50 anys del làser.

Aplicacions tècniques i científiques

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50 anys del làser...

Theodore Maiman, 16 May 1960

LASERS: Sumari

A) Introducció, amb una mica d'història

B) L'interior del làser *(breu)*

- Principis de funcionament.
- Varietat de tipus de làser segons el medi amplificador:

C) L'exterior del làser: la radiació làser

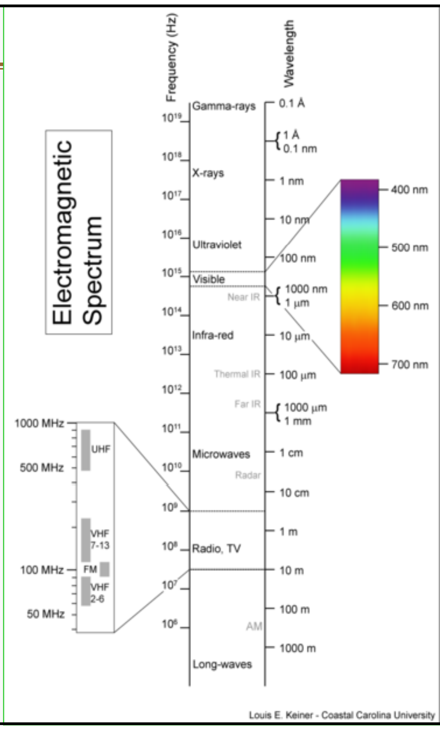
- Propietats de la radiació làser

D) Aplicacions científiques i tècniques (present i futur)

Introducció: Història del làser

"Light Amplification by Stimulated Emission of Radiation"

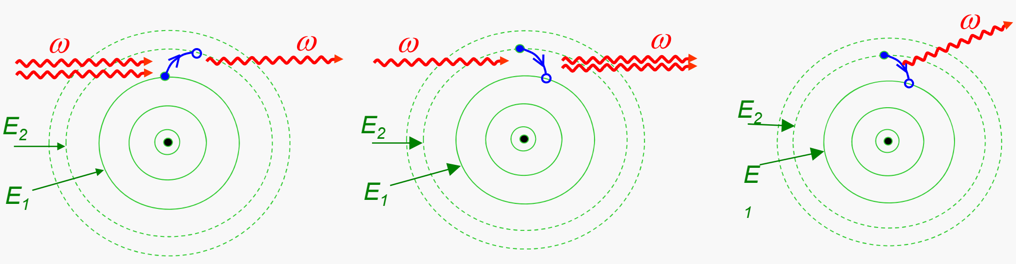
- **1917.- Einstein: concept of stimulated emission**
- **1928.- Ladenburg: confirms existence stimulated emission**
- **1939.- Fabrikant: predicts use of stim. emission to amplify "short" waves**
- **1947.- Lamb and Retherford: found apparent stimulated emission in hydrogen spectra**
- **1949-51.- Kastler: optical pumping [Nobel Prize in 1966] (+ Brossel)**
- **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]***



From: Wikipedia®

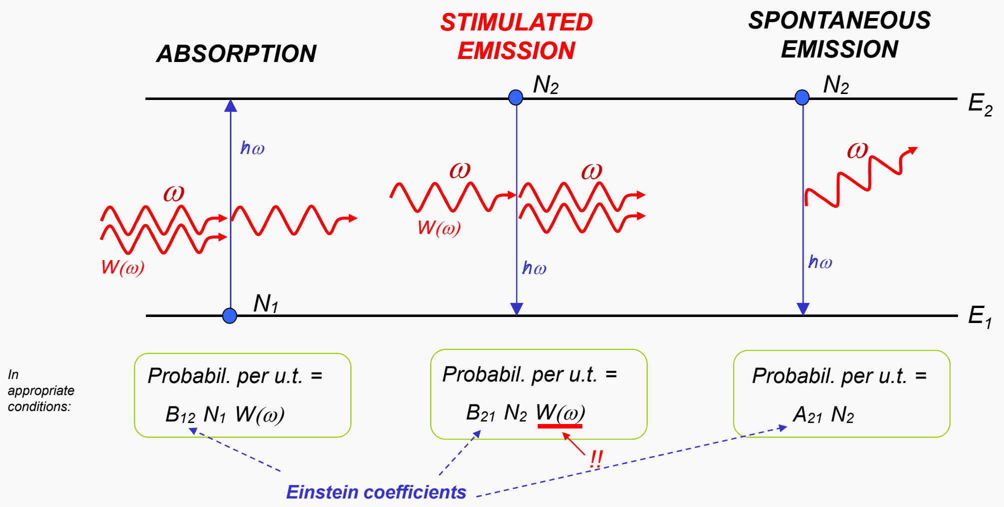
Basic (linear) interaction phenomena: Spontaneous emission, stimulated emission, absorption

Absorption **Stimulated emission** **Spontaneous emission**



$E_2 - E_1 = \hbar \cdot \omega$ *in all three cases*

Stimulated emission, an "ideal" process for light amplification...



Einstein coeff. properties: $B_{12} = B_{21}$, $A_{21} = B_{21} \frac{8 \pi h \nu_{21}^3}{c^3}$

Introducció: Història del làser

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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 Research 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, λ=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 λ's) , and quantum-dot laser**
- **1996.- Pulsed atom laser** **(matter instead of light)**
- **1996.- InGaN blue laser diode** **(semiconductor, λ = 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]**

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THUS TECHNICAL, AND EVEN FUNDAMENTAL, DEVELOPMENT CONTINUES…

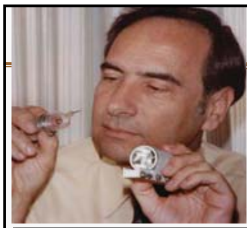
Albert Einstein

Charles H. Townes, 1954

Nikolai G. Basov

Alexander M. Prokhorov

50 anys del làser…



Charles H. Townes, 1954

Arthur Schawlow

Theodore Maiman, 1960

Charles H. Townes, 2010

NOBEL PRIZE 1981

Nicolaas Bloembergen

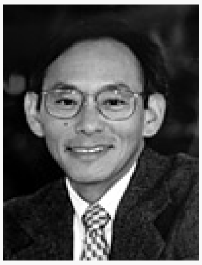
Harvard University, USA

Arthur L. Schawlow

Stanford University, USA

"For their contribution to the development of laser spectroscopy"

NOBEL PRIZE 1997



Steven Chu

Claude Cohen-Tannoudji

William D. Phillips

“For development of methods to cool and trap atoms with laser light"

NOBEL PRIZE 1999, CHEMISTRY

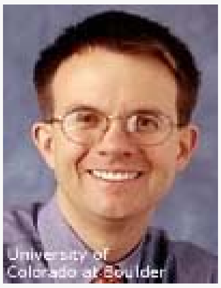
Ahmed Zewail

California Institute of Technology (Caltech), Pasadena, CA, USA

(Origin: Egipt)

“For his studies of the transition states of chemical reactions using femtosecond spectroscopy”

NOBEL PRIZE 2001



Eric A. Cornell

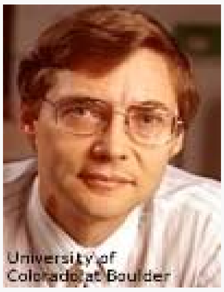
JILA* and *NIST
Boulder, CO, USA

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".

NOBEL PRIZE 2005

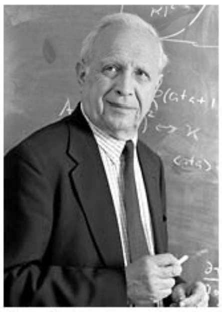


Photo: J.Reed
Roy J. Glauber

Photo: Sears.P.Studio
John L. Hall

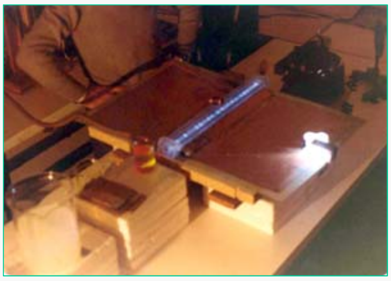
Photo: F.M. Schmidt
Theodor W. Hänsch

The Nobel Prize in Physics 2005 was divided, one half awarded to Roy J. Glauber *"for his contribution to the quantum theory of optical coherence"*,the other half jointly to John L. Hall and Theodor W. Hänsch *"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"*.

I … a Barcelona, què ??

- **Primers làsers comprats:**
  - *- Primer làser: probablement el làser de rubí del prof. Garrido (UB) (60's)*
  - *- Després: Làsers de He-Ne a la UB, a la UAB, a UPC,… (70's)*
  - *- Làsers de Ar^+ a les discoteques, a la UAB, … (finals 70's, 80's)*

- **Primer làser construit:**
  - *- Primer làser: Làser de N_2, a la UAB (curs 1979-80)*
  - *- Després: Làsers de CO_2, a CRILASER (principis dels 80's)*

LASERS: Sumari

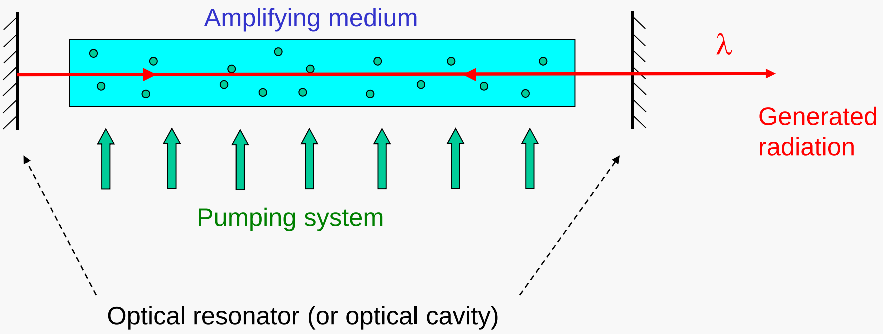
A) Introducció, i una mica d'històrica

B) L'interior del làser (breu)
- Principis de funcionament.
- Varietat de tipus de làser segons el medi amplificador:
- Paper jugat pel ressonador òptic.

