Laser Physics 20.

Laser systems and applications

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Laser systems and applications

Industrial laser market

	Industrial laser systems	m$	pc	$/pc
1	CO_2 flowing	963	5500	175091
2	Excimer	468	527	888046
3	Solid-state lamp-pumped	315	4890	64417
4	Fiber	189	6325	29881
5	Solid-state diode-pumped	134	4915	27263
6	CO_2 sealed	93	19050	4882

Total number of CO_2 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

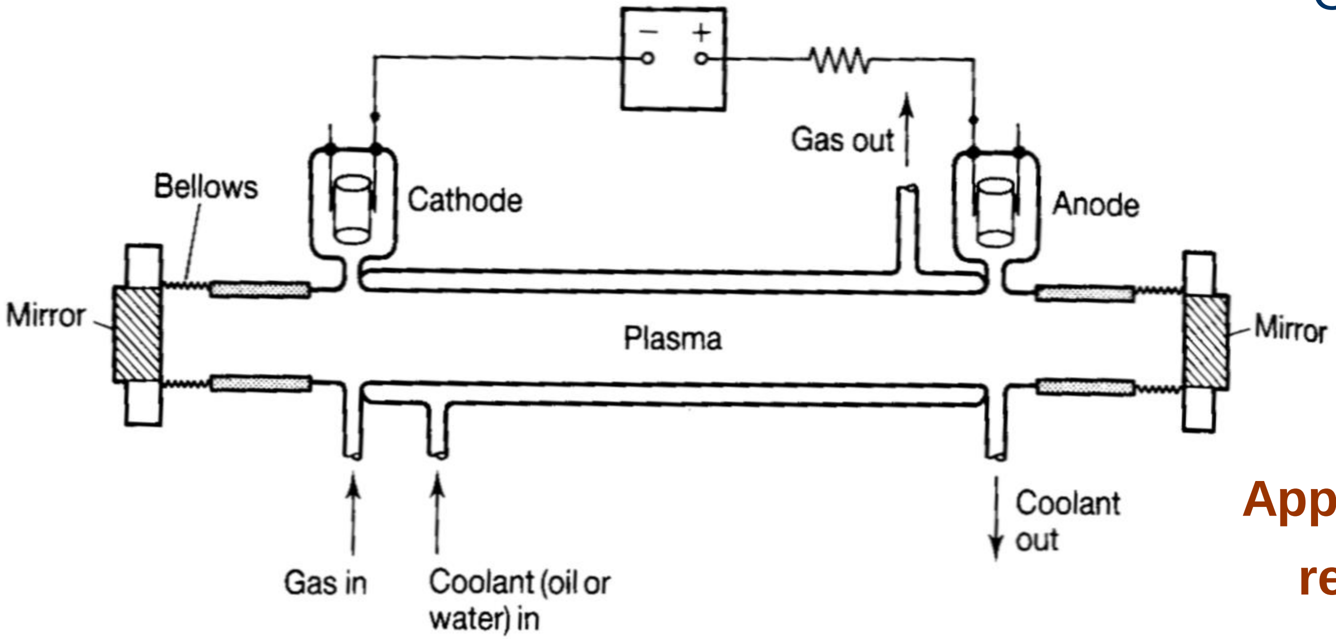
Laser systems and applications

Wavelength of different laser systems

Laser systems	λ [µm]
CO_2	10.6
Excimer	0.157- 0.35
Solid-state	
Nd^+:YAG	1.064
Er-YAG	2.94
Ho-YAG	2.1
Nd-YAP	1.079
Nd-YLF	1.053, 1.047, 1.31
Fiber	~1.07, 1.55

Laser systems and applications

CO$_2$ laser with slow axial flow **10.6 µm**



Gas mixture:

- CO_2 (10-20%),
- N_2 (10-20%),
- He (remainder)

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

Applications:

- **resistor trimming**
- **cutting ceramic plates (electronics industry)**
- **welding thin (<1 mm) metal sheets**

Laser systems and applications

CO_2 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 ($CO + O_2 \rightarrow CO_2$):

- 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_2 laser **10.6 µm**

Problem:

Because of the dissociation of the CO_2 molecule, the lifetime is only a few minutes in a sealed-off discharge with the usual gas mixture.

Solution:

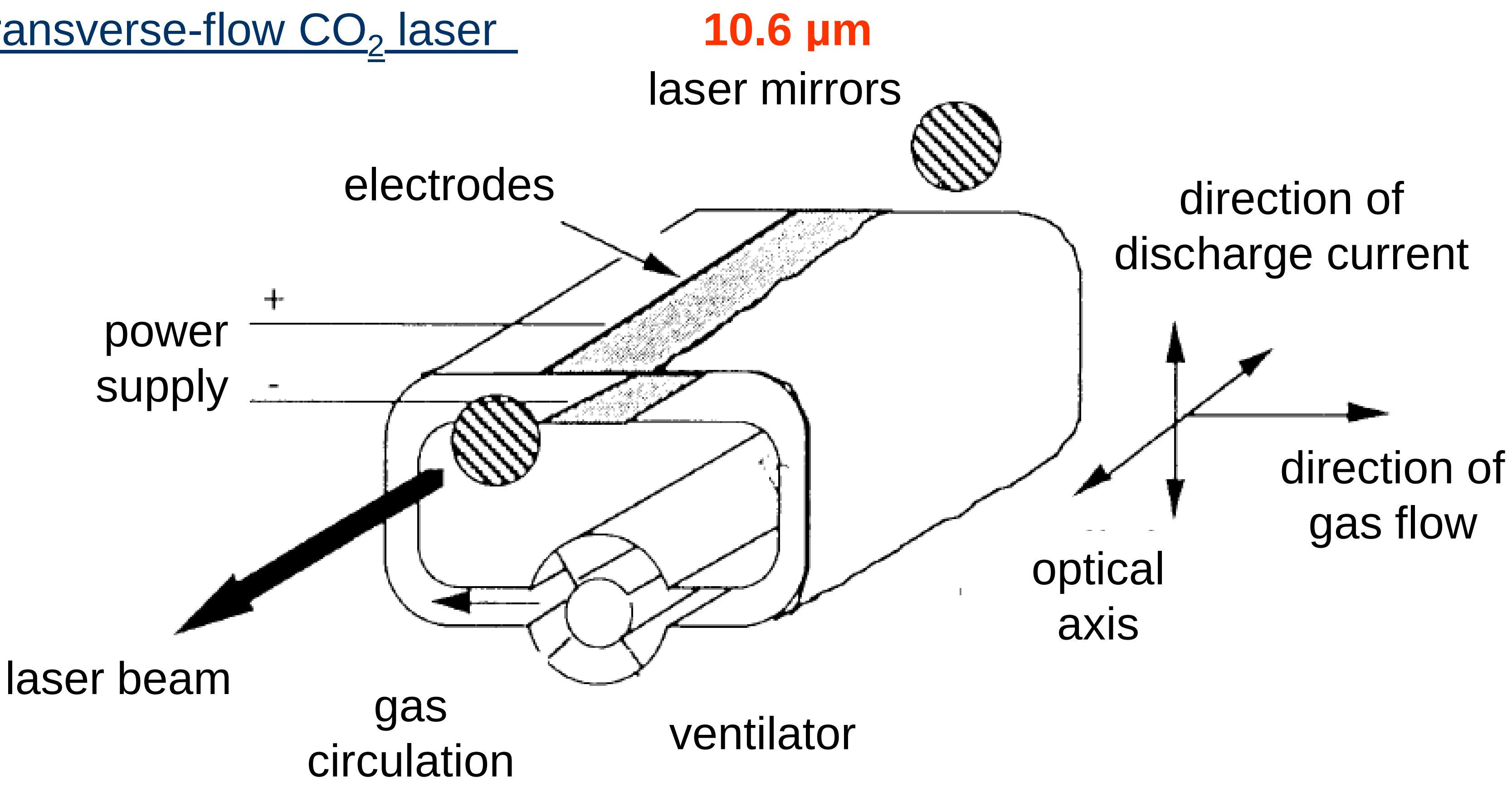
$CO \rightarrow CO_2$ regeneration with 1% H_2, Xe or a hot (300 ^oC) Ni cathode acting as a catalyst, >40000 hour lifetime feasible

