Laser Physics 20.
Laser systems and applications

Maák Pál

Atomic Physics Department
Laser systems and applications

Industrial laser market

<table>
<thead>
<tr>
<th>Industrial laser systems</th>
<th>m$</th>
<th>pc</th>
<th>$/pc</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  CO₂ flowing</td>
<td>963</td>
<td>5500</td>
<td>175091</td>
</tr>
<tr>
<td>2  Excimer</td>
<td>468</td>
<td>527</td>
<td>888046</td>
</tr>
<tr>
<td>3  Solid-state lamp-pumped</td>
<td>315</td>
<td>4890</td>
<td>64417</td>
</tr>
<tr>
<td>4  Fiber</td>
<td>189</td>
<td>6325</td>
<td>29881</td>
</tr>
<tr>
<td>5  Solid-state diode-pumped</td>
<td>134</td>
<td>4915</td>
<td>27263</td>
</tr>
<tr>
<td>6  CO₂ sealed</td>
<td>93</td>
<td>19050</td>
<td>4882</td>
</tr>
</tbody>
</table>

Total number of CO₂ and solid-state laser units is 24550 and 9805, resp.

Source: Laser Focus World, January 2008
Laser systems and applications

Main application fields of laser systems in the industry

Material (metal) processing: cutting, welding, hole drilling, trimming, heat treatment, surface alloying

Production of semiconductor and microelectronic components: lithography, inspection and control

Cleaning and marking of metal, semiconductor and nonmetals

Micromachining

Rapid prototyping
Laser systems and applications

Wavelength of different laser systems

<table>
<thead>
<tr>
<th>Laser systems</th>
<th>$\lambda$ [\mu m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>10.6</td>
</tr>
<tr>
<td>Excimer</td>
<td>0.157 - 0.35</td>
</tr>
<tr>
<td>Solid-state</td>
<td></td>
</tr>
<tr>
<td>Nd$^+$:YAG</td>
<td>1.064</td>
</tr>
<tr>
<td>Er-YAG</td>
<td>2.94</td>
</tr>
<tr>
<td>Ho-YAG</td>
<td>2.1</td>
</tr>
<tr>
<td>Nd-YAP</td>
<td>1.079</td>
</tr>
<tr>
<td>Nd-YLF</td>
<td>1.053, 1.047, 1.31</td>
</tr>
<tr>
<td>Fiber</td>
<td>~1.07, 1.55</td>
</tr>
</tbody>
</table>
Laser systems and applications

**CO₂ laser with slow axial flow**

- Laser wavelength: 10.6 µm

**Parameters:**
- Gas pressure: 10-20 torr, flow velocity: 20 l/minute
- Flow velocity of the coolant fluid: 7 l/minute
- Achievable power/length: 30-50 W/m
- >100 W power can be achieved by folded resonator

**Gas mixture:**
- CO₂ (10-20%),
- N₂ (10-20%),
- He (remainder)

**Applications:**
- Resistor trimming
- Cutting ceramic plates (electronics industry)
- Welding thin (<1 mm) metal sheets
Laser systems and applications

**CO₂ laser with fast axial flow** 10.6 µm

The heat is removed by removing the hot mixture from the discharge region, the mixture is then cooled outside the tube by a suitable heat exchanger, and regenerated by a suitable catalyst (CO + O₂ → CO₂):

- flow velocity of the gas mixture: 50 m/s
- almost sealed-off operation
- excitation by DC, AC, or RF
- 0.5 - 1 kW/m, up to 10 kW

**Applications:**

- cutting and welding of metals
Laser systems and applications

Sealed-off CO\textsubscript{2} laser 10.6 µm

Problem:
Because of the dissociation of the CO\textsubscript{2} molecule, the lifetime is only a few minutes in a sealed-off discharge with the usual gas mixture.

Solution:
CO → CO\textsubscript{2} regeneration with 1% H\textsubscript{2}, Xe or a hot (300 °C) Ni cathode acting as a catalyst, >40000 hour lifetime feasible

Micromachining (and medical applications).

<table>
<thead>
<tr>
<th>Model</th>
<th>Max Laser Power</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS-40</td>
<td>40W</td>
<td>70</td>
</tr>
<tr>
<td>RS-50</td>
<td>50W</td>
<td>1000</td>
</tr>
<tr>
<td>RS-60</td>
<td>60W</td>
<td>1200-1250</td>
</tr>
<tr>
<td>RS-80</td>
<td>80W</td>
<td>1600</td>
</tr>
<tr>
<td>RS-100</td>
<td>100W</td>
<td>16000-1800</td>
</tr>
<tr>
<td>RS-130</td>
<td>120W</td>
<td>1800-2000</td>
</tr>
</tbody>
</table>
Laser systems and applications

Transverse-flow CO$_2$ laser

10.6 µm laser mirrors

electrodes

power supply

+ -

laser beam
gas circulation

ventilator
direction of gas flow

direction of discharge current

optical axis

Pressure: ~100 torr, the direction of the discharge is perpendicular to the resonator axis
Power: 1-20 kW, but the quality of the beam is worse

Applications: welding, surface hardening, surface metal alloying
Laser systems and applications

Excimer (exciplex) laser

157 – 351 nm UV

excimer - 'excited dimer',
exciplex - 'excited complex'.

