The Abdus Salam International Centre for Theoretical Physics

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Winter College on Optics: Trends in Laser Development and Multidisciplinary Applications to Science and Industry

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High power cw, Q-switched, and mode-locked lasers (mainly for industrial applications). From R&D to laser production, roadmap to technological transfer

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High power CW, Q-switched, and mode-locked lasers (mainly for industrial applications)

From R&D to laser production, roadmap to technological transfer

Trends in laser development and multidisciplinary applications to science and industry

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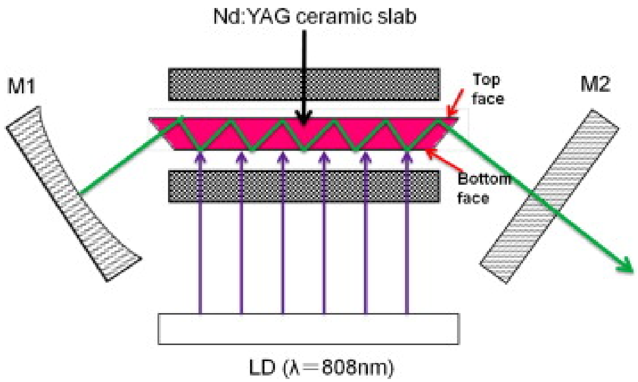
Introduction (I)

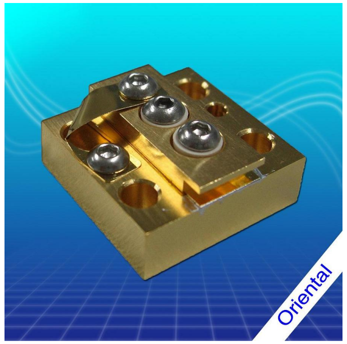
- In laser research labs many new technological aspects are continuously investigated (new materials and configurations)
- Only a few research projects become industrial products
- Many reasons can prevent research projects from becoming commercial lasers (technological, economical, applications, component suppliers, ...)
- Commercial products require further investigations in practical aspects (mechanical mounts, glues, cables, user interfaces ...)
- Long term performance analysis determine warranty durations
- Marketing impact

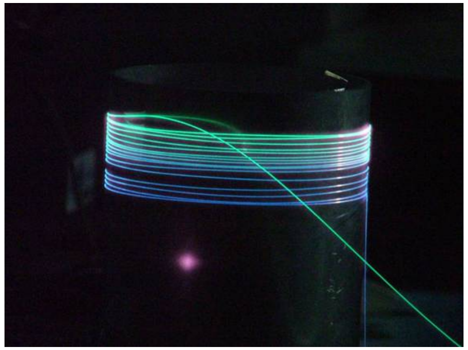
Introduction (II)

Some times research projects never become successful industrial products . . .



such as many materials or architectures (zigzag slab lasers for example)



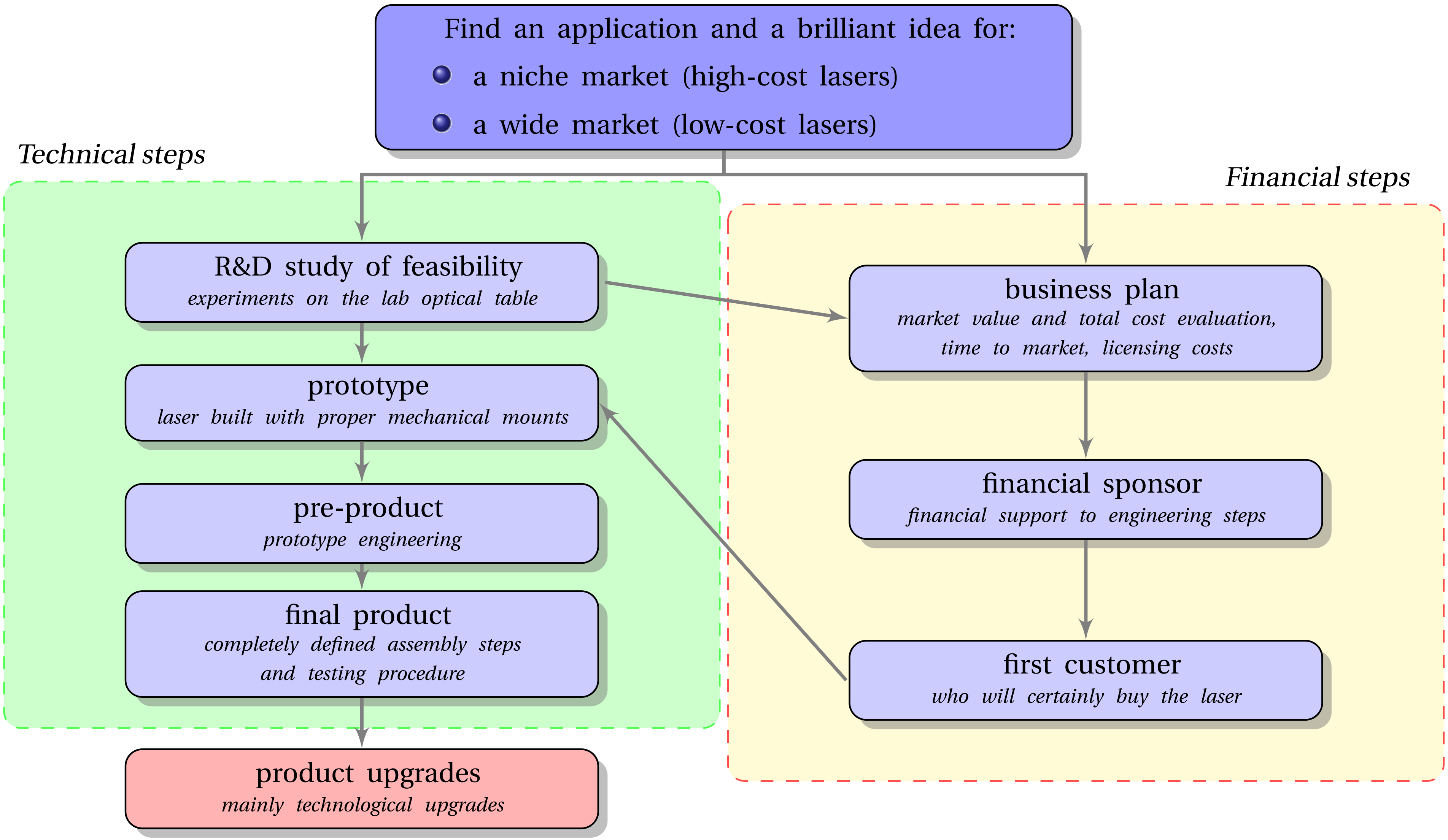


Some other times solid-state lasers were boosted by technological progress in other areas

Outline

- From R&D to laser production: basic principles
- Laser market review: trends in laser sells (last years)
- Industrial applications and typical performances of:
  - high power CW lasers
  - Q-switched lasers (ns-long pulses)
  - mode-locked lasers (ps-long pulses)
- Outstanding examples of famous laser companies

Roadmap to commercial products



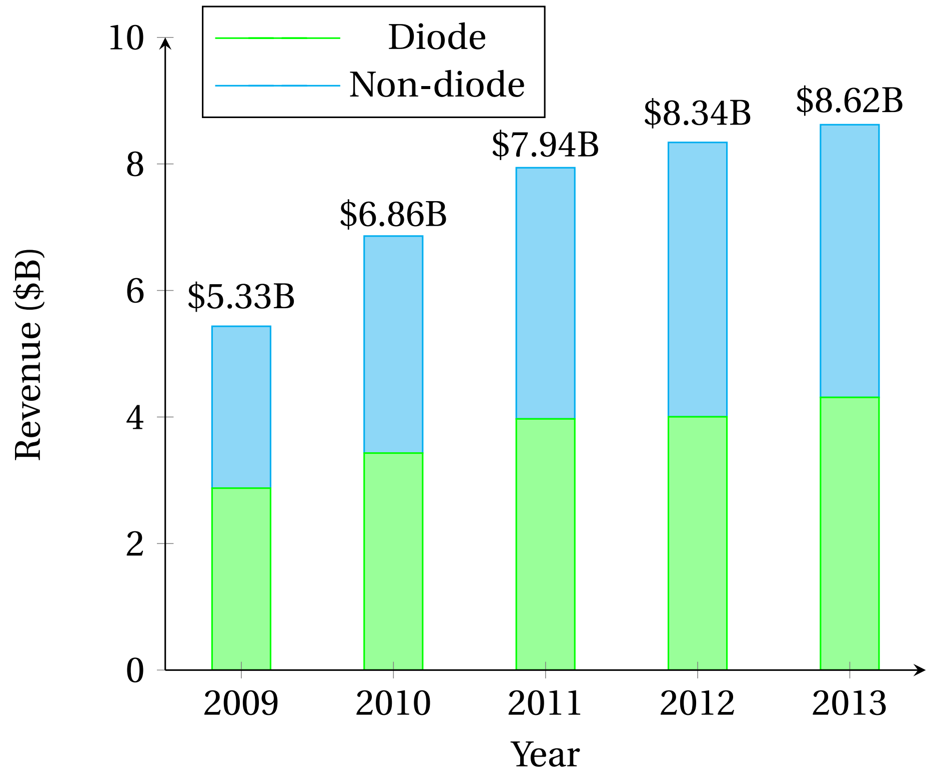
Licensing

- Scientific innovations and breakthrough technologies result in intellectual property that supports business and technology transfer
- Licenses aim to protect the intellectual property so that technologies become commercial products
- Licenses include:
  - Nondisclosure Agreements
  - Patent Licence Agreements
  - Copyright Licence Agreements
- In order to get licenses it is required a business plan including commercialization plan and anticipated market opportunities
- Licensing includes fees: up-front execution fees, royalties (fees to keep the license in place), ...

