Introduction to Laser Material Processing
Outline

• Brief History
• Design of Laser cavity
• Stability
• Types of Lasers
Laser History

• 1917 - Albert Einstein: Theoretical prediction of stimulated emission
• 1946 - G. Meyer-Schwickerather: first eye surgery with light
• 1950 - Arthur Schawlow and Charles Townes: Emitted photons may be in the visible range
• 1954 - N.G. Basow, A.M. Prochorow, and C. Townes: ammonia maser
• 1960 - Theodore Maiman: first laser (ruby laser)
• 1964 - Basow, Prochorow, Townes (Nobel prize): quantum electronics
• 1970 - Arthur Ashkin: laser tweezers
• 1971 - Dénes Gábor (Nobel prize): holography
Optical Cavity Design: Frequency and length

- Total electric field, $E$, at any point will be determined by the interference of the $E$ fields from the various reflected waves.
- Assuming the phase of the $E$ field is same after traversing a distance $2L$:

$$E(x, t) = E_0 \cos(kx - \omega t)$$

$$E(x + 2L, t) = E(x, t)$$

$$k2L = m2\pi$$

$$2L = m\lambda$$

$$v_m = \frac{c/n}{\lambda} = m \frac{c}{2nL}$$

The output frequency is function of Refractive index and length.
Optical Cavity Design

- Basic designs components
  - Totally reflecting mirror
  - Partially reflecting mirror
  - Mirror materials
    - ZnSe, GaAs and CdTe for CO₂ lasers
    - BK7 fused Silica
  - Key parameters
    - R1, R2, L
  - Multiple configurations
Stability of Laser Cavity

• Laser cavity could have two configurations:
  – Stable
  – Unstable
  • If the cavity is unstable, the beam size will grow without limit, eventually growing larger than the size of the cavity mirrors and being lost
Stability of Optical Cavity

A general spherical resonator formed by two mirrors $M_1$ and $M_2$ separated by a distance $L = z_2 - z_1$ having radii of curvatures, $R_1$ and $R_2$, respectively

$$R(z) = z \left(1 + \frac{\pi^2 w_0^4}{\lambda^2 z^2}\right) = z + \frac{K}{z}$$

$$K = \frac{\pi^2 w_0^4}{\lambda^2}$$

If the beam waist is located at $z=0$, the beam size of the Gaussian beam at plane $z$, $w(z)$, is given by:

$$w(z) = w_0 \left(1 + \frac{\lambda^2 z^2}{\pi^2 w_0^4}\right)^{0.5}$$
Stability Analysis

\[ z_1 + \frac{K}{z_1} = -R_1; \quad z_2 + \frac{K}{z_2} = R_2 \]

\[ z_2 - z_1 = L \]

\[ z_2 = \frac{L(L - R_1)}{(2L - R_1 - R_2)} \]

\[ g_1 = 1 - \frac{L}{R_1}; \quad g_2 = 1 - \frac{L}{R_2} \]

\[ z_2 = \frac{L(1-g_2)g_1}{(g_1+g_2-2g_1g_2)}; \quad z_1 = -\frac{L(1-g_1)g_2}{(g_1+g_2-2g_1g_2)} \]

\[ K = \frac{L^2(1-g_1g_2)g_1g_2}{(g_1 + g_2 - 2g_1g_2)^2} \]
Stability Analysis

\[ w^2(z_1) = \frac{\lambda L}{\pi} \left( \frac{g_2}{g_1(1-g_1g_2)} \right)^{\frac{1}{2}} \]

\[ w^2(z_2) = \frac{\lambda L}{\pi} \left( \frac{g_1}{g_2(1-g_1g_2)} \right)^{\frac{1}{2}} \]

- Above equation gives
- \( g_1g_2=1 \) or \( g_1g_2=0 \) are unfeasible and analysis breaks down.
Stability analysis for Optical Cavity

