Laser -
Light Amplification by Stimulated Emission of Radiation

By
Dr. J. K. Baria
Professor Of Physics
V. P. & R. P. T. P. Science College
Vidyanagar 388 120

Knowledge Keeps the mind always young

What is Laser ?

Laser is a acronym of Light Amplification by Stimulated Emission of Radiation

- A device produces a coherent beam of optical radiation by stimulating electronic, ionic, or molecular transitions to higher energy levels
- When they return to lower energy levels by stimulated emission, they emit energy.

Properties of Laser

- Monochromatic

  Concentrate in a narrow range of wavelengths (one specific colour).

- Coherent

  All the emitted photons bear a constant phase relationship with each other in both time and phase

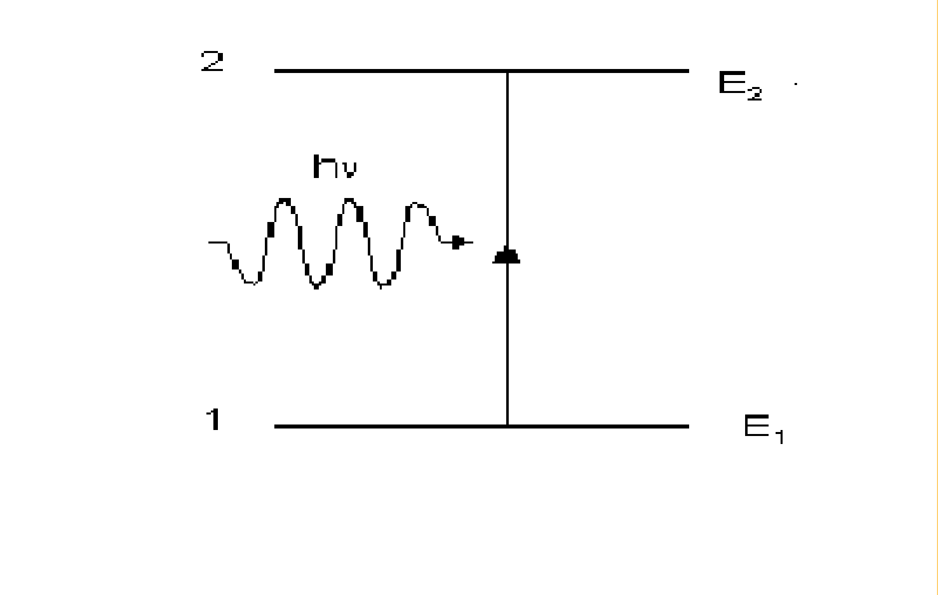
- Directional

  A very tight beam which is very strong and concentrated.

Basic concepts for a laser

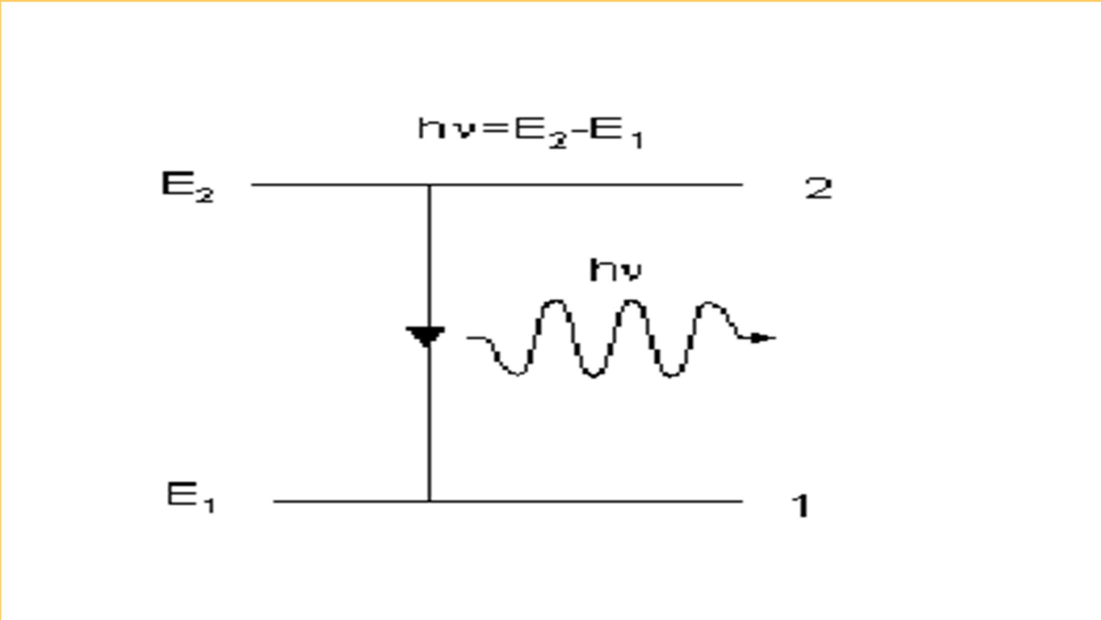
- Absorption
- Spontaneous Emission
- Stimulated Emission
- Population inversion

Absorption



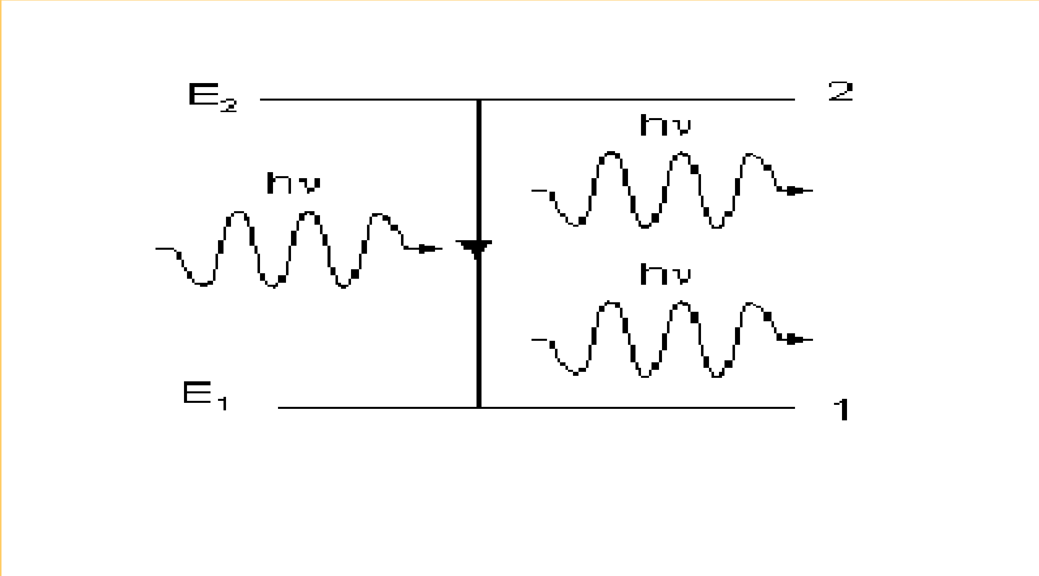
- Energy is absorbed by an atom, the electrons are excited into vacant energy shells.

Spontaneous Emission



- The atom decays from level 2 to level 1 through the emission of a photon with the energy *hv*. It is a completely random process.

Stimulated Emission



atoms in an upper energy level can be triggered or stimulated in phase by an incoming photon of a specific energy.

Stimulated Emission

The stimulated photons have unique properties:

- In phase with the incident photon
- Same wavelength as the incident photon
- Travel in same direction as incident photon

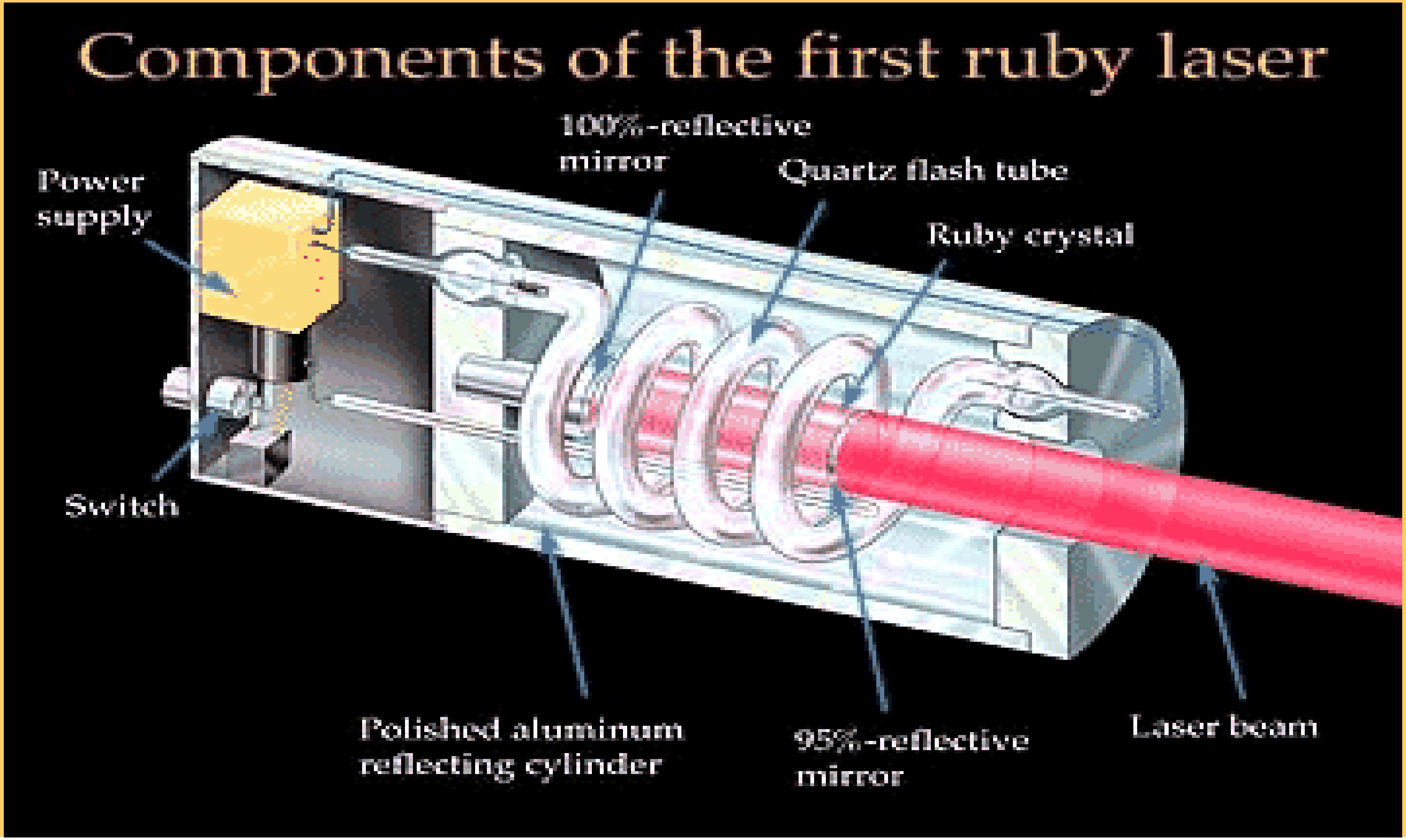
Population Inversion

- A state in which a substance has been energized, or excited to specific energy levels.
- More atoms or molecules are in a higher excited state.
- The process of producing a population inversion is called pumping.
- Examples:

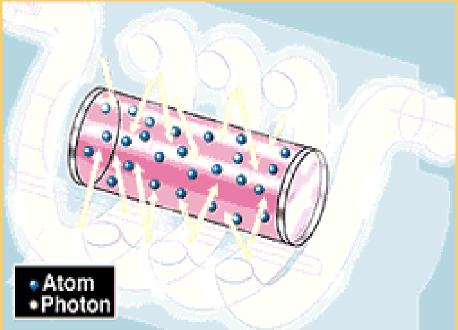
→by lamps of appropriate intensity

→by electrical discharge

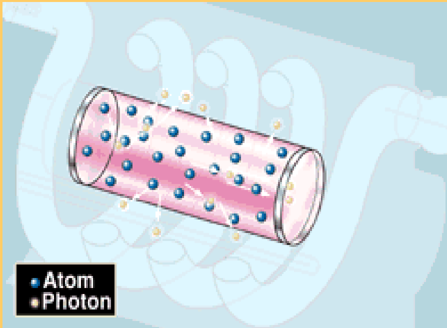
How a laser works?