Laser safety

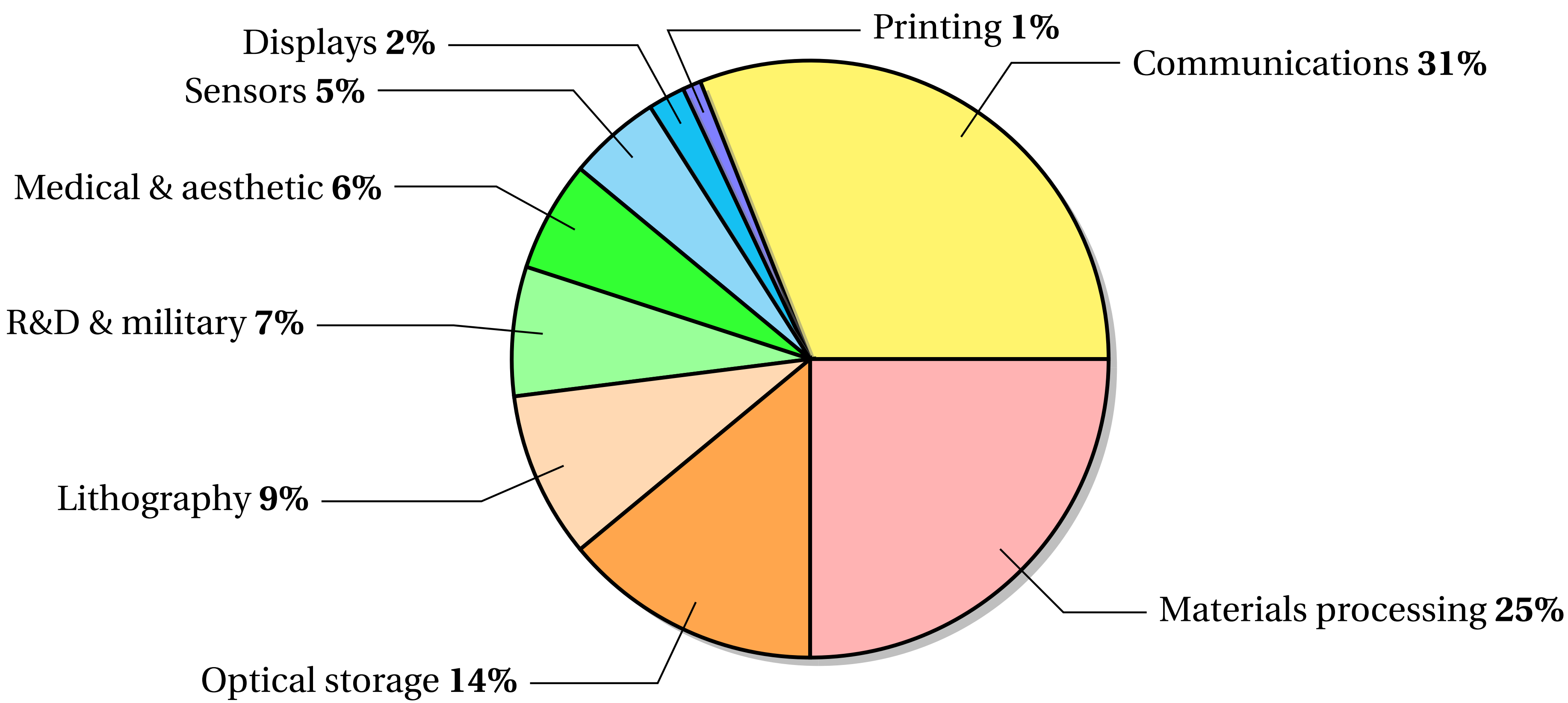
- A laser company has to consider safety issues both for the manufacturers and users
- Lasers has to be classified in classes which defines the hazard level
- All high power lasers used in industrial application are seriously dangerous
- Eye and skin hazards depend on the laser wavelength and operating regime
- Even though the intensity on the eye is low light is focused on the retina
- Near infrared lasers are more dangerous than visible lasers due to the lack of the blinking reflex
- UV lasers can produce cornea flash burns
- Mid infrared lasers at 3 μm and 10 μm can also be painful for the cornea
- Not only light is dangerous in lasers

Global laser market



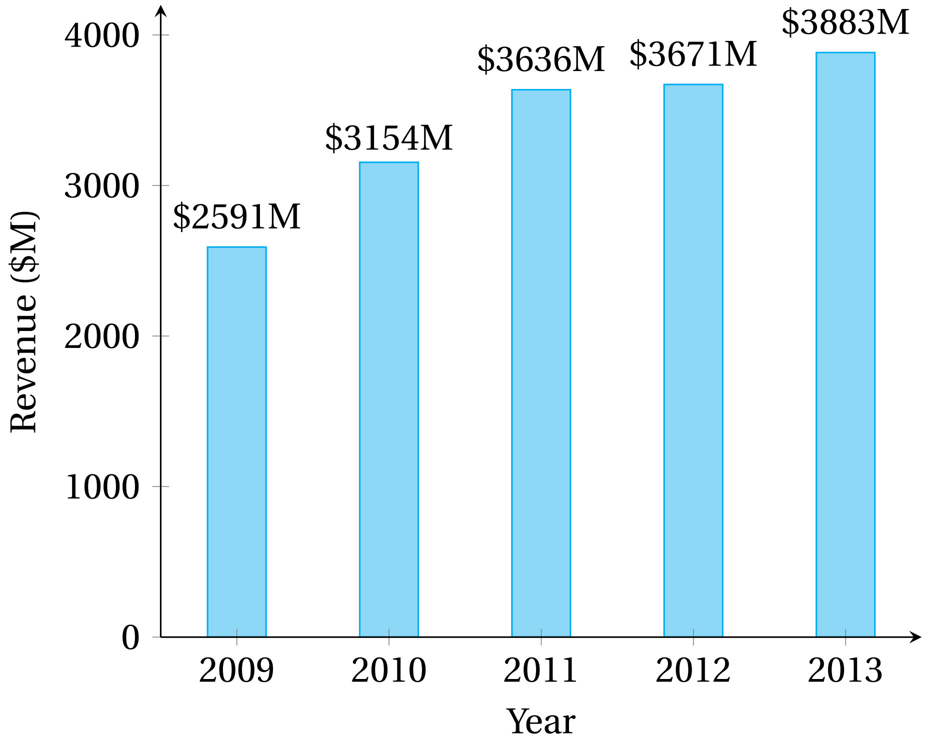
- In 2008 financial recession triggered by US housing crisis and magnified by credit default swaps and high-risk derivatives
- In 2012 new recession due to European sovereign dept crisis did not affect significantly
- Positive news in personal electronics sales, growth in manufacturing cost-reduction and improvements in automation strategies
- Laser are still enabling technologies in automotive and automation equipment

Laser market (2012)



