# 50 anys del làser.
## Aplicacions quotidianes i científiques

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Campus de Terrassa (Barcelona)



## 50 anys del làser...

# LASERS: Sumari

**A) Introducció**

- Motivació
- Història; emissió estimulada.

**B) L'interior del làser**

- Parts d'un làser i principis de funcionament.
- Tipus de làser segons el medi amplificador: gas, líquid, estat sòlid, semi-conductor, etc.
- Paper jugat pel ressonador òptic.

**C) L'exterior del làser: radiació làser**

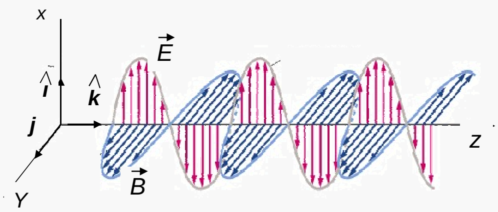
- Dimensions dels làsers
- Propietats de la radiació làser

**D) Aplicacions científiques i tècniques** (present i futur)



# Introducció: Motivació

## Què és la llum ?




$$\left\{ \begin{array}{l} \vec{E}(z,t) = \hat{i}\, E \cos(kz-\omega t+\varphi) \\ \vec{B}(z,t) = \hat{j}\, B \cos(kz-\omega t+\varphi) \end{array} \right.$$

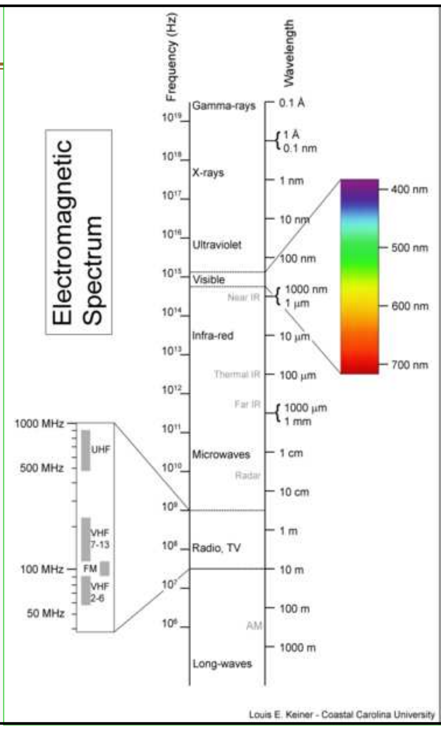
$B = E / v$

**Space**

- Wavelength: $\lambda$
- Wavenumber: $k = 2\pi / \lambda$

**Time**

- Period: $T$
- Frequency: $\nu = 1 / T$
- Angular frequency: $\omega = 2\pi \nu$
- Initial phase: $\varphi$



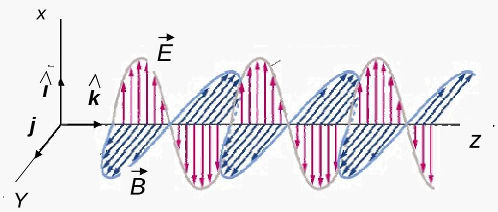

From: Wikipedia©





# Introducció: Motivació

**Quina diferència hi ha entre la llum làser i els altres tipus de llum?**

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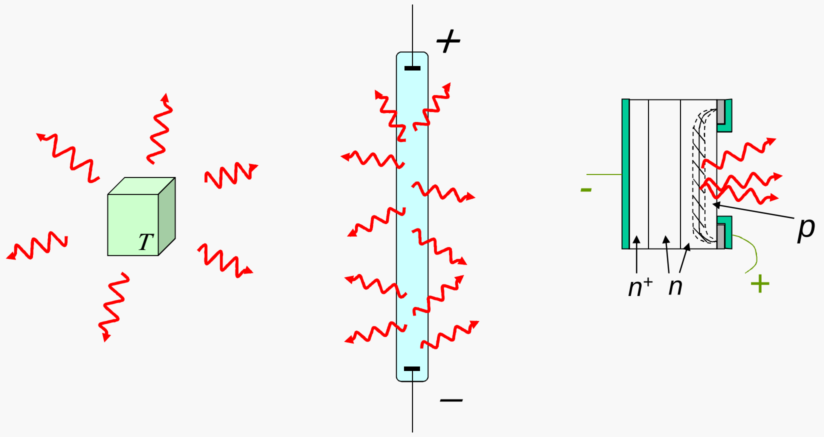
$B = E / v$

**Altres fonts de llum:**

- Radiació tèrmica (sol, bombetes de filament, cossos calents,...)
- Làmpades de descàrrega (tubs fluorescents, làmpades de baix consum)
- LED's
- Reacció química




*Radiació tèrmica*

*Descàrrega elèctrica*

*L.E.D.*



# *Introducció: Història del làser*

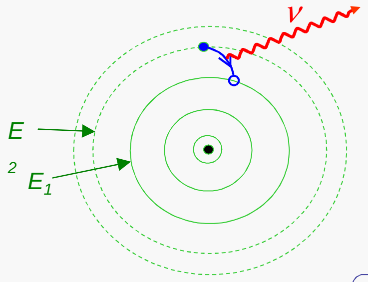
***"Light Amplification by Stimulated Emission of Radiation"***

- **1917.- Einstein: concept of stimulated emission**
- **1949-51.- Kastler: optical pumping [Nobel Prize in 1966]**
- **1954.- Townes: first MASER (at Columbia University)** [λ=1 cm, power=10 nW]
- **1956.- Bloembergen: first solid-state Maser (at Harvard University)**
- **1957.- Gould: ideas about a laser; first use of the acronym "laser" (Columbia Univ. grad. student)**
- **1958.- Schawlow, Townes: theoret. predictions about Laser (Bell Labs)** (Phys. Rev. Lett.)
  **Basov and Prokhorov: work on how to build a laser** (URSS)
- **1959-1960.- Begining of a 30-year Laser patent dispute!, between Gould (at TRG company) and Townes-Schawlow (at Bell Labs)** [also dispute with Fabrikant –at Moscow Power Institute-: he applied for a patent in URSS in 1951, it was approved in 1959].
- **1960** (May, 16).- **Maiman: first LASER (Rubi) (at Hughes Researh Laboratories, Calif.)** [3-level laser]
  ***Nature 187, 493-494 (1960) [no word "laser"; only 240 words; PRL rejected it]***

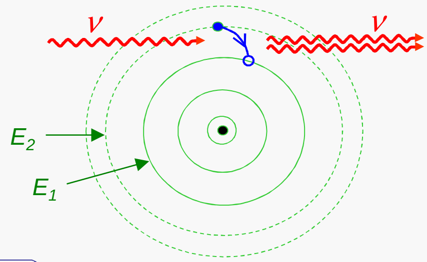
## A.1) INTRODUCCION: MEDIO AMPLIFICADOR

*Fenòmens bàsics que permeten la generació de llum:*

### Emissió espontánia




### Emissió estimulada




$$E_2 - E_1 = h \cdot \nu$$

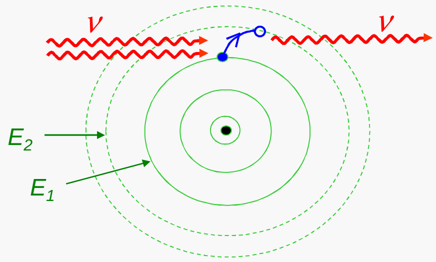
*$h \cdot \nu$ = energia d'un "fotó"*



## A.1) INTRODUCCION: MEDIO AMPLIFICADOR

*Fenòmen básic que permet la detecció de la llum:*

### Absorció




$$E_2 - E_1 = h \cdot \nu$$

"Light Amplification by Stimulated Emission of Radiation"

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  *Nature 187, 493-494 (1960) [no word "laser"; only 240 words; PRL rejected it]*



- 1960 (May, 16).- Maiman: first laser (Rubi) (at Hughes Researh Laboratories, Calif.) [3-level laser]
- 1960 (Nov).- Uranium laser :Sorokin & Stevenson (at IBM Research Center) [solid-state, 4-level]
- 1960 (Dec).- He-Ne Laser: Javan, Bennet, Herriot (at Bell Labs) [first cw laser, λ=1.15 μm]
- 1961.- Lasers appear in commercial market (Trion Instr., Perkin-elmer, Spectra-Physics,...)
- 1961 (Nov).- Nd:Glass laser.- Snitzer (American Optical Co.)
- 1961 (Dec).- 1st medical treatment (destroying retinal tumor with a rubi laser)
- 1962.- Q-switching in rubi laser: Hellwarth, McClung (Hughes Researh Labs) [theory in 1961]
- 1962.- GaAs Semiconductor laser (homojunction, cryogenically cooled) [GE, IBM & MIT's Lincoln Lab]
- 1962.- YAG laser (at Bell Labs.)
- 1962.- GaAsP visible-red laser diode (basis of present LEDs) (Holonya,k at GE Co. Lab)
- 1962.- First paper on Nonlinear Optics (Armstrong, Bloembergen, Ducuing and Pershan)
- 1963.- First mode-locked laser (He-Ne laser with acousto-optic modulator)
- 1963.- $1 million annual sales commercial laser market
- 1963.- Heterostructure semiconductor laser idea (Kroemer –Univ. California- & Alferov -Russia-).
  *Nobel Prize awarded later*.
- 1963.- $N_2$ laser *(confirm)*

## Introducció: Història del làser



- **1964.-** Ar$^+$ (pulsed), Kr$^+$, $CO_2$, Nd:YAG (Bell Labs) ,
- **1964.-** Nobel Prize to Townes, Basov and Prokhorov
- **1965.-** Chemical laser (HCl, $\lambda$=3.7 μm)
- **1966.-** Dye laser (tunable)
- **1970.-** Excimer laser and cw room-temperature semiconductor laser
- **1972.-** Quantum-well semiconductor laser
- **1976.-** Free-electron laser
- **1981.-** Nobel Prize to Schawlow and Bloembergen (laser spectroscopy)
- **1982.-** Ti:Sapphire laser (tunable)
- **1986.-** Fibre laser (Er-doped, single-mode, cw)
- **1994.-** Quantum-cascade laser (multiple $\lambda$'s) , and quantum-dot laser
- **1996.-** Pulsed atom laser (matter instead of light)
- **1996.-** InGaN blue laser diode (semiconductor, $\lambda$ = 417 nm)



Introducció: Història del làser



- **2004-07.-** Towards a Si laser: Si Raman laser and electr. powered hybrid Si laser, …
- **2009.-** NIF (National Ignition Facility, at LLNL): 192 laser beams firing onto targets.
- **2009-10.-** Intel's Light Peak fiber optic technology.
- **2009** (Dec.).- Prediction of 11% laser market growth for 2010; total revenue $5.9 billion.
- **2010** (Jan.).- NIF delivers enough laser energy to achieve fusion ignition: 1MJ in a few nanoseconds [peak power 500 times larger than any previous one in USA]
- **2010** (March).- Single-atom laser (with and without threshold) [Univ. of Innsbruck]
  - ⋮

*THUS TECHNICAL, AND EVEN FUNDAMENTAL, DEVELOPMENT CONTINUES…*


Albert Einstein

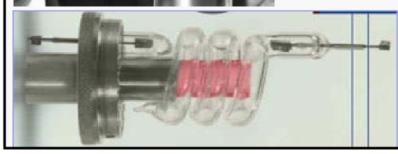

Charles H. Townes, 1954


Nikolai G. Basov

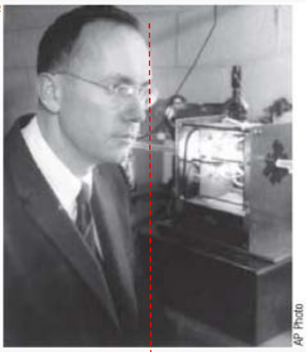

Alexander M. Prokhorov

# 50 anys del làser...





Theodore Maiman, 1960



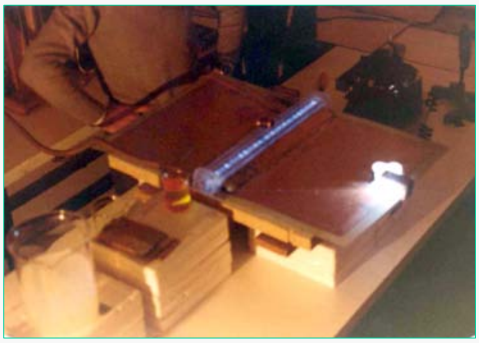

Charles H. Townes, 1954


Arthur Schawlow

Charles H. Townes, 2010

## Primer làser construit a Barcelona….

*Làser de $N_2$, Universitat Autònoma de Barcelona, curs 1979-80*





## LASERS: Sumari

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**B) L'interior del làser**

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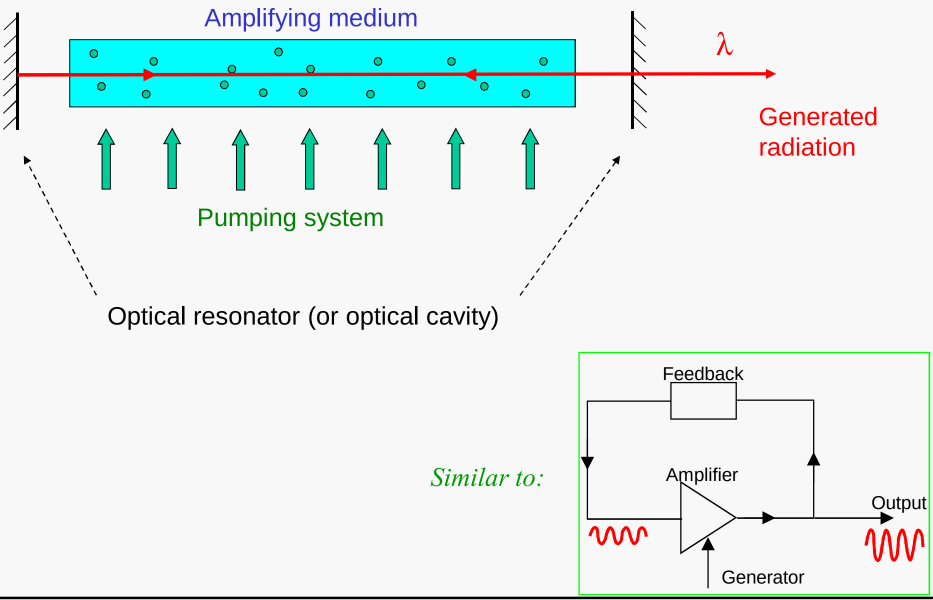
C) L'exterior del làser: radiació làser