Micromachining (and medical applications).

Model	Max Laser Power	Length (mm)
RS-40	40W	70
RS-50	50W	1000
RS-60	60W	1200-1250
RS-80	80W	1600
RS-100	100W	16000-1800
RS-130	120W	1800-2000

Laser systems and applications

<u>Transverse-flow CO_2 laser</u>

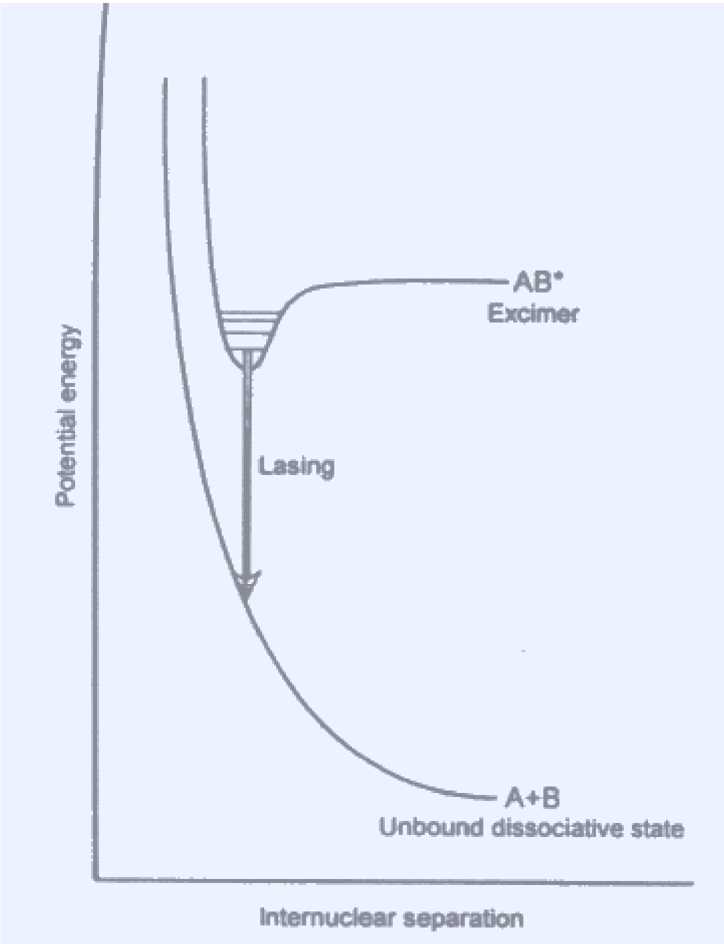


Pressure: ~100 torr, the direction of the discharge is perpendicular to the resonator axis
Power: 1-20 kW, but the quality of the beam is worse
Applications: welding, surface hardening, surface metal alloying

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,

τ_p = 10 – 50 ns,

E_p = 0.1- 4 J, f_{rep} up to a few kHz

P_{avr} = 50 – 200 W

lifetime: >10^9 pulses,

η = 0.2 – 2 %

Excimer	Wavelength
F_2 (fluorine)	157 nm
ArF (argon fluoride)	193 nm
KrF (krypton fluoride)	248 nm
XeBr (xenon bromide)	282 nm
XeCl (xenon chloride)	308 nm
XeF (xenon fluoride)	351 nm

Laser systems and applications

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/cm^2)**
- **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

<u>Excimer (exciplex) laser application examples</u> **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,

<u>193 nm argon fluoride laser</u> 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 (λ = 226 nm) = 1.395 (0°C, 1 atm),

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

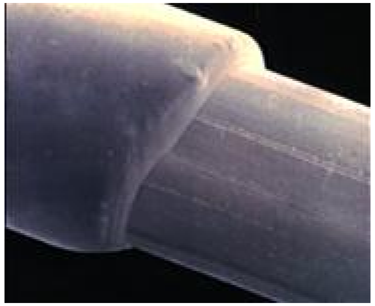
$\rightarrow$ sharper focus, allows fabrication of circuits with a *45 nm half-pitch*,

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**?**

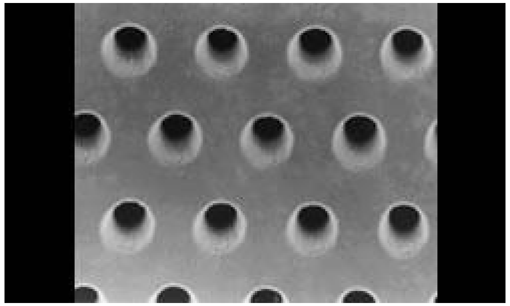
Laser systems and applications

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

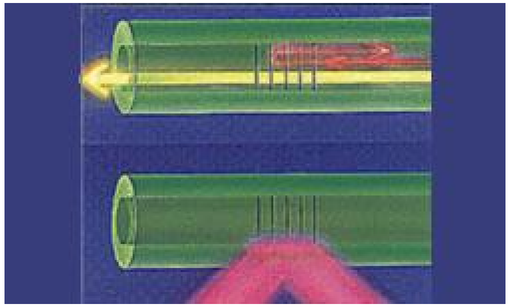


Stripping of fine gauge wires for hard disk drives. Very clean insulation removal, no loose particles and no damage to the core conductor. This is a gold/copper 47 gage wire, 50 microns in diameter with 8 microns of polyurethane insulation.

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.