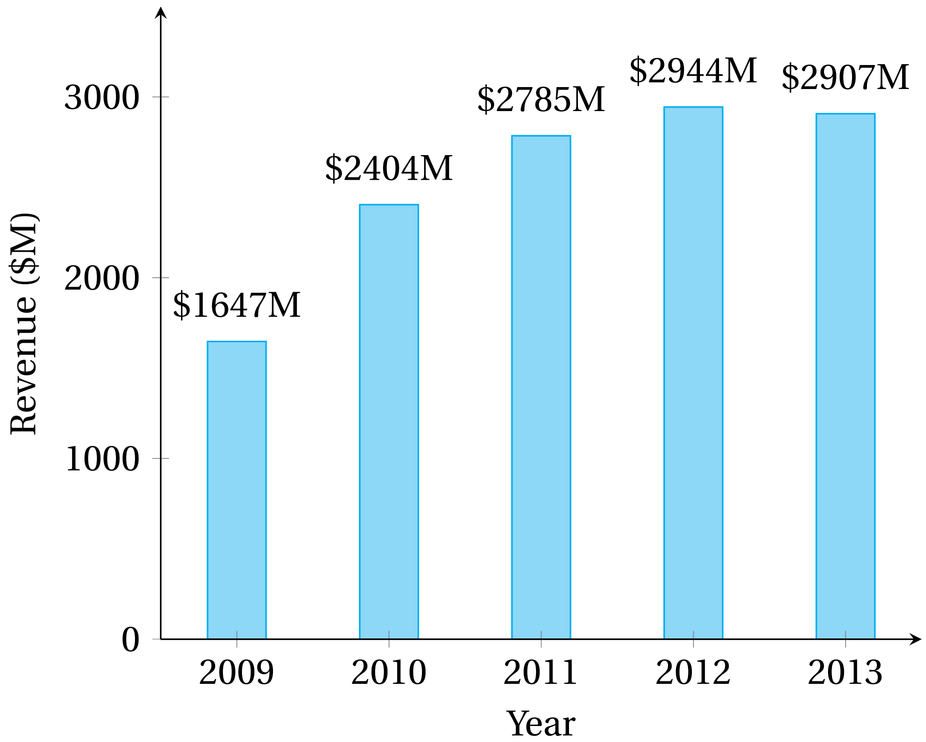
Laser Focus World, January 2013

Market: communications and optical storage



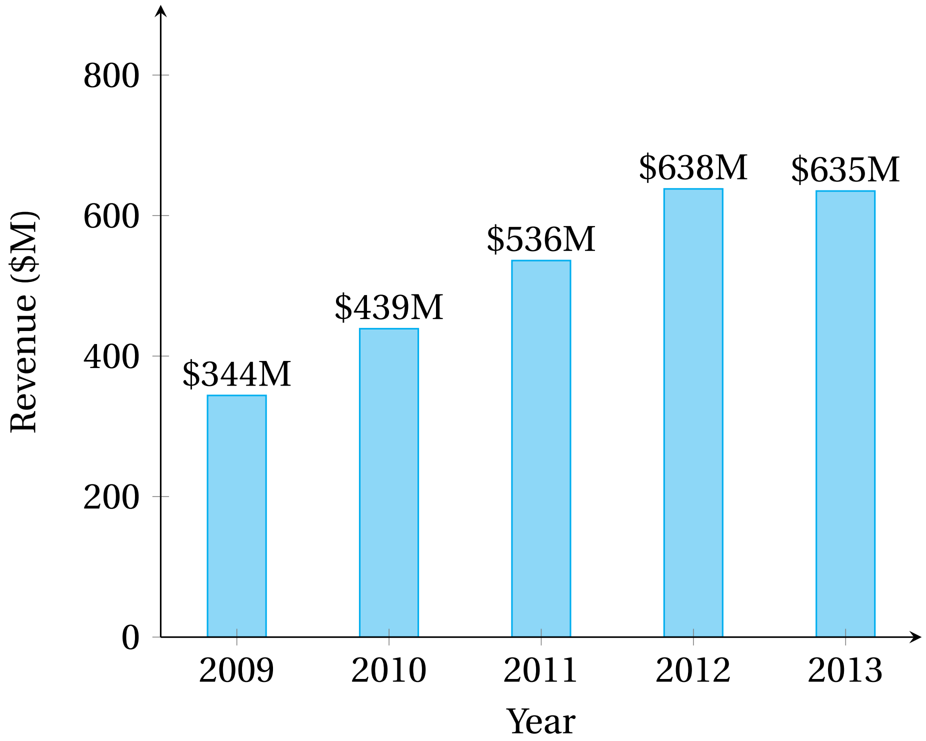
- It includes all laser diodes used in telecommunications, optical storage applications and for pumping optical amplifiers
- Telecom market slew down in 2012 while optical storage applications is rising about 2%

Market: materials processing and lithography



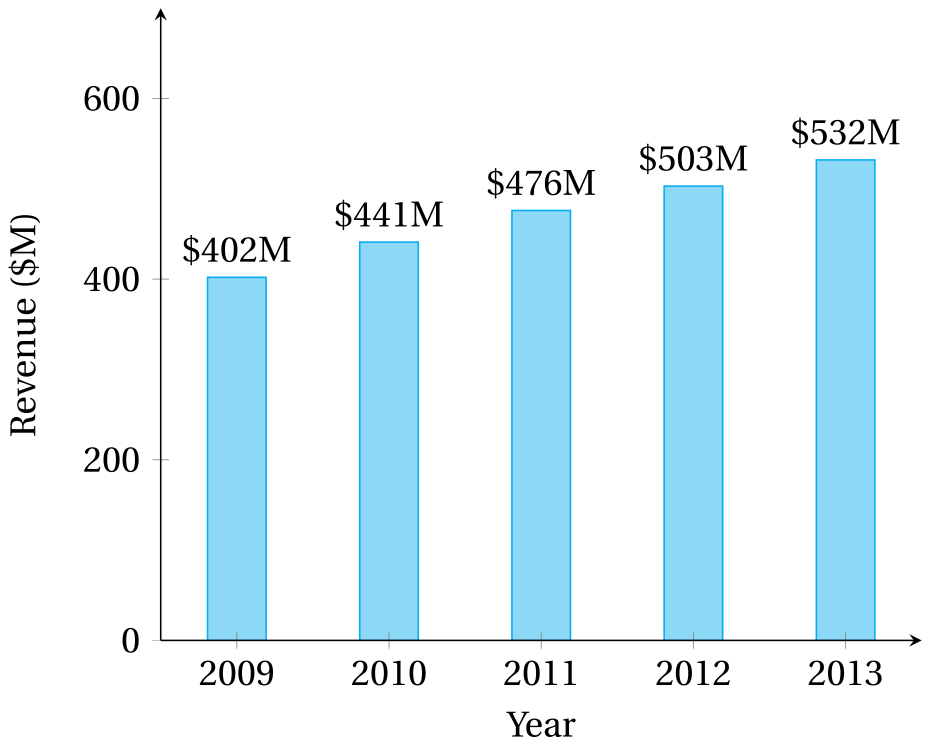
- It includes lasers used for:
  - metal processing (welding, cutting, drilling, annealing)
  - semiconductor and microeletronics manufacturing (lithography, scribing, defect repair)
  - laser marking
- Good news due to automotive equipment upgrades and consumer electronics sales
- Negative year for micro-lithography

Market: scientific research and military



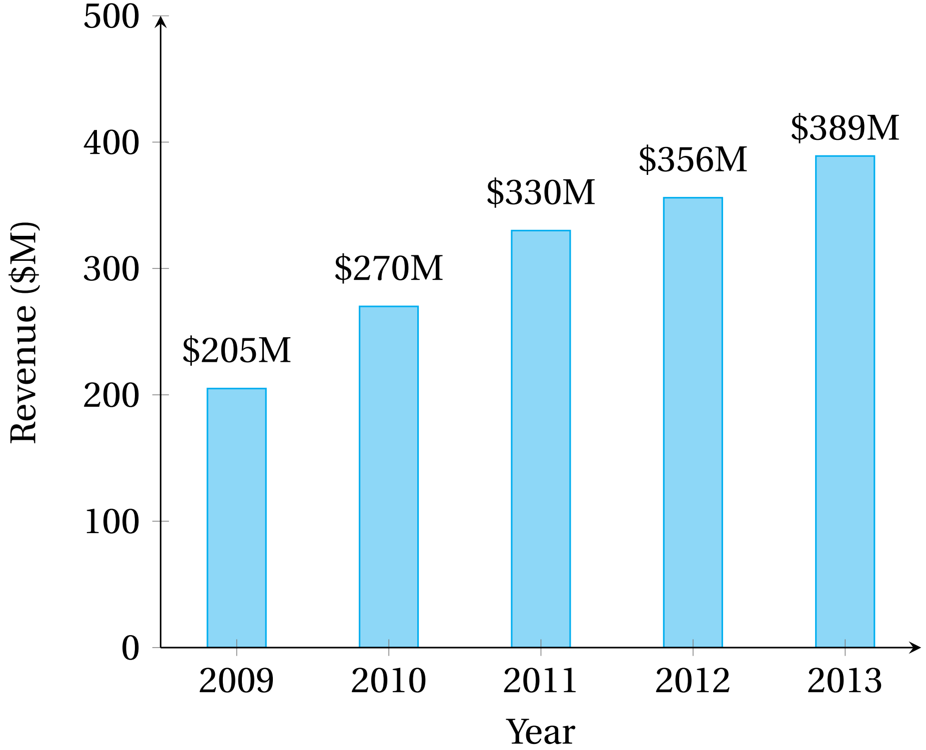
- It includes lasers used for fundamental research (such as universities and national laboratories) and for existing and new military applications (range-finders, directed-energy weapons research)
- Stimulus spending made this market to grow but a slowdown is expected due to budget limitations

Market: medical & aesthetic



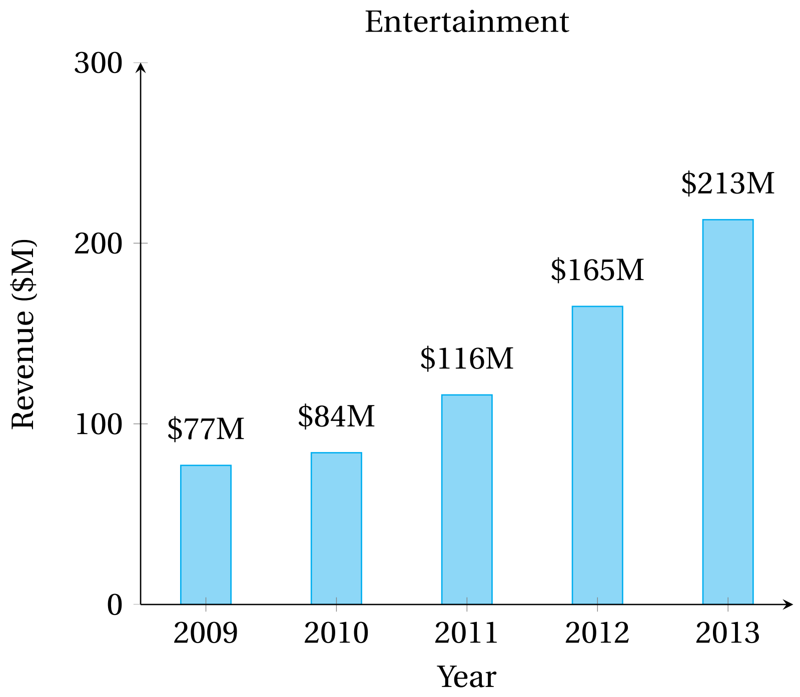
- Laser used for ophthalmology (refractive surgery and photo-coagulation), surgical, dental, skin, hair and cosmetic applications
- Despite not being usually covered by health insurance, cosmetic and dermatology applications gave the largest amount in laser revenues in this market segment