- Dimensions dels làsers
- Propietats de la radiació làser

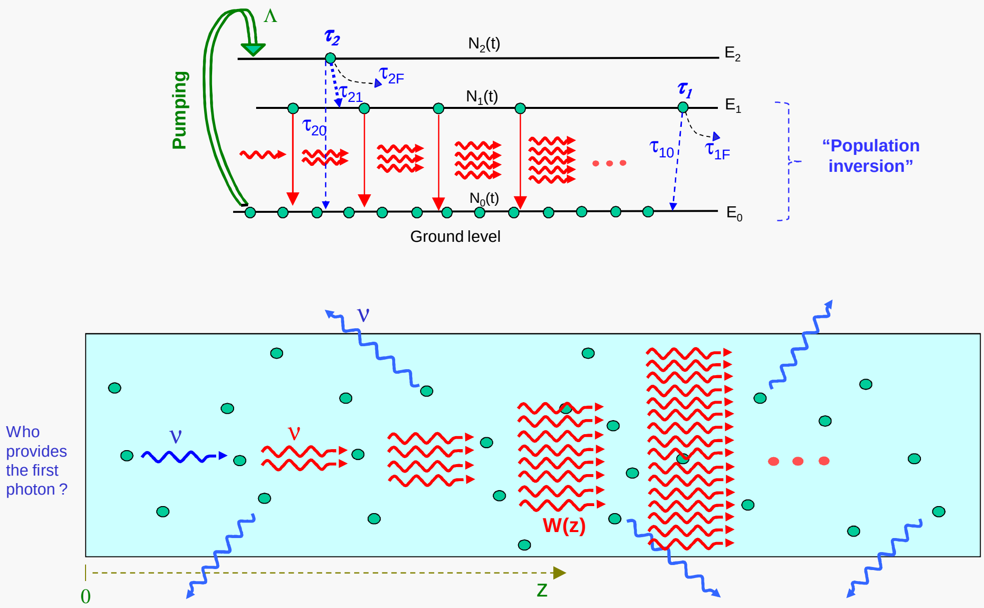
**D) Aplicacions científiques i tècniques** (present i futur)

## *Parts d'un làser, i principis de funcionament*





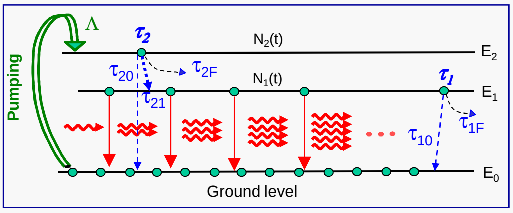

## *L'interior del làser: principis de funcionament*



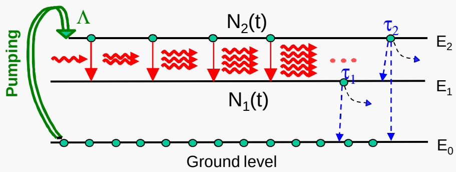
## L'interior del làser: principis de funcionament



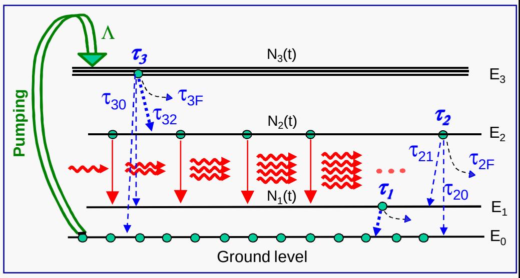
### "Three-level" configurations




Conditions to achieve population inversion: $\tau_{21} << \tau_{20}\ ,\ \tau_{2F}$ ; $\tau_{21} << \tau_1$




### "Four-level" configuration




Conditions to achieve population inversion: $\tau_{32} << \tau_{31}\ ,\ \tau_{30}\ ,\ \tau_{3F},\ \tau_2$ ; $\tau_1 << \tau_2$ (for cw operation)



## L'interior del làser: Tipus de medi amplificador



**LASERS: TYPES OF AMPLIFYING MEDIUM**

a) **GAS**

- ***Atoms:*** ***He-Ne***, *He-Cd, Cu.*
- ***Ions:*** ***$Ar^+$,*** *$Kr^+$.*
- ***Molecules:*** *Electronic (vibronic) transitions:* ***Excimer***, *$N_2$.*
  *Vibrational transitions:* ***$CO_2$***, *CO,* ***chemical lasers***.
  *Rotacional transitions:* *$NH_3$, $CH_3OH$, $CH_3F$.*

b) **LIQUID**

- ***Dye laser:*** ***Rhodamin 6G***, *coumarin, ….*

c) **SOLID STATE**

- ***Doped crystal:*** *Rubi,* ***Nd:YAG,*** *Nd:Glass,*
  ***Ti:Saphire,*** *Alexandrite*
  *Microxips,* ***microlasers***
- ***Optical fiber:*** ***$Er^{3+}$:Silicon ($Er^{3+}$:$SiO_2$)***
- ***Others:*** *Color centres, …*

d) **SEMICONDUCTOR (DIODE LASERS)**

- ***Near infrared:*** ***AlGaAs, InGaAsP***
- ***Visible:*** ***GaInP, AlGaInP, GaP***
- ***Mid infrared:*** ***…***
- ***Other types:*** ***VCSEL's, "arrays", high power, ...***

e) **OTHERS**

- ***Free electron laser,*** • ***X Ray,*** • ***Random lasers,*** • ***Quantum dot lasers,*** • ***Nanolasers,***
- ***Single-atom lasers***

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## B) GAS LASERS: Atomic or ionic

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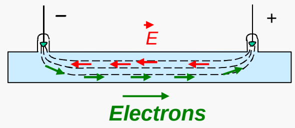
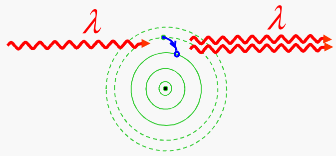
•*Pumping: electrical discharge*




• *Electronic transitions (λ ~ VIS, near IR)*




**Examples:**

| | | | |
|---|---|---|---|
| *-He-Ne laser:* | *λ = 632,8 nm (red) ,* | *η ≤ 0.1% ,* | *4-level scheme, reinforced* |
| *-Cu laser :* | *λ = 510 nm (green) ,*<br>*578 nm (yellow)* | *η ~ 1 % ,* | *3-level scheme (modified)* |
| *- $Ar^+$ laser :* | *λ = 488,0 nm (blue) ,*<br>*514,5 nm (green), ...* | *η < 1% ,* | *4-level scheme (modified)* |
| *- $Kr^+$ laser :* | *λ = 647,1 nm (red) ,* | *η < 0.1%* | *4-level scheme (modified)* |

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## B) GAS LASERS: Molecular

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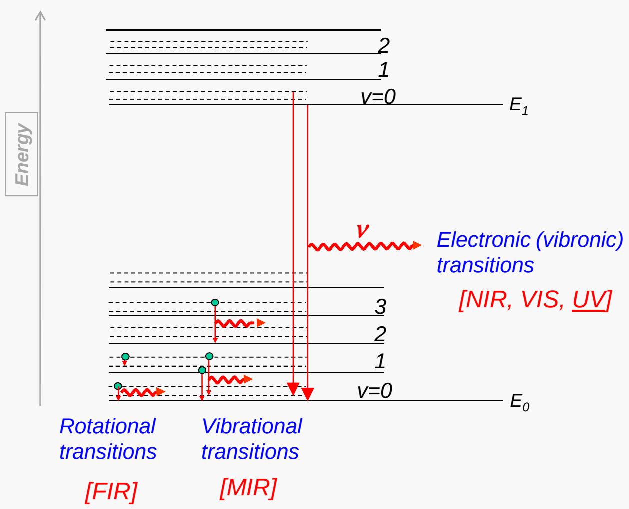
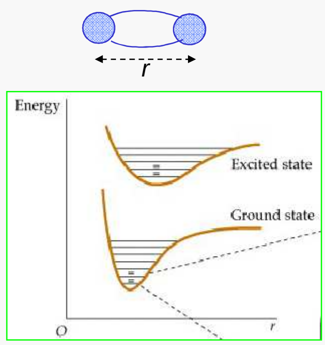
***Enery levels for a (simple) molecule*** :



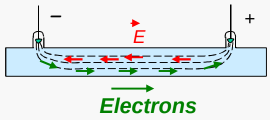



# B) GAS LASERS: Molecular (vibrational transition)

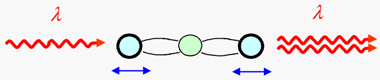




- Pumping: electrical discharge,
  or chemical reaction




- $\lambda \sim$ MIR




**Examples:**

- **$CO_2$ laser** : $\lambda = 10{,}6\ \mu m$ , $\eta \sim 10\text{-}25\%$ , 4-level scheme, reinforced
- CO laser : $\lambda \sim 5\ \mu m$ , $\eta \sim 20\text{-}30\%$ , 4-level scheme, modified
- **HF* laser**: $\lambda = 2.7\text{-}3.3\ \mu m$ , $\eta_{quím.} \sim$ high , Chemical reaction: $F + H_2 \rightarrow$ **HF*** $+ H$

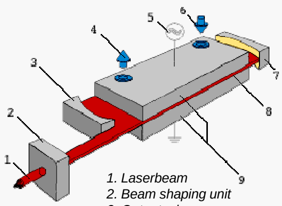


# $CO_2$ "Slab" laser





www.rofin.com




1. Laserbeam
2. Beam shaping unit
3. Output mirror
4. Cooling water
5. RF excitation
6. Cooling water
7. Rear mirror
8. RF excited discharge
9. Waveguiding electrodes

| | ROFIN DC 010 | ROFIN DC 015 | ROFIN DC 020 | ROFIN DC 025 |
|---|---|---|---|---|
| Excitation | HF | HF | HF | HF |
| Output power | 1000 W | 1500 W | 2000 W | 2500 W |
| Power range | 100-1000 W | 150-1500 W | 200-2000 W | 250-2500 W |
| Beam quality factor | K > 0,9 | K > 0,9 | K > 0,9 | K > 0,9 |
| Pulse frequency | 0 or 2 up to5000 Hz; cw | 0 or 2 up to5000 Hz; cw | 0 or 2 up to 5000 Hz; cw | 0 or 2 up to 5000 Hz; cw |

| | ROFIN DC 030 | ROFIN DC 035 | ROFIN DC 040 | ROFIN DC 045 |
|---|---|---|---|---|
| Excitation | HF | HF | HF | HF |
| Output power | 3000 W | 3500 W | 4000 W | 4500 W |
| Power range | 300-3000 W | 350-3500 W | 400-4000 W | 450-4500 W |
| Beam quality factor | K > 0,9 | K > 0,9 | K ≥ 0,9 | K ≥ 0,9 |
| Pulse frequency | 0 or 2 up to 5000 Hz; cw | 0 or 2 up to 5000 Hz; cw | 0 or 2 up to 5000 Hz; cw | - |

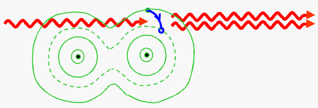
| | ROFIN DC 050 | ROFIN DC 060 W | ROFIN DC 080 W |
|---|---|---|---|
| Excitation | RF | RF | RF |
| Output power | 5000 W | 6000 W | 8000 W |
| Power range | 500-5000 W | 1500-6000 W | 800-8000 W |
| Beam quality factor | K ≥ 0,9 | K ≥ 0,9 | K ≥ 0,9 |
| Pulse frequency | - | - | - |

Can it propagate through an optical fiber?: **No** (Why?)

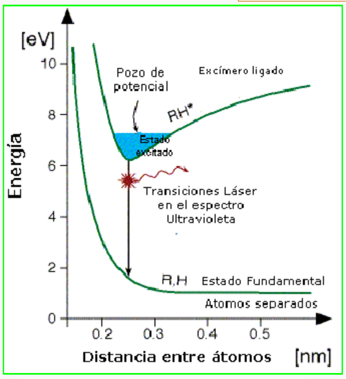
## B) GAS LASERS: Molecular (electronic transition)



- Pumping: electrical discharge (transverse) (make a drawing) →



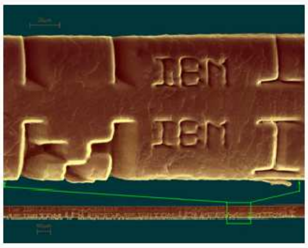

- λ ~ UV, VIS, NIR




- **Example: Excimer laser** (η ~ 1-10%, 3-level):

  **ArF** λ = 193 nm (UV)
  **KrF** λ = 248 nm (UV)
  **XeCl** λ = 309 nm (UV)
  **XeF** λ = 351 nm (UV)

  Only **pulsed emission** (**10-20 ns, MW** peak power) Why ?