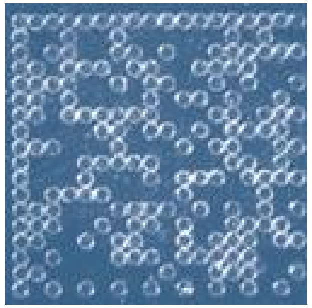
75 micron thick polyimide with 50 micron diameter holes.



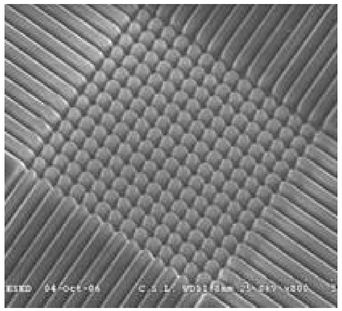
Fiber Bragg Gratings written into the core of single mode fibers with a KrF or ArF excimer laser.

Laser systems and applications

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

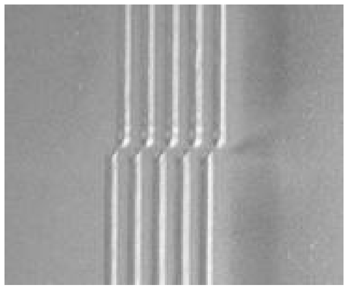


Applications include marking on contact lenses, flat panel displays. 2D matrix code is shown that is used on flat panel displays and other high value glass substrates. Glass marks are achieved using the excimer laser at 193 nm. Dot size is 100 microns

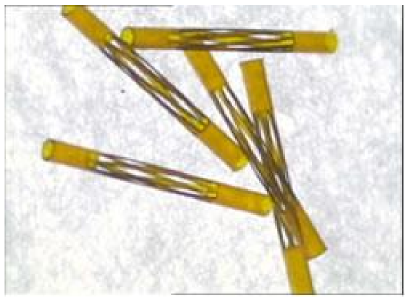


ZnSe lens array, pitch 6 µm.

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.



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 η = 1 – 3 %, LD pumped η = ~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
- **2ν (532 nm) – solid state alternative of Ar-ion laser, 3ν (355 nm) and 4ν (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 **1.07, 1.55 µm**

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

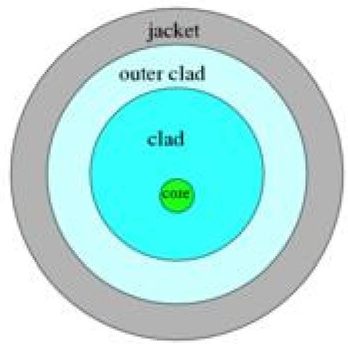
DCF - double-clad fiber

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

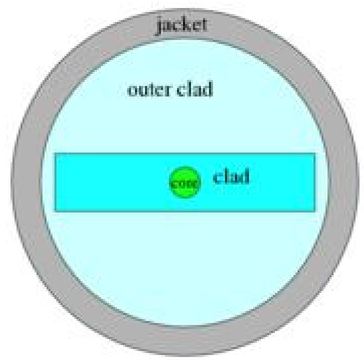
Resonator

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.



Cross-section of circular DCF with offset core.

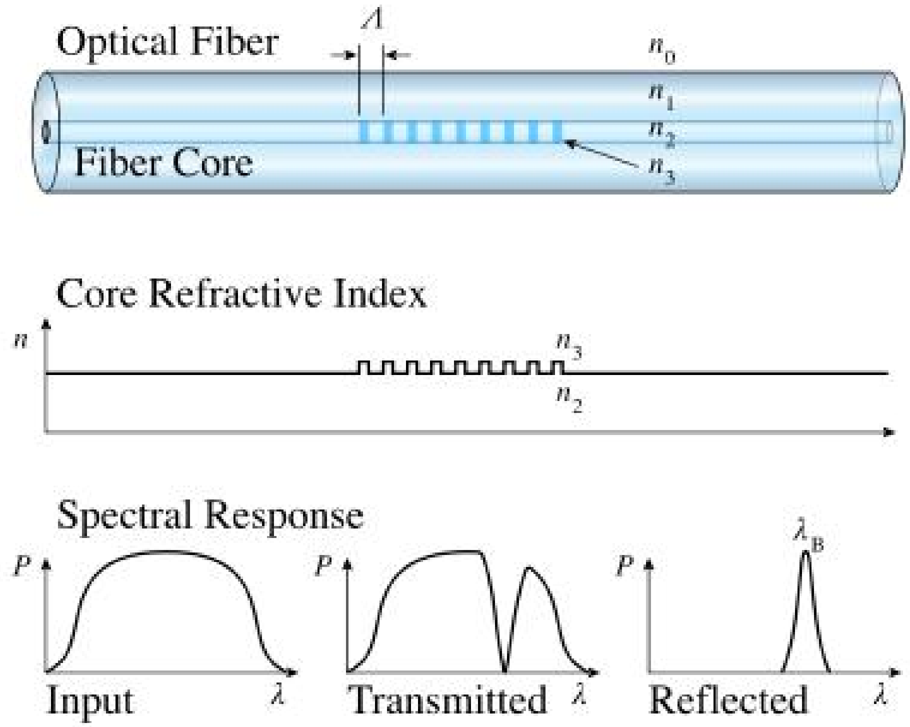


Cross-section of DCF with rectangular inner cladding.

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 , λ_{refl} depends on the period, the reflectivity depends on Δn



FBG structure, with refractive index profile and spectral response

Laser systems and applications

Fiber lasers **1.07, 1.55 μm**

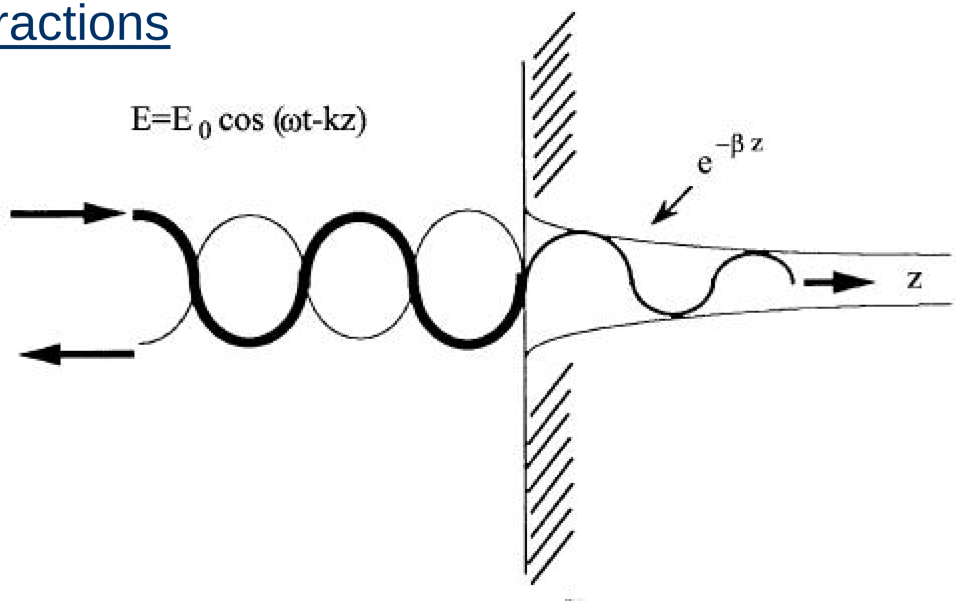
Advantages of application:

- **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, η **= 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.