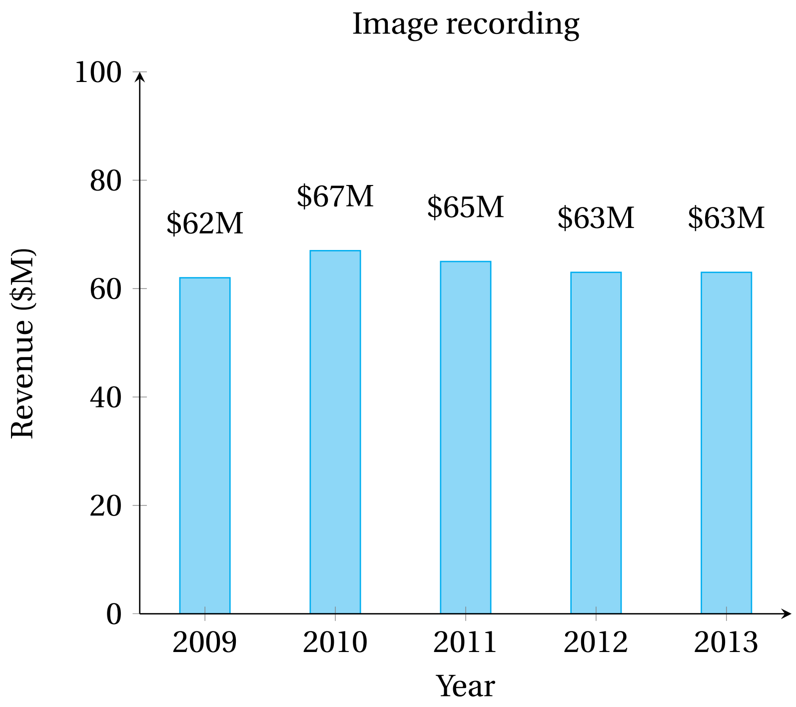
Market: instrumentation & sensors (aerospace)



This segment includes lasers within biomedical instruments, analytical instruments, metrology, wafer inspection, lidar and other sensors

Market: entertainment, image recording





This segment includes lasers for projectors, laser TVs, laser printers, ...

Laser machining

Laser machining is replacing traditional non-optical material removal methods due to efficiency, reliability and compactness. Common features are:

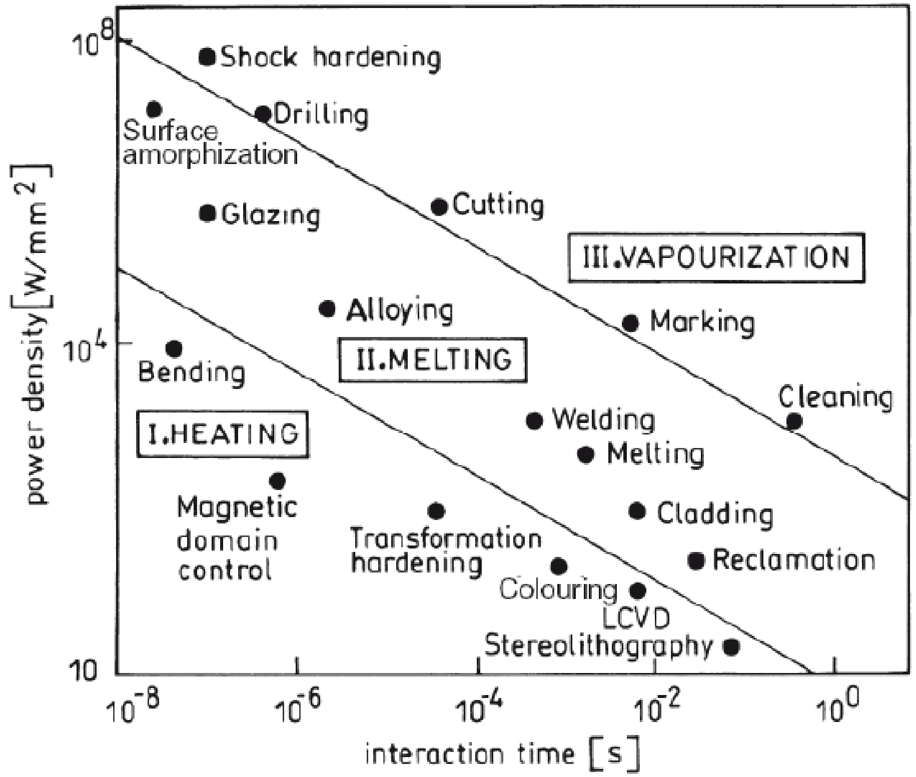
- *thermal process*: the efficiency depends on thermal and optical properties of materials rather than mechanical properties ☺
- *non-contact process*: no limits by maximum tool force and low workpiece contamination ☺
- *machining precision*: easy optical beam delivery and focusing ☺
- *high power density*: peak power is in the kW range in CW operation and can increase up to MW in pulsed operation ☺
- *low energy efficiency*: material removal requires melting or vaporization of a whole volume and therefore both energy and processing time are somehow higher than for non laser techniques ☹
- *material damage*: in metals heat conduction creates a heat affected zone (HAZ) on the erosion front ☹

Solid state laser applications

In material processing lasers can be used for:

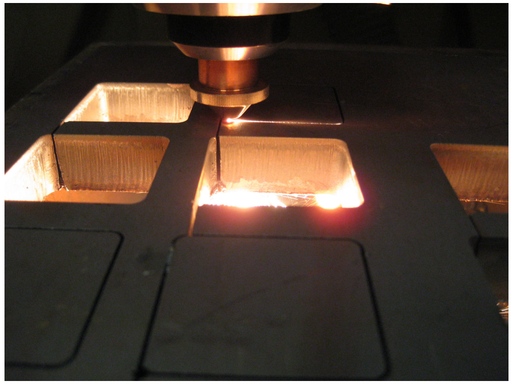
- laser cutting, drilling and piercing
- laser welding
- surface treatment (melting, alloying, cladding, marking, ...)
- rapid prototyping and low-volume manufacture
- laser ablation (macro- and micro-machining)
- laser bending or forming
- laser cleaning

thermal interactions

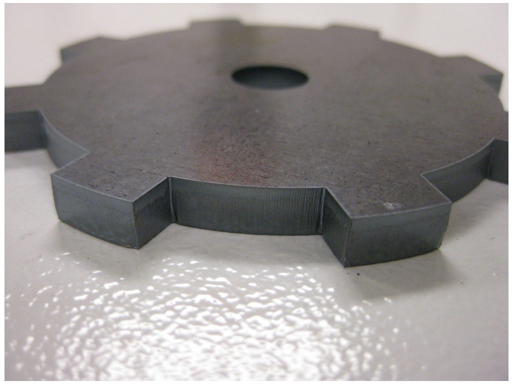


Laser cutting

20-mm-thick plate cutting



sharp corners



Pictures are courtesy of IPG Photonics

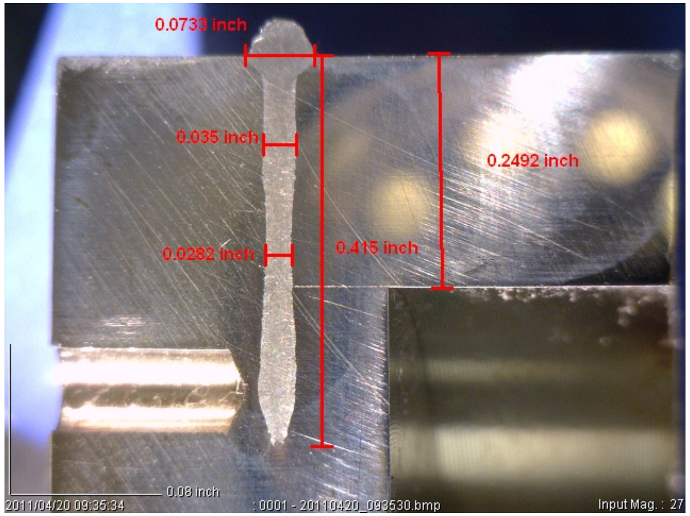
Major advantages in laser cutting:

- square cut and not rounded as it occurs with thermal or jet processes
- cut edge smooth and clean (no further clean or treatment required)
- cut edge clean enough to be re-welded
- cut depth depends on laser power (high quality cuts require CW power in the range 2-5 kW)
- fast process
- nearly all materials can be cut: friable, brittle, electric conductors or non-conductors, hard or soft
- only reflective materials such as gold, aluminium and copper can create problems, solvable with appropriate beam control

Laser cutting machines

- A laser cutting machine typically includes the laser itself with a shutter control (retractable mirror), beam guidance train, focusing optics and a means for moving the beam or the workpiece
- A coaxial gas jet is used to help the process and protect the focusing optics from spatter
- Reflective metal focusing mirrors are often used instead of transmissive optics to reduce thermal stress problems
- The laser evaporates a hole through the material and the drilling process is traversed

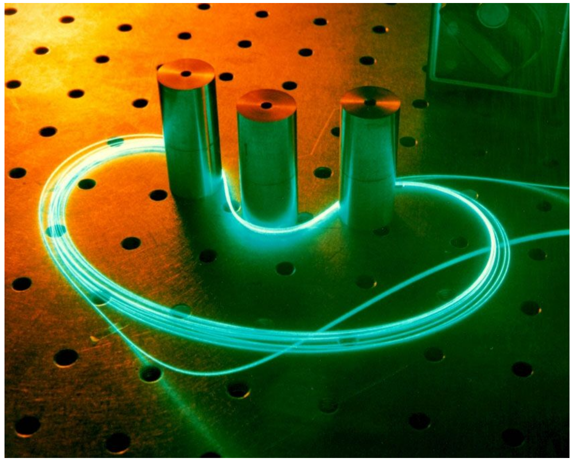
Laser welding



- Laser welding competes with ultrasonic, electron beam and thermal techniques
- Laser welding offers high speed, small heat affected zone (HAZ), good weld bead profile, narrow weld, little contamination, easy automation and operation at atmospheric pressure
- Laser requirements are similar to laser cutting (CW lasers with power in the kW range)
- Welding is done by locally melting materials

Lasers employed for cutting and welding (CW operation)

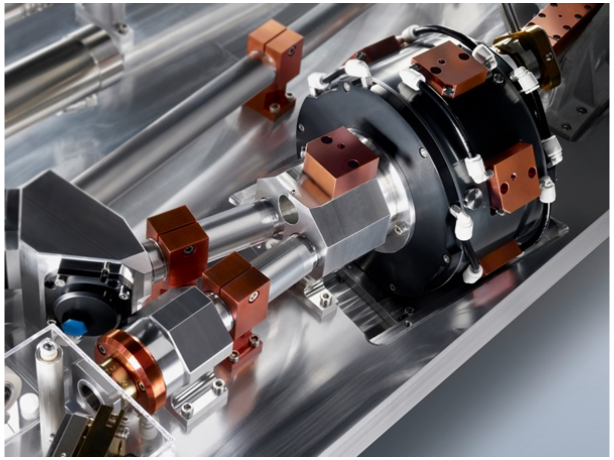
fiber laser



Courtesy of Laser Zentrum Hannover

- high beam quality
- high power generation
- wall-plug efficiency up to 30%
- turn-key operation and small size

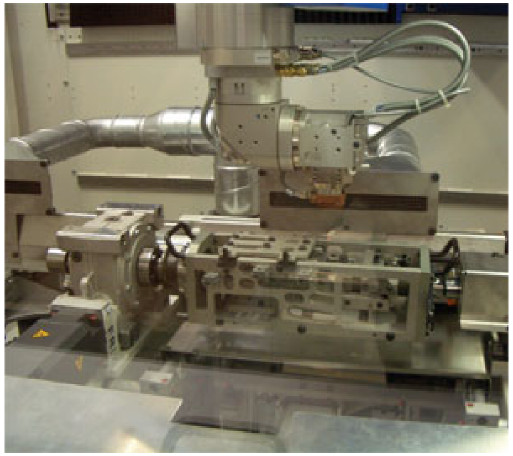
thin-disk laser



Courtesy of Trumpf Group

- easy power scalability (at the expenses of beam quality)
- used in automotive where beam quality does not matter

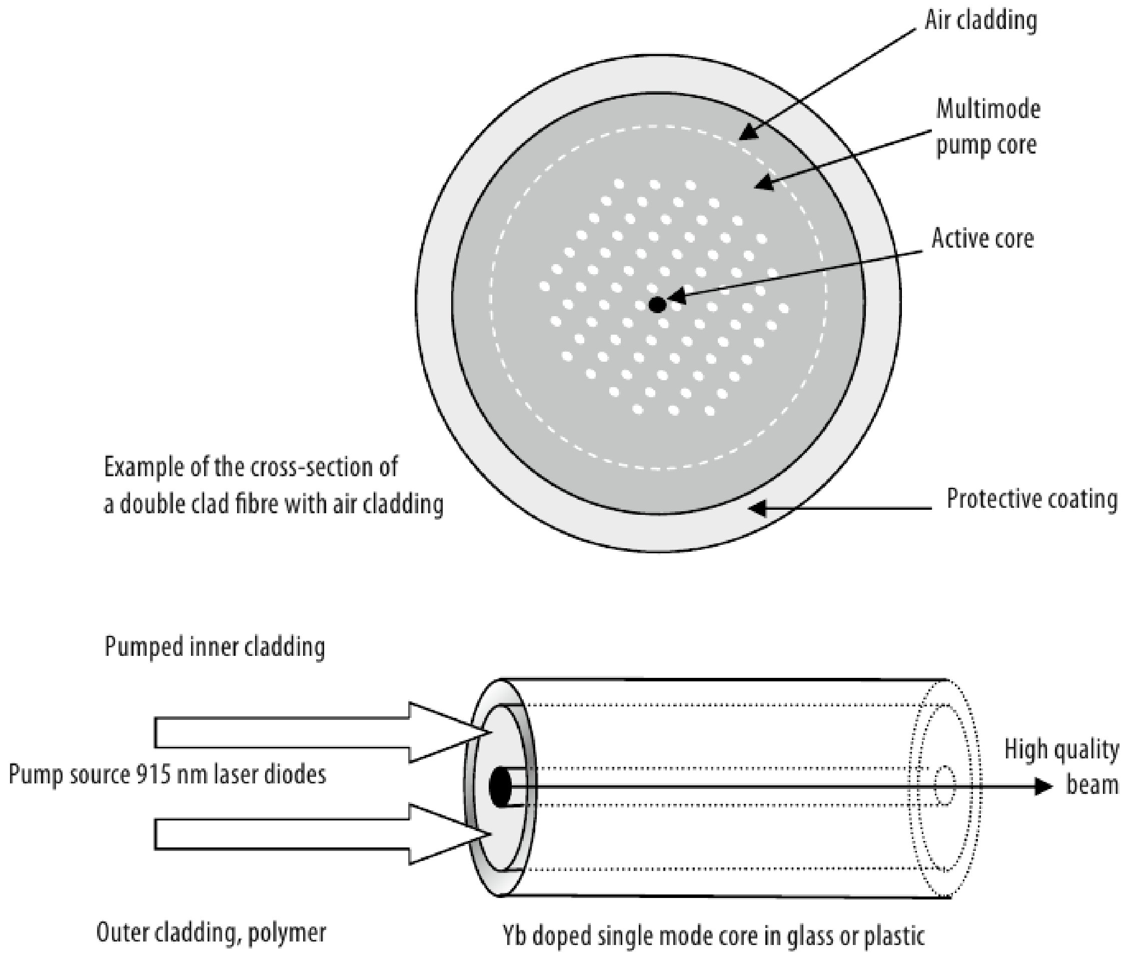
CO_2 laser



Courtesy of Amtek

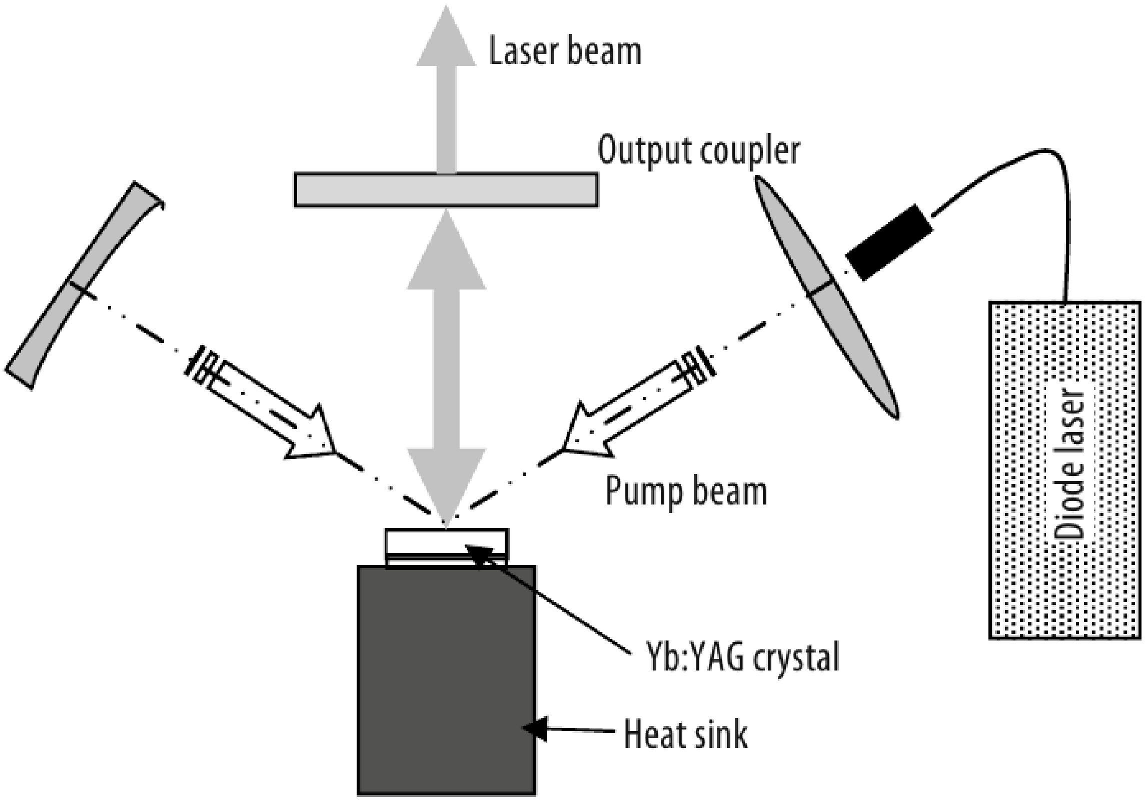
- λ =10-μm is best absorbed by most materials
- 10-μm is twice as fast cutting than 1-μm
- higher cut quality in sample thicker than 4 mm