Typical laser material:
an inert gas - Ar, Kr, or Xe
and a halogen - fluorine or chlorine

A pseudo-molecule called an excimer (or in case of noble gas halides, exciplex) is created, which exists only in the excited state. The transition by light emission to the non-bonded lower level provides laser light in the UV range.
Laser systems and applications

Excimer (exciplex) laser (cont.) 157 – 351 nm UV

Typical parameter:

gas mixture: 4-5 mbar halogen, 30-500 mbar noble gas and He or Ne buffer gas

pulsed mode, pumping by electric discharge,

\[ \tau_p = 10 - 50 \text{ ns}, \]

\[ E_p = 0.1 - 4 \text{ J}, \quad f_{\text{rep}} \text{ up to a few kHz} \]

\[ P_{\text{avr}} = 50 - 200 \text{ W} \]

lifetime: >10^9 pulses,

\[ \eta = 0.2 - 2 \% \]
Excimer (exciplex) laser (cont.)  157 – 351 nm UV

Applications:

- Lithography - generation of very fine patterns with photolithographic methods, e.g. in semiconductor chip production
- Material processing with laser ablation - absorption lengths are very short in many materials (few µm) → moderate pulse fluence is sufficient for ablation (few J/cm²)
- Laser marking and microstructuring of glasses and plastics
- Fabrication of fiber Bragg grating
- Pumping other lasers, e.g. certain dye laser
- (Medicine)
Laser systems and applications

Excimer (exciplex) laser application examples 157 – 351 nm UV

Lithography - Moore’s Law: the number of transistors on a chip should double every two years.

Chip fabrication steps of photolithography: 1. projecting the image of an original mask onto a light-sensitive material (photoresist), 2. chemically etching the resulting pattern into a semiconductor substrate.

Light sources of optical lithography:
- visible conventional light sources,
- ultraviolet mercury lamps,
- 248 nm krypton fluoride lasers,
  193 nm argon fluoride laser from ~2001, initial features size: 130 nm.

The introduction of 157 nm molecular fluorine laser was not successful because of problems with the calcium fluoride optics.
Laser systems and applications

Excimer (exciplex) laser application examples  157 – 351 nm UV

Lithography (cont.)

Instead of lowering the wavelength technological tricks:

*immersion lithography* - the 193 nm light is directing through water -

\[ n (\lambda = 226 \text{ nm}) = 1.395 \ (0^\circ \text{C}, 1 \text{ atm}), \]

\[ NA = n \cdot \sin(\Theta), \quad \text{spotsize} = 0.6 \frac{\lambda}{NA} \]

→ sharper focus, allows fabrication of circuits with a 45 nm half-pitch,

*double-patterning* can shrink the half-pitch to 32 nm in the new generation of fabrication lines coming on line this year.

Next step? 13.5 nm EUV light source?
Laser systems and applications

Excimer (exciplex) laser **micromachining** examples  157 – 351 nm UV

Stripping of fine gauge wires for hard disk drives. Very clean insulation removal, no loose particles and no damage to the core conductor. This is a gold/copper 47 gage wire, 50 microns in diameter with 8 microns of polyurethane insulation.

Ceramic chip capacitor marking, very small character sizes, high throughput, good contrast on most ceramics. Excimer marking is normally integrated into an automated test handler.

75 micron thick polyimide with 50 micron diameter holes.

Fiber Bragg Gratings written into the core of single mode fibers with a KrF or ArF excimer laser.
Laser systems and applications

Excimer (exciplex) laser micromachining examples 157 – 351 nm UV

Applications include marking on contact lenses, flat panel displays. 2D matrix code is shown that is used on flat panel displays and other high value glass substrates. Glass marks are achieved using the excimer laser at 193 nm. Dot size is 100 microns

Aerospace wire marking for Tefzel and Teflon (fluoropolymer) wire. The excimer laser marks are high contrast permanent marks that cannot be removed with solvents. No reduction in insulation strength.

ZnSe lens array, pitch 6 µm.