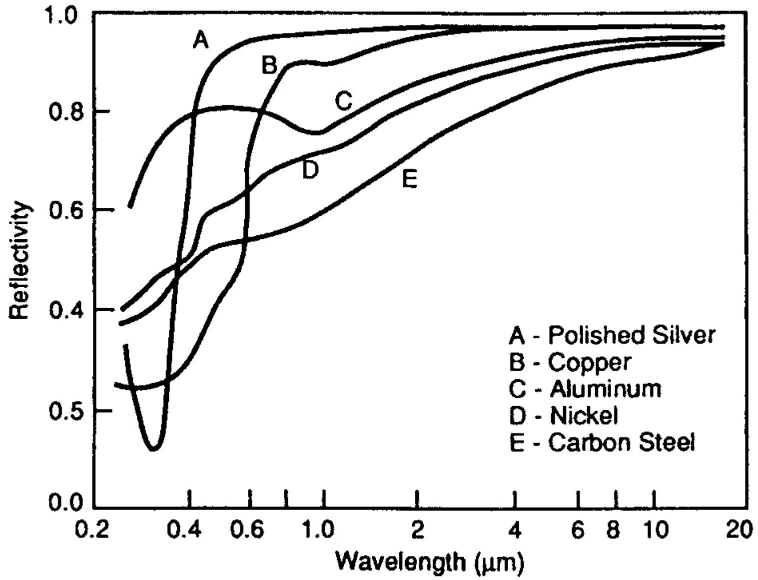
Laser systems and applications

Surface reflectivity – wavelength dependence

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

material	n''	n'	R
Al	8.5	1.75	0.91
Cu	6.93	0.15	0.99
Fe	4.44	3.81	0.64
Mo	3.55	3.83	0.57
Ni	5.26	2.62	0.74
Pb	5.4	1.41	0.84
Sn	1.6	4.7	0.46
Ti	4	3.8	0.63
W	3.52	3.04	0.58
Zn	3.48	2.88	0.58
glass	0	1.5	0.04

Complex refractive index and reflectivity (⊥) of different materials at λ = 1.06 µm (Nd:YAG)

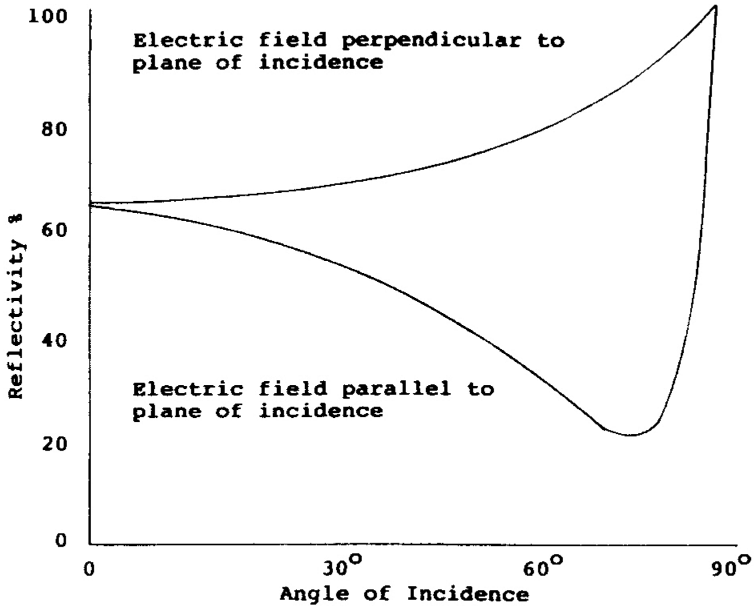


Reflectivity of different metals vs. the wavelength

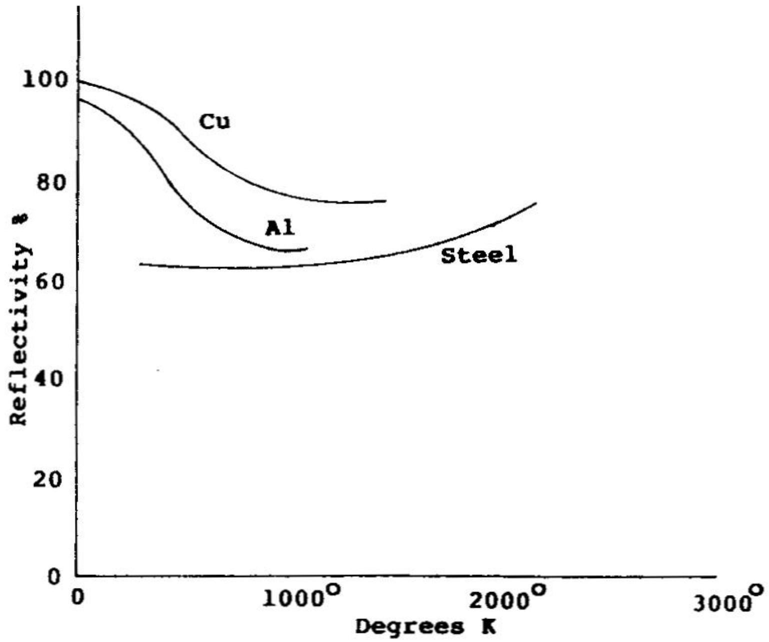
Source: LIA Handbook of Laser Materials Processing, ed. in chief John F. Ready, Laser Institute of America, 2001