C) L'exterior del làser: la radiació làser
- Propietats de la radiació làser

D) Aplicacions científiques i tècniques (present i futur)

Parts d'un làser, i principis de funcionament

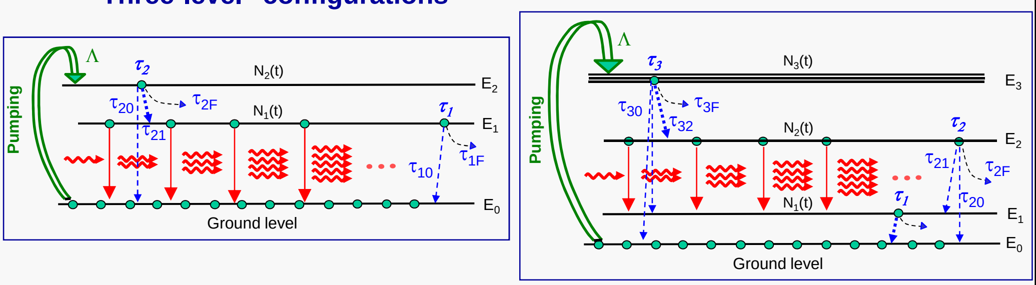


Sistema "dissipatiu"

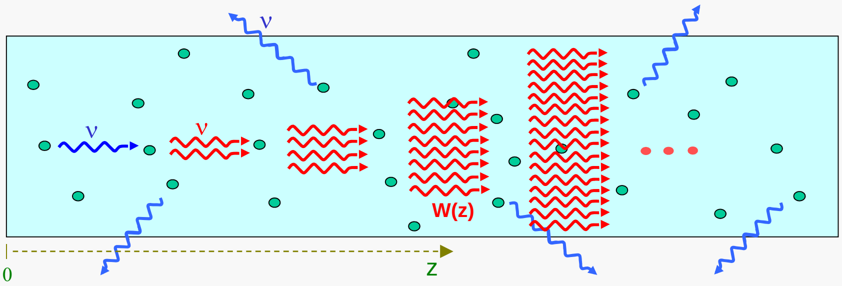
L'interior del làser: principis de funcionament

"Three-level" configurations

"Four-level" configuration

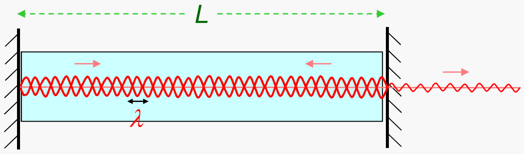


Who provides the first photon ?

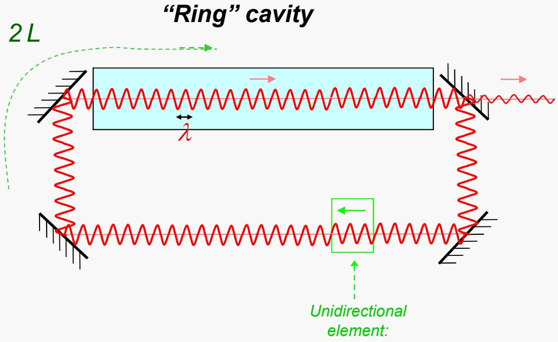


Optical cavity: longitudinal modes

"Fabry-Perot" cavity



"Ring" cavity



Resonance condition:

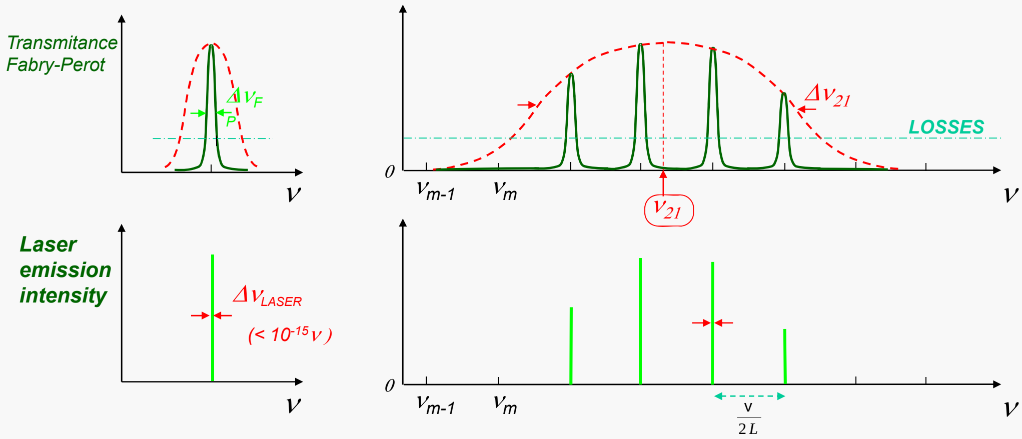
$$2L = m\,\lambda \quad = m\, v/\nu$$

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

Frequency of the longitudinal mode of order m

Optical cavity: longitudinal modes

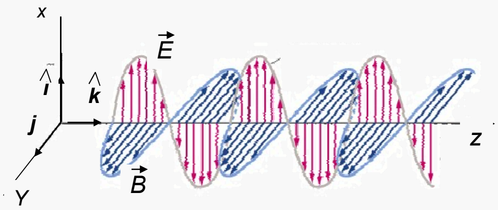
- ***Actually, the modes are much more monochromatic due to the competitive effect of stimulated emission !!:***



Single-mode case

Multi-mode case

En resum, la llum d'un làser és el que més s'assembla a l'ideal d'una Ona electromagnètica plana monocromàtica …



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

$B = E / v$

Space

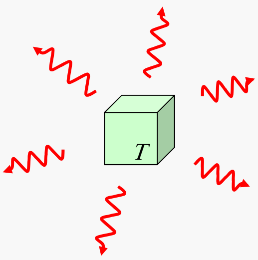
- Wavelength: λ
- Wavenumber: $k = 2\pi / \lambda$

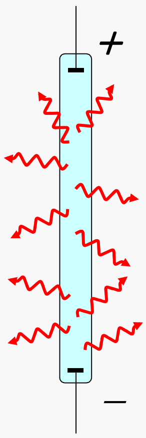
Time

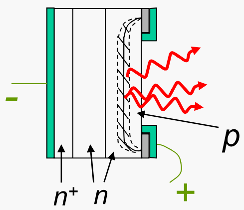
- Period: T
- Frequency: $\nu = 1 / T$
- Angular frequency: $\omega = 2\pi\nu$
- Initial phase: φ

+ els aspectes corpusculars (fotons)…

La llum làser és semblant als altres tipus de llum?







Radiació tèrmica

Descàrrega elèctrica

L.E.D.

Varietat de tipus de medi amplificador

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, **microchip**
  Ti:Saphire, Alexandrite
- **Optical fiber:** **Er^{3+}:Silica** **(Er^{3+}:SiO_2)**
- Others: Color centres, ...

d) **SEMICONDUCTOR (DIODE LASERS)**

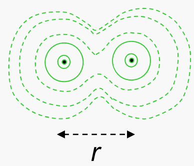
- **Near infrared:** **AlGaAs**, **InGaAsP**
- **Visible:** **GaInP**, **AlGaInP**, **GaP**
- **Mid infrared:** **…**
- **Other types:** **VCSEL's, "arrays", high power, quantum cascade, ...**

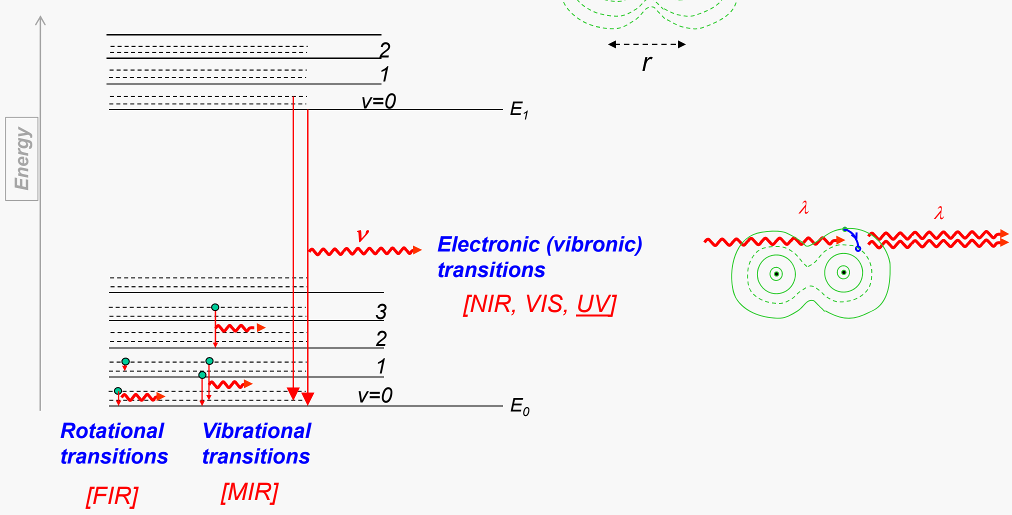
e) **OTHERS**

- **Free electron laser**, • **X Ray**, • Random lasers,
- **Micro- and nano-lasers (microdisc, microsphere, quantum dot, photonic crystal, plasmon laser…)**, • Single-atom lasers , • Làser d'àtoms