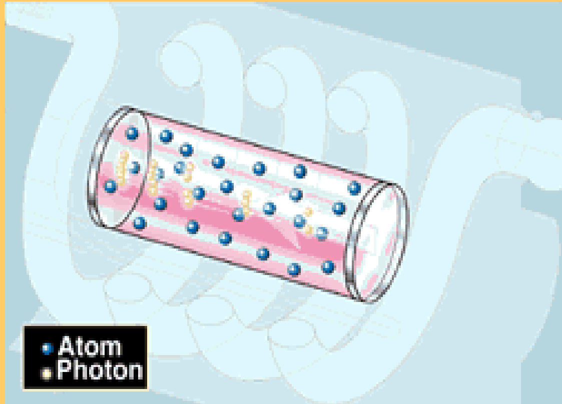
1. High-voltage electricity causes the quartz flash tube to emit an intense burst of light, exciting some of Cr^{3+} in the ruby crystal to higher energy levels.



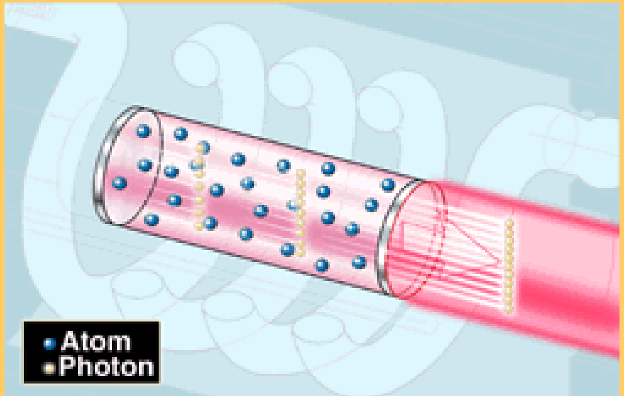
2. At a specific energy level, some Cr^{3+} emit photons. At first the photons are emitted in all directions. Photons from one Cr^{3+} stimulate emission of photons from other Cr^{3+} and the light intensity is rapidly amplified.



3. Mirrors at each end reflect the photons back and forth, continuing this process of stimulated emission and amplification.



4. The photons leave through the partially silvered mirror at one end. This is laser light.



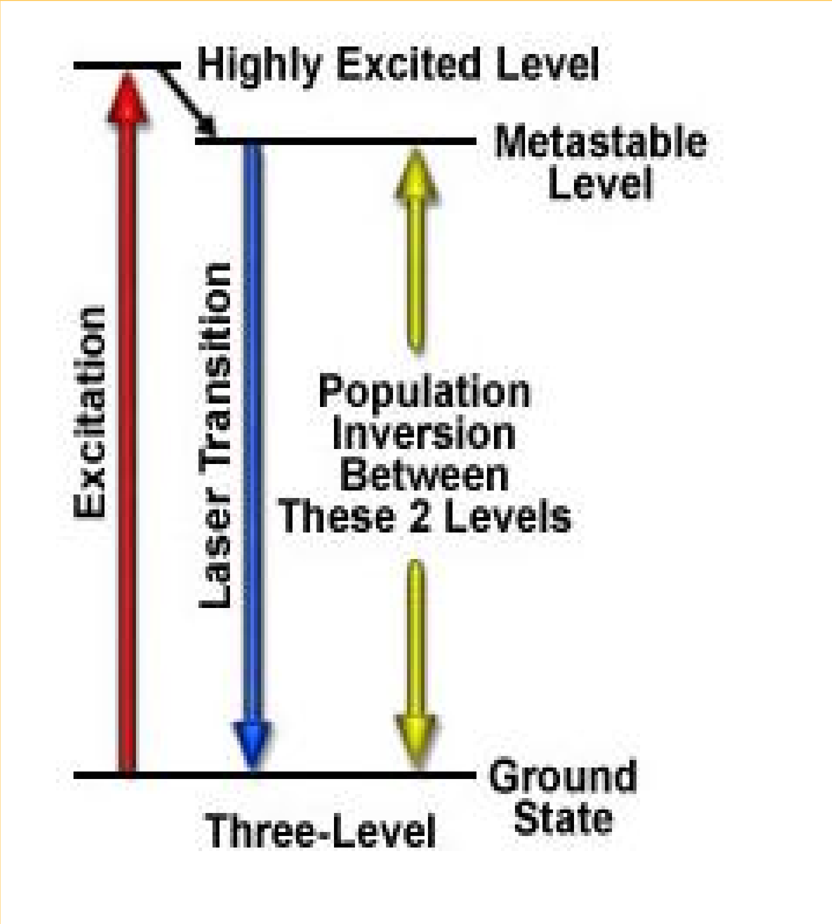
Two-level Laser System

- Unimaginable

  as absorption and stimulated processes neutralize one another.

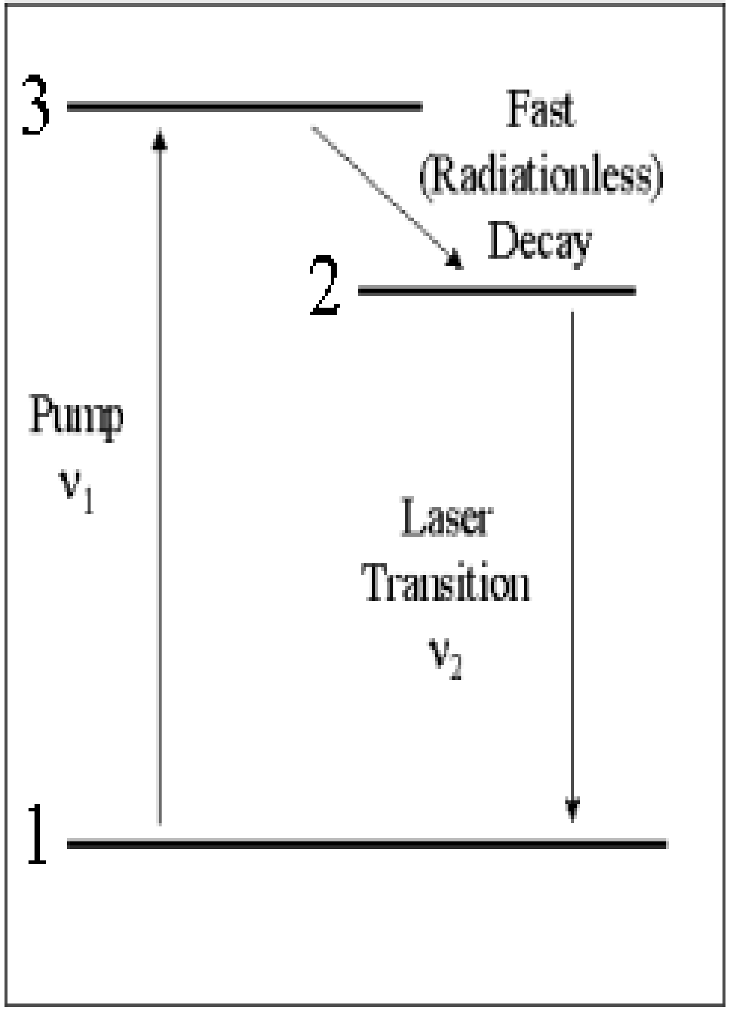
- The material becomes transparent.

Three-level Laser System



- Initially excited to a short-lived high-energy state .
- Then quickly decay to the intermediate metastable level.
- Population inversion is created between lower ground state and a higher-energy metastable state.

Three-level Laser System



Three Level Scheme

$\tau_3 << \tau_2$ $\tau_1 << \tau_2$

Nd:YAG laser

$$\lambda = 1.06 \quad \mu m$$

$$\tau_2 \approx 2.3 \times 10^{-4} s$$

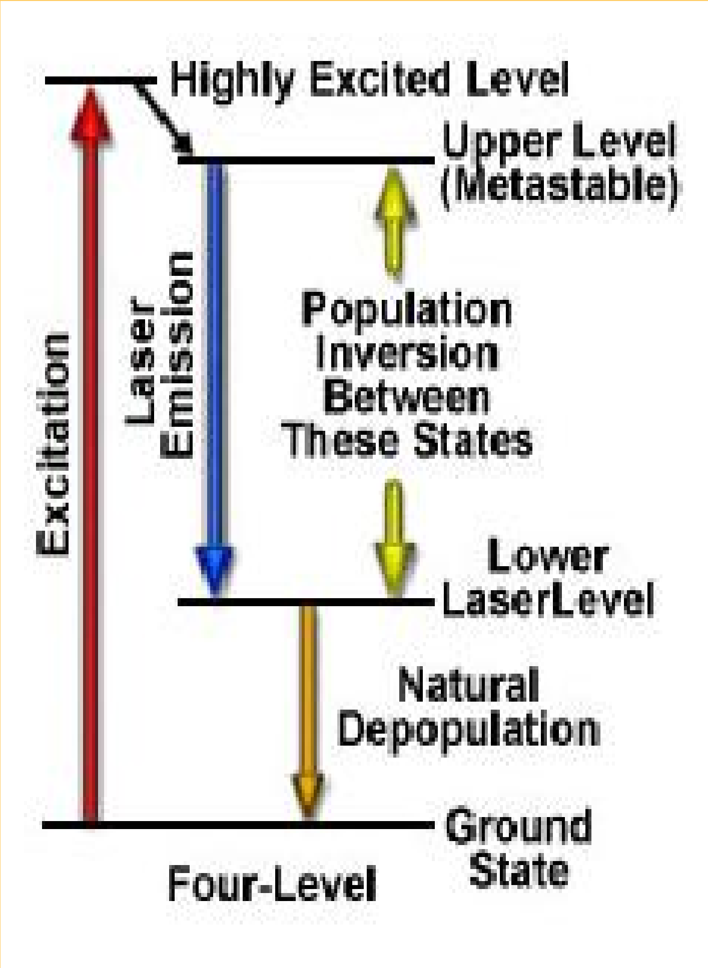
He-Ne laser

$$\lambda_1 = 3.39 \quad \mu m \qquad \lambda_2 = 0.6328 \quad \mu m$$

$$\lambda_3 = 1.15 \quad \mu m$$

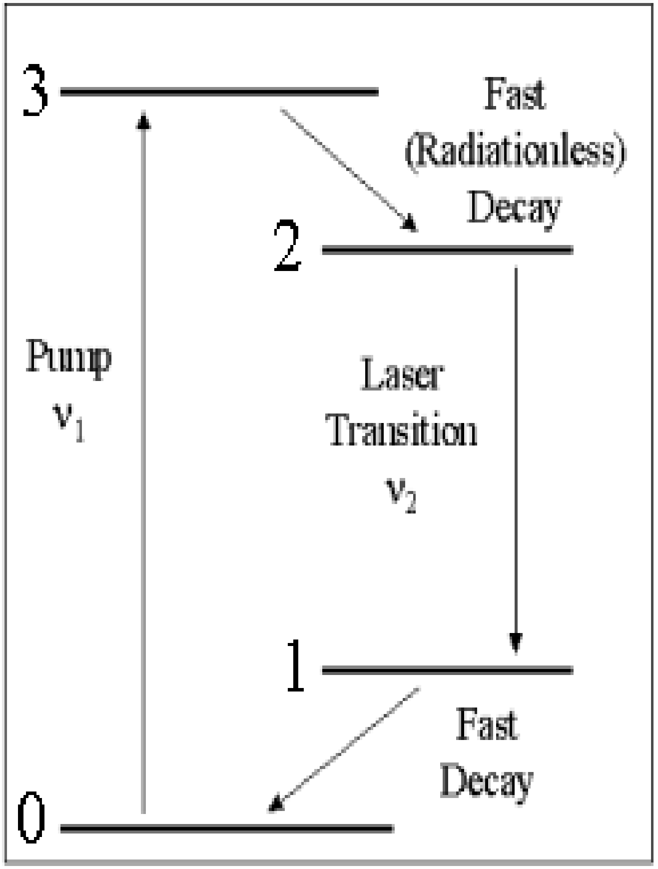
$\tau_2 \approx 100\text{ns}$ $\tau_1 \approx 10\text{ns}$

Four-level Laser System



- Laser transition takes place between the third and second excited states.
- Rapid depopulation of the lower laser level.