8 µm width and 8 µm pitch grooves in polycarbonate

Spiral slots in a Polyimide tubes (prototype polymer stent) ~ 0.8 mm dia.
Laser systems and applications

Nd:YAG laser 1.06 µm

Lamp pumped $\eta = 1 - 3\%$, LD pumped $\eta = \sim 10\%$, max. power 2.4 kW

Applications:

- **Drilling**: 50-100 W pulsed
  
  $E_p = 5 - 10$ J, $t_p = 1 - 10$ ms, $f_{rep} = 10 - 100$ Hz

- **Welding**: 2 kW coupled into glass fiber, flexible to use in robotics

- **Military applications**: laser range finder, target designator
  
  $E_p = 100$ mJ, $t_p = 5 - 20$ ns, $f_{rep} = 1 - 20$ Hz

- **$2\nu$ (532 nm)** – solid state alternative of Ar-ion laser, $3\nu$ (355 nm) and $4\nu$ (266 nm) systems - solid state alternative of excimer lasers
Laser systems and applications

Nd:YAG laser military applications 1.06 μm

Laser range finder - Time of flight (TOF) principle: measuring the running time of a short (ns) pulse reflected from the target ranges of 2 km up to 25 km

Accuracy: determined by the rise or fall time of the laser pulse and the speed of the receiver. Determination of ranges within a few millimeters are achievable.

Velocity measurement by using the Doppler-principle

Protection – laser absorbing paint
Laser systems and applications

Nd:YAG laser military applications 1.06 µm

Laser target designation - by the laser guidance technique

The target is illuminated by the (coded) pulse train of the laser

The missile, bomb, etc. detects the reflected or scattered laser light, determines the direction and follows the target.

Protection: designation of a phantom target.

Problems: weather conditions.

First laser guided bomb - Texas Instruments BOLT-117, 1967
Laser systems and applications

Fiber lasers

Active material – optical fiber doped with rare-earth elements such as erbium ($\lambda_{\text{pumping}} = 1.48 \, \mu\text{m}$, $\lambda_{\text{laser}} = 1.55 \, \mu\text{m}$), ytterbium ($\lambda_{\text{pumping}} = 0.95 \, \mu\text{m}$, $\lambda_{\text{laser}} = 1.07-1.09 \, \mu\text{m}$), neodymium, dysprosium, praseodymium, and thulium.

DCF - double-clad fiber

- Core – gain medium, high refractive index
- Inner cladding layer carries the pump beam, smaller refractive index
- Outer cladding – medium refractive index

Resonator

Monolithic construction by fusion splicing different types of fiber, instead of mirrors fiber Bragg gratings (FBG’s) are used

Pump beam has to be incoupled to the fiber.
Laser systems and applications

Fiber lasers

1.07, 1.55 μm

FBG’s instead of mirrors – a periodic variation of the refractive index of the fiber core, $\lambda_{\text{refl}}$ depends on the period, the reflectivity depends on $\Delta n$

FBG structure, with refractive index profile and spectral response
Laser systems and applications

Fiber lasers  
1.07, 1.55 µm

Advantages of application:

- **Light is already coupled into a flexible fiber, it can be easily delivered to a movable focusing element.** This is important for laser cutting, welding, and folding of metals and polymers.
- **High output power (few kW):** high optical gain because of the long active region (km)
- Efficient cooling because of the fiber's high surface area to volume ratio.
- High quality optical beam
- High efficiency, $\eta = 25 - 30\%$
- Compact size: the fiber can be bent and coiled to save space.
- Reliability: high vibrational stability, extended lifetime, and maintenance-free turnkey operation.

Main applications: material processing, optical communication (medicine).
Laser systems and applications

Laser-Material interactions

Laser-material interactions - coupling of optical energy into a solid.

Result: vaporization; ejection of atoms, ions, molecular species, and fragments; shock waves; plasma initiation and expansion; and a hybrid of these and other processes.

Absorption and reflection are not independent (complex refraction index), in metals the penetration depth is only 1-2 atom diameters.
Laser systems and applications

Surface reflectivity – wavelength dependence

\[ \tilde{n} = n' + jn'', \quad R_\perp = \frac{(1 - n')^2 + n''^2}{(1 + n')^2 + n''^2}, \quad E = E_0 e^{-2m^*d/\lambda} = E_0 e^{-\beta d} \]