GAS LASERS: Molecular

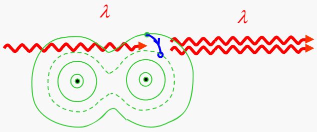
Enery levels for a (simple) molecule :





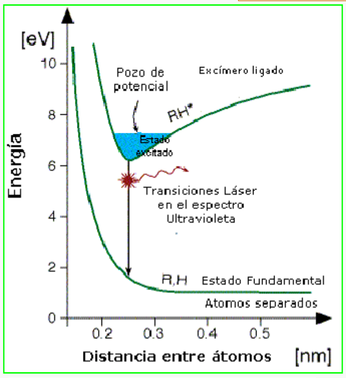
GAS LASERS: Molecular (Electronic transition)

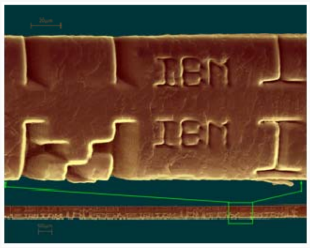
- Pumping: electrical discharge



- **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)

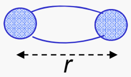


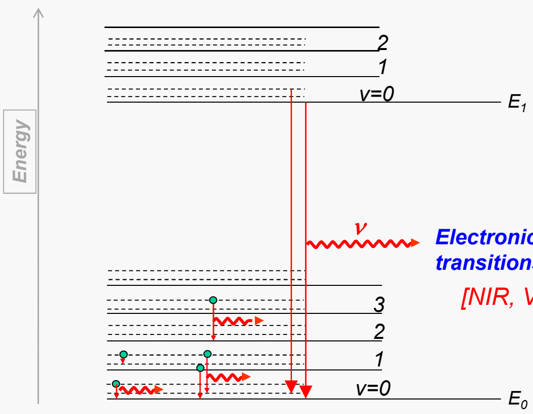


Human hair !

GAS LASERS: Molecular

Enery levels for a (simple) molecule :

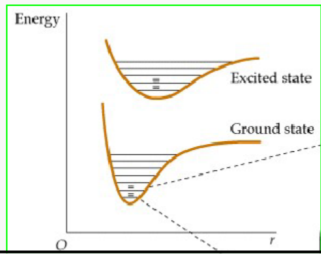




Electronic (vibronic) transitions
[NIR, VIS, UV]

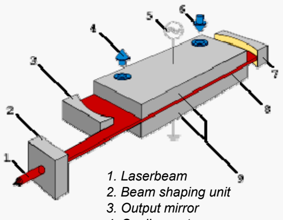
Rotational transitions
[FIR]

Vibrational transitions
[MIR]



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) 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, ….

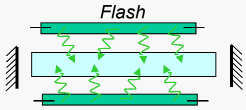
c) SOLID STATE
- **Doped crystal:** Rubi, Nd:YAG, Nd:Glass, microchip,… Ti:Saphire, Alexandrite
- **Optical fiber:** Er^{3+}:Silica ($Er^{3+}:SiO_2$)
- **Others:** Color centres, …

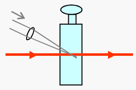
d) SEMICONDUCTOR (DIODE LASERS)
- **Near infrared:** AlGaAs, InGaAsP
- **Visible:** GaInP, AlGaInP, GaP
- **Mid infrared:** …
- **Other types:** VCSEL's, "arrays", high power, quantum cascade, ...

e) OTHERS
- Free electron laser, • X Ray, • Random lasers,
- Micro- and nano-lasers (microdisc, microsphere, quantum dot, photonic crystal, plasmon laser…), • Single-atom lasers , • Làser d'àtoms

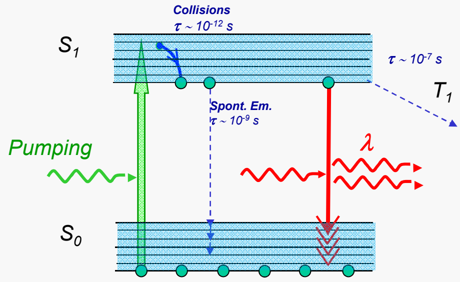
B) LIQUID LASERS: *Dye laser*

- *Pumping: optical: flash, or another laser*





- *"Vibronic" transitions*
  (λ ~ VIS, NIR, near UV)



- *λ ~ 350-1000 nm, **TUNABLE !!***

η ~ 1-35%

(how?)

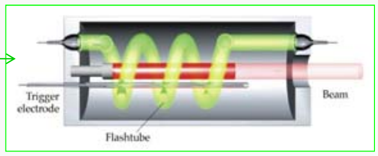
B) Existing types of lasers according to the amplifying medium

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, ….

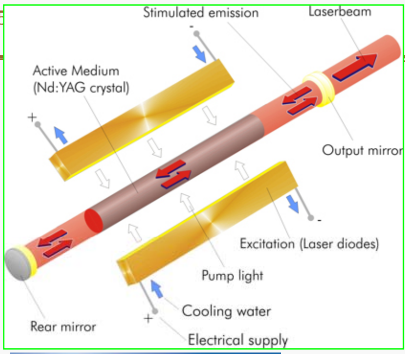
c) **SOLID STATE**
- **Doped crystal:** Rubi, **Nd:YAG**, Nd:Glass, **Ti:Saphire**, Alexandrite
- **Optical fiber:** **Er^{3+}:Silica (Er^{3+}:SiO_2)**
- Others: Color centres, microchip,…



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

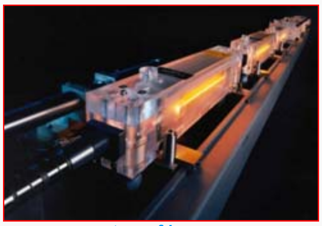


	ROFIN DP 010 HX	ROFIN DP 015 HX
Excitation	Laser diodes	Laser diodes
Output power (@collimator)	100 - 1000 W	150 - 1500 W
Beam parameter product	12 mm*mrad	12 mm*mrad
Fiber diameter	300 µm	300 µm

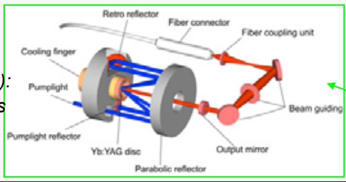
	ROFIN DP 020 HP	ROFIN DP 030 HP	ROFIN DP 040 HP
Excitation	Laser diodes	Laser diodes	Laser diodes
Output power (@collimator)	200 - 2000 W	300 - 3000 W	400 - 4000 W
Beam parameter product	25 mm*mrad	25 mm*mrad	25 mm*mrad
Fiber diameter	600 µm	600 µm	600 µm

www.rofin.com

High power: MOPA configuration



Also (new): disk series



Trumpf: up to 16 kW, BPP~ 2-8 mm·mrad

www.trumpf-laser.com

B) SOLID-STATE LASERS: Nd:YAG laser

Pulsed regimes: **cw, ms, µs, ns, ps** (and **fs** for Ti:sapphire)

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.

fs ↔ **for Ti:Sapphire** >~ 10^{12} W peak power, if amplified

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B) Existing types of lasers according to the amplifying medium

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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, quantum cascade, ...**

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

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SEMICONDUCTOR LASERS

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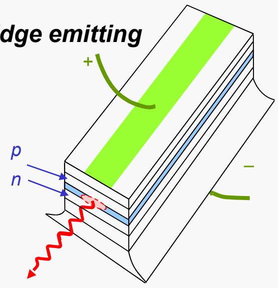
Edge emitting



"Double heterojunction"

Examples:

- (Al)GaAs laser: $\lambda \sim 850$ nm , IR $\eta \sim 20\text{-}60\%$,
- InGaAsP laser: $\lambda \sim 1300\text{-}1600$ nm , IR
- GaInP laser: $\lambda \sim 620\text{-}750$ nm [RED]
- GaN, InGaN laser: $\lambda \sim 450$ nm [BLUE laser]
- **Recently: InGaN**: $\lambda \sim 525$ nm [GREEN laser] (ideal: 530nm)
- Future **Si laser** ???

Also: 2 kW high power !