- Another Example: **N$_2$ laser** (λ = 337.1 nm; 4-level)

  Only **pulsed emission** (**5-10 ns, MW** peak power)

**Human hair !**

## B) Existing types of lasers according to the amplifying medium



**LASERS: TYPES OF AMPLIFYING MEDIUM**

a) GAS
- **Atoms:** **He-Ne**, He-Cd, Cu.
- **Ions:** **$Ar^+$**, $Kr^+$.
- **Molecules:** Electronic (vibronic) transitions: **Excimer**, $N_2$.
  Vibrational transitions: **$CO_2$**, CO, **chemical lasers**.
  Rotacional transitions: $NH_3$, $CH_3OH$, $CH_3F$.

b) LIQUID
- **Dye laser:** **Rhodamin 6G**, coumarin, ….

c) SOLID STATE
- **Doped crystal:** Rubi, **Nd:YAG**, Nd:Glass, **Ti:Saphire**, Alexandrite, Microxips, **microlasers**
- **Optical fiber:** **$Er^{3+}$:Silicon ($Er^{3+}$:$SiO_2$)**
- **Others:** Color centres, …

d) SEMICONDUCTOR (DIODE LASERS)
- **Near infrared:** **AlGaAs**, **InGaAsP**
- **Visible:** **GaInP**, **AlGaInP**, **GaP**
- **Mid infrared:** …
- **Other types:** **VCSEL's, "arrays", high power, ...**

e) OTHERS
- **Free electron laser,** • **X Rays, g rays,** • **Random lasers, (etc.)**

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## B.c) SOLID-STATE LASERS: doping with Impurity ions

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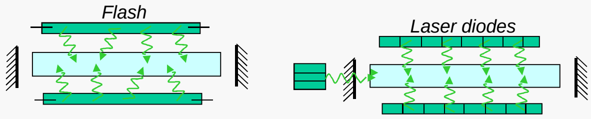
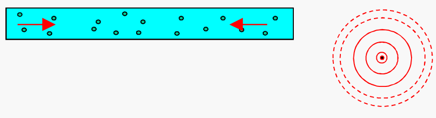
-Pumping: flash, or diode lasers




- Electronic transitions in impurity ions
- $\lambda \sim$ **NIR, VIS**




**Examples:**

- **Nd:YAG laser**: $\lambda$ = 1064 nm (NIR), $\eta \sim$ 1-10% , 4-level scheme
- **Rubi laser**: $\lambda$ = 694,3 nm (red), $\eta \sim$ 0.1% , 3-level scheme
- **Ti:sapphire laser**: $\lambda \sim$ 660-990 nm (NIR), **tunable** , 4-level scheme modified

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## B.c) SOLID-STATE LASERS: Impurity ions

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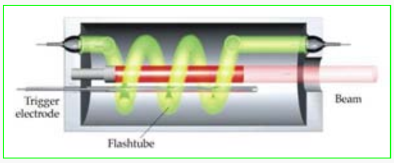
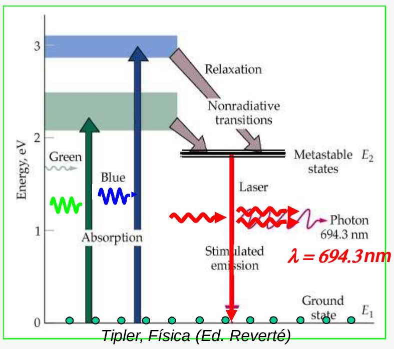
**Rubi laser** ($Cr:Al_2O_3$)

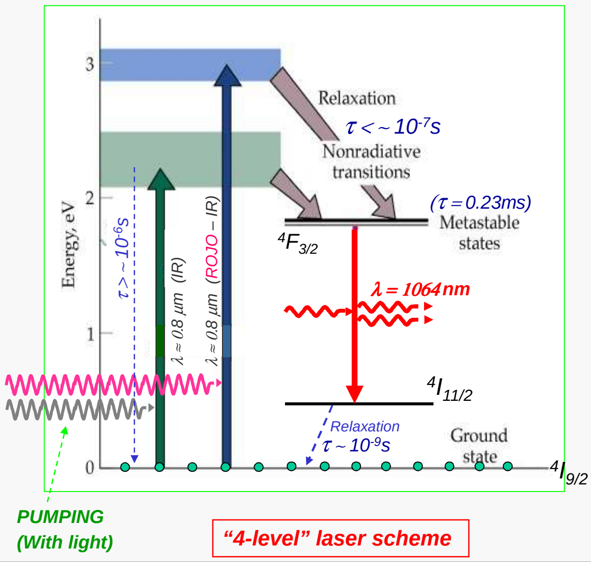



Tipler, Física (Ed. Reverté)

**"3-level" laser scheme**

**Nd:YAG laser** ($Nd:Y_2Al_5O_{12}$)

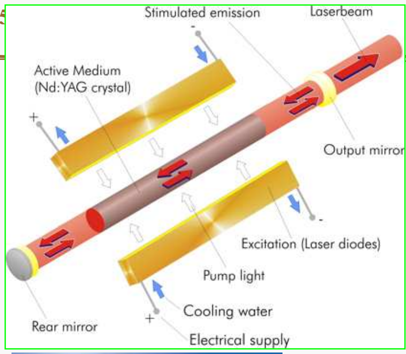



PUMPING (With light)

**"4-level" laser scheme**

## B.c) SOLID-STATE LASERS: Nd:YAG laser



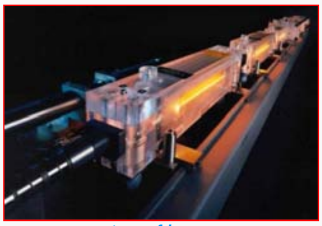



| | ROFIN DP 010 HX | ROFIN DP 015 HX |
|---|---|---|
| Excitation | Laser diodes | Laser diodes |
| Output power (@collimator) | 100 - 1000 W | 150 - 1500 W |
| → Beam parameter product | 12 mm*mrad | 12 mm*mrad |
| → Fiber diameter | 300 µm | 300 µm |

| | ROFIN DP 020 HP | ROFIN DP 030 HP | ROFIN DP 040 HP |
|---|---|---|---|
| Excitation | Laser diodes | Laser diodes | Laser diodes |
| Output power (@collimator) | 200 - 2000 W | 300 - 3000 W | 400 - 4000 W |
| Beam parameter product | 25 mm*mrad | 25 mm*mrad | 25 mm*mrad |
| Fiber diameter | 600 µm | 600 µm | 600 µm |

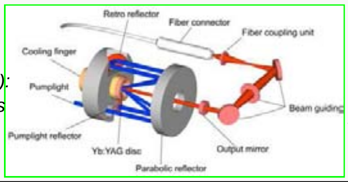

www.rofin.com

**High power:**
**MOPA configuration**



www.trumpf-laser.com

Also (new): disk series




Trumpf: up to 16 kW, BPP ~ 2-8 mm·mrad





## B) SOLID-STATE LASERS: Nd:YAG laser



### Important features:

1) **It can propagate through an optical fiber**

2) **Pulsed regimes**: **cw**, ms, µs, **ns**, **ps**

**cw** ↔ up to 10 W (and up to 4 kW in MOPA config.)

**ns** ↔ **"Q-switching"** ~ $10^8$ W peak power

**ps** ↔ **"Mode locking"** ~ $10^9$ W peak power

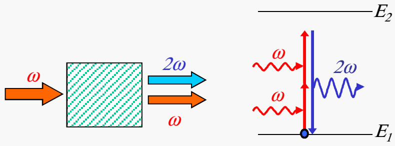

Cold processing with picosecond pulses on a match-head.

3) **Nonlinear effects: SHG, THG, FHG, OPO** ⇒ Generation of new frequencies!

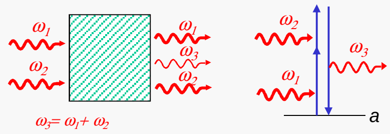
**SHG**

# "ÒPTICA NO LINEAL"

- Second harmonic generation (SHG)

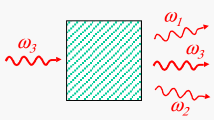



- Sum frequency generation (SFG)



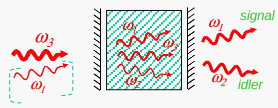

$\omega_3 = \omega_1 + \omega_2$

- Down conversion (parametric fluorescence)




$\omega_3 = \omega_1 + \omega_2$

- Optical parametric oscillation (OPO)




$\omega_3 = \omega_1 + \omega_2$



## B) Existing types of lasers according to the amplifying medium

**LASERS: TYPES OF AMPLIFYING MEDIUM**

a) GAS

- **Atoms:** **He-Ne**, He-Cd, Cu.
- **Ions:** **$Ar^+$**, $Kr^+$.
- **Molecules:**
  - Electronic (vibronic) transitions: **Excimer**, $N_2$.
  - Vibrational transitions: **$CO_2$**, CO, **chemical lasers**.
  - Rotacional transitions: $NH_3$, $CH_3OH$, $CH_3F$.

b) LIQUID

- **Dye laser:** **Rhodamin 6G**, coumarin, ….

c) SOLID STATE

- **Doped crystal:** Rubi, **Nd:YAG**, Nd:Glass, **Ti:Saphire**, Alexandrite, Microxips, **microlasers**
- **Optical fiber:** **$Er^{3+}$:Silicon ($Er^{3+}$:$SiO_2$)**
- **Others:** Color centres, …

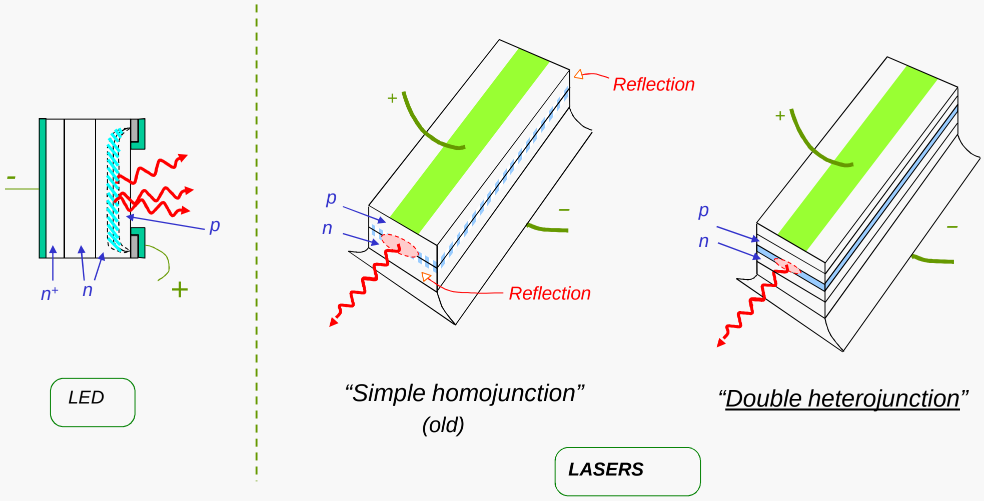
d) SEMICONDUCTOR (DIODE LASERS)

- **Near infrared:** **AlGaAs**, **InGaAsP**
- **Visible:** **GaInP**, **AlGaInP**, **GaP**
- **Mid infrared:** **…**
- **Other types:** **VCSEL's, "arrays", high power, ...**

e) OTHERS

- Free electron laser, • X Rays, g rays, • Random lasers, (etc.)

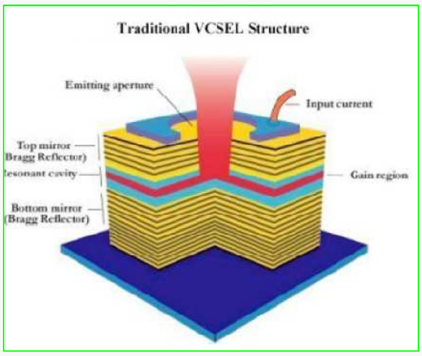
## B.d) SEMICONDUCTOR LASERS






## B.d) SEMICONDUCTOR LASERS: Other types

### 1) VCSEL type:




***Advantages***:
- *Better directionality and coupling to an optical-fiber*
- *Very low emission threshold (high-reflectance mirrors)*
- *Multi-laser emission in parallel (laser matrix)*

## B.d) SEMICONDUCTOR LASERS: Other types




### 2) High-power lasers:

- Battery of edge-emitting lasers, of larger dimensions
- Up to 2 kW
- Low beam quality (BPP large): good for welding of different types of materials.

### 3) Quantum-cascade lasers:

### 4) Near future: Silicon lasers ? (Si photonics)

**Si lasers, or more likely, hybrid Si lasers, would the ideal step to combine microelectronics and photonics !! (for integrated computing at terabit levels, extending Moore's law; etc.)**



## L'interior del làser: Tipus de medi amplificador




LASERS: TYPES OF AMPLIFYING MEDIUM

a) GAS
- **Atoms:** **He-Ne**, He-Cd, Cu.
- **Ions:** **$Ar^+$**, $Kr^+$.
- **Molecules:**
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  - Rotacional transitions: $NH_3$, $CH_3OH$, $CH_3F$.

b) LIQUID
- **Dye laser:** **Rhodamin 6G**, coumarin, ….

