 1000+ W of laser power
- Wavelength of 1070nm (NIR)
- One 7 or 15 um fiber core
- 0.34-0.41mm*mrad beam divergence

T x H x D = 60 x 33 x 4.7 cm
Efficiency (DC) > 35%
Building blocks (modules) for HPFLs
11.3 Fiber-optic Communications

Why?

The carrier frequency of light ($\sim 10^{14} \text{ Hz}$) and subsequently the transmitted bandwidth is much larger than what can be achieved by electronics.
Fiber transmission line

- Transatlantic US - UK
- 560 Mb/s per fiber pair
- 80,000 simultaneous voice channels
- Repeaters 100 km apart

input signal

signal processing

transmitter

amplifier/repeater

receiver

signal processing

6000 km

InGaAsP diode laser
12. Chemical Lasers

12.1 Introduction

- population inversion is produced by a chemical reaction

\[ \text{A + BC} \rightarrow \text{AB} + \text{C*} \]

- electrical power supply is not needed
- airborne lasers
- first chemical laser: 1964

Examples:

<table>
<thead>
<tr>
<th>reaction</th>
<th>active medium</th>
<th>wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{F + D}_2 \rightarrow \text{DF*} + \text{D} )</td>
<td>DF</td>
<td>3.5 - 4.1 µm</td>
</tr>
<tr>
<td>( \text{Cl + HI} \rightarrow \text{HCl*} + \text{I} )</td>
<td>HCl</td>
<td>3.5 - 4.1 µm</td>
</tr>
<tr>
<td>( \text{H + Br}_2 \rightarrow \text{HBr*} + \text{Br} )</td>
<td>HBr</td>
<td>4.0 - 4.7 µm</td>
</tr>
<tr>
<td>( \text{F + H}_2 \rightarrow \text{HF*} + \text{H} )</td>
<td>HF</td>
<td>3.5 - 4.1 µm</td>
</tr>
<tr>
<td>( \text{I + O}_2* \rightarrow \text{I*} + \text{O}_2 )</td>
<td>I</td>
<td>1.31 µm</td>
</tr>
</tbody>
</table>
12.2 The chemical oxygen-iodine laser

**Chemical reaction:**

\[ \text{O}_2^{(1\Delta)} + I \leftrightarrow \text{O}_2^{(3\Sigma)} + I^* \]

**Steps:**

1. Generation of singlet oxygen
   \[ \text{Cl}_2 + \text{H}_2\text{O}_2 + 2\text{NaOH} \rightarrow \text{O}_2^{(1\Delta)} + 2\text{H}_2\text{O} + 2\text{NaCl} \]

2. Production of excited iodine
   \[ \text{O}_2^{(1\Delta)} + I \leftrightarrow \text{O}_2^{(3\Sigma)} + I^* \]

3. Lasing of excited iodine
schematic diagram of a chemical iodine laser

parameters

- MW output power
- wavelength 1.315 micron
- pulsed and cw

atmospheric absorption

1 km propagation in atmosphere