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L'interior del làser: Tipus de medi amplificador

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LASERS: TYPES OF AMPLIFYING MEDIUM

a) GAS

- **Atoms:** **He-Ne**, He-Cd, Cu.
- **Ions:** Ar^{+}, Kr^{+}.
- **Molecules:** Electronic (vibronic) transitions: **Excimer**, N_2.
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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,** • Atom laser

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B.e) Other types of lasers

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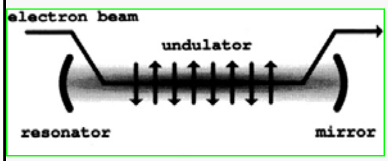
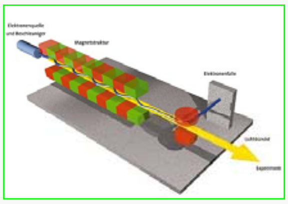
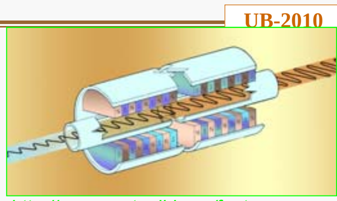
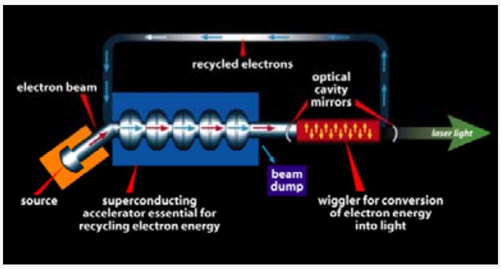
- Free-electron laser (FEL)



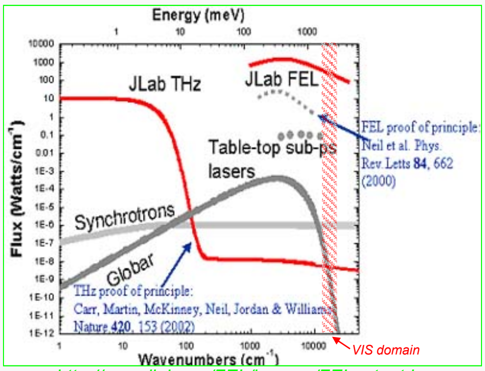




http://newscenter.lbl.gov/feature-stories/2007/11/14/into-the-future-at-the-s of-light/



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

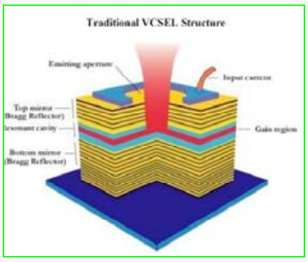


http://www.jlab.org/FEL/images/FELoutput.jpg

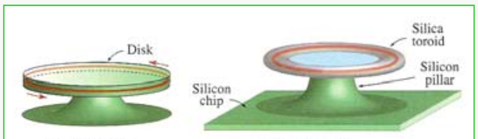
Antics intents de construir un laser de raigs X

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

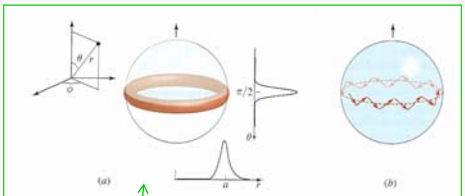
Micro- and nano- optical resonators

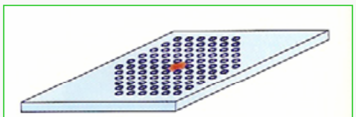


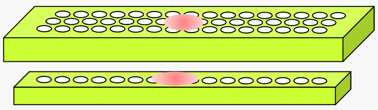
Micropillar

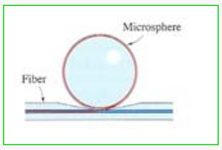


(b) Microdisk (c) Microtoroid



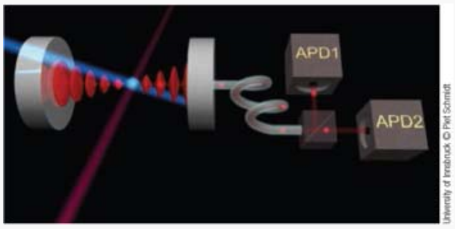

Photonic-crystal


Wave-guide photonic-crystal cavity



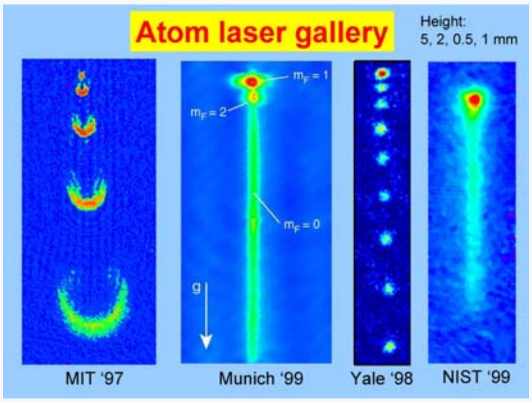

Integrated-optic-ring

Single-atom laser



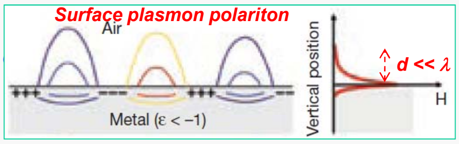
A high-finesse optical cavity consisting of two mirrors traps and accumulates the photons emitted by the ion into a mode. The ion is excited cyclically by an external laser and at each cycle a photon is added to the cavity mode, which amplifies the light.

"Atom laser"

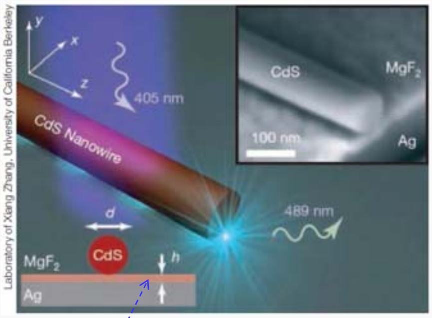


"Plasmon laser" (or "spaser"?): The smallest semiconductor laser:

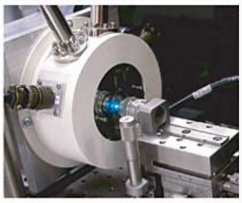
- Norfolk + Purdue + Cornell Univs. :
  A 44-nm-diameter "Cornell dot" with a gold
  Noginov et al., **Nature** 460, 1110 (2009)



- UC at Berkeley:
  A cadmium sulfide nanowire with a silver surface separated by an insulating gap of only 5 nm (a laser with a 5 × 30 nm lasing region)
  Oulton, …,Zhang, **Nature** 461, 629 (2009)



The gap region stores light within an area 20 times smaller than its wavelength



Berkeley researchers eventually hope to shrink the lasing cavity to **1 nm** (the wavelength of an electron), opening up new applications in **molecular probing (biomedical,…), faster communications, and quantum computing**.

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LASERS: Sumari

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A) Introducció, i una mica d'històrica

B) L'interior del làser *(breu)*

- Principis de funcionament.
- Varietat de tipus de làser segons el medi amplificador:
- Paper jugat pel ressonador òptic.

C) L'exterior del làser: la radiació làser emesa

- Propietats de la radiació làser

D) Aplicacions científiques i tècniques (present i futur)

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Summary of properties of laser light

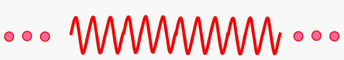
UB-2010

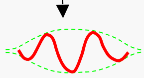
1) FREQUENCY *(ν)*

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

2) DURATION *(Δt)*

cw - ms - µs - ns - ps - fs - (as)





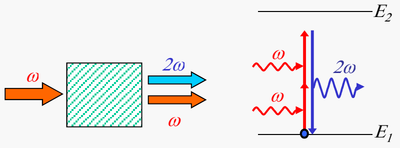
To go below ~100 fs special pulse compression techniques are needed.

Record value (2010): 123 as (Milano)

PERMETRÀ FER FOTOS INSTANTÀNIES DEL MOVIMENT DE L'ELECTRÓ EN UN ÀTOM!

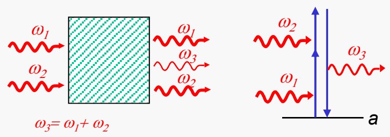
"ÒPTICA NO LINEAL"

- **Second harmonic generation (SHG)**

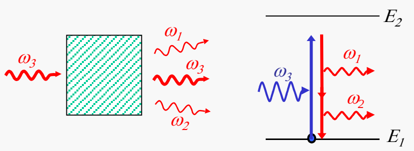


Exemple punter làser verd…

- **Sum frequency generation (SFG)**



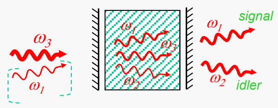
- **Down conversion (parametric fluorescence)**



$\omega_3 = \omega_1 + \omega_2$

Molt utilitzat en Òptica Quàntica !

- **Optical parametric oscillation (OPO)**



$\omega_3 = \omega_1 + \omega_2$

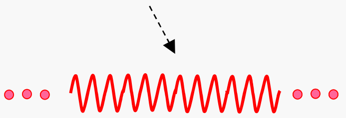
Summary of properties of laser light

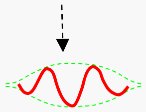
1) FREQUENCY (ν)

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

2) DURATION (Δt)

cw - ms - μs - ns - ps - fs - (as)





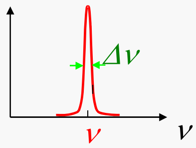
To go below ~100 fs special pulse compression techniques are needed.

Record value (2010): 123 as (Milano)

PERMETRÀ FER FOTOS INSTANTÀNIES DEL MOVIMENT DE L'ELECTRÓ EN UN ÀTOM!

D) Summary of properties of laser light

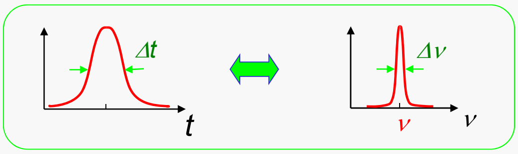
3) MONOCHROMATICITY ($\Delta\nu$)



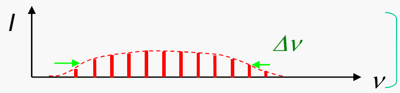
- **cw regime:**
  - Typical values (commercial lasers): $\Delta\nu/\nu \sim 10^{-3} - 10^{-5}$
  - Record values: → $\Delta\nu/\nu \sim 10^{-12} - 10^{-14}$!!