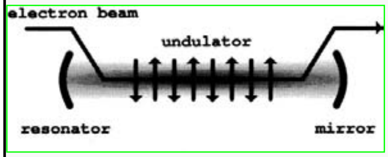
c) SOLID STATE
- **Doped crystal:** Rubi, **Nd:YAG**, Nd:Glass, **Ti:Saphire**, Alexandrite, Microxips, **microlasers**
- **Optical fiber:** **$Er^{3+}$:Silicon** ($Er^{3+}$:$SiO_2$)
- **Others:** Color centres, …

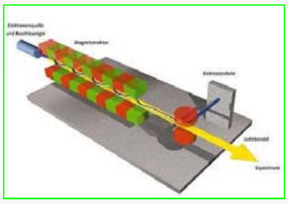
d) SEMICONDUCTOR (DIODE LASERS)
- **Near infrared:** AlGaAs, InGaAsP
- **Visible:** GaInP, AlGaInP, GaP
- **Mid infrared:** …
- **Other types:** VCSEL's, "arrays", high power, ...

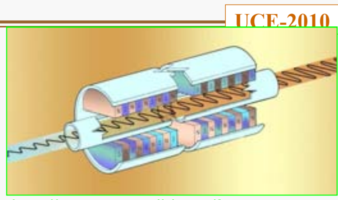
e) OTHERS
- **Free electron laser,** • **X Ray,** • **Random lasers,** • **Micro- and nano-lasers** (microdisc, microsphere, quantum dot, guided-wave photonic crystal,…), • **Single-atom lasers**

# B.e) Other types of lasers

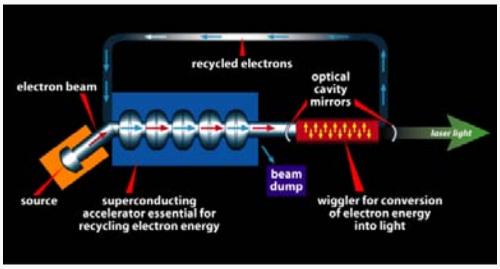
## - Free-electron laser (FEL)



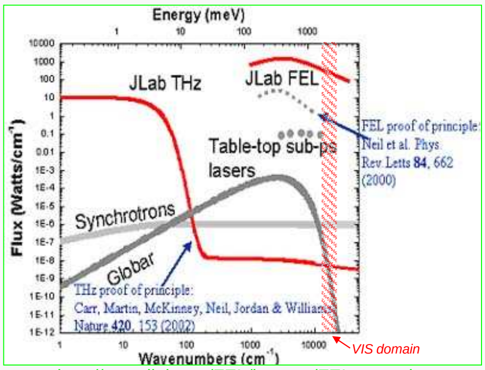





http://newscenter.lbl.gov/feature-stories/2007/11/14/into-the-future-at-the-s of-light/




http://www.jlab.org/FEL/images/FELdiagram.gif



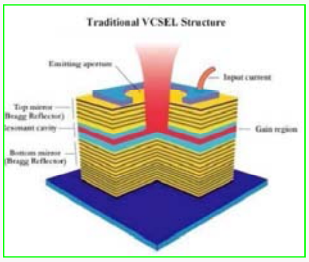

http://www.jlab.org/FEL/images/FELoutput.jpg



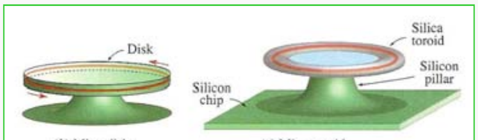
***Antics intents de construir un laser de raigs X***

*(actualment s'hi està arribant per lavia del làser d'electrons lliures i de la generació d'harmonics elevats)*

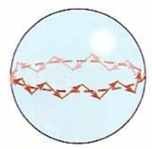
# Micro- and nano- optical resonators

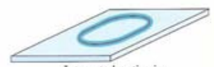


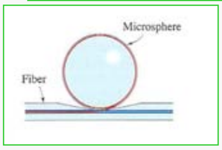

Micropillar

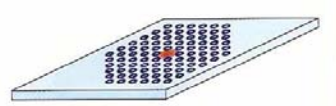


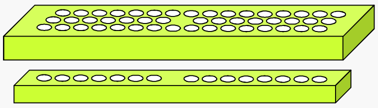
(b) Microdisk
(c) Microtoroid

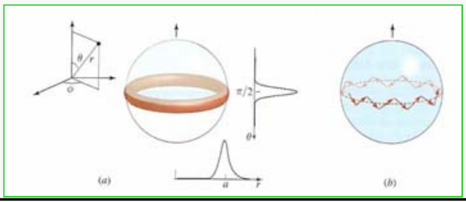

Microsphere


Integrated-optic-ring



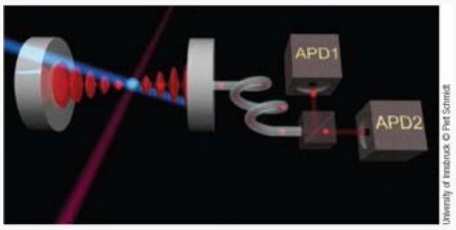


Photonic-crystal


Wave-guide photonic-crystal cavity
(the smallest laser?)






# Single-atom laser




A high-finesse optical cavity consisting of two mirrors traps and accumulates the photons emitted by the ion into a mode. The ion is excited cyclically by an external laser and at each cycle a photon is added to the cavity mode, which amplifies the light.

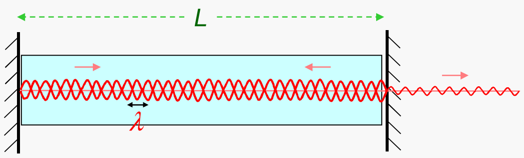
## LASERS: Contents



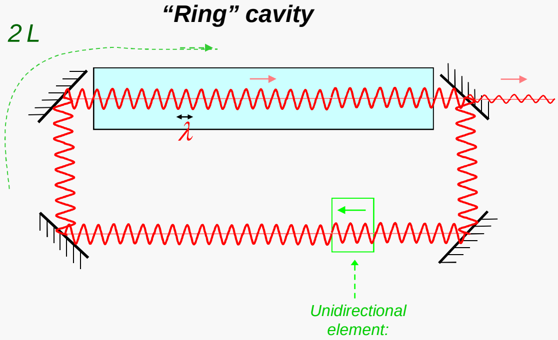


## A.3) Optical cavity: longitudinal modes

**"Fabry-Perot" cavity**




**"Ring" cavity**




*Resonance condition:*

$$2L = m\,\lambda \quad = m\, v/\nu$$

⇩

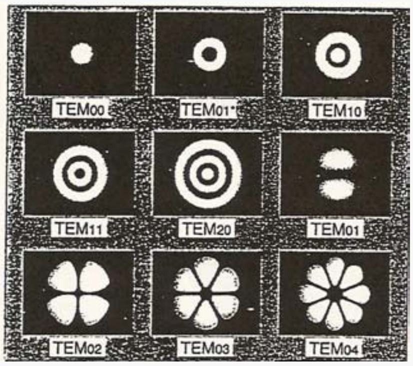
$$\nu_m = m \frac{v}{2L}$$

*Frequency of the longitudinal mode of order m*

A.3) **Optical cavity: Transverse modes**

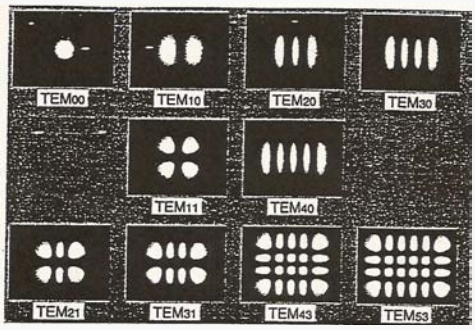
*(point of view of electromagnetic optics)*






*Transverse modes for a cavity with circular transverse section*

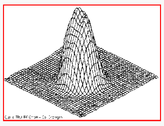
*(Gauss-Laguerre modes)*




*Transverse modes for a cavity with rectangular transverse section*

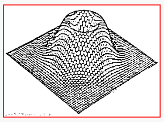
*(Gauss-Hermite modes)*

$TEM_{00}$



*Gaussian distribution*

$TEM_{01}$







**LASERS: Contents**



A) Introducció
- Motivació
- Història; emissió estimulada.

B) L'interior del làser
- Parts d'un làser i principis de funcionament.
- Tipus de làser segons el medi amplificador: gas, líquid, estat sòlid, semi-conductor, etc.
- Paper jugat pel ressonador òptic.

**C) L'exterior del làser: radiació làser**
- Dimensions dels làsers
- Propietats de la radiació làser

D) Aplicacions científiques i tècniques (present i futur)

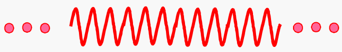
## Summary of properties of laser light

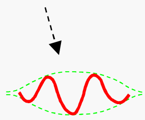
### 1) FREQUENCY ($\nu$)

LASERs + nonlinear crystals (SHG, OPO): ~ cover most of the spectral optical domain

### 2) DURATION ($\Delta t$)

cw - ms - $\mu$s - ns - ps - fs - (as)



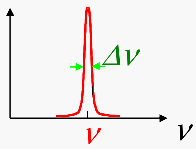


To go below ~100 fs special pulse compression techniques are needed



## D) Summary of properties of laser light

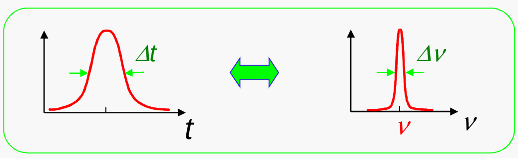
### 3) MONOCHROMATICITY ($\Delta\nu$)



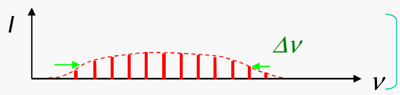

- **cw regime:**
  - Typical values (commercial lasers): $\Delta\nu/\nu \sim 10^{-3} - 10^{-5}$
  - Record values: → $\Delta\nu/\nu \sim 10^{-12} - 10^{-14}$ !!

- **Pulsed regime:**

$\Delta t \bullet \Delta\nu \geq 2\pi$




· Pump modulation: ms, $\mu$s
· Q-switching: ns
· Mode-locking: ps
· Additional manipulations: fs, as.



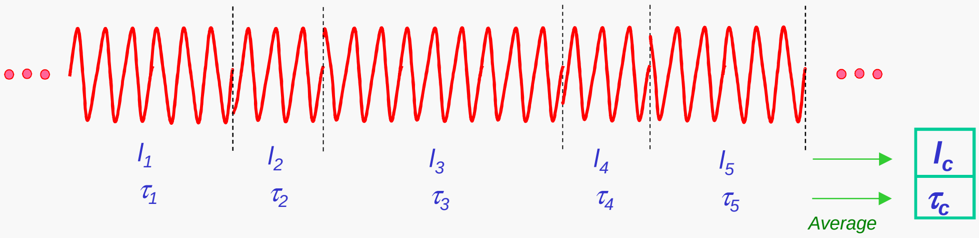
50 aniv. Làser

49

## D) Summary of properties of laser light

UCE-2010

### 4) TEMPORAL COHERENCE (or LONGITUDINAL COHERENCE)




$l_c$ = Coherence length

- Typical values (commercial lasers): $l_c \sim 1 - 10 - 100$ cm
- Record values: $l_c \sim 10^3$ km !!
- Values for other light sources: $l_c \gtrsim 10\ \mu$m (record: 30 cm)

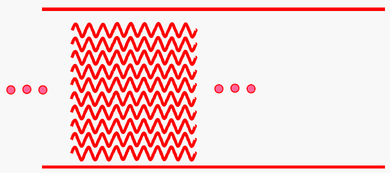
50 aniv. Làser

50

## D) Summary of properties of laser light

UCE-2010

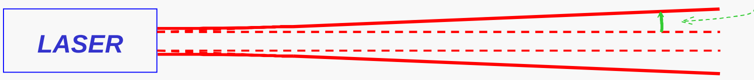
### 5) SPATIAL COHERENCE (or TRANSVERSAL)



**For a laser:**
**Maximum possible value (for single-mode transverse emission)**

### 6) DIRECCIONALITY:

$$\theta \approx \frac{\lambda M^2}{\pi W_0}$$




Only limit: **difracción**

Example: impact over the Moon < 1 km of diameter (if initial diameter enlarged with the objective lens of a telescope)

($\Rightarrow$ measurement of distance moom-earth with precision: ~ 20 cm !!)

## D) Summary of properties of laser light

### 7) POWER

- Limited by: **Capacity of heat extraction !**
- Pulsed lasers: shorter duration ⇒ higher peak power
- **Typical powers:**

| | |
|---|---|
| **He-Ne** | 0.5 a 50 mW |
| **Diode láser** | 0.5 mW to 2 kW |
| **$CO_2$** | 1 W to 20000 W |
| **Nd:YAG** | 0.1 a 4000 W (cw or long pulses) |
| | < ~ $10^8$ W (peak power) ("Q-switched") |
| | < ~ $10^9$ W ( " " ) ("mode-locked") |

- Record powers:
  - **cw** → 2 MW !! (chemical laser)
  - **Pulses $10^{-9}$ s** → 10 TW !! (nuclear fusion)
  - **Pulses fs, as** > PW !! (with amplification out of the cavity)



### B) Existing types of lasers according to the output power:

**Power (cw regime)** (W)

- $10^6$: Chemical lasers
- $10^3$: $CO_2$; Nd:YAG; Diode lasers (battery)
- Optical fiber lasers
- 1: Diode laser (single)
- He-Ne
- $10^{-3}$: Microlasers
- Nanolasers?