Laser systems and applications

<u>Surface reflectivity</u> – angle, polarization and temperature dependence



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

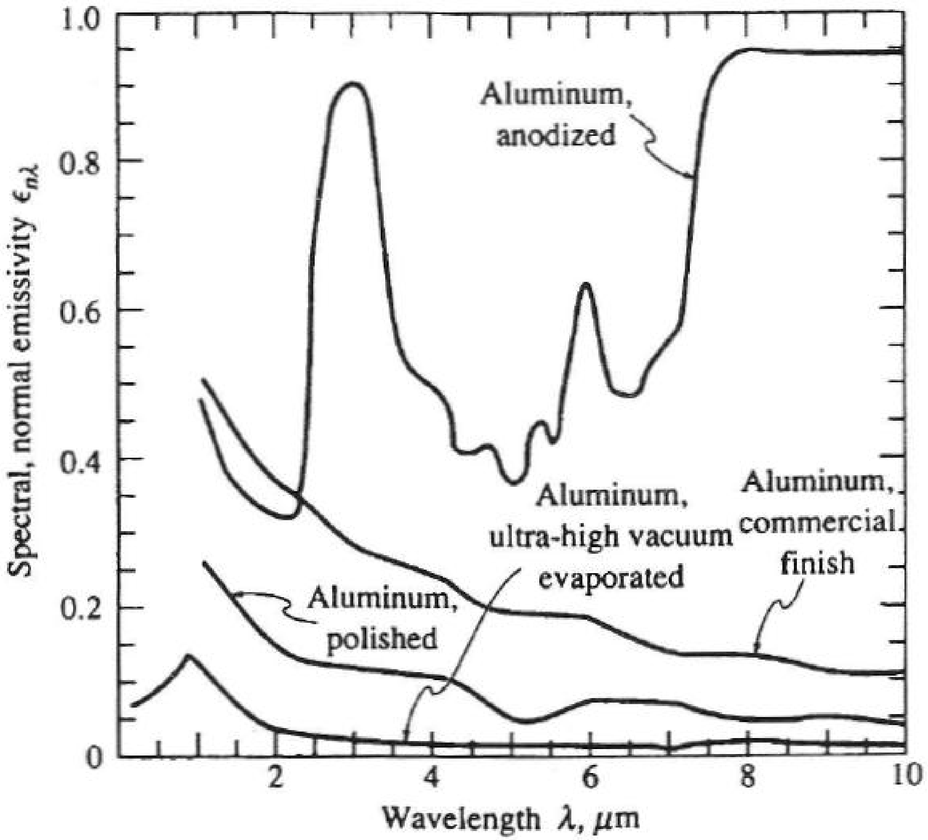


Reflectivity vs. temperature (1.06 µm)

Source: LIA Handbook of Laser Materials Processing, ed. in chief John F. Ready, Laser Institute of America, 2001

Laser systems and applications

Surface reflectivity – dependence on surface finish and coating



Spectral, normal emissivity for aluminum with different surface finishes

The emissivity ε is a non-dimensional property:

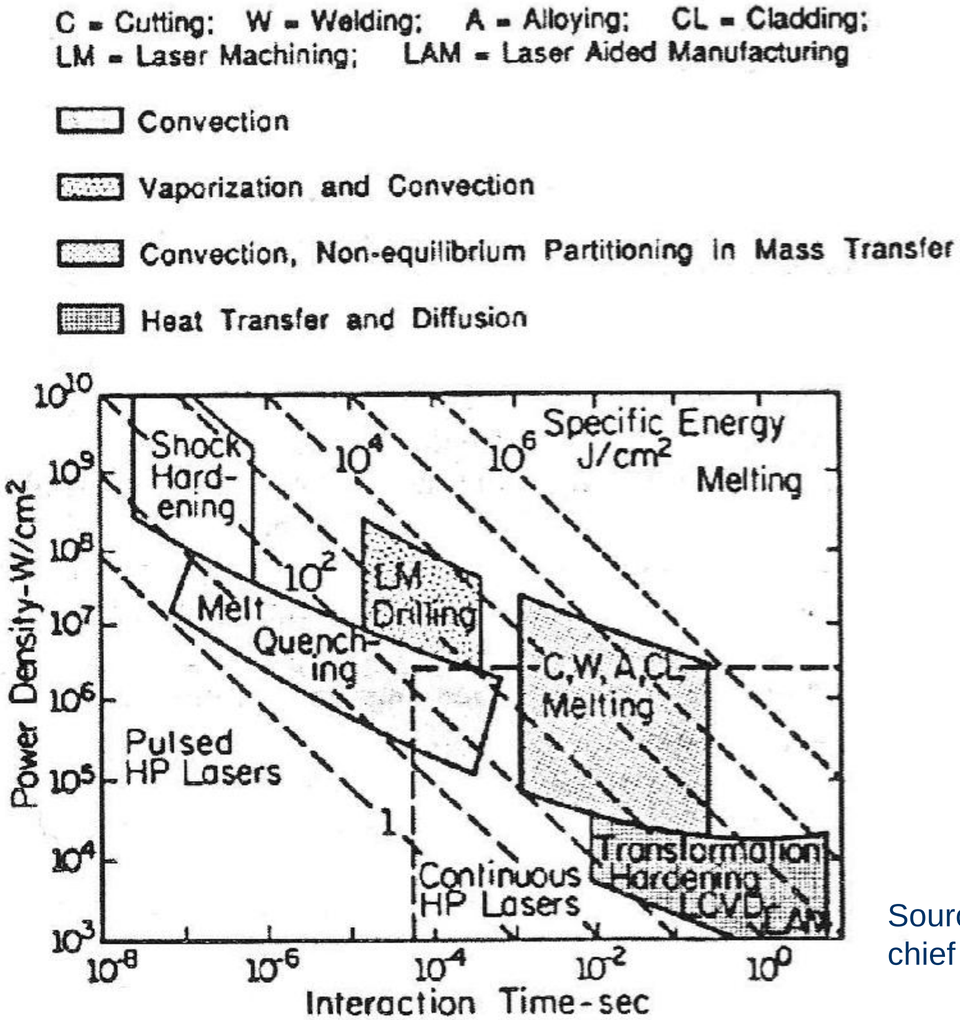
energy emitted from a surface / energy emitted by a black surface at the same temperature

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

Source: LIA Handbook of Laser Materials Processing, ed. in chief John F. Ready, Laser Institute of America, 2001

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.

Source: LIA Handbook of Laser Materials Processing, ed. in chief John F. Ready, Laser Institute of America, 2001