- **Pulsed regime:**

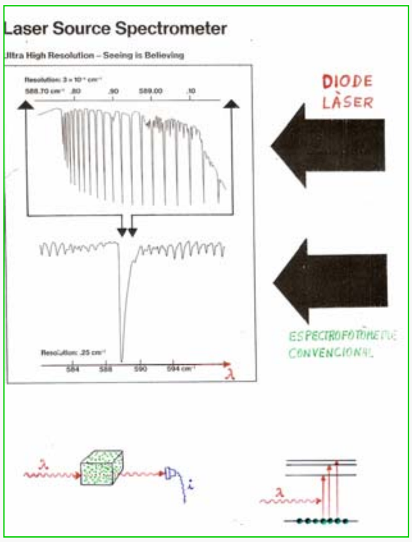
$\Delta t \cdot \Delta\nu \geq 2\pi$

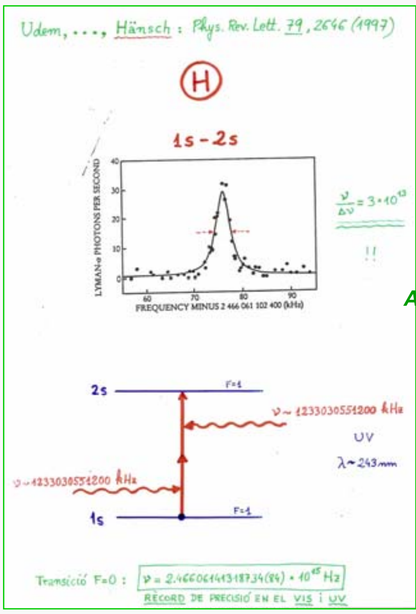


· Pump modulation: ms, μs
· Q-switching: ns
· Mode-locking: ps
· Additional manipulations: fs, as.



Application of laser monochromaticiy to Spectroscopy

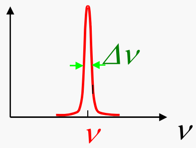




Applications even in Cosmology ...

D) Summary of properties of laser light

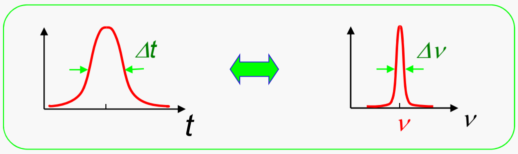
3) MONOCHROMATICITY (Δν)



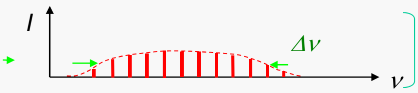
- **cw regime:**
  - Typical values (commercial lasers): $\Delta\nu/\nu \sim 10^{-3} - 10^{-5}$
  - Record values: → $\Delta\nu/\nu \sim 10^{-12} - 10^{-14}$!!

- **Pulsed regime:**

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

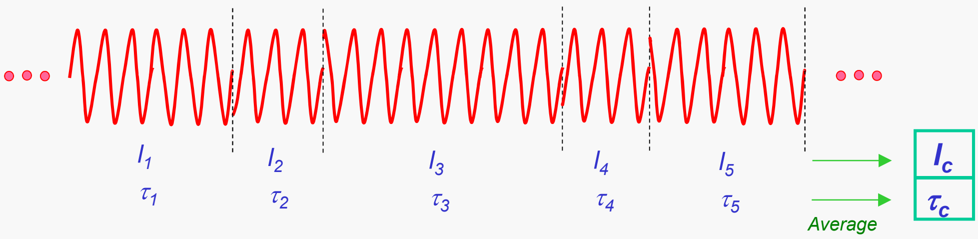


· Pump modulation: ms, μs
· Q-switching: ns
· Mode-locking: ps
· Additional manipulations: fs, as.



D) Summary of properties of laser light

4) TEMPORAL COHERENCE (or LONGITUDINAL COHERENCE)

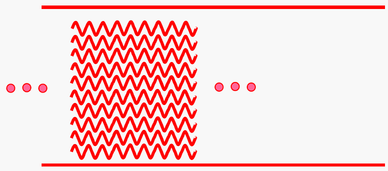


l_c = Coherence length

- 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)

D) Summary of properties of laser light

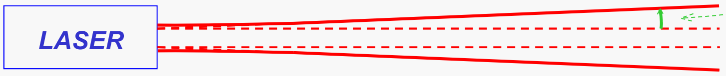
5) SPATIAL COHERENCE (or TRANSVERSAL)



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

6) DIRECCIONALITY:

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



Only limit: diffraction

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

(⇒ measurement of distance moom-earth with precision: ~ 20 cm !!)

Existing types of lasers according to the output power:

7) POWER

Power (cw regime) (W)

- 10^6 Chemical lasers
- 10^3 CO_2, Nd:YAG, Diode lasers (battery)
- Optical fiber lasers
- 1 Diode laser (high power)
- He-Ne
- Diode laser (low power)
- 10^{-3} Microlasers, Nanolasers?

Power (pulsed regime) peak power (W)

- 10^{17} 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?

D) Aplicacions científiques i tècniques dels làsers

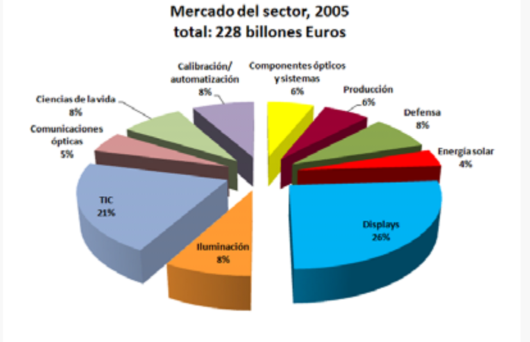


Figura 4: Mercado del sector (Fuente: Optech Consulting, Octubre 2007). Reproducido de FOTONICA 21

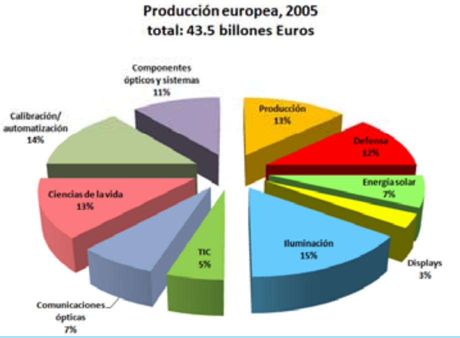
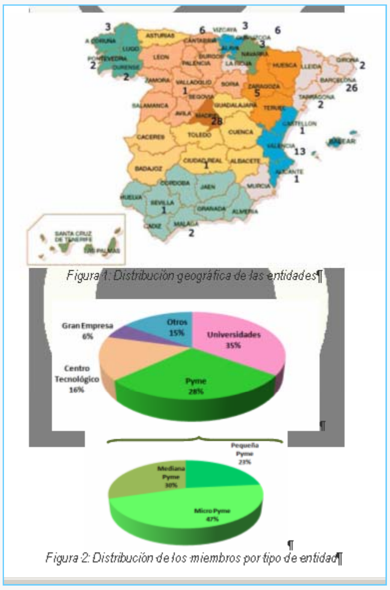


Figura 5: Producción europea del sector (Fuente: Optech Consulting, Octubre 2007). Reproducido de FOTONICA 21

Present forecast (2010):

- ***LASER:*** ***$ 300 billion***
- ***MICROELECTRONICS:*** ***$ 270 billion***

Laser overtakes Micro-Electronics for the first time!



Recent: SECPhO Cluster

Làsers: Aplicacions científiques i tècniques

POTÈNCIA

Gran

- *Fusió nuclear*
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- *Aplics. militars*

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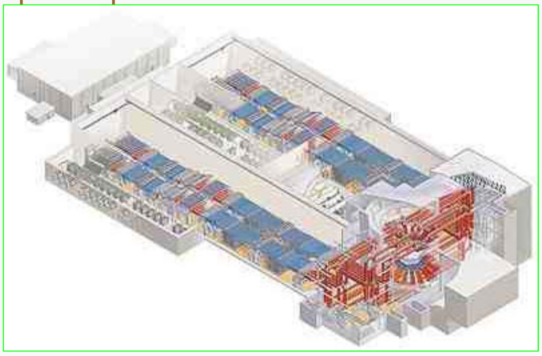
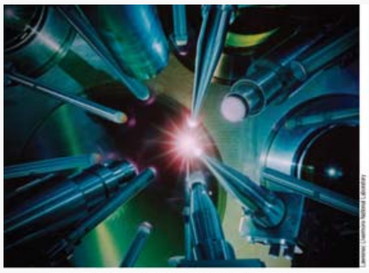
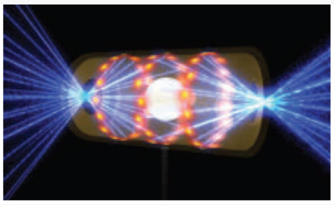
NIF (National Ignition Facility)
LLNL, Lawrence Livermore Nat. Lab., California





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.



NIF/LLNL

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.