<table>
<thead>
<tr>
<th>material</th>
<th>( n'' )</th>
<th>( n' )</th>
<th>( R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>8.5</td>
<td>1.75</td>
<td>0.91</td>
</tr>
<tr>
<td>Cu</td>
<td>6.93</td>
<td>0.15</td>
<td>0.99</td>
</tr>
<tr>
<td>Fe</td>
<td>4.44</td>
<td>3.81</td>
<td>0.64</td>
</tr>
<tr>
<td>Mo</td>
<td>3.55</td>
<td>3.83</td>
<td>0.57</td>
</tr>
<tr>
<td>Ni</td>
<td>5.26</td>
<td>2.62</td>
<td>0.74</td>
</tr>
<tr>
<td>Pb</td>
<td>5.4</td>
<td>1.41</td>
<td>0.84</td>
</tr>
<tr>
<td>Sn</td>
<td>1.6</td>
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<tr>
<td>Ti</td>
<td>4</td>
<td>3.8</td>
<td>0.63</td>
</tr>
<tr>
<td>W</td>
<td>3.52</td>
<td>3.04</td>
<td>0.58</td>
</tr>
<tr>
<td>Zn</td>
<td>3.48</td>
<td>2.88</td>
<td>0.58</td>
</tr>
<tr>
<td>glass</td>
<td>0</td>
<td>1.5</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Complex refractive index and reflectivity (\( \perp \)) of different materials at \( \lambda = 1.06 \, \mu m \) (Nd:YAG)

Reflectivity of different metals vs. the wavelength

Laser systems and applications

Surface reflectivity – angle, polarization and temperature dependence

Reflectivity of steel for polarized 1.06 µm light (Nd:YAG)

Reflectivity vs. temperature (1.06 µm)

Laser systems and applications

Surface reflectivity – dependence on surface finish and coating

The emissivity $\varepsilon$ is a non-dimensional property:

\[
\text{energy emitted from a surface} / \text{energy emitted by a black surface at the same temperature}
\]

For any given wavelength and direction the emissivity is equal with the absorptivity (absorbed ratio of incoming radiation) – known as Kirchoff’s law.

Spectral, normal emissivity for aluminum with different surface finishes

Laser systems and applications

Process map for various laser applications in material processing

Laser materials processing involves a wide range of power densities, interaction times, and transport phenomena, and deals with objects of sizes ranging from nanometers to meters. Figure presents a picture of the operational regimes and associated transport phenomena for various laser processing techniques.

Laser systems and applications

Application example – cutting

Main advantages:
- the lack of physical contact (there is no cutting edge which can become contaminated by the material or contaminate the material),
- there is no wear of the laser,
- cutting of complex shape,
- high precision, tolerances between 0.05 – 0.1 mm

The cutting head combines the focusing optics and the gas nozzle. The device includes the mountings, adjustments, cooling and the inlet connections for gas and sometimes also the water supply.

Laser systems and applications

Laser cutting – relative motion of the cutting head and the workpiece

Flying optic laser cutting geometry for flat sheets. (Source: Petri Metsola, Lappeenranta University of Technology, Finland)

Play: 5axis1(500k).wmv

The cutting head is fixed above the moving workpiece (Source: J. C. Ion, Laser processing of Engineering Materials)
Laser systems and applications

Cutting methods

1. Laser fusion cutting (or inert gas melt shearing):

A narrow penetrating cavity is formed → melts surrounding material → removal of the melting material by the shearing action of a coaxial jet of inert assist gas.

Materials: metals, alloys, thermoplastics, some ceramics, glasses

Inert gas: N₂ and Ar, responsible also for shielding the heated material from the surrounding air

Cut edge: free of oxides

Laser systems and applications

Cutting methods

2. Laser oxidation cutting (or active gas melt sharing)

Reactive gas: \( \text{O}_2 \) or air

Additional exothermic reaction of the oxygen with the material → less laser pulse energy, higher cutting speed.

Oxide layer formation on the cutting edge increases the absorption.

Materials: ferrous alloys, thermoset polymers

Cutting methods

3. Laser vaporization cutting
Material is heated rapidly to the vaporization temperature → material removal by an inert gas jet.
Material: PMMA, wood

4. Chemical degradation (or cold cutting)
The high photon energy (UV lasers) is enough to break chemical bonds and to form new Compounds.
Materials: wood, thermoset polymers, elastomers and some composites.

Laser systems and applications

Cutting methods

5. Scribing
The objective is to create a groove or a series of blind holes at the workpiece surface. Low energy, high power density pulses cause vaporization with a restricted heat affected zone (HAZ). The notches serve to raise stress locally and the material can be fractured along a defined line under subsequent bending.

Materials: some ceramics (alumina), some glasses and composites. Very high processing rates are possible.


1 mm thick AlN scribed and broken

Scribed and broken 1 mm thick Al₂O₃-substrate
Laser systems and applications

Cutting methods

6. Special - Laser MicroJet® Technology (LMJ)

- Laser is focused in water jet nozzle
- Laser is entirely contained within the water jet as a parallel beam
- Laser is guided by total internal reflection, similar in principle to an optical fiber
Laser systems and applications

Cutting methods

6. Special - Laser MicroJet® Technology (LMJ)

http://www.youtube.com/watch?v=2jm4_HikMgk