**Power (pulsed regime)** peak power (W)

- $10^{18}$: fs & attosecond lasers (Ti:Sapphire + ⋯)
- $10^{12}$: ns Nd:YAG lasers (with amplifiers for nuclear fusion)
- $10^9$: ps Nd:YAG lasers; ns Nd:YAG lasers; ns excimer lasers; ns &ps & fs Optical fiber lasers
- $10^6$: µs & ms $CO_2$ lasers
- $10^3$: Microlasers? Nanolasers?

# Aplicacions científiques i tècniques dels làsers



## LASERS: Contents

## From: FOTONICA 21

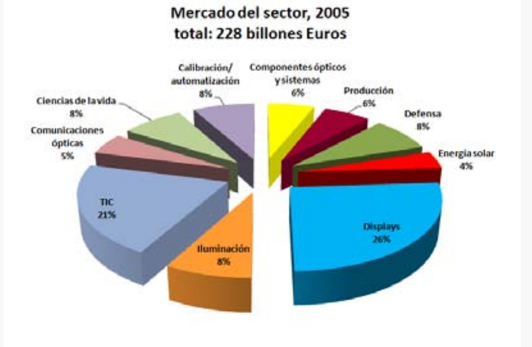



Figura 4: Mercado del sector (Fuente: Optech Consulting, Octubre 2007)

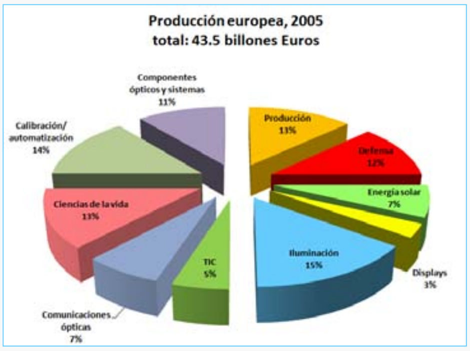



Figura 5: Producción europea del sector (Fuente: Optech Consulting, Octubre 2007)



## Làsers: Aplicacions científiques i tècniques

POTÈNCIA

**Gran**

- *Fusió nuclear*
- *Làser d'electrons lliures, làser de raigs X*
- *Làsers de Terawatt: generació d'altes freqüències i de polsos ultra-curts (atto-segons), aplicacions a Física Atómica i Nuclear, acceleració de partícules.*
- *Transport d'energia a distància (futur)*
- *Aplics. militars*

**Mitjana**

- *Processat de materials: tall, soldadura, perforació, marcatge, tractaments de superfície, prototipat 3D (100 nm resol amb femtosecond 2-photon), …*
- *Espectacles lluminosos*
- *Fotoquímica: estimulació i control de reaccions químiques (fins i tot unir atoms freds), foto-dissociació, foto-ionització, …*
- *Òptica no lineal, per a diverses aplicacions (incloent la generació de extrem UV -13.5 nm- per a dissenyar petites estruct. electròniques i extendre Moore's law, informació quàntica,…)*
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**Petita**

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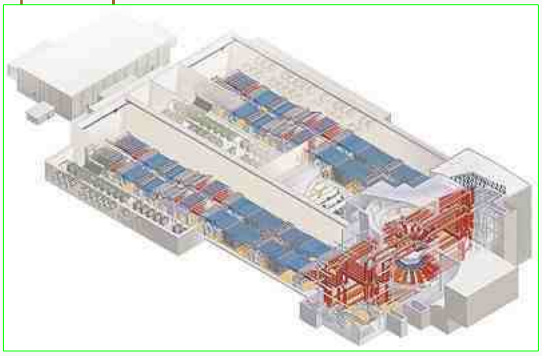
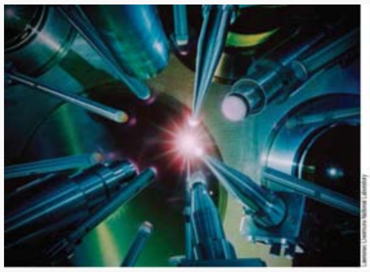
- *Òptica integrada, integració amb micro-electrònica (computació, etc.). Micro- i nano-làsers.*
- *Nanolàsers i single-atom lasers per a informació quàntica, …*

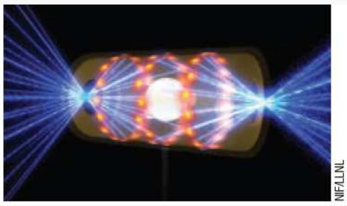
## *NIF (National Ignition Facility)*
## *LLNL, Lawrence Livermore Nat. Lab., California*





The international inertial confinement fusion community, including LLNL researchers, uses the OMEGA laser at the University of Rochester's Laboratory for Laser Energetics to conduct experiments and test target designs and diagnostics. The 60-beam OMEGA laser at the University of Rochester has been operational since 1995.

This artist's rendering shows an NIF target pellet inside a hohlraum capsule with laser beams entering through openings on either end. The beams compress and heat the target to the necessary conditions for nuclear fusion to occur. Ignition experiments on NIF will be the culmination of more than 30 years of inertial confinement fusion research and development, opening the door to exploration of previously inaccessible physical regimes. Credit is given to Lawrence Livermore National Security LLC, Lawrence Livermore National Laboratory and the US Department of Energy, under whose auspices this work was performed.






## *Làsers d'alta potència*

### ELI: "Extreme Light Infrastructure"

**Megalasers to pulse in several new EU countries**

**As the world celebrates 50 years since the invention of the laser, a European facility approaching exawatt power is expected to stimulate new research areas and communities.**

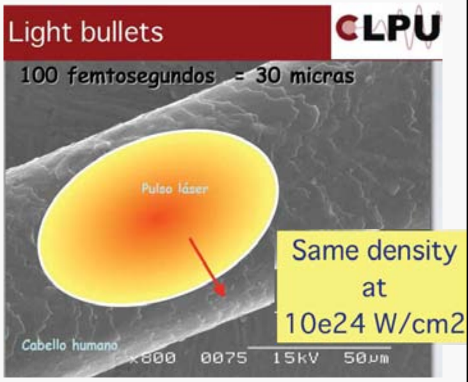
**Lasers planned for the Extreme Light Infrastructure***

| Country | Facility focus | Power (PW) | Pulse energy (J) | Pulse width (fs) | Rep rate (Hz) |
|---|---|---|---|---|---|
| Romania | Nuclear physics | 10 (×2) | 200 | 20 | 0.1 |
| Hungary | Attosecond physics | 1 | 5 | 5 | 1000 |
| | | 20 | 400 | 20 | 0.1 |
| Czech Republic | Secondary beam radiation, high-energy particles | 1 | 10 | 10 | 10 |
| | | 5 | 50 | 10 | 10 |
| | | 10 (×2) | 200 | 20 | 0.1 |
| To be determined | High intensity | 10 beams of 10–20 PW each, phased and combined to create total power of 100–200 PW | | | |

*Laser parameters still subject to change.

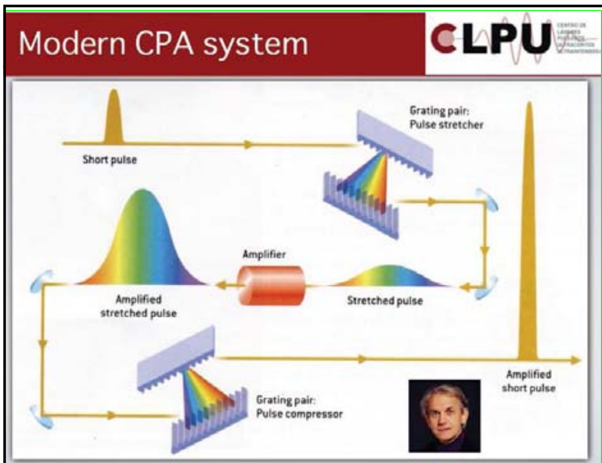
# *Terawatt short-pulse lasers*

*"Table Top Terawatt" laser ($T^3$)*


*Copy of transparencies from Prof. Luis Roso, Salamanca)*







*"Table Top Terawatt" laser ($T^3$)*


*Copy of transparencies from Prof. Luis Roso, Salamanca)* laser beams transport energy to places that are not easily reached via conventional methods. Examples include supplying energy to remote military camps or to a zeppelin (airship) stationed above a specific area for observation tasks.

The space elevator is another project on

only to have laser pointers in a Swiss army knife, as we do today, but also even to replace the stainless steel blade with a laser blade. Just imagine the possibilities for a moment: You could cut down that tree in your backyard with a laser.

Now that we've speculated about the

bet that lasers will be around long after I'm gone.

**Meet the author**
Jochen Deile is the manager of new laser products for Trumpf Inc. in Farmington, Conn.; e-mail: jochen.deile@us.trumpf.com.

Photonics Spectra July 2010 PHOTONICS MEDIA 57

# *Power beaming*

UCE-2010

*Traslladat energia a llocs llunyans o inaccessibles.*

- *Un petitet avió ha sigut propulsat des de terra!*
- *Elevador espacial*
- *Comunicacions inter-planetàries*
- *Captar energia dalt i enviar-la cap a la terra* *(o a l'inrevés)*

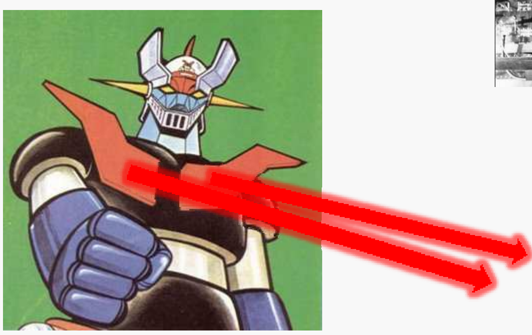


50 aniv. Làser

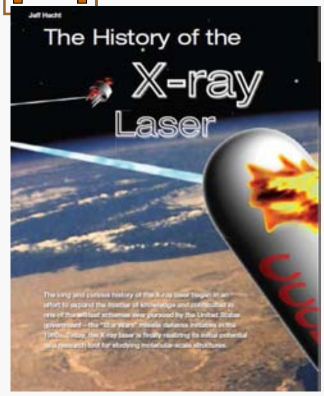
# *Aplics. militars?*

UCE-2010

*James Bond ...*



*Is Mazinger possible?*




*Cold-war fever in the 1980s…*

Lockheed aerospace engineer Maxwell Hunter put forth the boldest plans—a fleet of 18 orbiting chemical laser battle stations, which he claimed could block a surprise attack by thousands of Soviet nuclear missiles. *[Around year 1980]*



# Làsers: Aplicacions científiques i tècniques

POTÈNCIA: Gran

- *Fusió nuclear*
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- *Làsers de Terawatt: generació d'altes freqüències i de polsos ultra-curts (atto-segons), aplicacions a Física Atómica i Nuclear, acceleració de partícules.*
- *Transport d'energia a distància (futur)*
- *Aplics. militars*

POTÈNCIA: Mitjana

- ***Processat de materials:** **tall, soldadura, perforació, marcatge, tractaments de superfície, prototipat 3D** (100 nm resol amb femtosecond 2-photon)**, …***
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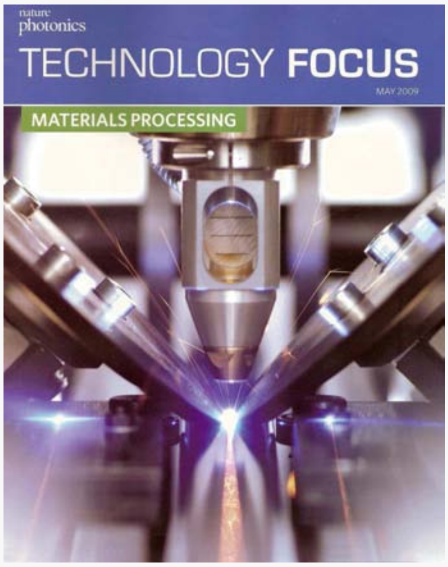
- ***Nanolàsers i single-atom lasers per a informació quàntica, …***

## *Applications of high-power lasers (Nd:YAG, $CO_2$) in MATERIALS PROCESSING*





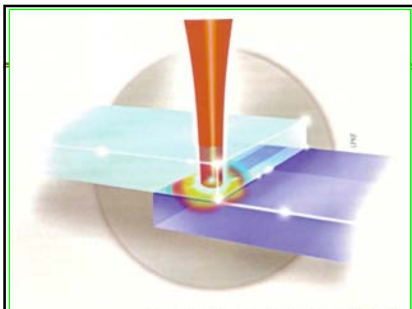



Figure 1 | Principle of laser transmission welding of two plastic components. The laser beam passes through the upper plastic layer but is absorbed by the lower one, generating heat that fuses the two components together, which then cool and harden.

Figure 5 | Electric shaver welded by laser.

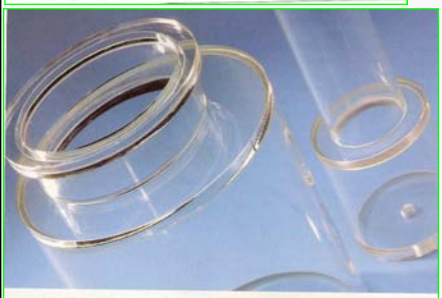
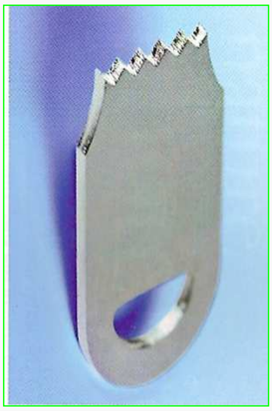


Figure 2 | Example of high-quality laser welding of transparent plastic parts using the Clearweld technology. A light-absorbing dye is sandwiched between the components to be joined. On illumination with a laser it heats up, melting the interface between the parts. Advantageously, the dye becomes colourless in the process leaving a weld seam that is invisible to the naked eye.