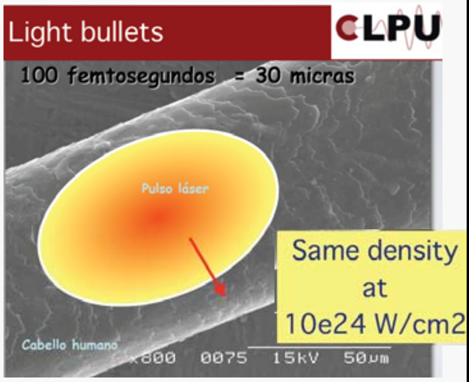
Lasers planned for the Extreme Light Infrastructure*

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			

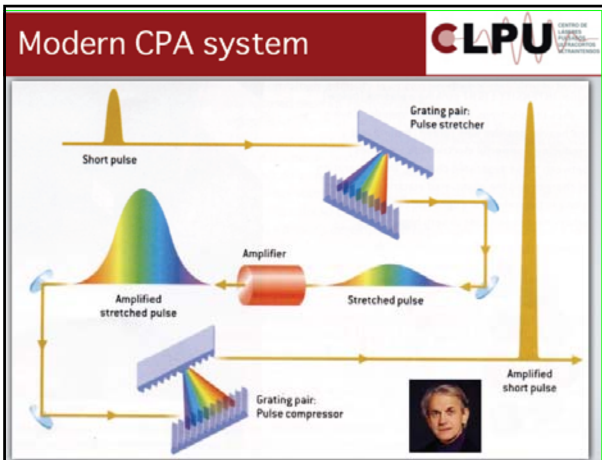
*Laser parameters still subject to change.

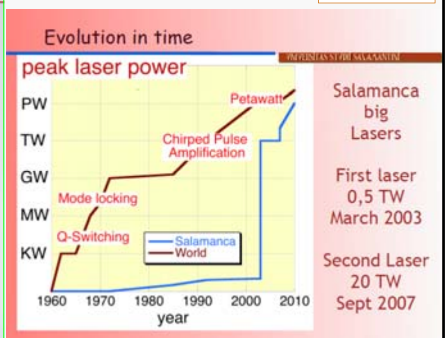
Terawatt short-pulse lasers

"Table Top Terawatt" laser (T^3)



Copy of transparencies from Prof. Luis Roso, Salamanca)





"Table Top Terawatt" laser (T^3)

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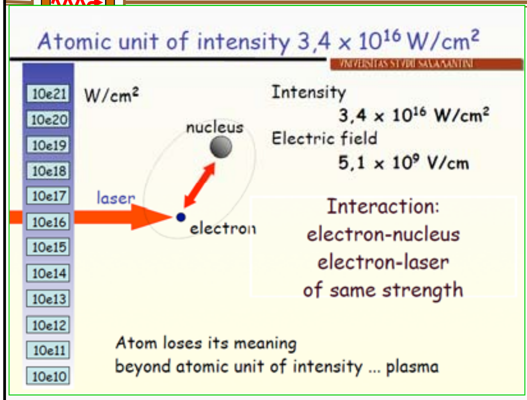
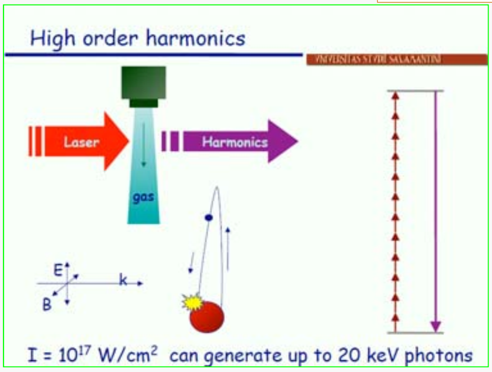




10^{17} W/cm^2 : ***Nuclear effects***

10^{18} W/cm^2 : ***Relativistic effects: particle accleleration!! (beyond 100 TW)***

10^{26} W/cm^2 : ***unstable vacuum: virtual pair (electron-positron) creation !!***

Copy of transparencies from Prof. Luis Roso, Salamanca)

Power beaming

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.

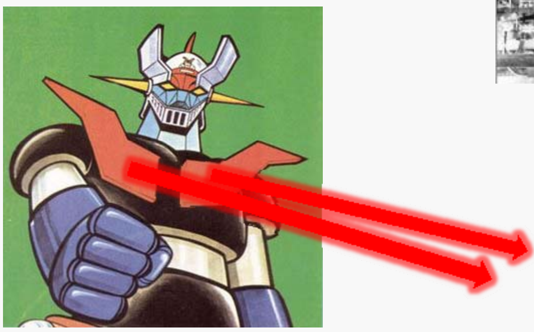
Photonics Spectra July 2010 PHOTONICS MEDIA 57

Traslladat energia a llocs llunyans o inaccessibles.

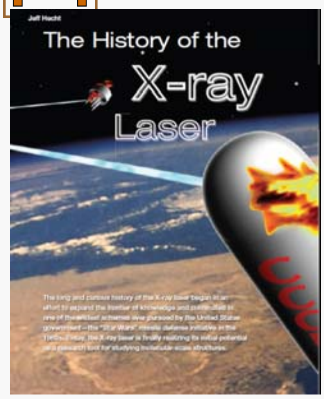
- ***Un petitet avió ha sigut propulsat des de terra!***
- ***Elevador espacial***
- ***Comunicacions inter-planetàries***
- ***Captar energia dalt i enviar-la cap a la terra*** *(o a l'inrevés)*

Aplics. militars?

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]*

50 aniv. Làser

Làsers: Aplicacions científiques i tècniques

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50 aniv. Làser

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

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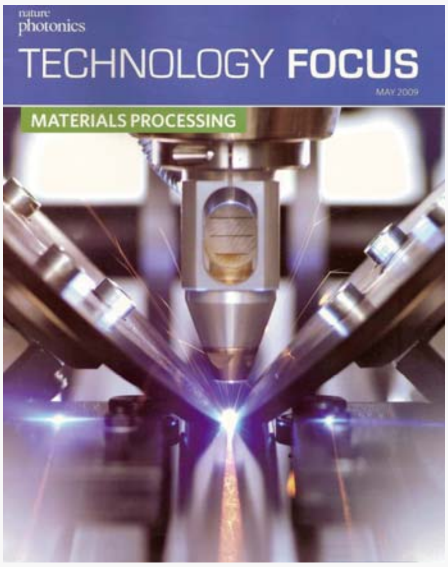


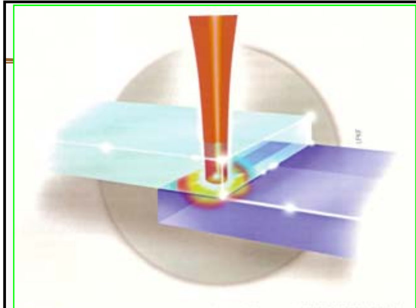


Figure 1 | Principle of laser transmission welding of two plastic components. The laser beam passes through the upper plastic layer but is absorbed by the lower one, generating heat that fuses the two components together, which then cool and harden.

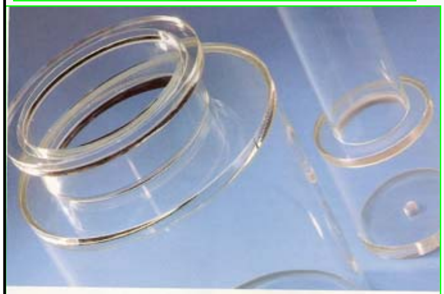
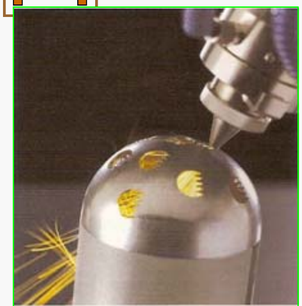


Figure 2 | Example of high-quality laser welding of transparent plastic parts using the Clearweld technology. A light-absorbing dye is sandwiched between the components to be joined. On illumination with a laser it heats up, melting the interface between the parts. Advantageously, the dye becomes colourless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

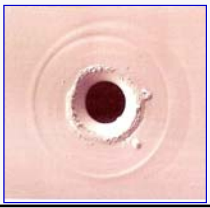
Nature Photonics, May 2009

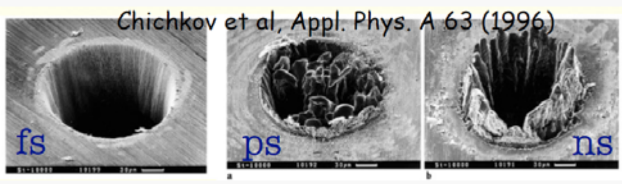
Figure 5 | Electric shaver welded by laser.

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



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

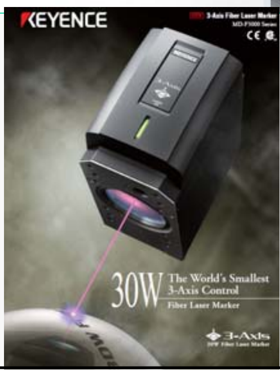


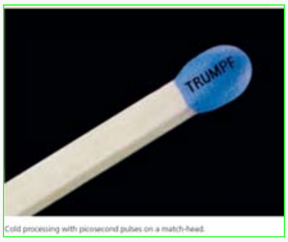


Marking on PET bottles

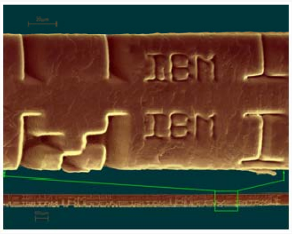
Laser Engraving on Implant Products

From Keyence - 2010





Cold processing with picosecond pulses on a match-head



Human hair !