Four-level Laser System



Four Level Scheme

$\tau_3 << \tau_2$

Ruby laser

$$\lambda_1 = 0.6943\ \mu m$$

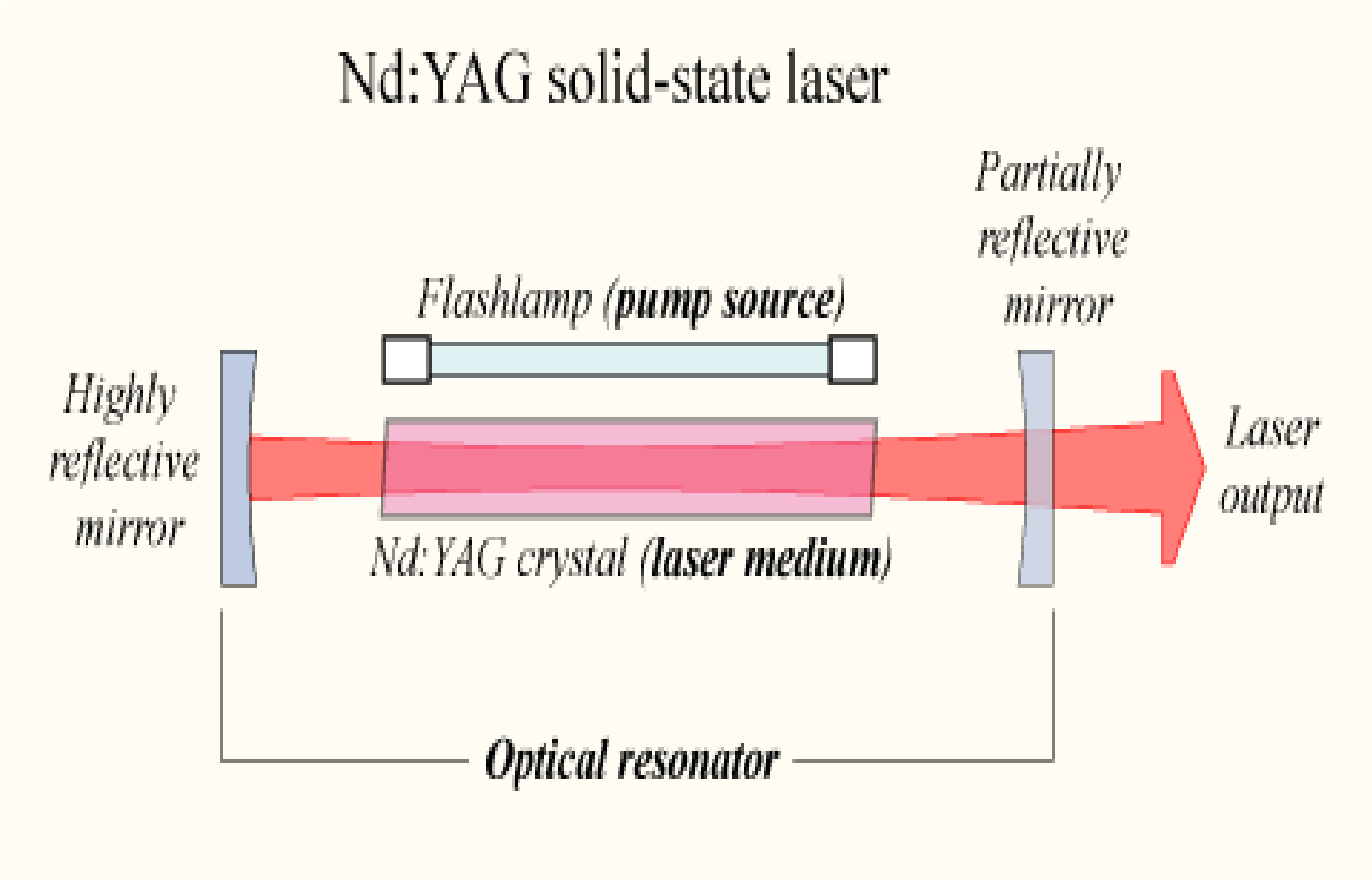
$$\lambda_2 = 0.6928\ \mu m$$

$\tau_3 \approx 10^{-7} s \quad \tau_2 \approx 3 \cdot 10^{-3} s$

Laser Construction

- A pump source
- A gain medium or laser medium.
- Mirrors forming an optical resonator.

Laser Construction



Pump Source

- Provides energy to the laser system
- Examples: electrical discharges, flashlamps, arc lamps and chemical reactions.
- The type of pump source used depends on the gain medium.

→A helium-neon (HeNe) laser uses an electrical discharge in the helium-neon gas mixture.

→Excimer lasers use a chemical reaction.

Gain Medium

- Major determining factor of the wavelength of operation of the laser.
- Excited by the pump source to produce a population inversion.
- Where spontaneous and stimulated emission of photons takes place.
- Example:

  solid, liquid, gas and semiconductor.

Optical Resonator

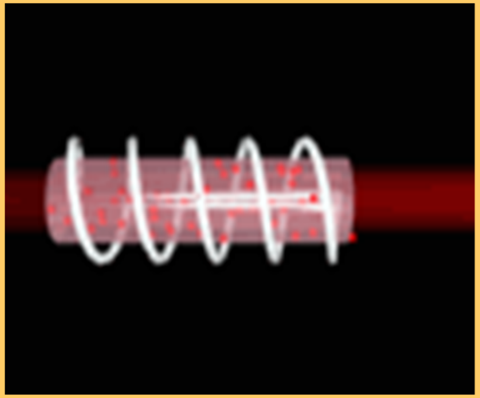
- Two parallel mirrors placed around the gain medium.
- Light is reflected by the mirrors back into the medium and is amplified .
- The design and alignment of the mirrors with respect to the medium is crucial.
- Spinning mirrors, modulators, filters and absorbers may be added to produce a variety of effects on the laser output.

Laser Types

- According to the active material:
  solid-state, liquid, gas, excimer or semiconductor lasers.

- According to the wavelength:
  infra-red, visible, ultra-violet (UV) or x-ray lasers.

Solid-state Laser



- Example: Ruby Laser
- Operation wavelength: 694.3 nm (IR)
- 3 level system: absorbs green/blue

•Gain Medium: crystal of aluminum oxide (Al_2O_3) with small part of atoms of aluminum is replaced with Cr^{3+} ions.

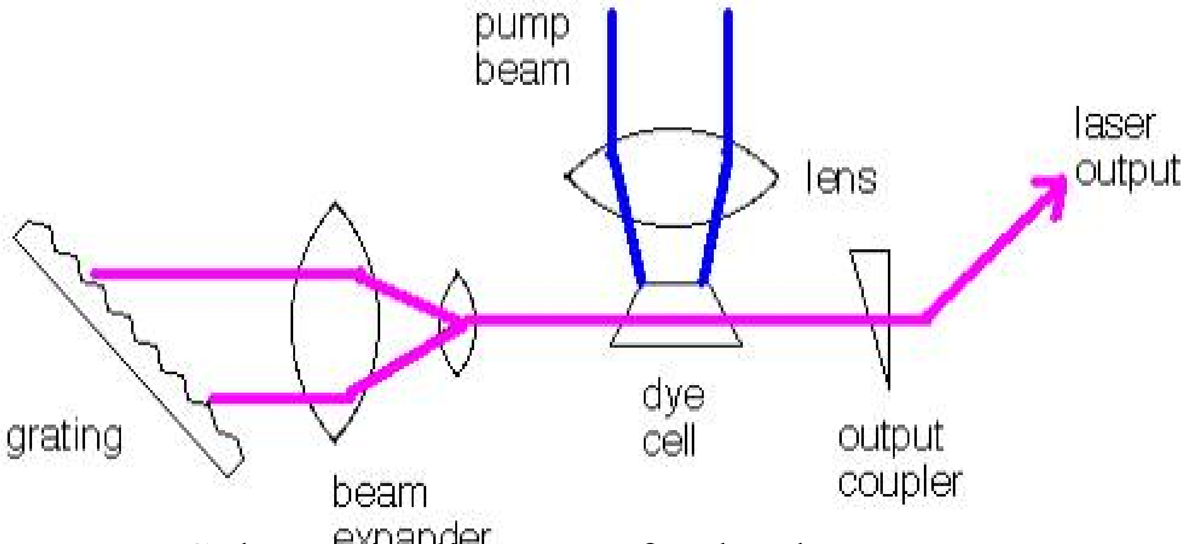
•Pump source: flash lamp

•The ends of ruby rod serve as laser mirrors.

Liquid Laser

- Example: dye laser
- Gain medium: complex organic dyes, such as rhodamine 6G, in liquid solution or suspension.
- Pump source: other lasers or flashlamp.
- Can be used for a wide range of wavelengths as the tuning range of the laser depends on the exact dye used.
- Suitable for tunable lasers.