Figure 4 | A hybrid system with an example application of an automotive tail light.



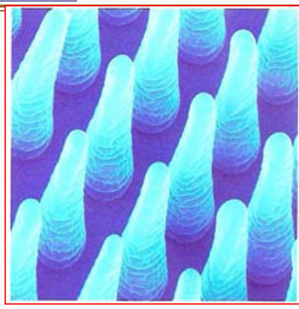
*Nature Photonics, May 2009*

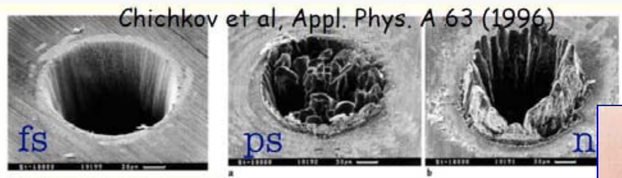
## Applications of high-power lasers (Nd:YAG, $CO_2$) in CESSING

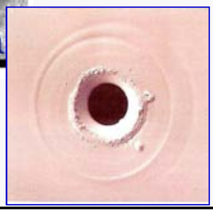




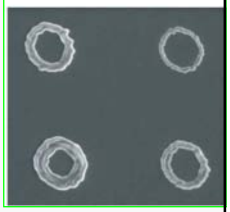
A solid-state laser cutting a series of fine patterns in a medical instrument.



Optical tweezers boost direct-write nanolithography
Opt. Express 17, 3640–3650 (2009)





## Prototipat, sinterització





Figure 1 | Laser sintering in action. A laser beam melts a layer of metal powder which then solidifies. By repeating the process a three-dimensional part can be made.

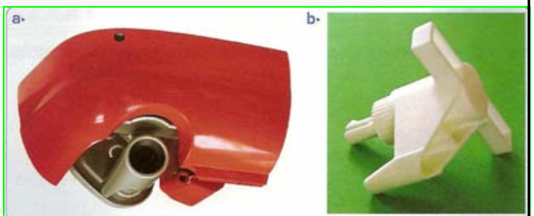


Figure 2 | Laser sintering and cars. a, Close-up of the laser-sintered prototype bumper section for the Jaguar XJ. The painted model was used to visualize the fit and finish of key components before production. b, The laser-sintered plastic tool that assists operators working on the new Jaguar XK production line to position window lift mechanisms during assembly.

*Nature Photonics, May 2009*

Figure 3 | Prototype plate bender, used to contour plates for spinal surgery, built by DePuy using a laser-sintering system.

Digital light processing (DLP) technology used in concert with a laser-assisted manufacturing, rapid-prototyping process can speed dental and hearing aid implant manufacture by varying the illumination intensity (and corresponding cure depth) pixel-by-pixel in the fabrication process. (*Courtesy of EnvisionTEC*)

50 aniv. Làser

# Làsers: Aplicacions científiques i tècniques

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POTÈNCIA

**Gran**

- *Fusió nuclear*
- *Làser d'electrons lliures, làser de raigs X*
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- *Aplics. militars*
- *Processat de materials: tall, soldadura, perforació, marcatge, tractaments de superfície, prototipat 3D (100 nm resol amb femtosecond 2-photon), …*

**Mitjana**

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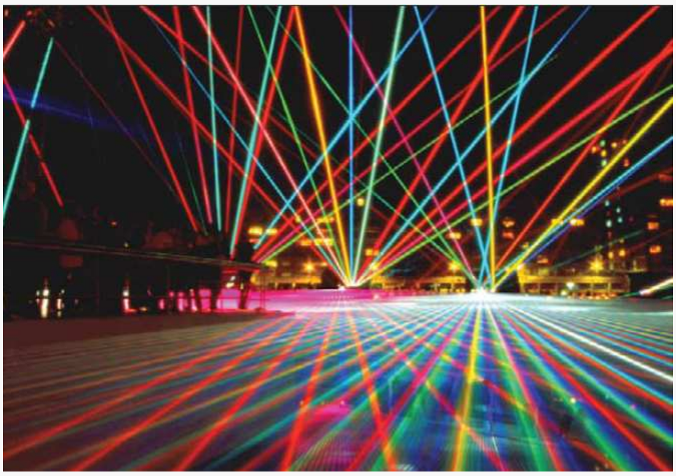
- ***Nanolàsers i single-atom lasers per a informació quàntica, …***

50 aniv. Làser

18

UCE-2010



**See the light**
Artist Hiro Yamagata linked science with art at his "Photon 999" exhibition, where multiple laser systems immersed the viewers in a moving-light show.

# Làsers: Aplicacions científiques i tècniques



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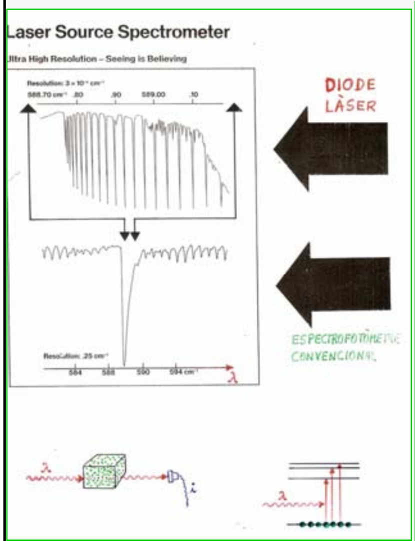
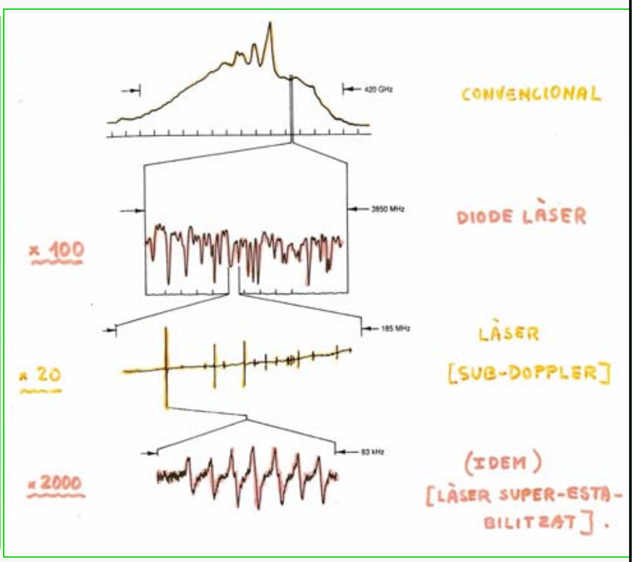
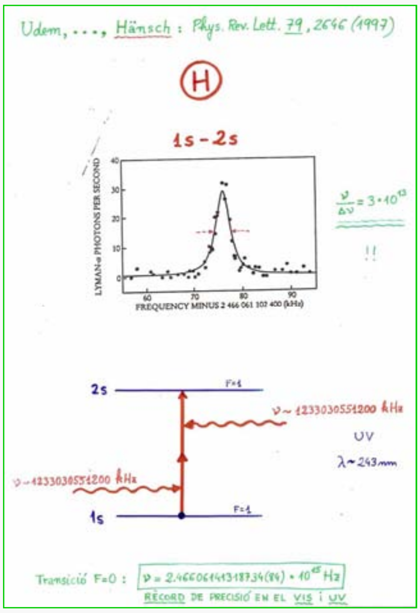
## *Application of laser monochromaticly to Spectroscopy*





## High-resolution nonlinear laser spectroscopy




Applications even in Cosmology…



## Control remot:

- *LIDAR,*
- *Control de l'atmosfera,…*

## Làsers: Aplicacions científiques i tècniques

POTÈNCIA

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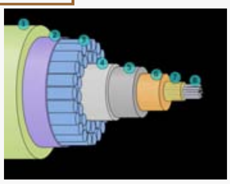
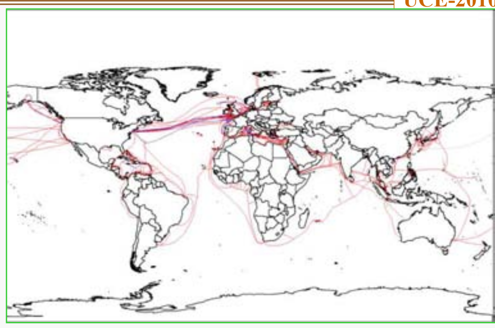
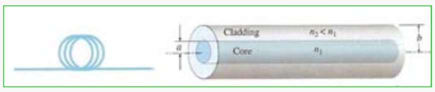
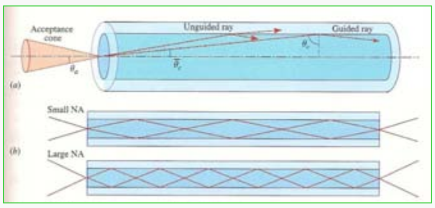
## OPTICAL FIBRES

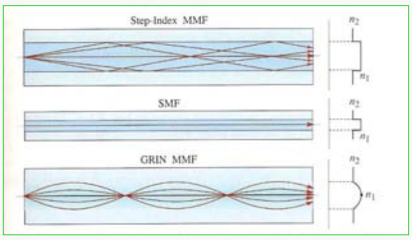


OPTICAL FIBERS






$NA = \sin\ \theta_a$

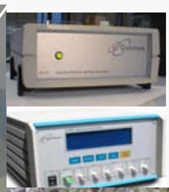
$V = (2\pi a/\lambda_0)\cdot NA$

"Fiber parameter"

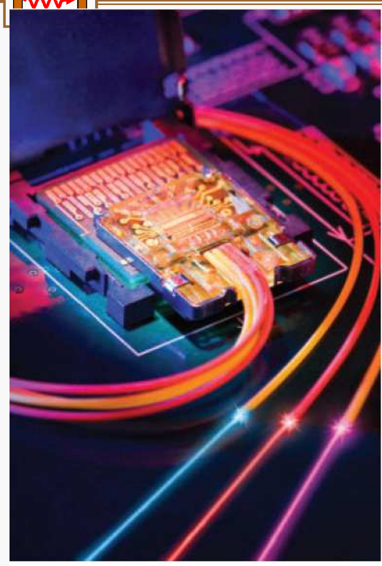
## MANIFESTATIONS OF THE SUPERPOSITION PRINCIPLE (and Quantum measurement) (III): QUANTUM CRYPTOGRAPHY



http://www.idquantique.com/



Jeffrey Tseng/Intel

Light Peak module close-up with laser light added for illustration (actual infrared light is invisible to the eye).

## *Applications in biology (biophotonics) and medecine:*

- ***Vision: LASIK, retina problems in diabetes, …***
- ***Skin***
- ***Rheumatism***
- ***Laser thermotherapy –by heat-, photodynamic therapy –by light activated drugs-:***
  ***Remove obstructions in arteries and veins, ulcers, tumors (cancer),…***
  ***(use of drugs, fluophores, plasmon particles,…)***
- ***Surgery: laser scalpel***
- ***Measurement of blood concentration of particles, velocities, tissue coagulation***
  ***(by light scattering, Doppler shift,…)***
- ***Analysis of cells and tissues by: single-photon spectroscopy*** *(helped with fluophores,…)*
  ***two-photon spectroscopy,***
  ***Optical coherence tomography (OCT),***
  ***etc.***
-
-
-

# Làsers: Aplicacions científiques i tècniques

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- *Processat de materials: tall, soldadura, perforació, marcatge, tractaments de superfície, prototipat 3D (100 nm resol amb femtosecond 2-photon), …*

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- *Holografia, interferometria, Optica en general (futurs displays, projectors?)*
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- *Comunicacions òptiques; comunicacions quàntiques (criptografia quàntica, etc.)*
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- ***Òptica integrada, integració amb micro-electrònica (computació, etc.). Micro- i nano-làsers.***
- ***Nanolàsers i single-atom lasers per a informació quàntica, …***

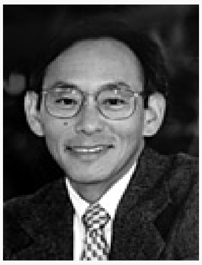


***Action over the center of mass of the atoms:***

## *Controlling the movement of atoms with laser light*

- ***Cooling and trapping of atoms***
- ***Bose-Einstein condensation (BEC)***

## PHYSICS NOBEL PRIZE 1997



Steven Chu

Claude
Cohen-Tannoudji

William D. Phillips

"For development of methods to <u>cool and trap atoms with laser light</u>"



## PHYSICS NOBEL PRIZE 2001


**Eric A. Cornell**

JILA and NIST

Boulder, CO, USA

*Born in 1961 (Palo Alto)*

*PhD 1990 (MIT)*


**Wolfgang Ketterle**

MIT

Cambridge, MA, USA

*Born in 1957 (Heidelberg)*

*PhD 1986 (Universität München and Max-Planck-Institut für Quantenoptik, Garching)*