- Ray transfer matrix analysis

\[
0 \leq \left(1 - \frac{L}{R_1}\right) \left(1 - \frac{L}{R_2}\right) \leq 1
\]

\[
g_1 = \left(1 - \frac{L}{R_1}\right)
\]

\[
g_2 = \left(1 - \frac{L}{R_2}\right)
\]
Plot of stability

• $0 \leq g_1 g_2 \leq 1$
Cavity Length

• The cavity length/width of aperture determines number of off-axis modes between the mirrors
  – \( L \) = cavity length
  – \( a \) = radius of aperture
  – \( \lambda \) = wavelength of laser radiation
  – \( n \) = number of fringes or off axis modes

\[
L + n\lambda = \frac{2a}{\lambda}
\]
Fresnel Number

• Using Pythagoras Theorem and ignoring higher order terms,

\[ a^2 + L^2 = (L + n\lambda)^2 \]
\[ a^2 = 2Ln\lambda \]
\[ n = \frac{a^2}{2L\lambda} \]

• \( n = \) Fresnel Number/2
• Total number of fringes observed if the back mirror is uniformly illuminated
Fresnel No. (Contd.)

- Low Fresnel number gives low-order mode
- Off axis oscillations are lost in diffraction
- A high Fresnel number cavity can be controlled by using mirror design
  - Flatter of Curved?

- Off axis modes define Transverse Electromagnetic Mode
Types of Lasers

• Most of the lasers can be classified into following categories
  – Gas lasers (CO$_2$, He-Ne, Excimer)
  – Solid state lasers (Ruby, Nd:YAG, Fiber)
  – Diode lasers
  – Dye lasers
  – Ultra-short pulsed lasers
CO$_2$ Lasers

• The traveling photon formed due to energy loss or collision:
  – It can take molecule $10^00$ to $00^01$
  – Get diffracted
  – Strike the excited molecule at higher energy

• The molecule at higher energy will emit photon of identical wavelength in same phase and direction
KrF Excimer Laser at IIT Bombay

• No oscillator
• Very High Powers (0.2 J/pulse on 20 ns pulse width)
• Expensive
Fiber Laser at IIT Bombay

- 100 W CW
- Frequency 100 KHz
- Pulse width of the order of μs
3 kW Fiber Laser @ IITB
Industrial Lasers-Slow Flow

• Slow Flow Lasers
  – Cooling through walls of the cavity

• Analysis of cooling in slow flow lasers
  – Heat generated/length = \( Q\pi r^2 \)
  – Heat removed/length = \(-2\pi kr(dT/dr)\)
  – \( Q \) = rate of volumetric heat flow
Analysis for Slow Flow Lasers

\[
\int_0^a dT = \int_{r} \frac{Qr}{2k} dr
\]

*MaxTemp @ r = 0, T max = Taxis*

\[
Taxis = \frac{Qa^2}{4k} + Tc
\]

*Volumetric Heat,*

\[
\eta Q = \frac{P}{\pi a^2 L}
\]

\[
P = 4\pi \eta kL(T_{\text{max}} - Tc)
\]
Slow Flow-Waveguide Cooling

• A variation of conduction route
  – Thin slit between electrodes is the laser cavity
  – Laser is wave guided within the narrow passage

• Analysis of cooling in slow flow lasers
  – Heat generated in cross-section A, and thickness, \( x = QAx \)
  – Heat removed by conduction = \(-kA(dT/dx)\)
Waveguide Analysis

\[
\int_{T}^{T_c} dT = \int_{x}^{g} -\frac{Q_x}{k} \, dx
\]

MaxTemp @ \(x = 0\), \(T_{max} = T_{axis}\)

\(T_{axis} = \frac{Qg^2}{2k} + T_c\)

Volumetric Heat,

\(\eta Q = \frac{P}{A2g}\)

\(P = 4 \frac{A}{g} \eta k (T_{max} - T_c)\)
Slow-Flow Lasers

- Cooling efficiency governs the output power
- 50W/m - 80 W/m output power
- Good mode for rod systems
- Elliptical profile and arrayed beams for wave guide
Fast Axial Flow Lasers