dye laser

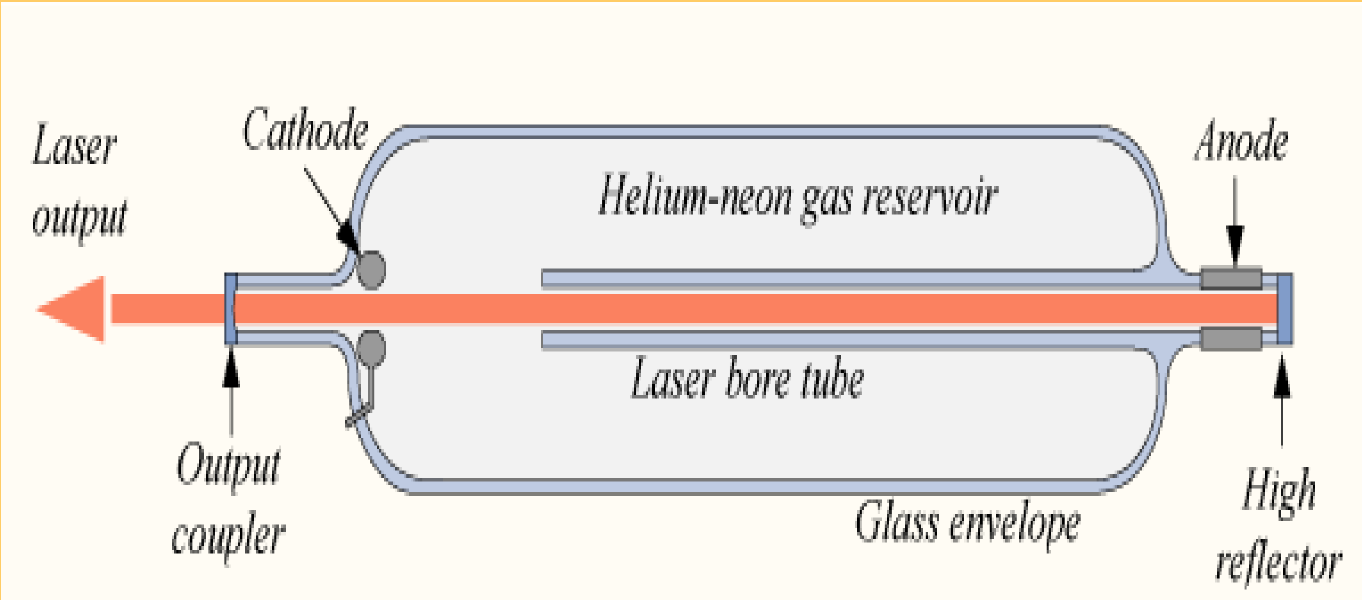


Schematic diagram of a dye laser

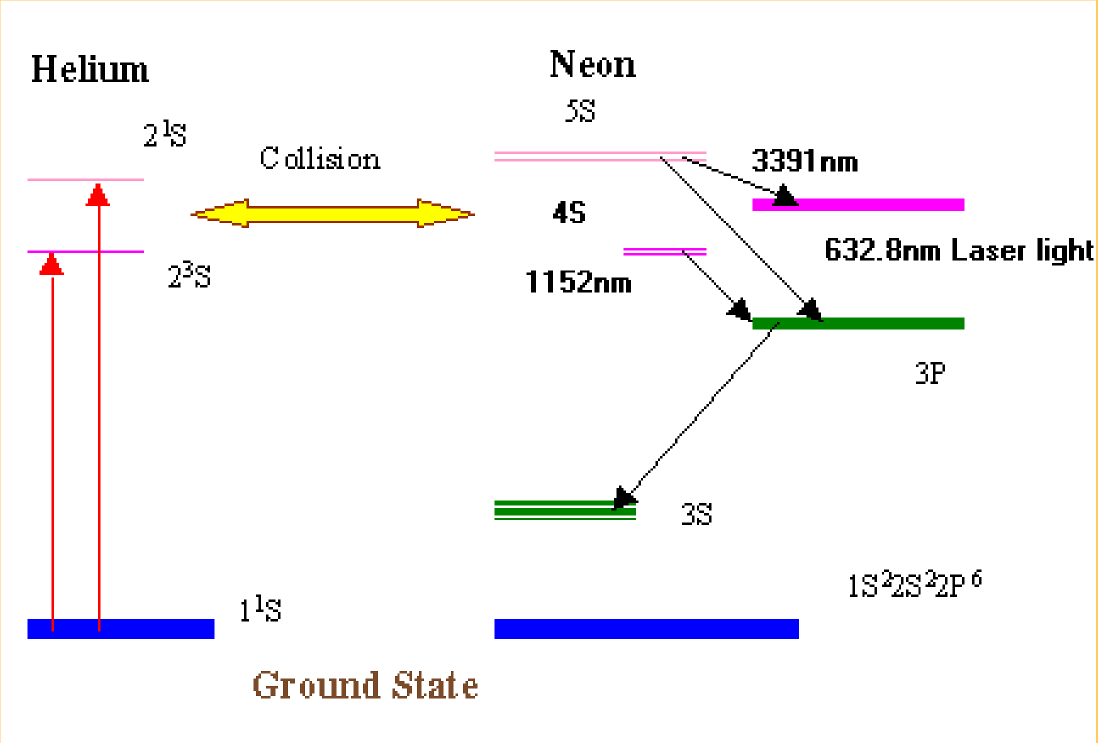
A dye laser can be considered to be basically a four-level system.
The energy absorbed by the dye creates a population inversion, moving the electrons into an excited state.

Gas Laser

- Example: Helium-neon laser (He-Ne laser)
- Operation wavelength: 632.8 nm
- Pump source: electrical discharge
- Gain medium : ratio 5:1 mixture of helium and neon gases



He-Ne laser



$$\lambda_1 = 3.39\,\mu\text{m} \quad \lambda_2 = 0.6328\,\mu\text{m} \quad \lambda_3 = 1.15\,\mu\text{m}$$

Excimer Laser

- cool laser.
- Incredibly precise.
- laser eye surgery.

Excimer laser used for eye surgery.

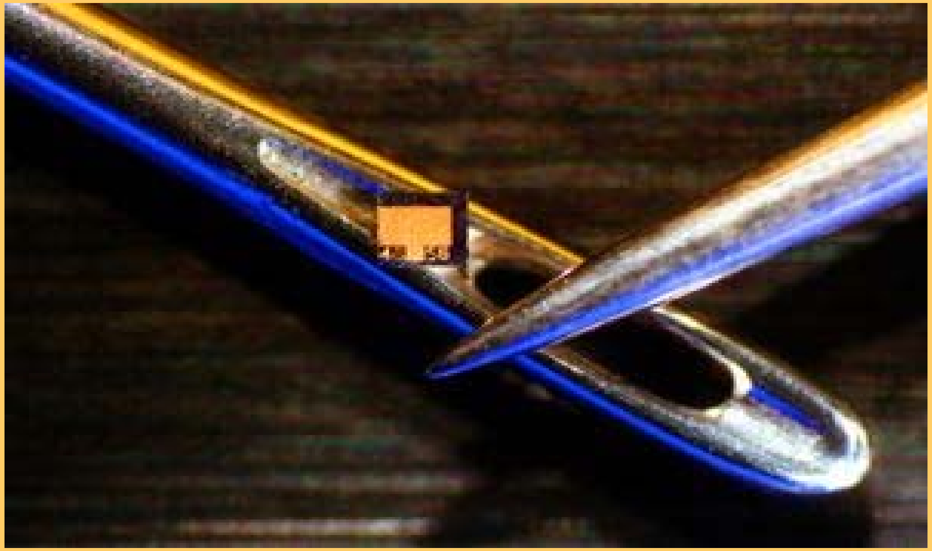
Exciplex Laser

- Gain medium: excited dimer
- Noble gas halide type, e.g. ArF, XeBr and KrF.
- Pump source: excimer recombination via electrical discharge.
- Produce light in the ultraviolet range.

Exciplex	Wavelength (nm)
ArF	193
XeBr	282
KrF	248

Semiconductor laser

Semiconductor laser is a laser in which semiconductor serves as photon source.



Semiconductors (typically direct band-gap semiconductors) can be used as small, highly efficient photon sources.

Applications of laser

- 1. Scientific

    a. Spectroscopy

    b. Lunar laser ranging

    c. Photochemistry

    d. Laser cooling

    e. Nuclear fusion

Applications of laser

- 2 Military
  - a. Death ray
  - b. Defensive applications
  - c. Strategic defense initiative
  - d. Laser sight
  - e. Illuminator
  - f. Rangefinder
  - g. Target designator

Applications of laser

- 3. Medical

Laser pointer

eye surgery

cosmetic surgery

Applications of laser

- 4. Industry & Commercial

    a. cutting, welding, marking

    b. CD player, DVD player

    c. Laser printers, laser pointers

    d. Photolithography

    e. Laser light display

Laser Cutting

- Established as a manufacturing process in the 80’s
- 1000 companies using laser cutting the UK
- Many more buy in laser cut parts
- Metals cutting is a major market
- But many non-metals applications as well.

Cutting

Key features of laser cutting includes:

Application to a wide range of materials

Narrow kerf width

Non contact

Good edge quality (square ,clean and no burrs)

Very narrow HAZ, low heat input

Very high repeatability and reliability

Virtually any material can be cut

Cutting

Latest developments are:

High Speed laser cutting machines

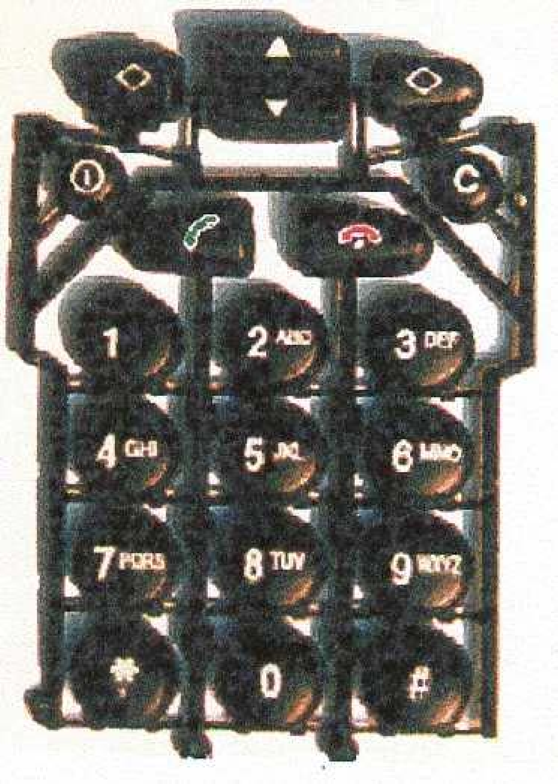
Complete automatic laser cutting installations for lights out operation

Higher power lasers offer cut thickness in excess of 25mm

Cloth & Plastics Cutting

- Low power CO2 laser machines for cutting thin non-metals, (plastics, cloth) are now becoming commonplace.
- Combined engraving / cutting machines common in schools / colleges

Laser Marking



Laser marking the worlds largest laser application

Relevant to all sectors

Virtually any material can be laser marked to produce robust images, texts and codes

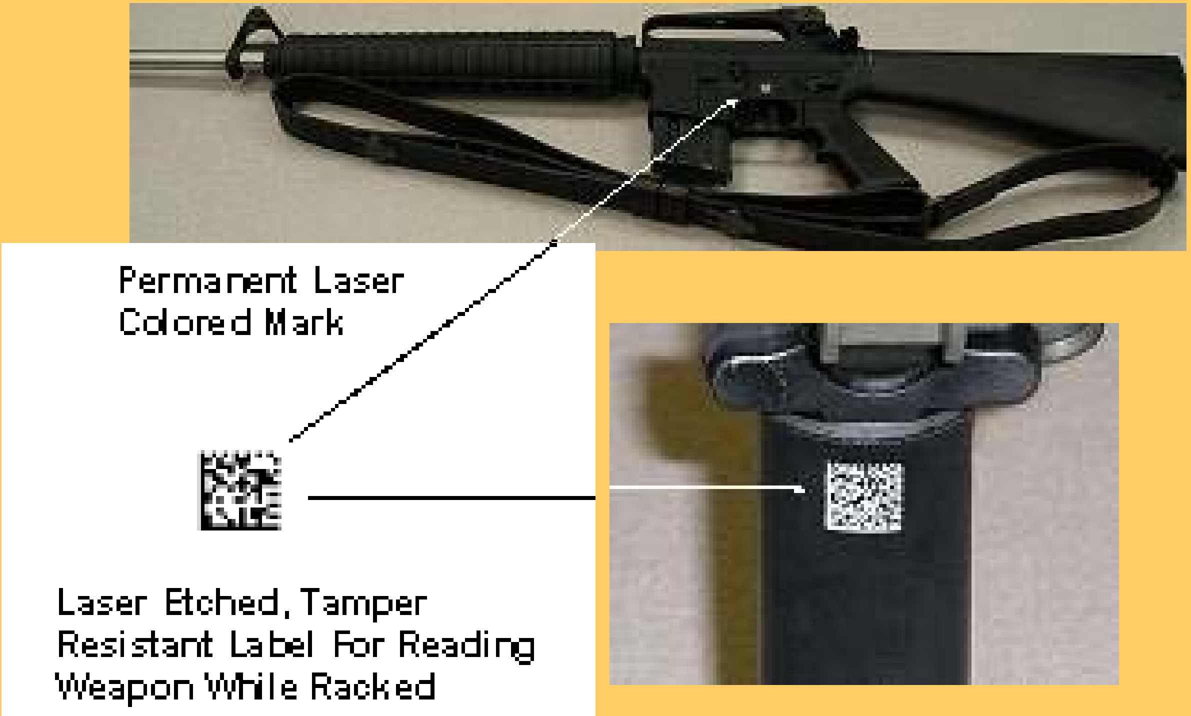
An example of a plastic keypad laser marked