High power CW fiber lasers



- Yb-doped active fibers for high power lasers have a double clad structure
- The inner cladding is for pump power propagation
- Low brightness diodes can be combined for high total pump power
- Small core means high beam quality of the laser output

Thin disk lasers



- The thin-disk geometry simplifies the heat removal
- High Yb doping concentrations allow small disk thickness
- Easy power scalability by simply increasing the pump spot size
- Difficult to keep beam quality while scaling up power unless cavity length is increased

High power CW laser performances

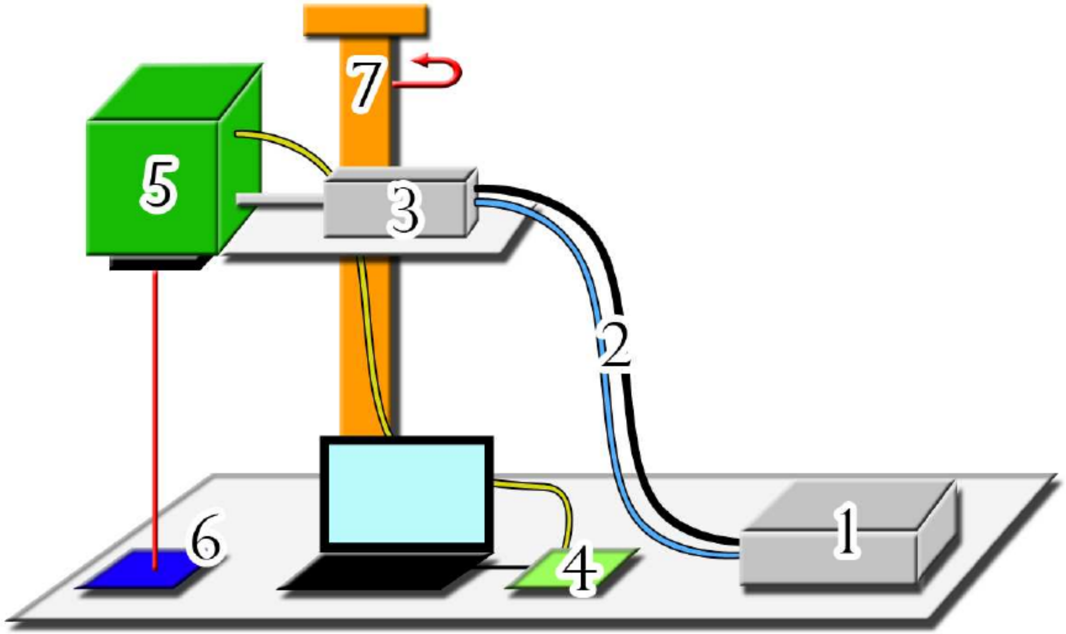
YLS Series (IPG): CW fiber lasers

Wavelength	1070 – 1080 nm
Output power	500 W - 50 kW
Wall-plug efficiency	> 30%
Output fiber diameter	from SM to 300 μm (power dependent)

TruDisk (TRUMPF): CW disk lasers

Models	TruDisk 4002	TruDisk 16002
Power	4 kW	16 kW
Wavelength	1030 nm	1030 nm
M^2	< 25	< 25

Laser marking and scribing

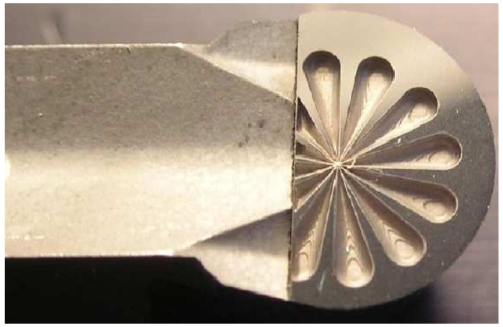


1 Pumping unit and power supply
2 Pump delivery and electric cables
3 Laser resonator
4 Marking hardware module
5 Scan head
6 Marking field
7 Slide for distance settings

- Lasers mark a wide range of materials that includes metals, glass, ceramics, plastics, organics or semiconductors due to good absorption of most materials in IR and visible region
- fast and flexible process
- marked objects might be alphanumeric codes, graphics, logos, barcodes and bitmaps

Laser marking: engraving and contrast

Synthetic diamond engraving



Surface contrast on plastics

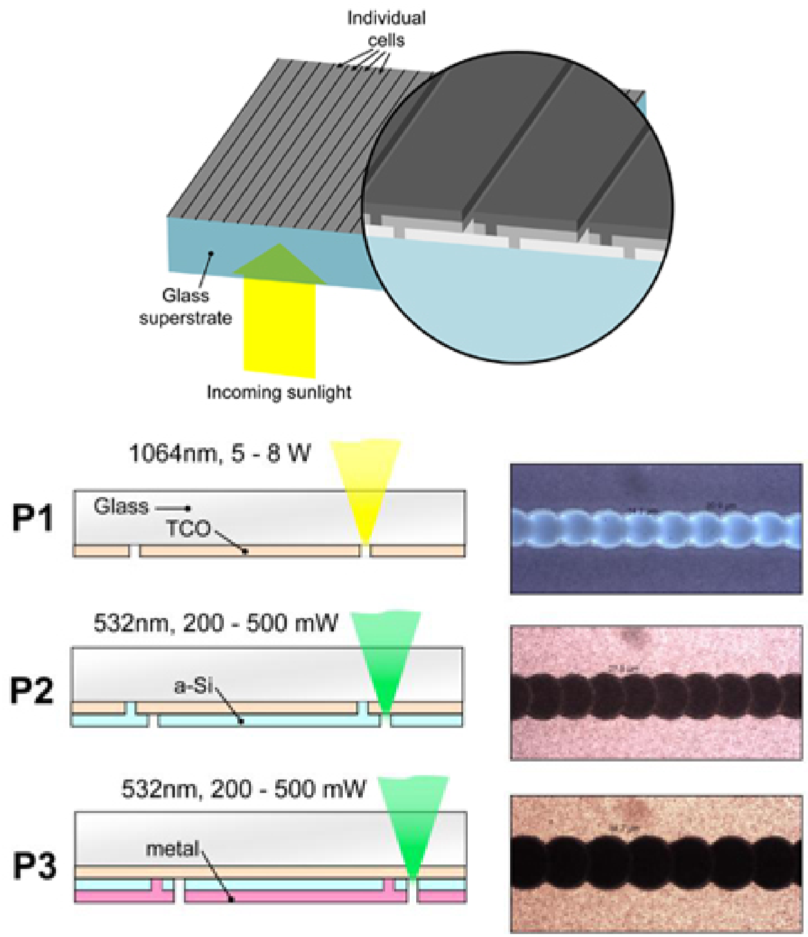
Glass engraving

Glass 2D marking

Laser marking is an ablation process.
There are different marking processes:

- *engraving*: material removal by creating a depression in the sample
- *thin-film ablation*: partial removal of coating layers from the base material
- *surface contrast*: in plastics, color can be changed with laser exposure
- *annealing*: temperature dependent annealing colors in metals when heated

Thin-film patterning



Courtesy of Coherent Inc.