Laser Marking Test Report

Marking 2D Barcodes on Engine Components Using a High-Powered Fiber Laser

Direct part marking of automotive parts is quickly shifting away from engraving to laser marking. In this report, a 30-watt fiber laser is used to print 2D barcodes on an engine block and crankshaft. The report and its photos highlight laser marking's advantages over conventional engraving methods.

More Details

Keyence

50 aniv. Làser

Prototipat (per sinterització, etc.)

UB-2010

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.

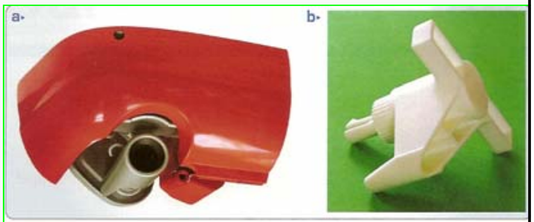


Figure 2 | Laser sintering and cars. a, Close-up of the laser-sintered prototype bumper section for the Jaguar XJ. The painted model was used to visualize the fit and finish of key components before production. b, The laser-sintered plastic tool that assists operators working on the new Jaguar XK production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

Nature Photonics, May 2009

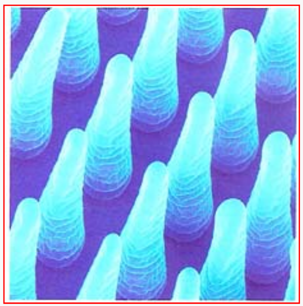
Figure 3 | Prototype plate bender, used to contour plates for spinal surgery, built by DePuy using a laser-sintering system.

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

UB-2010

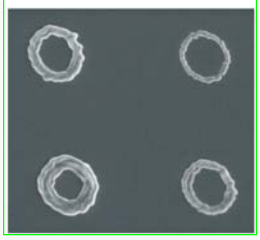
Prototipat (per two-photon induced polymerization)



Nature Photonics, May 2009

Optical tweezers boost direct-write nanolithography

Opt. Express **17**, 3640–3650 (2009)



Làsers: Aplicacions científiques i tècniques

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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.

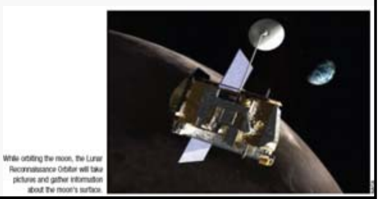
LIDAR (measuring distances, controlling atmosphere pollution, etc.

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



Applications in biology (biophotonics) and medecine:

(En parlarà el prof. David Artigas…)

Laser interferometry for gravitational wave observation: LISA and LISA Pathfinder

FELIPE GUZMÁN CERVANTES
NASA Goddard Space Flight Center
Greenbelt, Maryland, UNITED STATES

The Laser Interferometer Space Antenna (LISA) is a planned NASA-ESA gravitational wave observatory in the frequency range of 0.1mHz-100mHz. This observation band is inaccessible to ground-based detectors due to the large ground motions of the Earth.

Gravitational wave sources for LISA include galactic binaries, mergers of supermassive black-hole binaries, extreme-mass-ratio inspirals, and possibly from as yet unimagined sources.

LISA is a constellation of three spacecraft separated by 5 million km in an equilateral triangle, whose center follows the Earth in a heliocentric orbit with an orbital phase offset of 20 degrees. Challenging technology is required to ensure pure geodetic trajectories of the six onboard test masses, whose distance fluctuations will be measured by interspacecraft laser interferometers with picometer accuracy.

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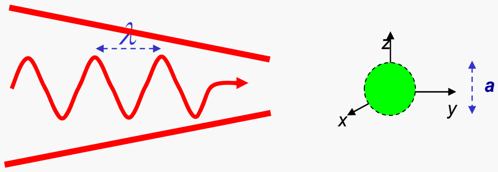
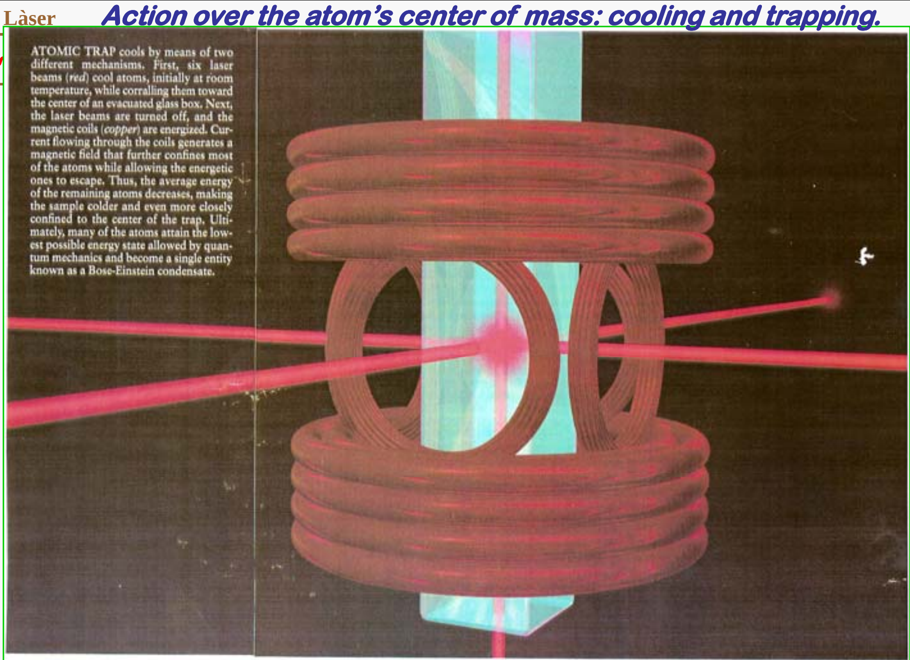
Action over the atom's center of mass: cooling and trapping of atoms



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

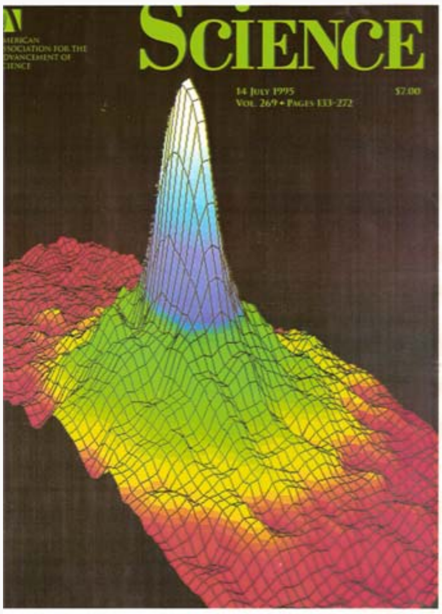
- Radiation pressure: ⇒ "OPTICAL MOLASSES"
- Dipolar (if λ>>a) or momentum-exchange (if λ<<a) ⇒ "OPTICAL TWEEZERS"

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

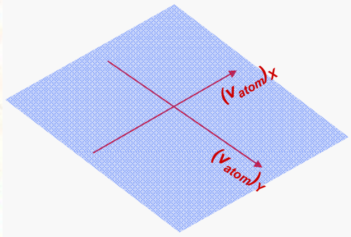


E.A. Cornell, C.E. Wieman : Sci. Am. (March 1998), p. 26

First achievement of BEC (Bose-Einstein condensation)

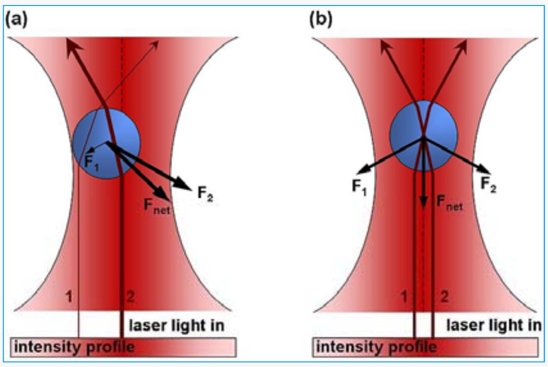


• Anderson, Ensher, Matthews, Wieman, Cornell: Science 269, 198-201 (1995)



Optical tweezers

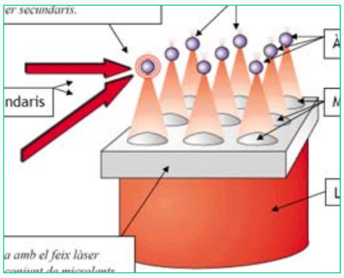
b) (General Mie regime): λ << a . The gradient forces is dominated by the momentum reaction to the light deviation by refraction inside the sphere (if it is transparent), on the walls: "Momentum–exchange" force. *(Many applications in biology)*



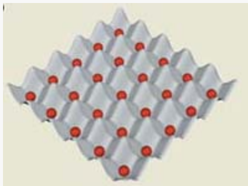
***Ray-optics and linear-momentum explanation**:*

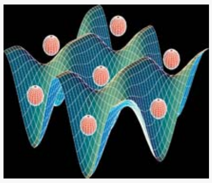
When the bead is displaced from the beam center, as in (a), the larger momentum change of the more intense rays cause a net force to be applied back toward the center of the trap. When the bead is laterally centered on the beam, as in (b), the net force points toward the beam waist.
(www.wikipedia.org)