**Carl E. Wieman**

JILA and Univ. of Colorado

Boulder, CO, USA

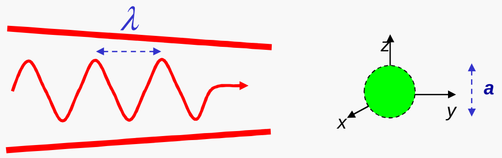
*Born in 1951( Oregon)*

*PhD 1977 at Stanford University*

For the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates

## Action over the atom's center of mass: cooling and trapping.






***Forces over an object (atom,…), from an electromagnetic wave :***

- ***Radiation pressure:***

  ***Longitudinal*** *force, due to the* ***photon momentum****, usually in the propagation direction (if photon is absorbed)*

  $$\vec{F} = \vec{p}_{1\,photon} \cdot \frac{dn}{dt}$$

  *n = number of photons/sec absorbed*

- ***Dipolar (if λ>>a) or momentum-exchange (if λ<<a) :***

  ***Transverse*** *(and longitudinal) component, associated usually to focused beams, with a* ***gradient of intensity****. Example for λ>>a:*

  $$F = \frac{1}{2}\alpha \cdot \nabla E^2$$

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50 aniv. Làser

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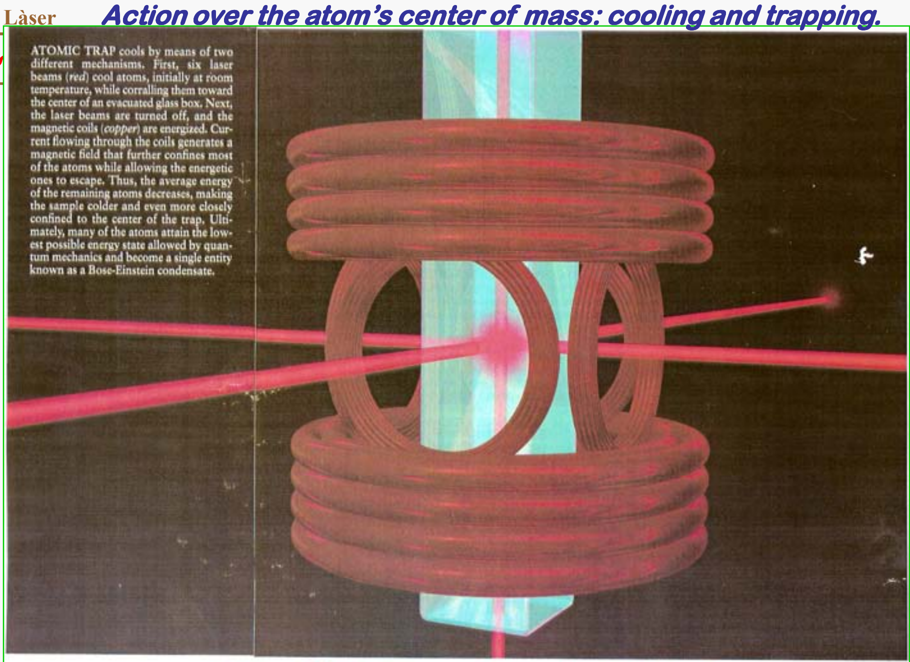
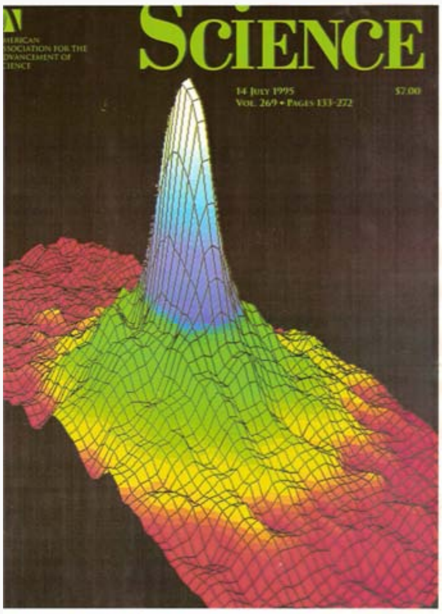
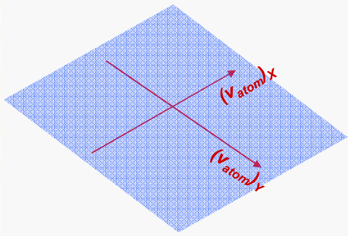



E. A. Cornell, C. E. Wieman : Sci. Am. (March 1998), p. 26

## First achievement of BEC (Bose-Einstein condensation)

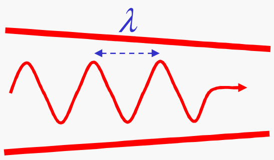


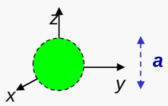

• Anderson, Ensher, Matthews, Wieman, Cornell: Science 269, 198-201 (1995)






## Action over the atom's center of mass: gradient forces.

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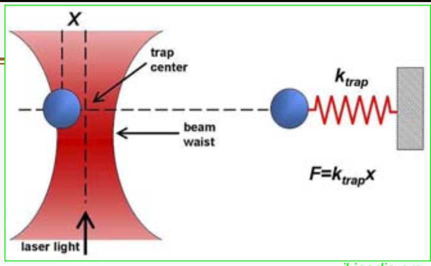
# Optical tweezers




www.wikipedia.org

*Two regimes*:

a) ***Rayleigh regime***: $\lambda >> a$ (a = radius sphere) The gradient force is the force of a non–uniform field over an induced dipole: "dipolar force". (It applies in particular to atoms)

$$F = \frac{1}{2}\alpha \cdot \nabla E^2$$

$\alpha$ = polarizability of the sample

b) (General *Mie regime*): $\lambda << a$ . The gradient forces is dominated by the momentum reaction to the light deviation by refraction inside the sphere (if it is transparent), on the walls: "Momentum–exchange" force. (Many applications in biology)

- Forces are, typically, in the **pico-Newton** range
- Ashkin was able to trap larger particles (10 to 10,000 nanometers in diameter) but it fell to Chu to extend these techniques to the trapping of neutral atoms (0.1 nanometers in diameter) utilizing resonant laser light and a magnetic gradient trap.



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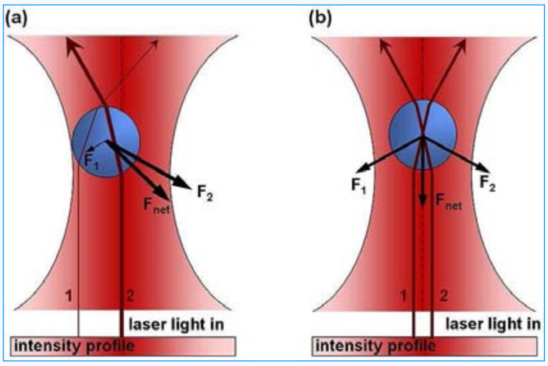


***Ray-optics and linear-momentum explanation***:

*When the bead is displaced from the beam center, as in (a), the larger momentum change of the more intense rays cause a net force to be applied back toward the center of the trap. When the bead is laterally centered on the beam, as in (b), the net force points toward the beam waist.* (www.wikipedia.org)

# Làsers: Aplicacions científiques i tècniques

POTÈNCIA

**Gran**

- *Fusió nuclear*
- *Làser d'electrons lliures, làser de raigs X*
- *Làsers de Terawatt: generació d'altes freqüències i de polsos ultra-curts (atto-segons), aplicacions a Física Atómica i Nuclear, acceleració de partícules.*
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*Simple combinations:*

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  (a) In transverse (or horizontal, or X, or Y) direction [linear, angular]
  (b) In longitudinal (or in depth, or vertical, or Z) direction
  (c) In transverse & longitudinal directions (2D and 3D) (more complex)

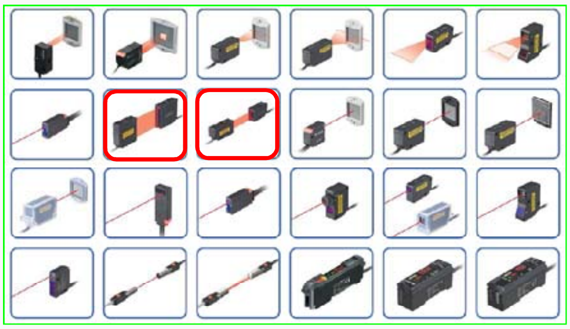
  See next page

- *(Other types of systems –more complex-):* other interferometric devices, spectroscopic devices, etc.

## Distance meter in the transverse direction:

- Diameter or gap measurements by "light curtain" (gaging, laser micrometer)

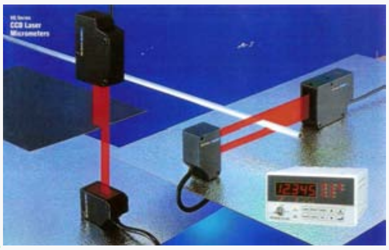
Need a scanning system, and/or a CCD detector.

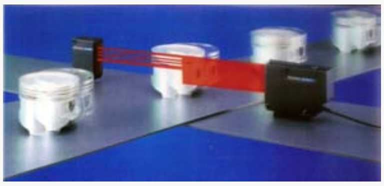


Several types of small devices, for different pourposes

www.keyence.com

www.keyence.com





Laser micrometer (for gaging)



Distance meter in the transverse direction:

- LASER DOPPLER VELOCIMETRY (OR ANEMOMETRY)

For measuring velocities of particles in suspension in a fluid, moving in transverse direction

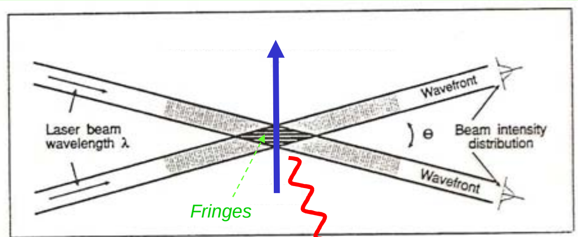
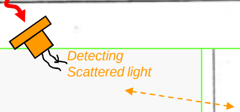



Figure 10. Two laser beams crossing.



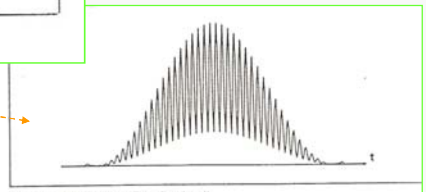




Figure 11. Doppler burst (Doppler signal).

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Some EXAMPLES of combinations of

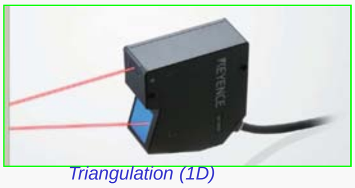
## one photoemitter + one photodetector



UCE-2010

Measuring distances in Z (longitudinal) direction, by TRIANGULATION (1D)

November 2009

Triangulation (1D)

Triangulation (2D)

www.keyence.com

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UCE-2010

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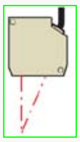
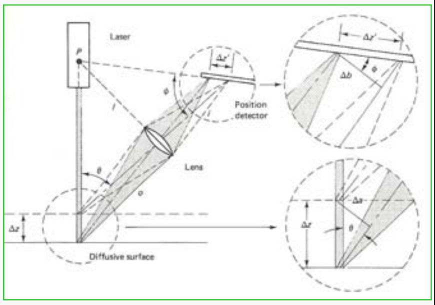
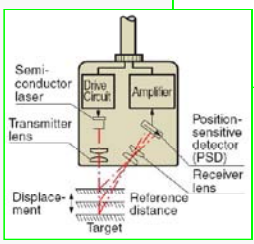
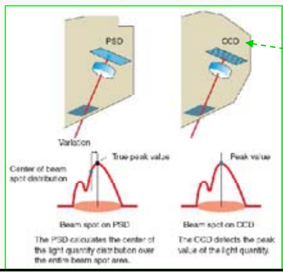


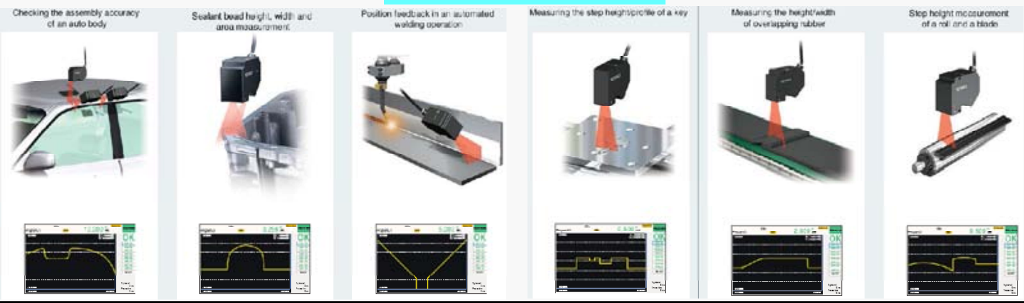

See previous transparency: Nov-2009: CMOS

www.keyence.com

## TRIANGULATION (1D)


www.keyence.com

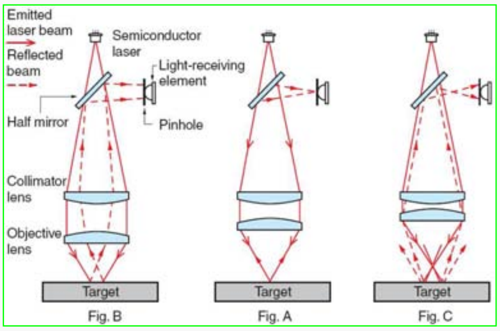
## TRIANGULATION (2D)