Thin-film panels

- Series interconnections of many stripes allows low voltages to be added-up while keeping the generated current low
- Layers must be patterned during the thin-film deposition stages
- Solar industry is one the the area where laser machining is most commonly used
- Patterning steps are performed with short-ns-pulsewidth low-power (20 W) DPSSLs at 1064 nm, 532 ns or 355 nm
- Wavelength choice determined by different materials absorptions
- Shorter pulses provide cleaner selective material removals
- Higher repetition rates provide faster processing on large panels

Lasers employed for marking (Q-switching operation)

LUCE (Bright Solutions): active Q-switching

Models	40 W	6 W	2.5 W
Wavelength	1064 nm	532 nm	355 nm
Rep rate	10 to 200 kHz		
Pulsewidth	7 to 40 ns	4 to 30 ns	5 to 30 ns
M^2	2.5	< 2	< 2

WEDGE (Bright Solutions): passive Q-switching

Models	HB-1064	HF-1064
Wavelength	1064 nm	1064 nm
Pulsewidth	1 ns	700 ps to 3 ns
Pulse energy	up to 2 mJ	40 to 200 μJ
Peak Power	up to 2 MW	up to 300 kW
Rep rate	up to 2 kHz	10 to 100 kHz
M^2	< 2	< 1.5

Q-switched fiber lasers

YLP Series (IPG): Q-switched fiber laser

Average power	200 W
Rep Rate	1 – 50 kHz
Pulse energy	up to 10 mJ (20 kHz)
Wavelength	from 1055 to 1075 nm
Bandwidth	2 nm
Pulse duration	400 ns
M^2	< 10

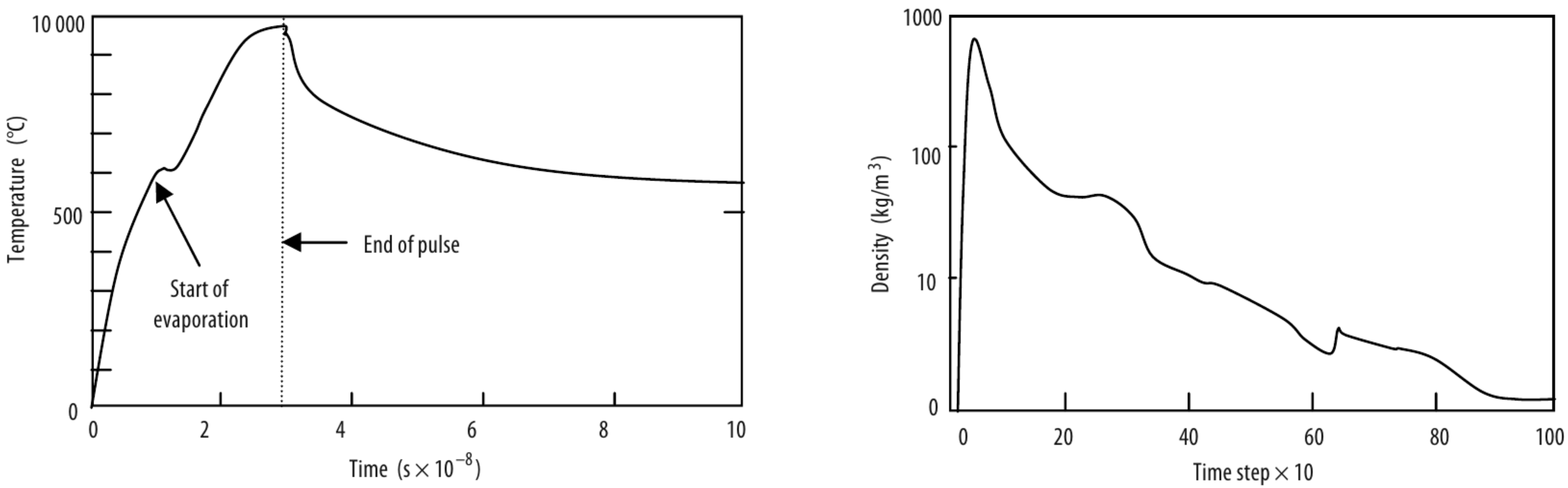
With respect to Q-switched bulk lasers, fiber lasers has:

- longer pulse durations, due to longer resonators (longer round-trip time)
- superior beam quality (set by fiber diameter) due to easier heat removal
- random polarization and poorer spectral properties (efficiency penalty in frequency conversions)

Pulse duration affects material processing:

- Short pulse durations (few ns, bulk lasers) are ideal for materials with high damage threshold (diamond, glass, ...) for high precision ablation processes
- Long pulse durations (100's ns, fiber lasers) are ideal for large material removal and for aluminium or brass: longer pulse durations → longer interaction times with lower energies → no dominant plasma effects

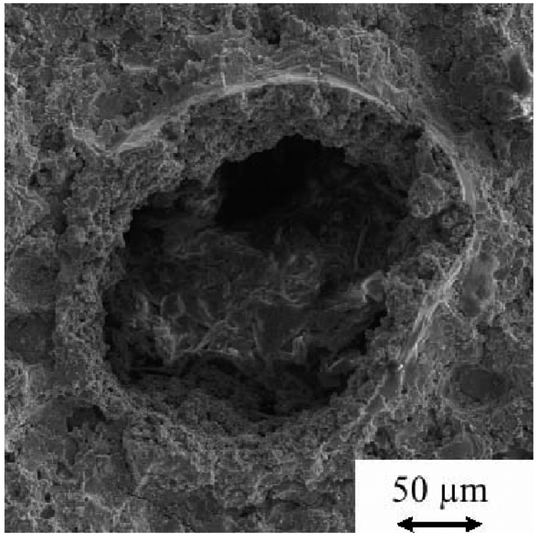
Laser ablation processes (I)

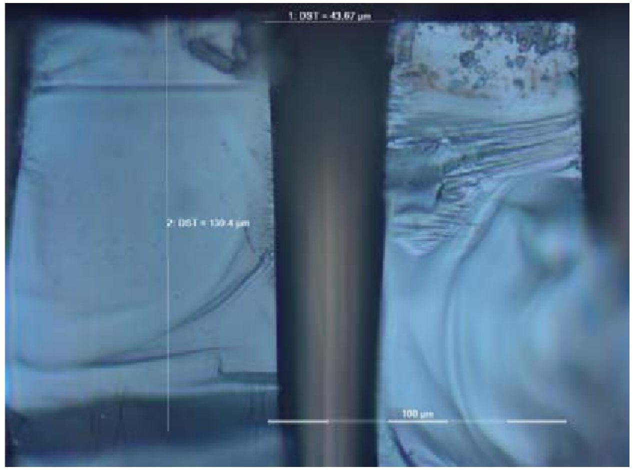


Calculated history of temperature and plasma density with a 30-ns 400-kW peak power pulse
Steen, Mazumder, LASER MATERIAL PROCESSING, *4th ed.*

- Heat is transferred from electrons to the lattice (time scale in the order of picoseconds)
- With CW lasers heat flows by thermal conduction → the material removal by boiling after melting or by photo-thermal ablation (in polymers)
- With ns pulses high pressure (several thousand atmospheres) plasma is generated and *shot peening* might occur

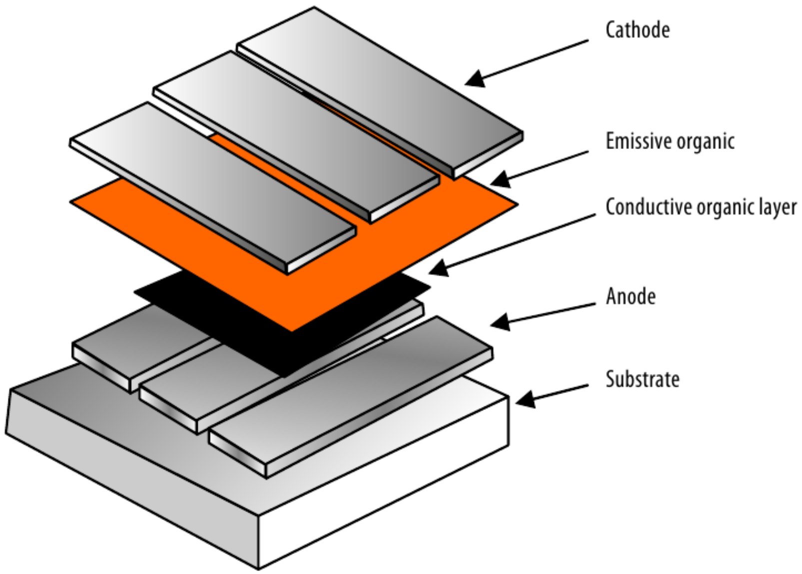
Laser ablation processes (II)



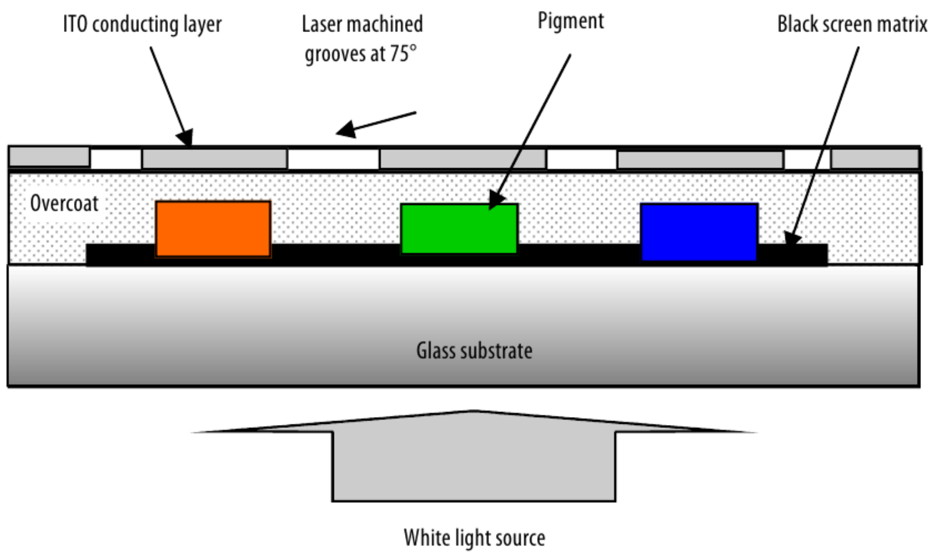


- Shot peening induced by ns pulses might produce cracks in soft materials (left picture)
- With ultrashort pulses (ps or fs) peak power is high enough to strip electrons away from atoms
- Charged electrons repel each other and material is removed without heating the surroundings
- Material removal by cold ablation is crack-free (right picture)