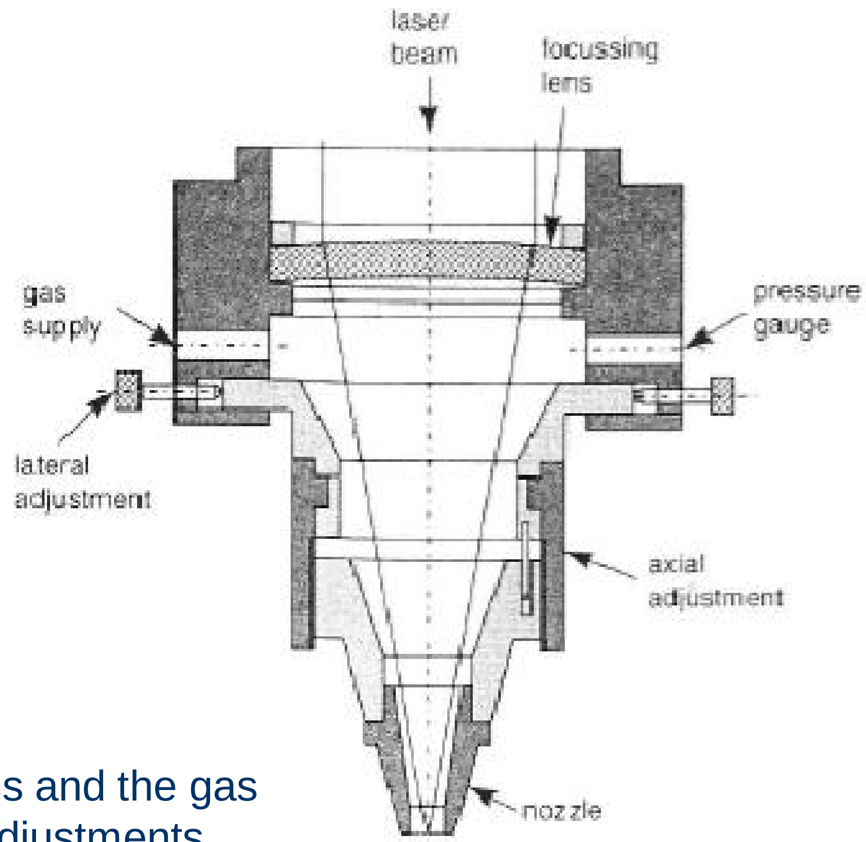
Laser systems and applications

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

Laser beam cutting head

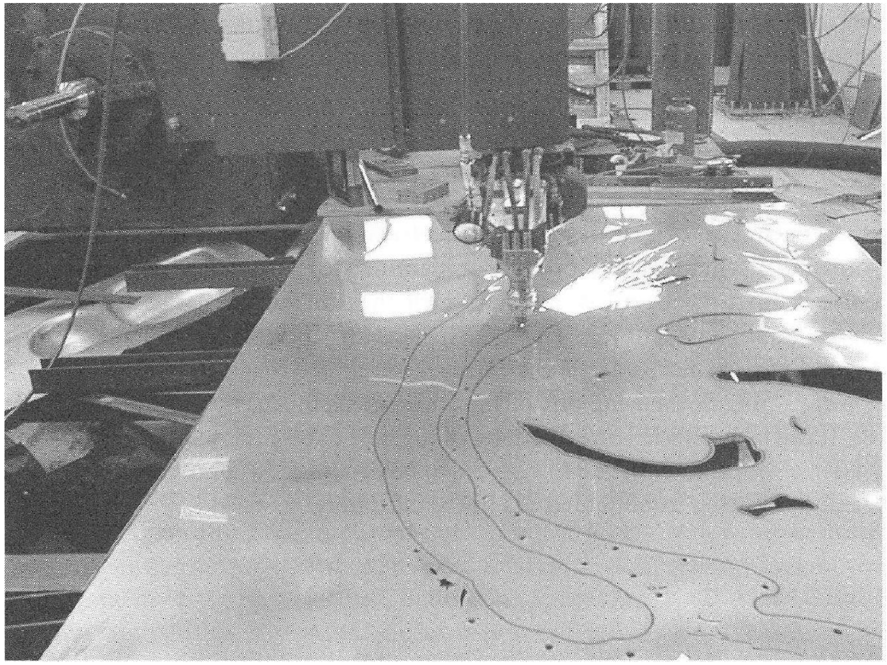


The cutting head combines the focusing optics and the gas nozzle. The device includes the mountings. adjustments, cooling and the inlet connections for gas and sometimes also the water supply.

Source: LIA Handbook of Laser Materials Processing, ed. in chief John F. Ready, Laser Institute of America, 2001

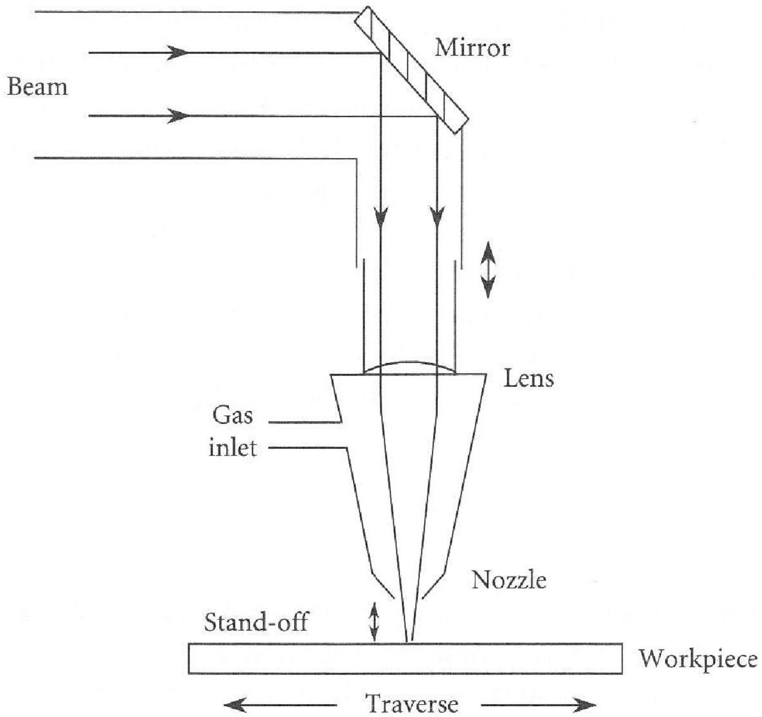
Laser systems and applications

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

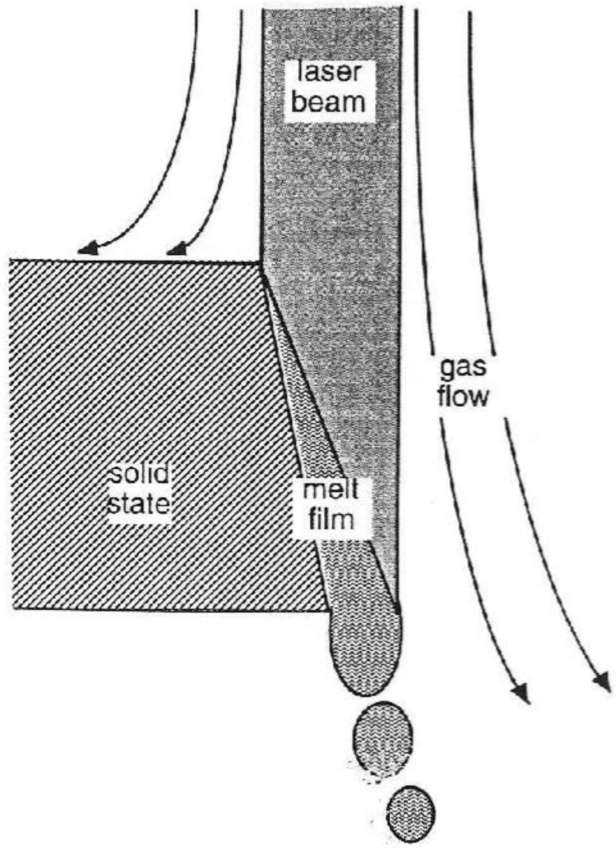
1. Laser fusion cutting (*or inert gas melt shearing*):