Marking

Applications include part marking and serialisation, asset tracking, etc.
Applying brand logos and emergency info on moulded components
Marking of fabrics (e.g. faded jeans)and seat coverings

Marking

New marking codes, e.g. ID Matrix Code



Can loose up to 45% of the mark and you can still read it

Developments in Laser Marking

- Fibre lasers:
  - High beam quality, high efficiency laser sources give high quality marks on metals at increased speeds

Better "engraving" performance on metals
Internal glass marking

Laser Welding

Established in the early 80’s
Now used on many production lines
Low volume applications and subcontract limited to niche areas such as mould tool repair, jewellery and dentistry

Welding

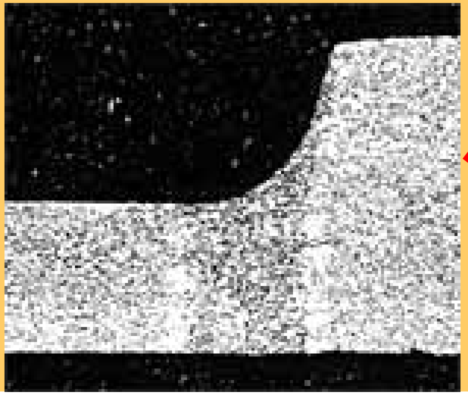
Key features of deep penetration laser welding include:

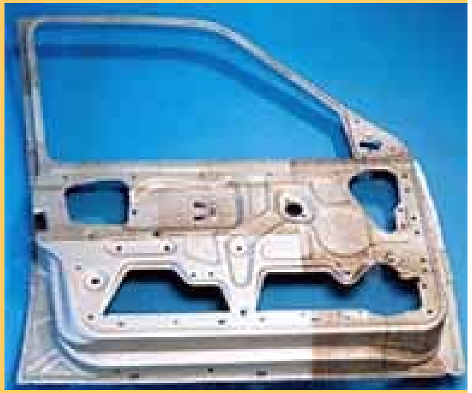
High energy density – Keyhole welding	*Less distortion*
High processing speeds	*High throughput*
Rapid start / stop	*Unlike arc processes*
Welds at atmospheric pressures	*Unlike EB welding*
No filler required	*But good fit up is essential*
Narrow welds	*Less distortion*
Very accurate welding possible	*Good fit up & fixturing needed*
Good weld bead profiles	
No beam wander in magnetic fields	*Unlike EB*
Little or no contamination	*Depending on gas shroud*

Welding

Automotive applications include components, 3D body welding and Tailored blanks

VW over 200 lasers, Jaguar (Castle Bromwich) 1, Nissan (Sunderland) 2 lines





Welding

A 10 kW fibre laser used in shipbuilding

A hybrid laser welding system

Spot and MicroWelding

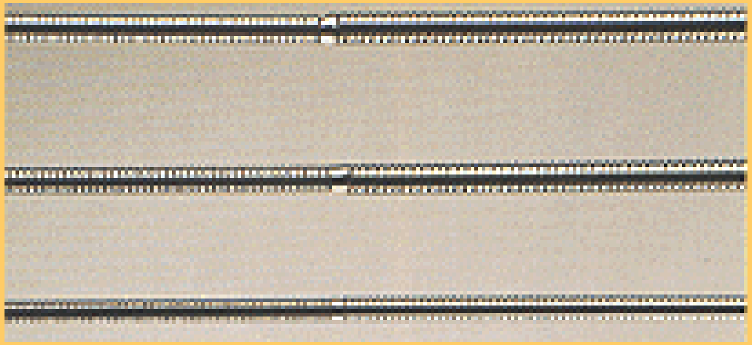
Repairing mould tools

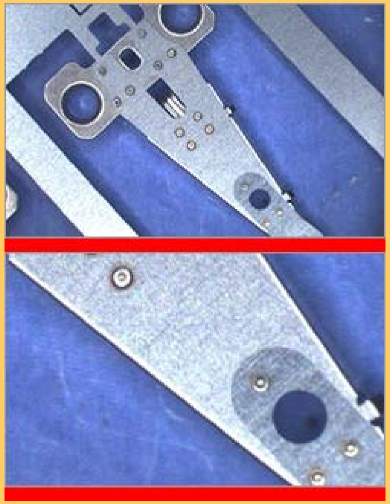
Medical devices

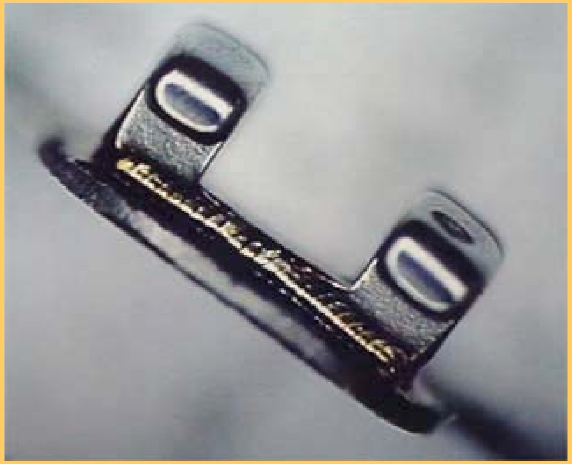
- 400µm spot welds on a orthodontic bracket

Sensors

Read / Write heads







Orthodontic Bracket

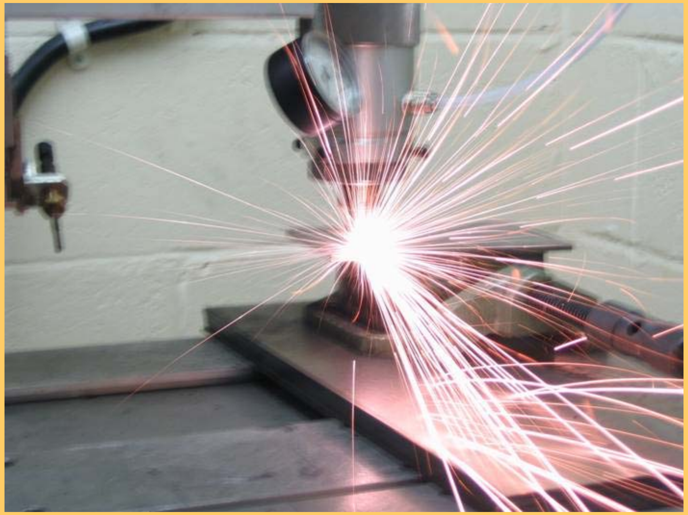
Other Laser Welding applications

- Plastics and Polymer Welding
  - Possible to use laser to weld transparent plastic to opaque plastic (n.b. “transparent and “opaque” refer to laser wavelengths)
- Clearweld®
  - Uses absorbing dye in joint interface to weld two nominally transparent polymers
  - Can even be used for clothing!

Laser Welding Developments

- Hybrid Welding
  - Uses combination of arc and laser processes
    - More tolerant to poor fit up
    - Filler metals can positively modify weld metal
    - Over performance better than expected for this combination
- "Remote Welding"
  - Use high beam quality "slab" and fibre lasers coupled to a scanning head to weld at multiple x-y-z positions

Drilling



Material Removal Process

Hole diameters dependent on laser source, Cu-vapour - Nd-Yag

Small Holes – dependent on drilling mode

- ***Trepanning: small / large holes > 0.6mm***
- ***Percussion: small holes < 0.6mm***

Advantages of Trepanning

- ***Shaped holes***

Advantages of Percussion

- ***Drilling on the fly***

Drilling

Main market sector for laser drilling is in aerospace industry

Nickel based alloys

Cooling hole

- ***Turbine blades / nozzle guide vanes***
- ***Combustion chamber > 40,000 holes***

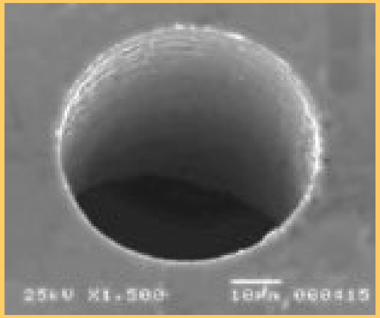
Boeing / GE drilling composites to improve acoustic quality of a jet engine

Micro drilling of wing surface to reduce drag

- ***Hole size 50μm, Number of holes 10^8***

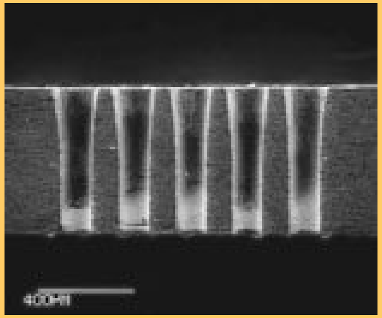
Drilling

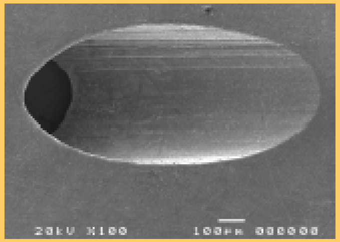
Micro machining



50 μm diameter hole in steel, CVL

125 μm diameter holes in 0.5 mm alumina, CVL





Laser drilled injector holes, 60 Deg

Via drilling

- Significant application in PCB manufacture
- Often use mixed laser processing – CO_2 and Excimer
- Machines manufactured by likes of Hitachi
- Regularly get Google alerts based on "laser drilling"

Cleaning

Emerging process, particularly driven by art and monument restoration (I.e. National Museums and Galleries on Merseyside (NMGM) conservation centre.

Engineering applications are being identified – dry cleaning of metal components prior to welding and PCB's and component leads prior to soldering.

Cleaning

Advantages of laser cleaning

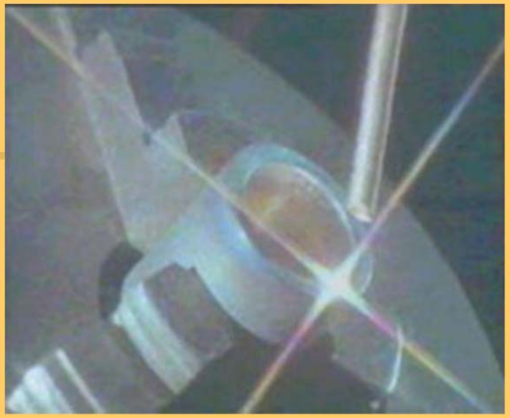
- ***Laser Cleaning does not damage***
  - ***No abrasive effect (No abrasive)***
  - ***No mechanical contact***
  - ***No heat effect***
- ***Laser cleaning does not pollute***
  - ***No solvents***
  - ***No polluted effluents***
  - ***Fumes extracted easily***

The operator protection is reduced to a simple eye protection

Cleaning

Engineering applications of laser cleaning are being developed.
Applications include mould tool cleaning
Stripping of paint from aircraft

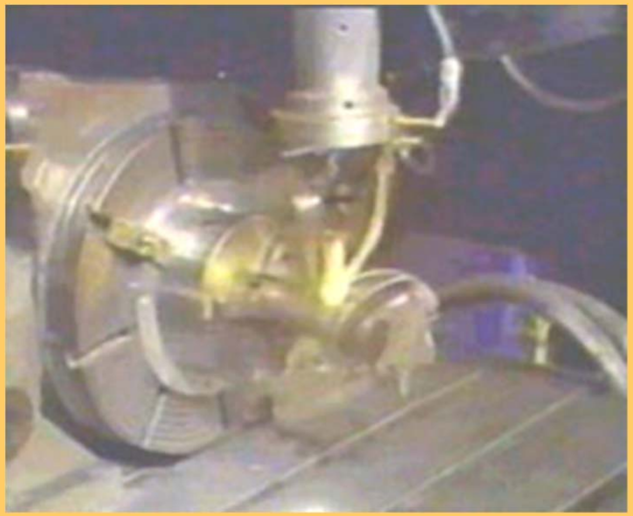
Surface treatments



Laser hardening

Three main processes – hardening, melting and alloying. Aim to improve surface properties such as wear and corrosion resistance, one can:

Temper
Laser Hardening
Laser fusing / cladding (depositing a hardwearing corrosion resistant surface
Alloying surfaces
Nitrate
Treat many different materials



Laser Alloying

Surface treatments

Special hardening process for titanium

Surface is laser heated

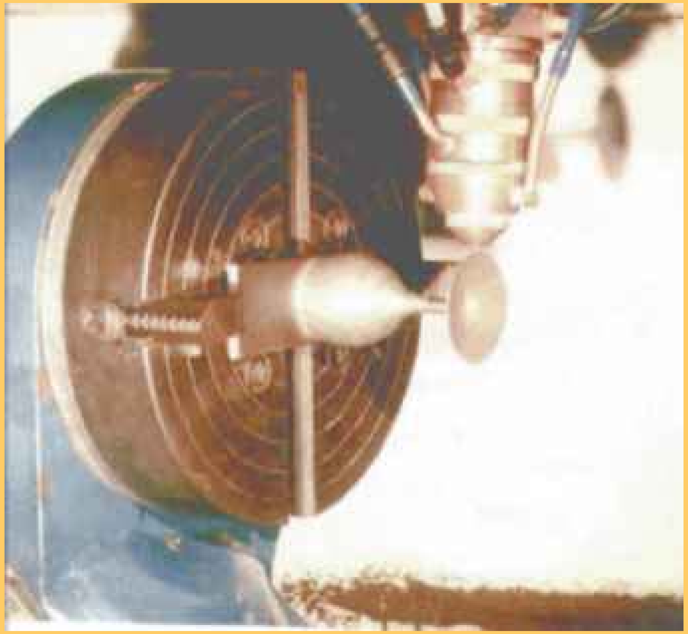
Nitrogen is blown over the surface forming titanium nitride under on the surface

The surface hardness is increased many times compared with the parent material

Laser Cladding

- Deposition of wear and corrosion resistant materials
- Reduced heat input gives lower distortion

Direct Laser Fabrication



DLF combines 4 common technologies

- *CAD*
- *CAM*
- *Powder Metallurgy*
- *Laser Technology*

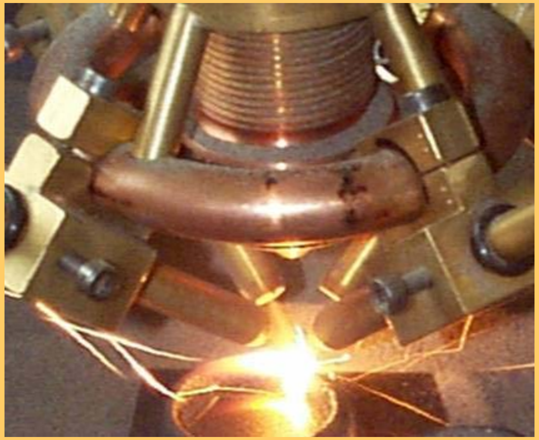
A high powered laser creates a melt pool

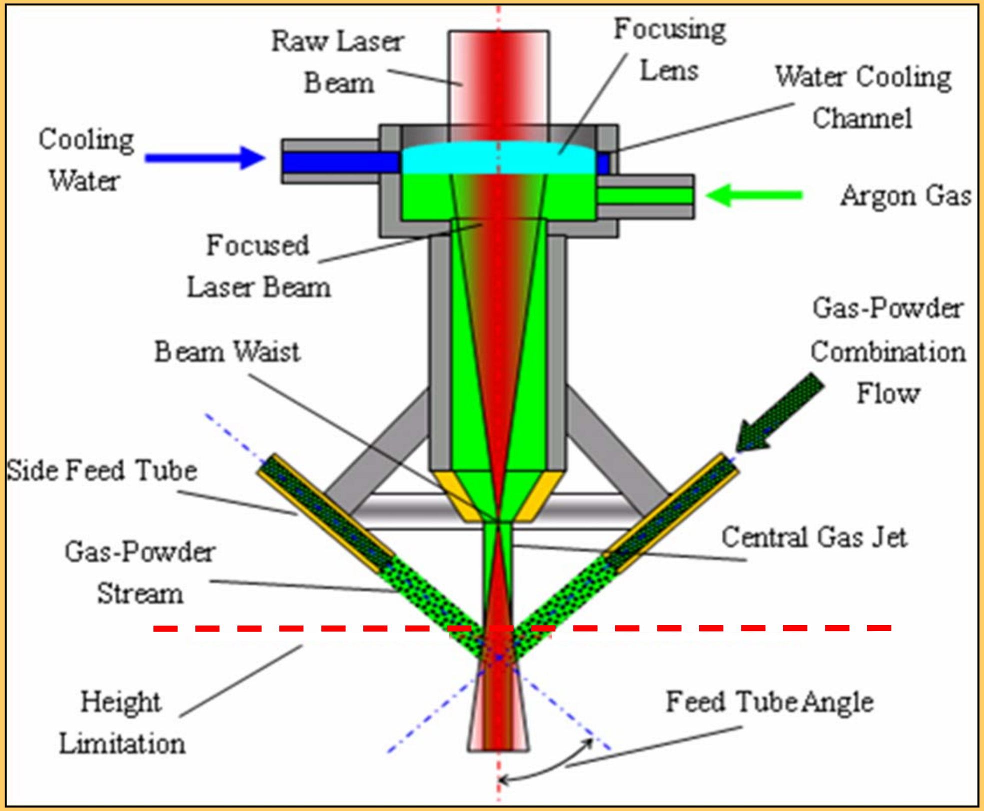
Powder is deposited into the melt pool

Moving the laser beam in a prescribed pattern a component is traced out layer by layer

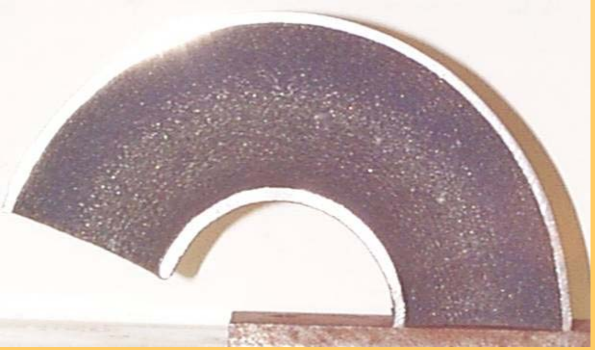
Direct Laser Fabrication

General set-up of Direct Metal Deposition

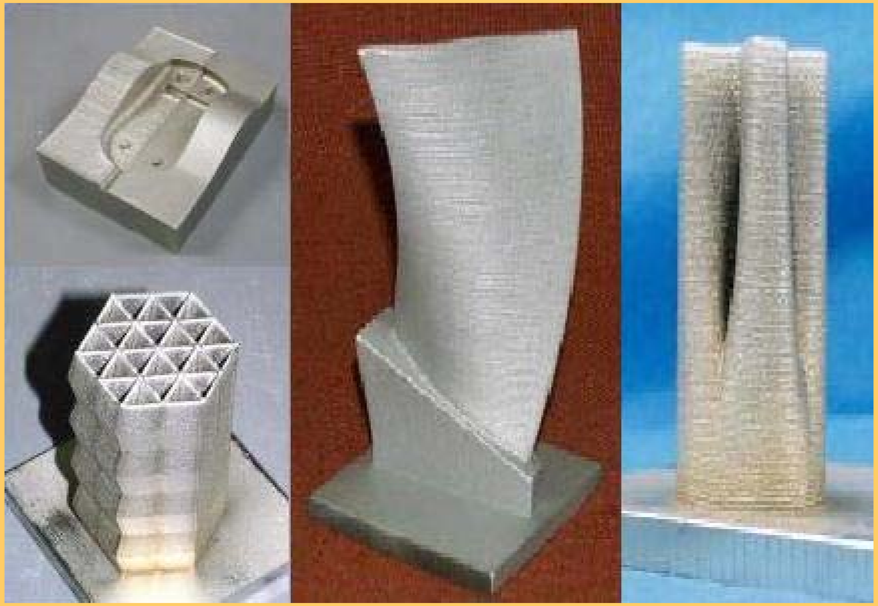




Direct Laser Fabrication



- *Tool repair*
- *Mould repair*
- *Turbine blade repair*
- *Rapid Prototyping*



Selective Laser Sintering

- ***Parts built up layer by layer***
- ***A CO2 laser beam selectively melts powder into a designated shape***
- ***The component sinks into the bed***, a layer of powder is deposition above the component
- The process repeats until the component is finished

Laser Forming - an emerging process

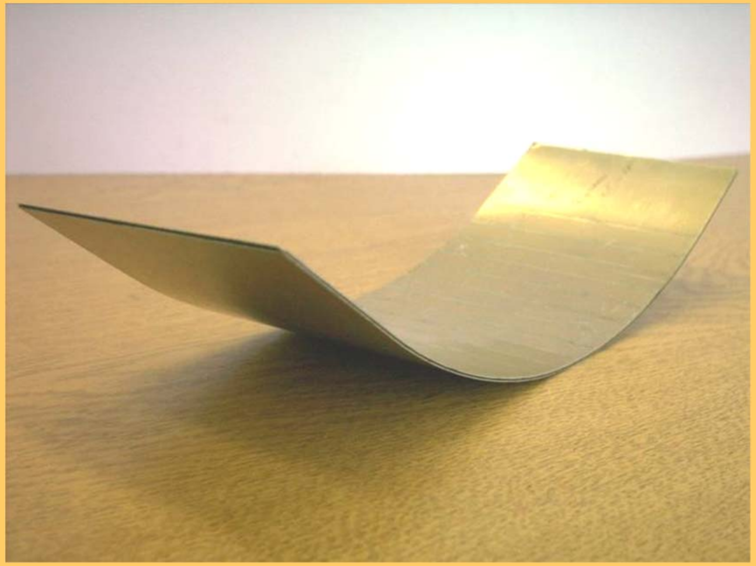
- ***Bending metal with light***
- ***Laser beam induces thermal stresses***
- ***The plate expands, cools and contracts***
- ***The flat plate deforms into a new shape***

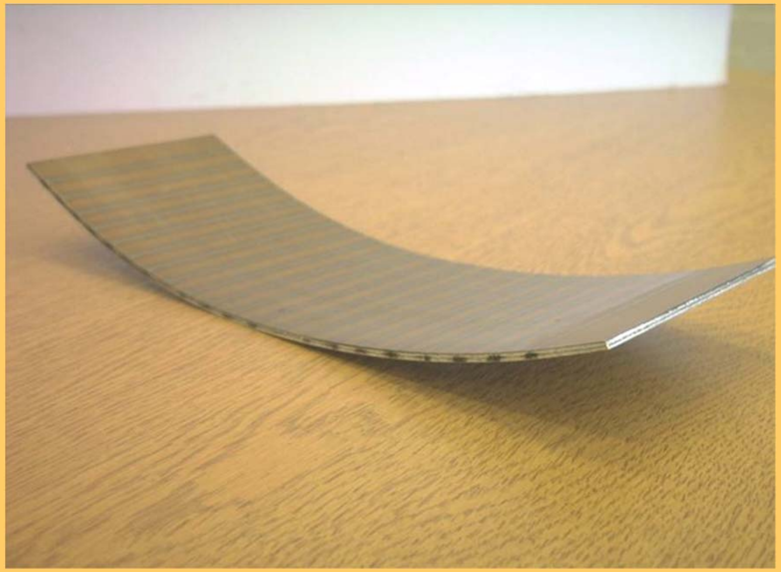
- ***Industrial sectors***
  - ***Aerospace***
  - ***Automotive***
  - ***Marine***