Industrial applications of ultrashort pulses



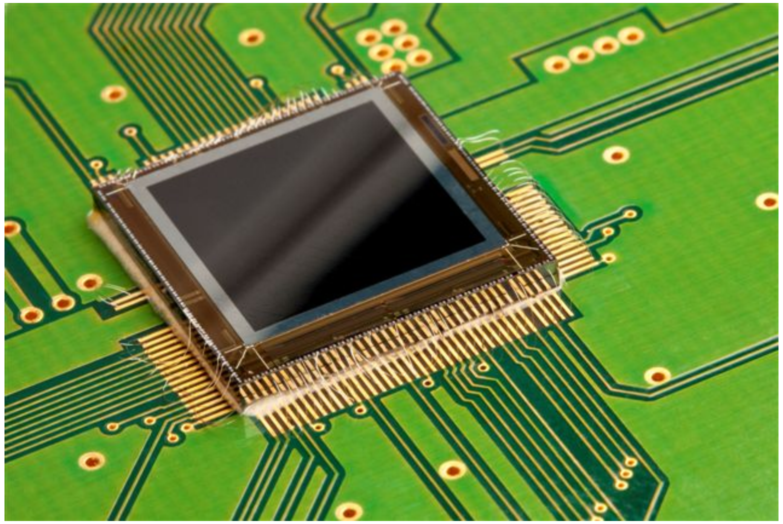
OLED structure

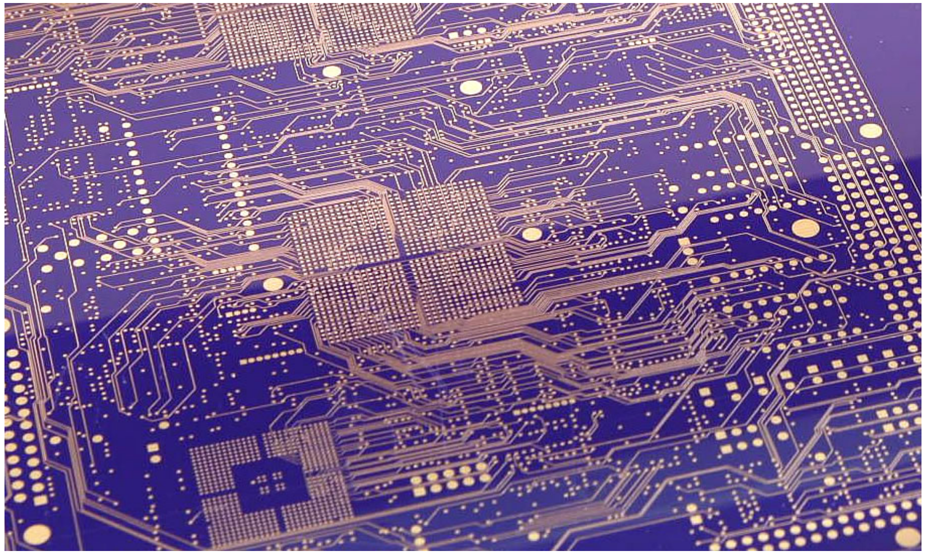


Flat-panel display

- OLEDs consists of many layers of different materials of 100-200 μm thickness. The patterning requires removal of one or more layers without debris deposition. Competing technology is printing, which is limited in scale
- In flat-panel displays ultrashort lasers are used for dry etching of the colour filters as a replacement for chemical techniques. The contact pattern has to be etched in the indium tin oxide without damaging the black mask

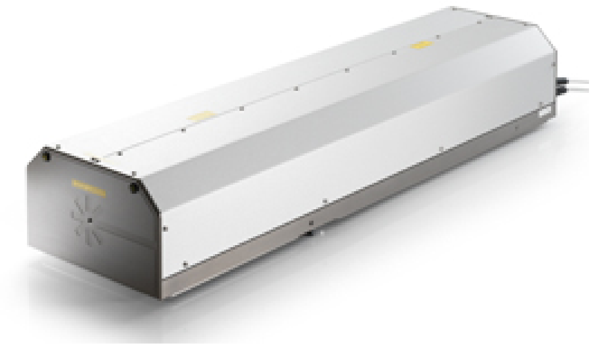
Ultrashort pulses in microeletronics manufacturing





- Ultrafast UV lasers are commonly used in microelectronics manufacturing for wafer inspection, mask or memory repair or laser direct imaging (LDI)
- By using laser direct imaging manufacturers of high density PC boards can achieve tighter resolution and layer-to-layer registration

Mode-locked lasers for industrial applications



Paladin Advanced (Coherent): mode-locked laser

Model	Paladin 532	Paladin 355
Output power	20 W	> 24 W
Rep rate	80 MHz	80 MHz
Wavelength	532 nm	355 nm
Pulse duration	> 10 ps	> 15 ps

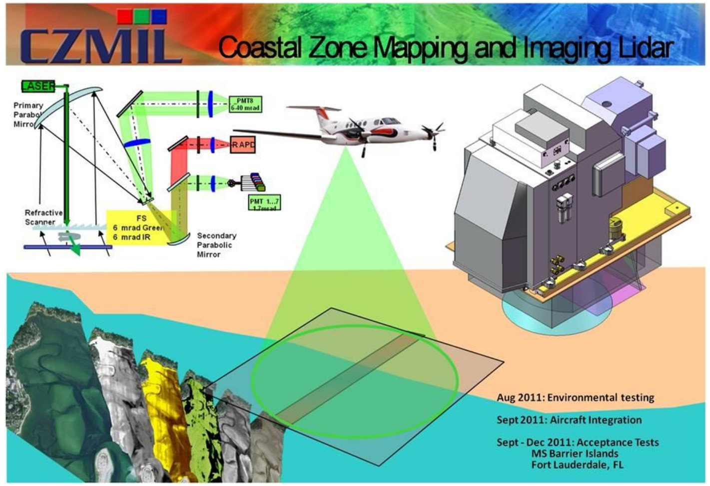
Talisker Ultra (Coherent): mode-locked fiber laser

Model	Talisker Ultra 532	Talisker Ultra 355
Output power	> 8 W	> 4 W
Rep rate	200 kHz	200 kHz
Wavelength	532 nm	355 nm
Pulse duration	< 15 ps	< 15 ps

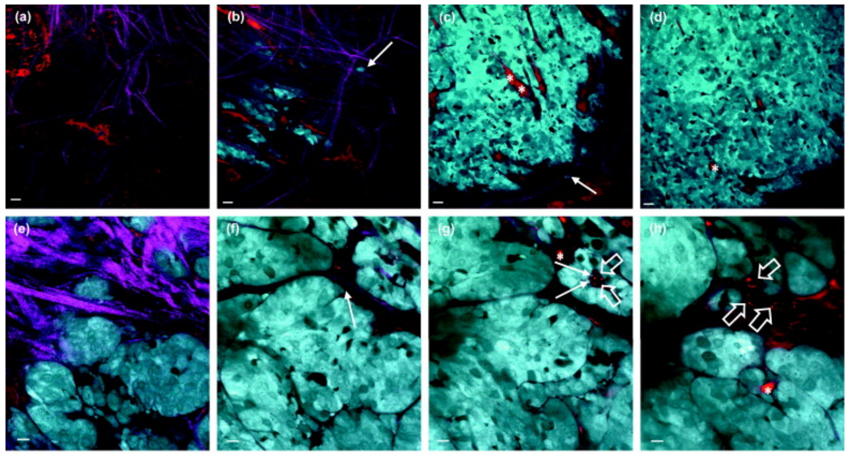
Other applications

In addition to industrial applications solid state lasers can be employed in other areas:

- Aerospace applications: LIDAR (Light Detection and Ranging), similar to RADAR, used for distance or velocity evaluation of hard objects, pollutant detection, oceanographic maps . . .



- Biomedical applications: non-linear microscopy (ultrafast lasers, particularly Ti:Sapphire), ophthalmology, dental surgery, brain surgery, . . .
- Research: ultrafast spectroscopy, THz generation, high energy physics, satellite ranging, . . .



Drug Discovery Today: Disease Models

Outstanding examples of famous laser companies

Spectra Physics was founded in 1961 by R. Rempel to capitalize the invention of He-Ne lasers. In 2004 Spectra Physics was acquired by Newport Corporation

Coherent Inc. was founded in 1966 by J. Hobart, following the invention of CO_2 lasers. The first laser was built in a laundry room.