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: N_2 and Ar, responsible also for shielding the heated material from the surrounding air

Cut edge: free of oxides



Source: LIA Handbook of Laser Materials Processing, ed. in chief John F. Ready, Laser Institute of America, 2001

Laser systems and applications

Cutting methods

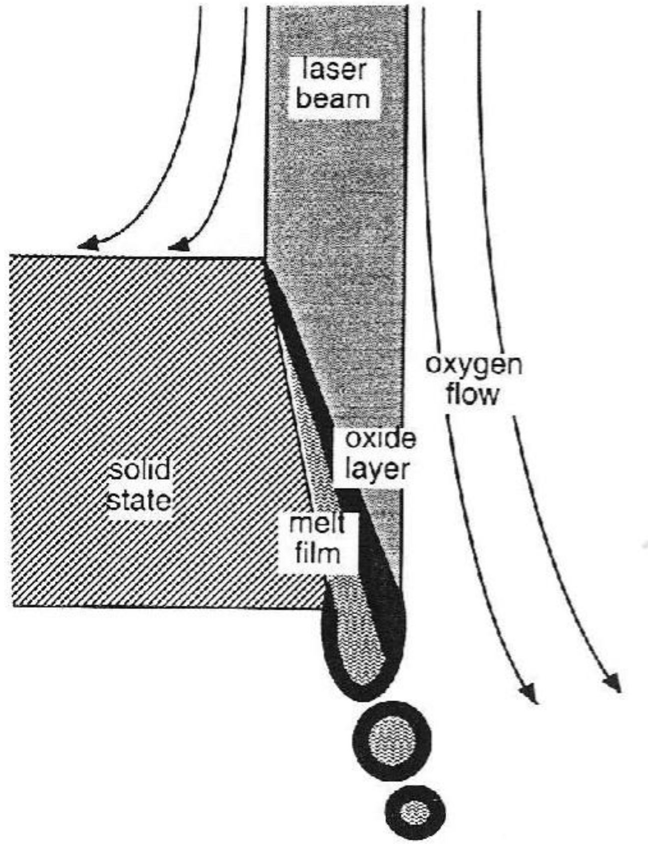
2. Laser oxidation cutting (*or active gas melt sharing*)

Reactive gas: 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



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Laser systems and applications

Cutting methods

3. Laser vaporization cutting

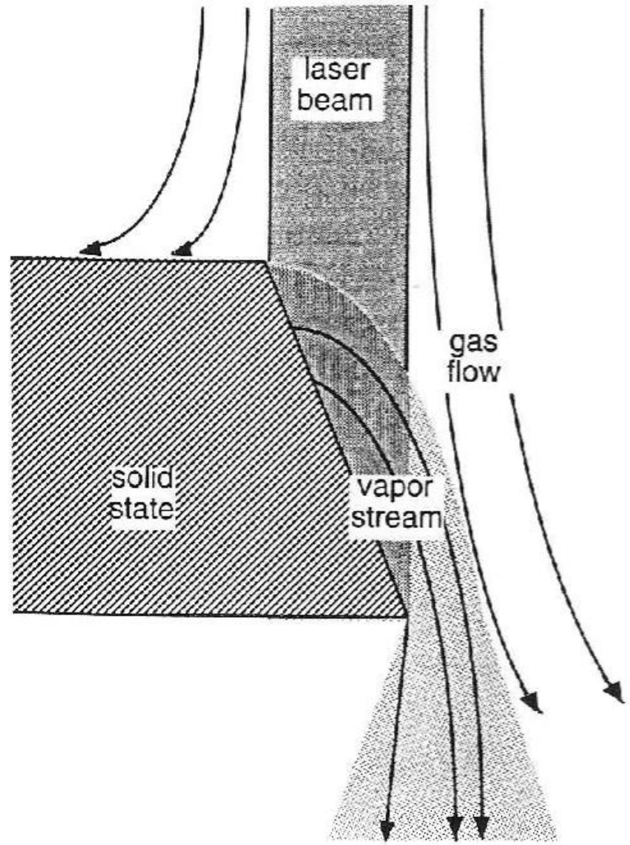
Material is heated rapidly to the vaporization temperature → material removal by an inert gas jet.

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.



Source: LIA Handbook of Laser Materials Processing, ed. in chief John F. Ready, Laser Institute of America, 2001

Laser systems and applications

Cutting methods

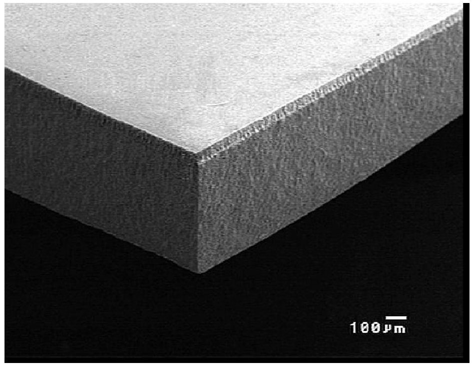
5. Scribing

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

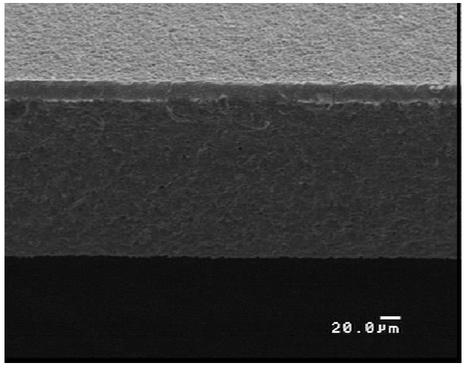
notches serve to raise stress locally and the material can be fractured along a defined line under subsequent bending.

Materials: some ceramics (alumina), some glasses and composites.

Very high processing rates are possible.