Laser Forming

Potential application in difficult to form materials

- ***Laser forming of GLARE (metal composite) as used in the A380***

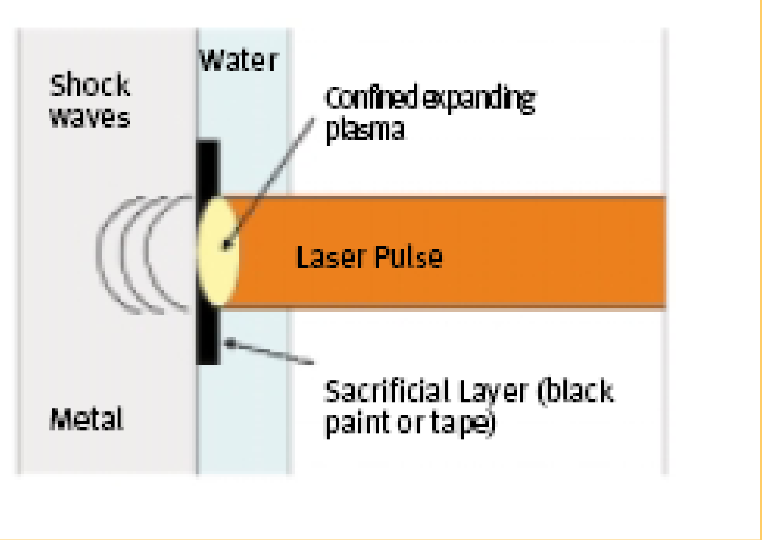




- ***220x80mm 2/1 Self-Reinforced Polypropylene based MLC***

Laser Shock Peening

- *Laser shock peening used to induce compressive shocks within a component*
- *Penetration far greater than traditional methods*

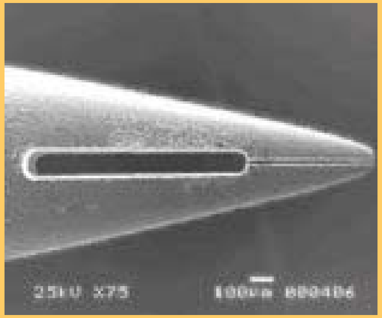


Microprocesses

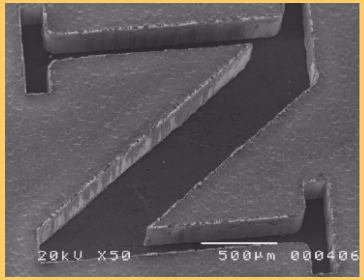
- The precision and small spot sizes (down to less than 1um) makes the laser an ideal tool for "microprocessing" and nanotechnology.
- Universities of Liverpool and Manchester won £2.5m NWSF funding to set up Northwest Laser Engineering Consortium

Fine Cutting

Micro-cutting

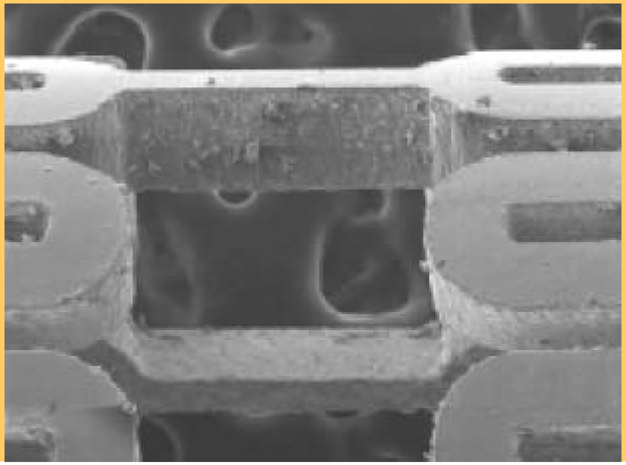


A wafer cut in 100 μm silicon



A 0.01 X 0.1 mm slot cut in Tungsten

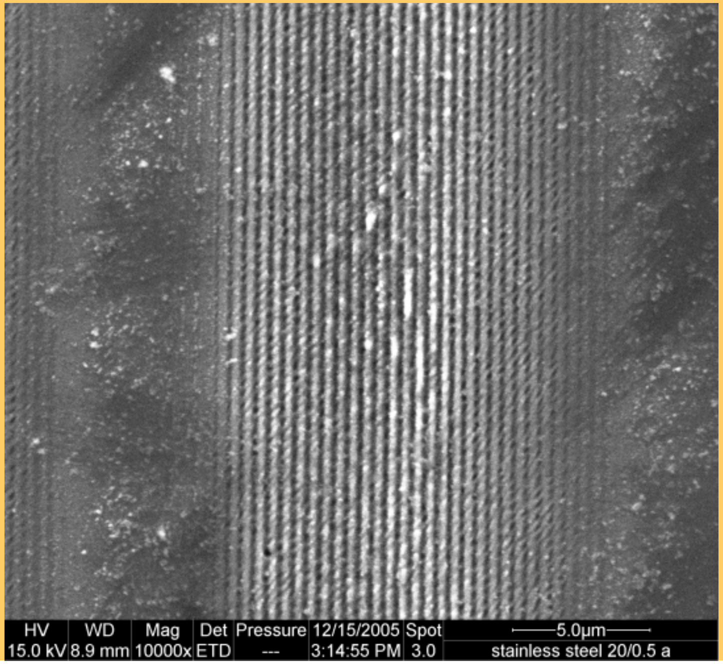
Stent cutting, Kerf width >20 microns



Wall thickness 100 microns

Structuring and texturing

- Periodic Structures (with period <1um) machined into metals and ceramics, and also produced by material modification in polymers