- Fast axial flow lasers
  - Gas flow rates 300-500 m/s in discharge zone
  - Cavity length is of low Fresnel number
  - Good for high power compact lasers
  - Cooling is done by the flowing gas during its time of interaction in discharge zone

Courtesy: Steen 3rdEdition
Analysis – Fast Axial Flow

\[ \delta Q = -Q \cdot dt \]

*where* \( Q = \text{Volumetric heat (J/m}^3) \)

\[ Q = \text{rate of volumetric heat generation (W/m}^3) \]

\[ \int_{T}^{T_c} \rho C dT = -\int_{x}^{L} \frac{Q \cdot dx}{V} \]

\[ \eta Q = \frac{P}{AL} \]

\[ P = \eta \rho AVC(T_{\text{max}} - T_c) \]
Fast Axial Flow Lasers

- Power is proportional to area and velocity
- Mode number $a^2/L \lambda \sim A/L \lambda$ is typically very high and difficult to focus finely
- Very high power generation
  - $650 \text{ W/m}$
Transverse Flow Lasers

• For very high powers lasers are convectively cooled in transverse direction

• Asymmetric beam power due to heating of the gas while traversing the lasing space

• Asymmetric beam power is obtained

• UTRC 25 KW laser, MLI laser
UTRC Laser
Solid State Lasers

• Solid state lasers have three key design features
  – Pumping power for lasing
  – Cooling
  – Avoiding distortion or breakage due to thermal load

• Nd-YAG
  – Pumped by flash lamp or diode
  – Nd\(^{3+}\) ions in YAG rod
  – Q switching for pulse rates (0-50 kHz)
    • Spoils lasing oscillation in controlled way
    • Mechanical chopper, bleachable dye, optoelectric shutter, acousto-optic switch
Nd-YAG Construction

- Nd-YAG laser can be passed through barium borate (BBO) or lithium niobate (LBO) crystals can yield 530 nm
- This process is called frequency doubling
Diode Pumped Solid State Lasers

- Tiny fraction of the power is absorbed by Nd$^{3+}$
- Waste heat causes distortion
- Diode lasers have high wall plug efficiency and good coupling with Nd$^{3+}$
Diode Lasers

- Similar to LED
- Difference in Fermi energy in conduction and valence band at p-n junction
- Photons can be emitted
- Stacked configuration
High Power Diode Lasers
Diode Pumped Fiber Lasers

• A laser in which the active gain medium is an optical fiber doped with rare-earth elements
  – Erbium, ytterbium, neodymium, dysprosium, praseodymium, and thulium
• Doped fiber amplifiers provide light amplification without lasing
• Pumped by diode lasers
Fiber Laser

- Input light
- Double clad
- Rare earth doped core
- Laser output from core
- Low divergence single mode beam
Advantages

- High beam quality
- High wall plug efficiency
- Portability
- Long life
### Wavelengths of Solid State Lasers

<table>
<thead>
<tr>
<th>Laser Type</th>
<th>Wavelengths accessible with common solid state lasers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wavelength (μm)</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>Holmium-YAG</td>
<td></td>
</tr>
<tr>
<td>Erbium-Glass</td>
<td></td>
</tr>
<tr>
<td>Nd-YAP</td>
<td>*</td>
</tr>
<tr>
<td>Nd-YAG</td>
<td>***</td>
</tr>
<tr>
<td>Nd-YLF</td>
<td>*</td>
</tr>
<tr>
<td>Nd-Silica Glass</td>
<td>*</td>
</tr>
<tr>
<td>Nd-Phosphate Glass</td>
<td>*</td>
</tr>
<tr>
<td>Ti-Sapphire</td>
<td></td>
</tr>
<tr>
<td>Cr-Alexandrite</td>
<td>***</td>
</tr>
<tr>
<td>Cr-Ruby</td>
<td></td>
</tr>
</tbody>
</table>

* approximate region of principle wavelengths.
Functioning of Excimer Laser

- Excitation by 35-50 kv pulse
- Current density up to 1 kA/cm²
- Optics
  - Fused silica,
- Gas 4-5 MPa
Excimer Laser Reactions