1 mm thick AlN scribed and broken



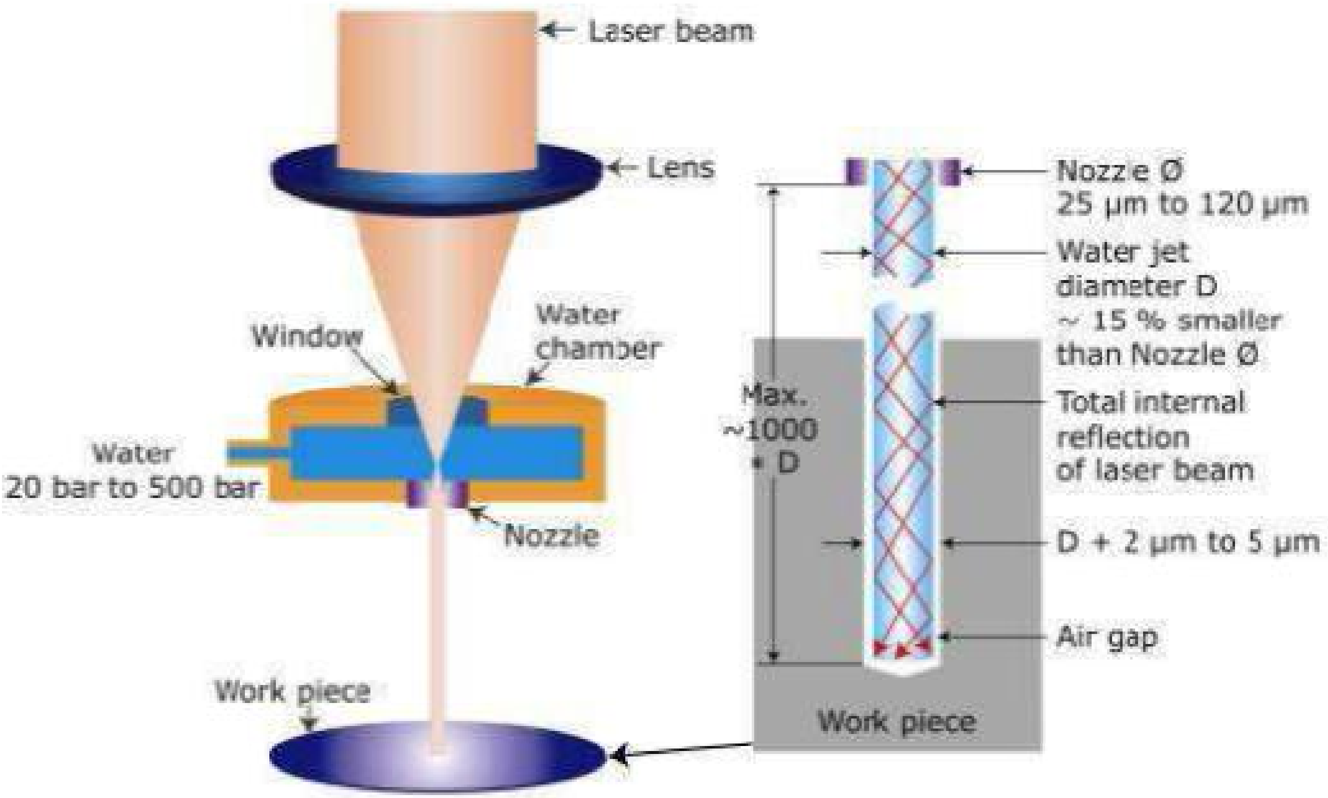
Scribed and broken 1 mm thick Al_2O_3-subtrate

Source: http://www.lasermicronics.com/_mediafiles/20.pdf

Laser systems and applications

Cutting methods

6. Special - Laser MicroJet® Technology (LMJ)

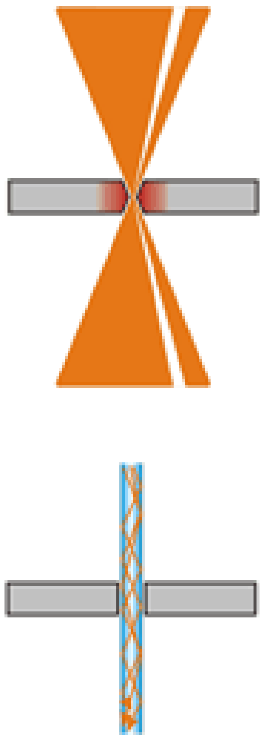


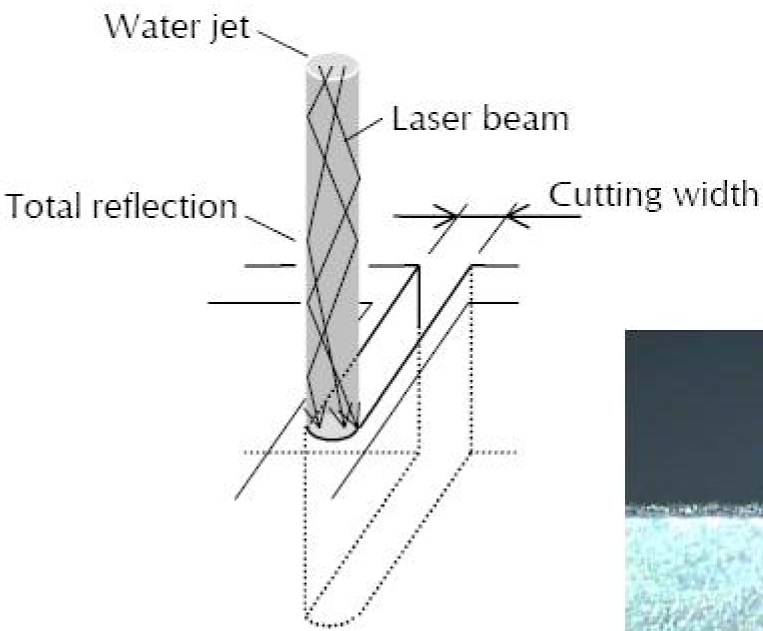
- Laser is focused in water jet nozzle
- Laser is entirely contained within the water jet as a parallel beam
- Laser is guided by total internal reflection, similar in principle to an optical fiber

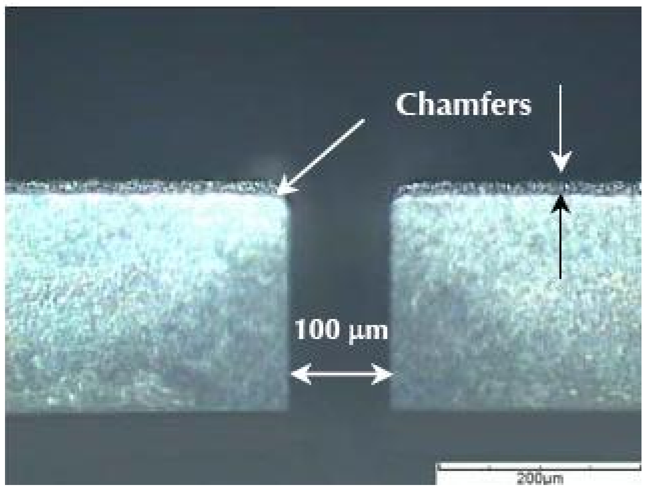
Laser systems and applications

Cutting methods

6. Special - Laser MicroJet® Technology (LMJ)







http://www.youtube.com/watch?v=2jm4_HikMqk