Beam coupler

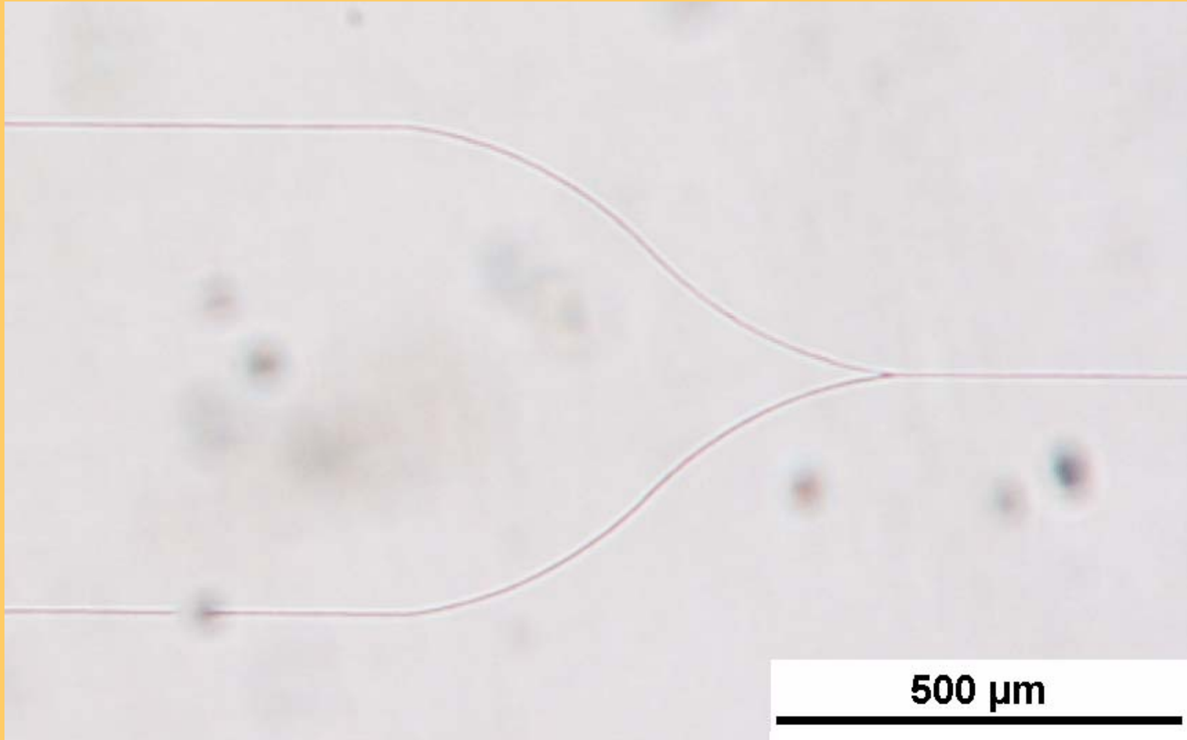
PMMA

387nm

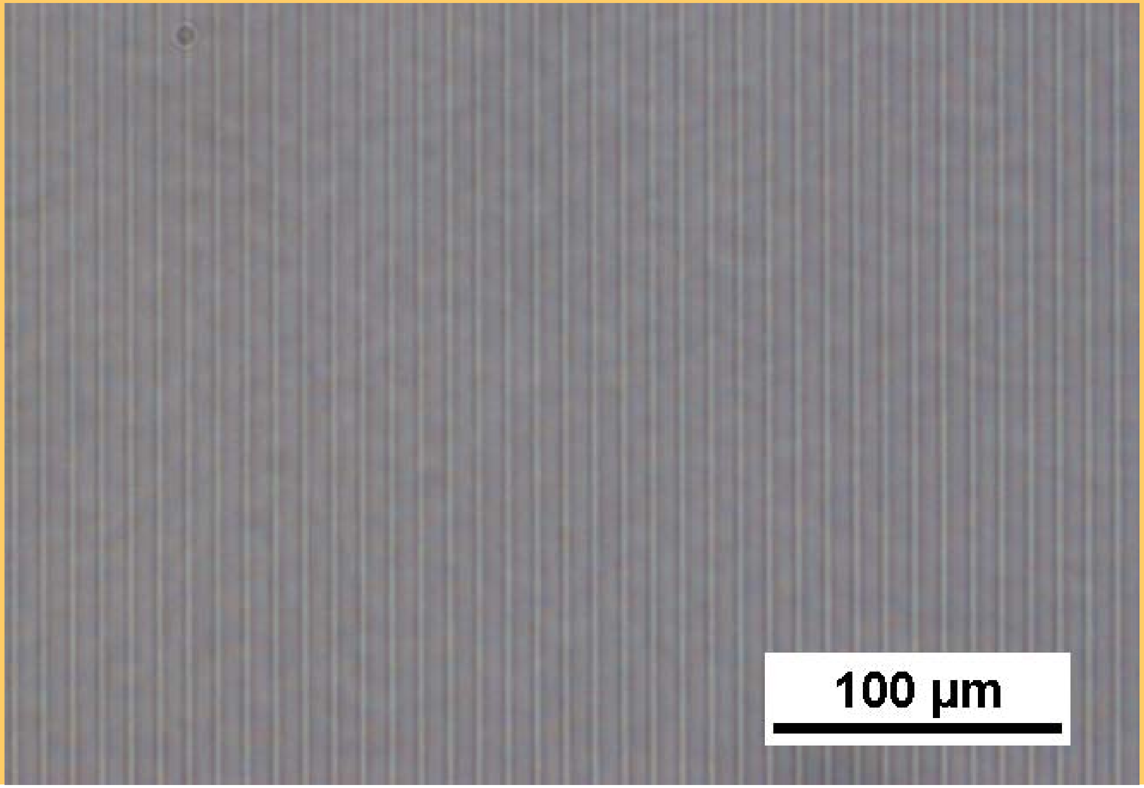
0.1μJ/pluse

0.1mm/s

0.3NA objective



Direct writing in Fused Silica



Pulse duration **100**fs,

Wavelength 400nm,

Pulse energy 0.8µJ

Scan speed 200 µm/s

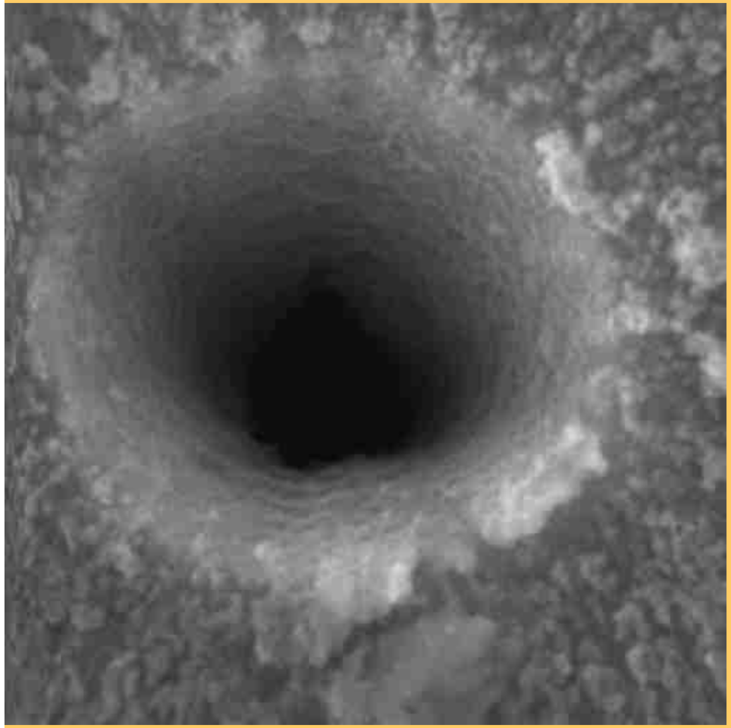
10 µm pitch, 0.5NA

Parallel Processing with SLM

- The "cold" machining of materials using fS and pS lasers requires low pulse energies. Many laser systems are low repetition rate (<50kHz) high energy (100uJ+), and beam have to be attenuated to obtain ideal energy
- Low throughput
- Use a spatial light modulator (diffractive optical element) to produce multiple beams (50+) for parallel processing
- Improved throughput
- Developed under NWLEC, now a TSB project at UoL

Drilling

- Small hole arrays in thin foils.
  - Uses a “Femtosecond” laser
  - A “Cold” process

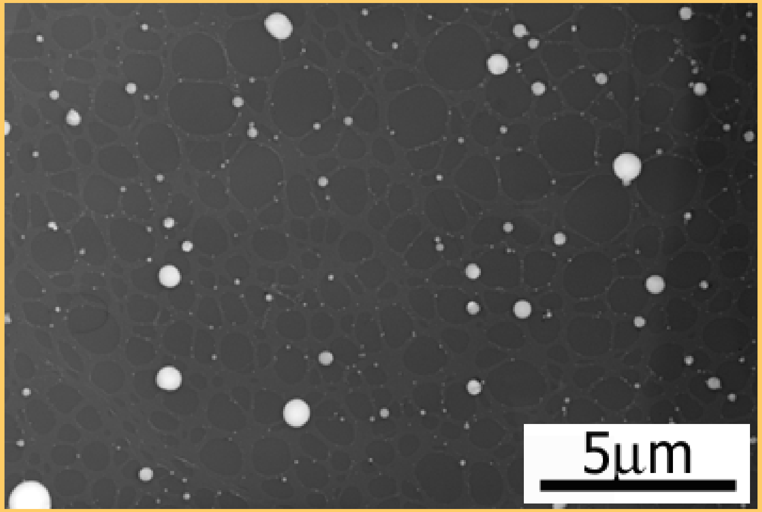


Hole in 30um Ti foil

10um

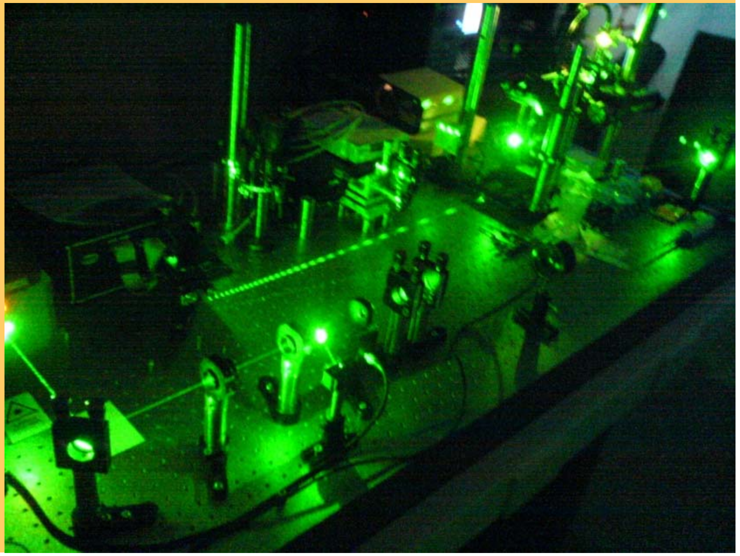
CW Fibre laser generation of Nanoparticles

- High intensity laser beams vapourise materials that then condense as sub-micron powders.
- CW fibre laser combine high intensity with high intensity



Tweezers

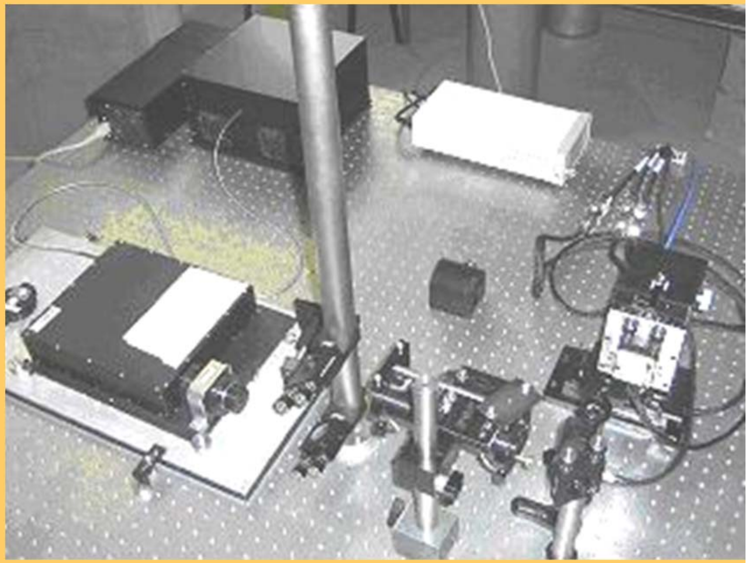
- Want to look at tweezers as the way of moving and manipulating nanoparticles
- Potential microbuilding process
- Combine with UV polymerisation RP machines



pS fibre lasers

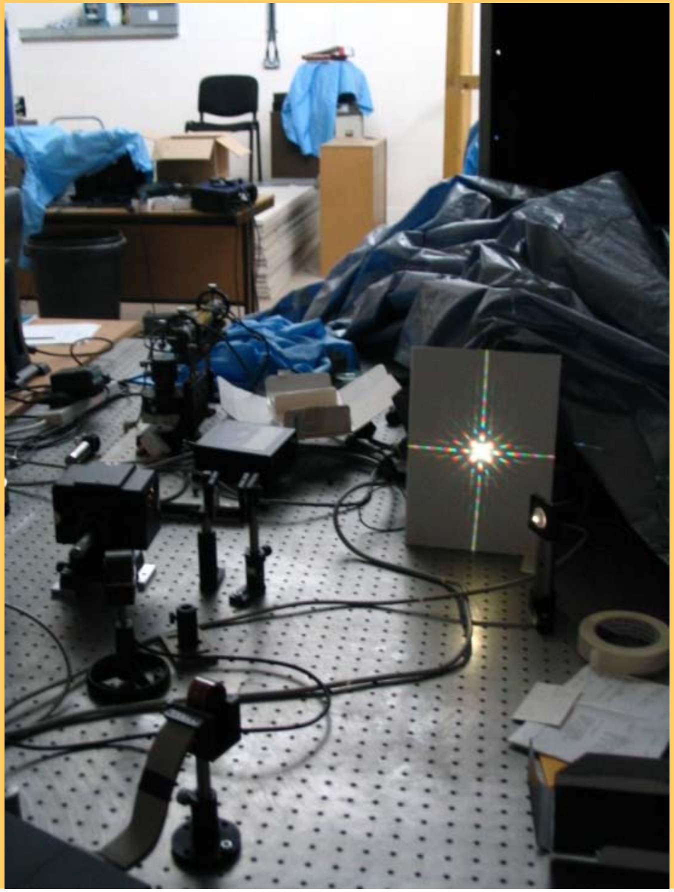
Fianium laser system:

- Pulse Length 20ps.
- Wavelength 1064 nm.
- Rep Rate 200kHz or 500kHz
- Maximum Pulse Energy 6 μJ
- Laser Power 2.1W
- Experimental Spot Size 26μJ



DTI Funded project "Ultrafast" completed at LLEC – scored 56/60 in final assessment

White laser beams

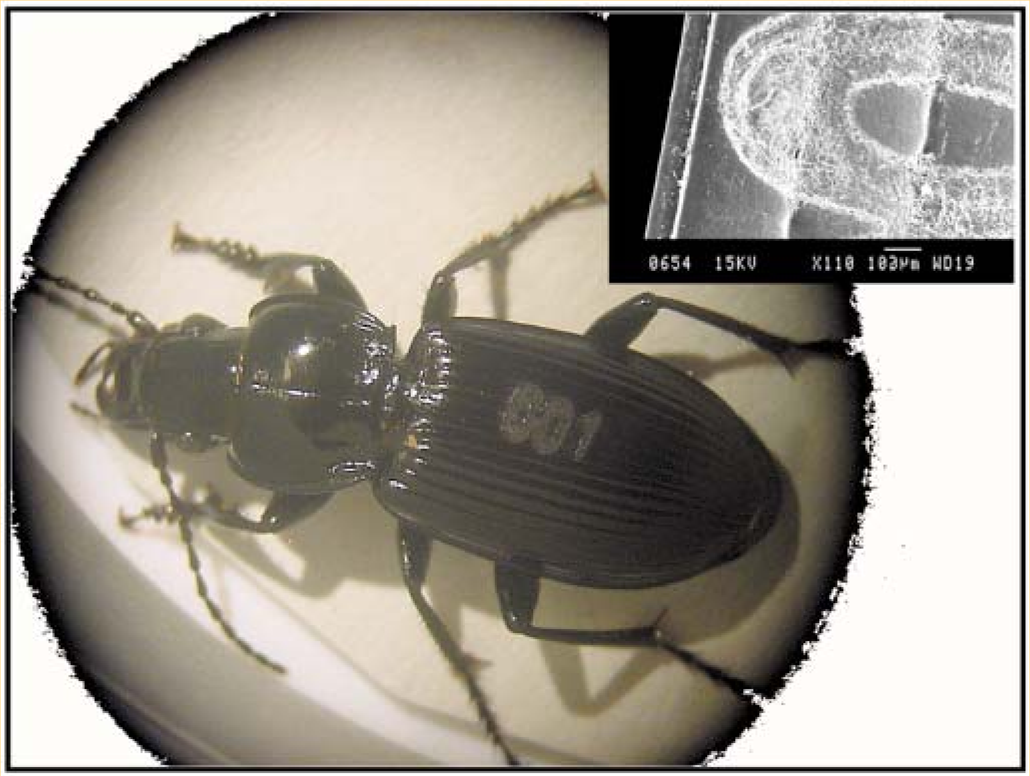


- Any ideas?

Laser cutting of cheese

- Using an freq quadrupled laser!
- Max cut depth at 1mm/min is 3mm!
- Av Power 2W

Laser marking beetles



Ecological Entomology, (2001), 26, p662

Thank You

Any questions?