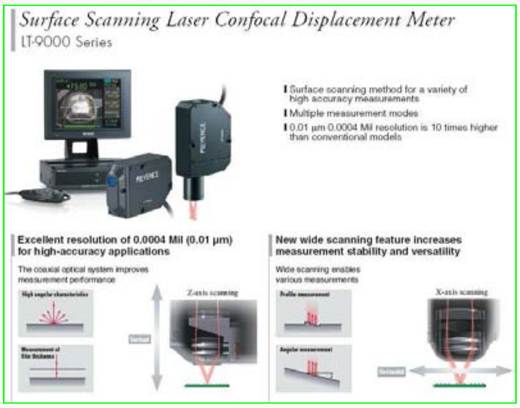





## Some EXAMPLES of combinations of one photoemitter + one photodetector

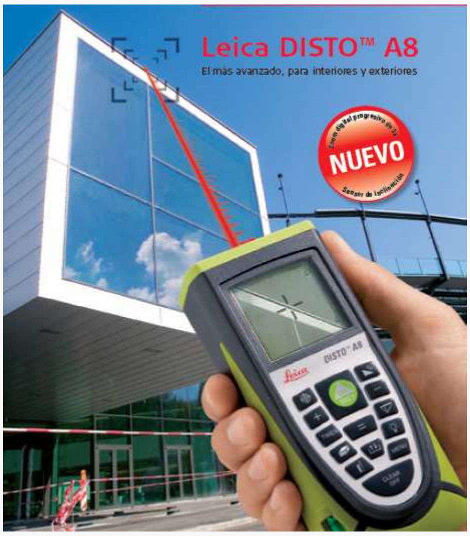
### CONFOCAL IMAGING PROFILER (3D)



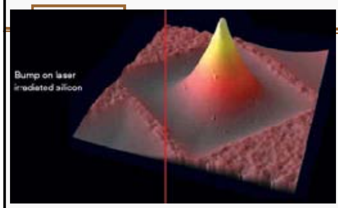



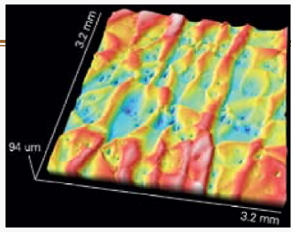

*Confocal profiling provides the highest lateral resolution that may be achieved by an optical profiler. This makes it possible to reduce the spatial sampling to 0.10 µm, which is ideal for critical dimension measurements.*

www.keyence.com

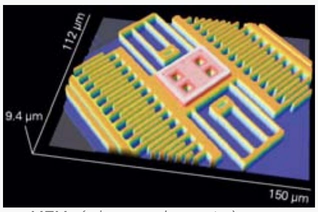




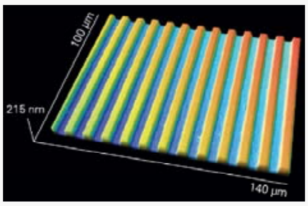



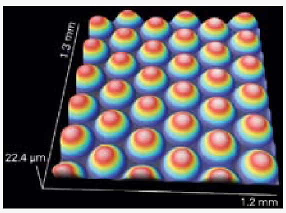

*Biotechnology (leader)*



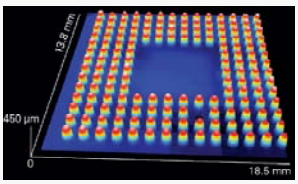

*MEMs (micro-accelerometer)*




*Semiconductors: $SiO_2$ structure on Si substrate*




*Micro-optics: array af glass microlenses*




*IC's: IC-soldering tool*

OPTICAL IMAGING PROFILER (3D):

Confocal
+
interferometer (PSI+VSI)

www.sensofar.com

*Confocal + Interferometer (3D)*

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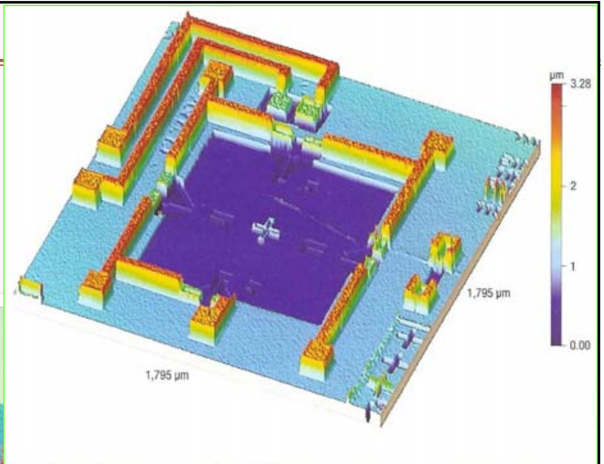
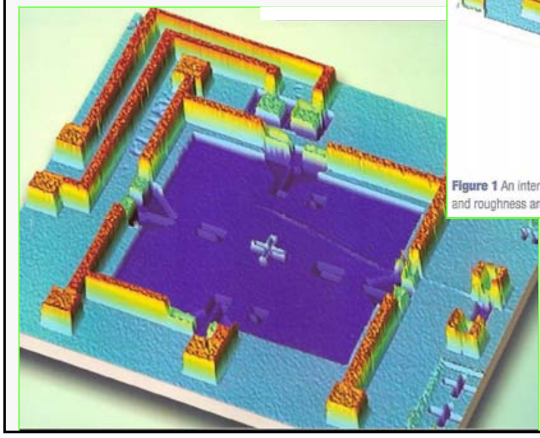



**Figure 1** An interferometry measurement of a MEMS piezoelectric pressure sensor. Typically both the step height and roughness are of interest to ensure that the device works correctly.

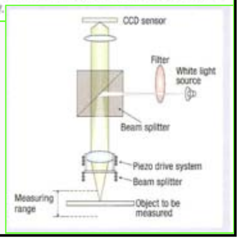
3D white-light Vertical Scanning Interferometry (VSI)

*Measurement of a MEMS piezoelectric pressure sensor, by the VSI*



*Taylor Hobson*

*(Ametek, UK)*

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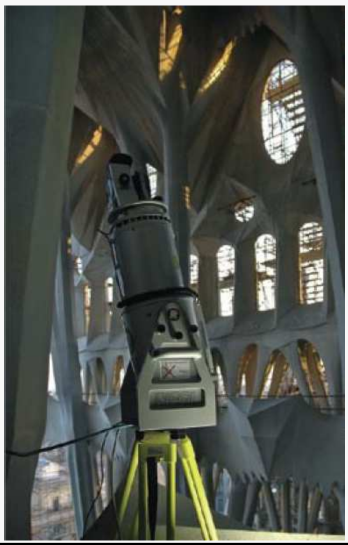
## No sols a curtes distàncies:

- Arquitectes:

  *mesura ràpida de distàncies, escannejat 3-D d'edificis…*

- etc.



***Estudi sobre la Sagrada Familia***
*J. Regot et al., 2006*
*(Escola d'Arquitectura, Univ. de Barcelona)*

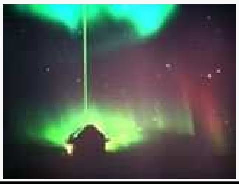
## LIDAR (measuring distances, controlling atmosphere pollution, etc.)

A FASOR used at the Starfire Optical Range for LIDAR and laser guide star experiments is tuned to the sodium D2a line and used to excite sodium atoms in the upper atmosphere

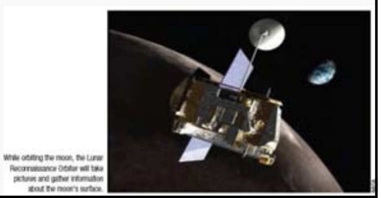


Chet Gardner, Univ. of Illinois

**Also on earth, mobile (with a van), to measure air pollution near a factory, etc.)**

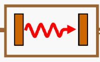


The lidar operating at Davis with an aurora in the background.
Photo: David Correll









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Some *EXAMPLES* of combinations of

## 1 photoem. + 1 photodet. :

## Spectroscopic devices



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Simple device to masure the % of oxigenation of blood:

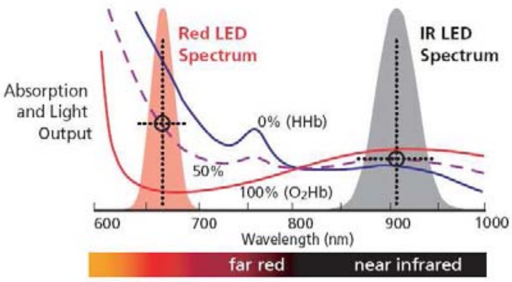


**Figure 1**
Overlay of typical LED-emitted light spectrum and relative light absorption spectra of oxygenated and deoxygenated hemoglobin. The dashed purple line indicates the spectra of 50%-saturated blood, with the relative absorbance in the red and IR indicated by the black circles.

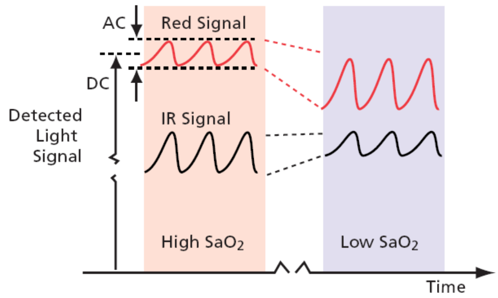


**Figure 2**
Red and IR light signals at high and low arterial oxygen saturation. At high saturation, the red "pulse amplitude" (AC/DC) is smaller than in the IR. At low saturation, the ratio of relative amplitudes is reversed.

A Technology Overview of the Nellcor· OxiMax· Pulse Oximetry System

*Nellcor Technical Staff*

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## Làsers: Aplicacions científiques i tècniques



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POTÈNCIA

**Gran**

- *Fusió nuclear*
- *Làser d'electrons lliures, làser de raigs X*
- *Làsers de Terawatt: generació d'altes freqüències i de polsos ultra-curts (atto-segons), aplicacions a Física Atómica i Nuclear, acceleració de partícules.*
- *Transport d'energia a distància (futur)*
- *Aplics. militars*

**Mitjana**

- *Processat de materials: tall, soldadura, perforació, marcatge, tractaments de superfície, prototipat 3D (100 nm resol amb femtosecond 2-photon), …*
- *Espectacles lluminosos*
- *Fotoquímica: estimulació i control de reaccions químiques (fins i tot unir atoms freds), foto-dissociació, foto-ionització, …*
- *Òptica no lineal, per a diverses aplicacions (incloent la generació de extrem UV -13.5 nm- per a dissenyar petites estruct. electròniques i extendre Moore's law, informació quàntica,…)*
- *Biofotònica, aplicacions mèdiques*
- *Control remot: LIDAR, control de l'atmosfera*
- *Arts gràfiques, impressores, memòries (CD, DVD),… [Futur: imatges color i projectors, il·lum.]*
- *Holografia, interferometria, Optica en general (futurs displays, projectors?)*
- *Espectroscopía: anàlisi de materials, de contaminants, etc.*

**Petita**

- *Comunicacions òptiques; comunicacions quàntiques (criptografia quàntica, etc.)*
- *Atrapament i refredament d'àtoms, condensació de Bose-Einstein (BEC)*
- *Sensors: de presència, posició, vibració i moviment. Lectors de codis, etc.*
- *Metrologia: mesura de distàncies, angles, relleus,… Velocitat llum, ones gravitacionals,*
- ***Òptica integrada, integració amb micro-electrònica (computació, etc.). Micro- i nano-làsers,***
- ***Nanolàsers i single-atom lasers per a informació quàntica, …***

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# Photonic circuits: the dream........

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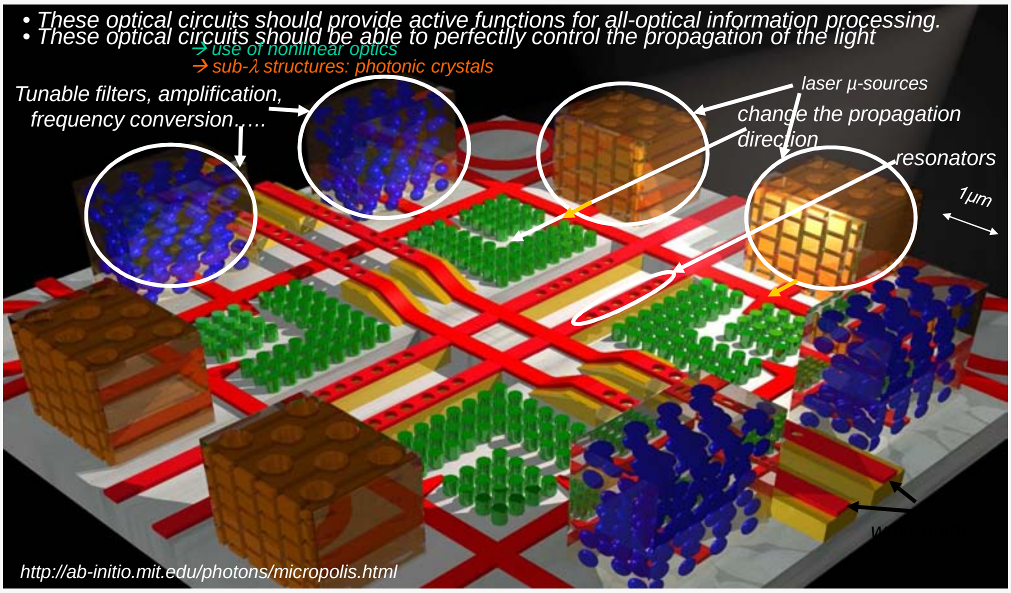


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# Integrated photonics

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Light Peak module close-up with laser light added for illustration (actual infrared light is invisible to the eye).

**Future: Si photonics ?**

# Futur ...?

- Millora eficiències, en tots tipus de làsers i aplicacions
- Micro- i nano-lasers: sensors, integració electrònica-fotònica, computació, comunicacions
- Més progrés en biofotònica (aplics. en biologia i medicina)
- Imatge, projecció
- Comunicacions a l'espai, a molt llarga distància
- "Power beaming"
- Fusió nuclear controlada?
- Informació quàntica? (criptografia, simulació, computació, teleportació,...)
- ? ? ?