Pumping (Microwave or gas discharge is used),
\[ e + Kr \rightarrow Kr^+ + e + e \]
Positive inert gas ion formation,

\[ e + Kr \rightarrow Kr^* + e \]
Inert gas in metastable condition,

\[ e + F_2 \rightarrow F^- + F^+ \]
Negative halogen ion formation,

\[ Kr^* + F^- + M \rightarrow KrF^* + M \]
KrF production,
\[ Kr^* + F_2 \rightarrow KrF^* + F \]

Stimulated emission,
\[ KrF^* + hv \rightarrow Kr + F + 2hv \] (248 nm) -laser emission
Ultra Short Pulsed Lasers

• Ultrashort Pulse Lasers: Most of the lasers operate in a CW mode or pulsed mode of the order of 100 picoseconds by either q-switching or mode locking.

• Ultrashort pulsed are lasers which have femtosecond duration pulses. This ultrashort pulse duration enables very high peak powers ($\sim 10^{15} \text{ W/cm}^2$).

• Many methods have been developed for creating ultrashort pulse laser beams. However, one of the basic methods is chirped pulse amplification.
  
  – It is known that the spectrum of the laser beam is inversely proportional to the pulse duration. Hence, a laser gain medium with broad continuous spectrum is essential for ultrashort pulse.
  
  – The active media that can support femtosecond lasers are Ti-Sapphire (6 fs), Nd:Glass (100 fs), Yb:Glass, Yb:YAG, Cr:YAG, and dye.
  
  – The generation starts from mode locking which results in a frequency of 100 MHz.
Chirped Pulse Amplification

Oscillator → Stretcher → Amplifier → Compressor
Comparison Between Lasers - Power

![Graph comparing laser power](image)

- **Excimer**
- **Nd-YAG**
- **YAG2**
- **HF**
- **CO**
- **CO₂**
### Efficiency-1

<table>
<thead>
<tr>
<th>Table 1.2</th>
<th>Efficiency of main types of industrial lasers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td><strong>Wavelength µm</strong></td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>10.6</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>5.4</td>
</tr>
<tr>
<td>Nd-YAG</td>
<td>1.06</td>
</tr>
<tr>
<td>Nd-Glass</td>
<td>1.06</td>
</tr>
<tr>
<td>Excimer (KrF)</td>
<td>0.249</td>
</tr>
</tbody>
</table>
Capital Cost

- 1987 data
Operating Cost

- 1987 data
## Comparison with Fiber

Properties of various lasers (courtesy IPG Photonics)

<table>
<thead>
<tr>
<th>Properties</th>
<th>Fiber Laser</th>
<th>Nd:YAG</th>
<th>CO$_2$</th>
<th>Disc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Plug Efficiency</td>
<td>30%</td>
<td>~ 5%</td>
<td>~10%</td>
<td>15%</td>
</tr>
<tr>
<td>Output Powers</td>
<td>to 50kW</td>
<td>to 6kW</td>
<td>to 20kW</td>
<td>to 4kW</td>
</tr>
<tr>
<td>BPP (4/5 kW)</td>
<td>&lt; 2.5</td>
<td>25</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Life</td>
<td>100,000</td>
<td>10,000</td>
<td>N.A.</td>
<td>10,000</td>
</tr>
<tr>
<td>Cooling</td>
<td>Air/water</td>
<td>water</td>
<td>water</td>
<td>water</td>
</tr>
<tr>
<td>Floor Space (4/5 kW)</td>
<td>&lt; 1 sq. m</td>
<td>6 sq. m</td>
<td>3 sq. m</td>
<td>4 sq. m</td>
</tr>
<tr>
<td>Operating Cost</td>
<td>$21.31</td>
<td>$38.33</td>
<td>$24.27</td>
<td>$35.43</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Not Required</td>
<td>Often</td>
<td>Required</td>
<td>Often</td>
</tr>
</tbody>
</table>
Market Share
Laser-Summary

• Types of Lasers
• Optical cavity Design
• Cooling
• Comparative study