Optical lattices created with optical tweezers



Optical lattices allow us to study entanglement between atoms





Làsers: Aplicacions científiques i tècniques

- *Fusió nuclear*
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- *Aplics. militars*
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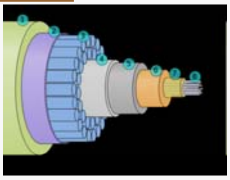
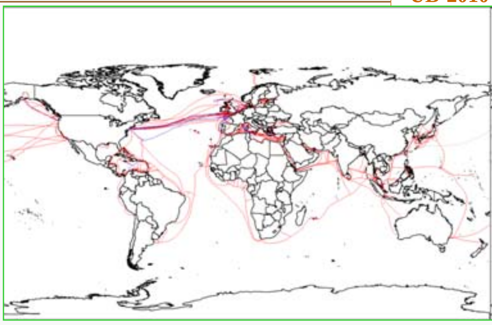
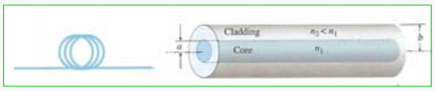
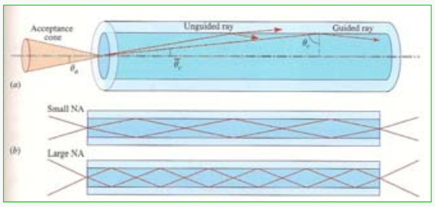
OPTICAL FIBRES

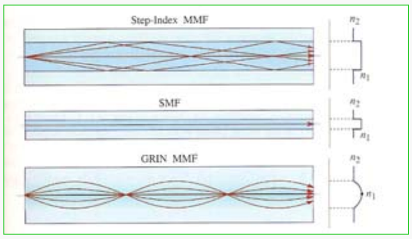


OPTICAL
FIBERS









$NA = \sin\ \theta_a$

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

"Fiber parameter"

Jeffrey Tseng/Intel

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

50 aniv. Làser

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

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Cryptography based on chaos…

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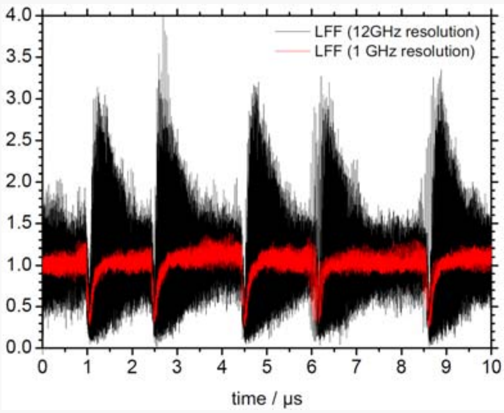

High-dimensionality chaos generated by a semiconductor laser with feedback

Ingo Fisher et al, IFISC, 2010

J. García-Ojalvo and R. Roy, Phys. Rev. Lett. 86, 5204 (2001).

Làsers: Aplicacions científiques i tècniques

POTÈNCIA

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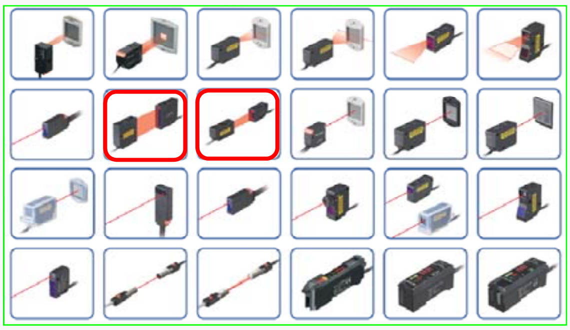
Some EXAMPLES of combinations of *one photoemitter + one photodetector*

Distance meter in the transverse direction:

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

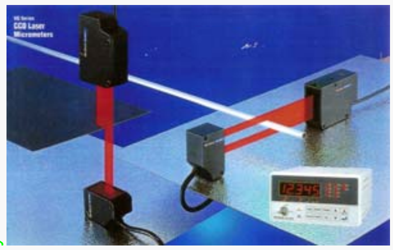
Need a scanning system, and/or a CCD detector.

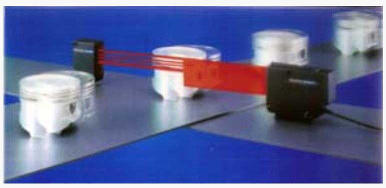


Several types of small devices, for different pourposes

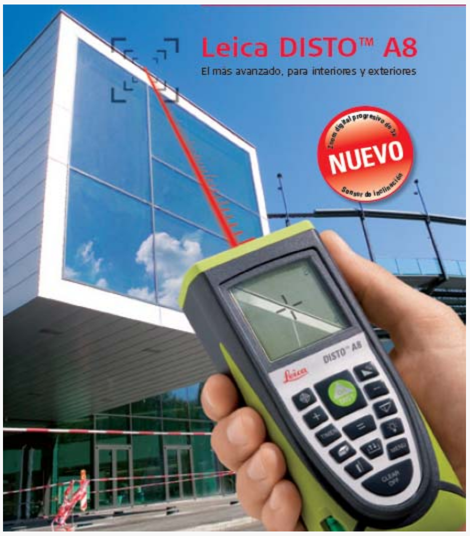
www.keyence.com

www.keyence.com





Laser micrometer (for gaging)



Some *EXAMPLES* of combinations of

one photoemitter + one photodetector

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

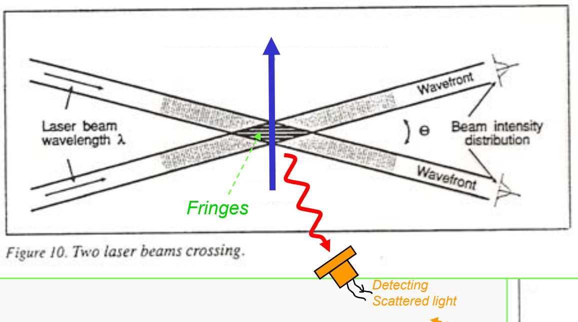


Figure 10. Two laser beams crossing.

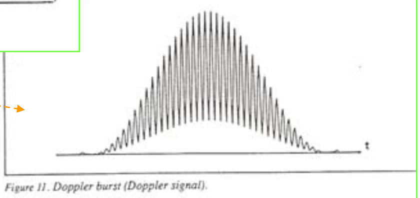


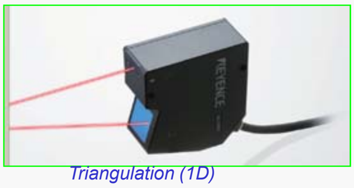
Figure 11. Doppler burst (Doppler signal).

Some EXAMPLES of combinations of

one photoemitter + one photodetector

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

November 2009



Triangulation (1D)

Triangulation (2D)

www.keyence.com

TRIANGULATION (1D)

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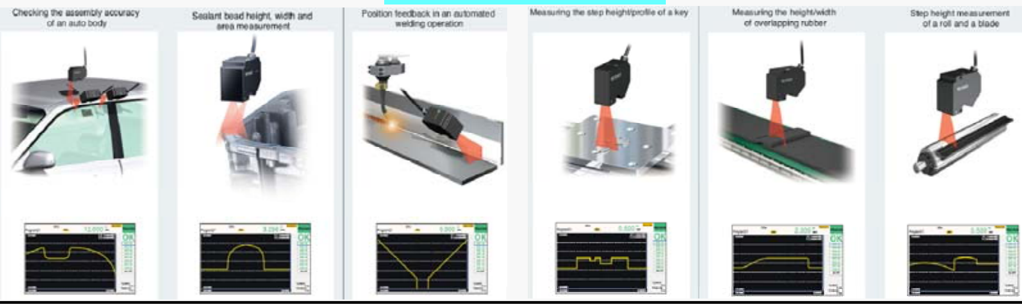
TRIANGULATION (2D)

www.keyence.com



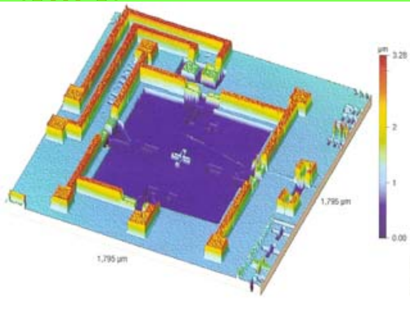
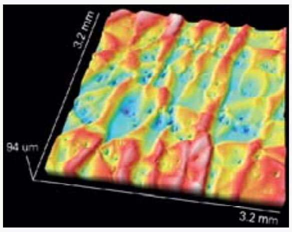


Figure 1 An interferometry measurement of a MEMS piezoelectric pressure sensor. Typically both the step height and roughness are of interest to ensure that the device works correctly.



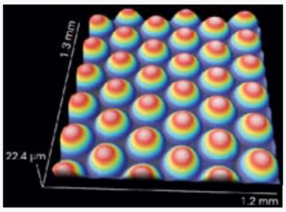
Biotechnology (leader)

OPTICAL IMAGING PROFILER (3D):

Confocal
+
interferometer (PSI+VSI)

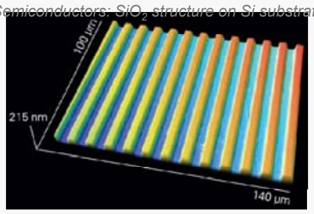
www.sensofar.com

Confocal + Interferometer (3D)



Micro-optics: array af glass microlenses

Semiconductors: SiO_2 structure on Si substrate



Semiconductors: SiO_2 structure on Si substrate

No sols a curtes distàncies:

- Arquitectes:

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

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

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Photonic circuits: the dream…….

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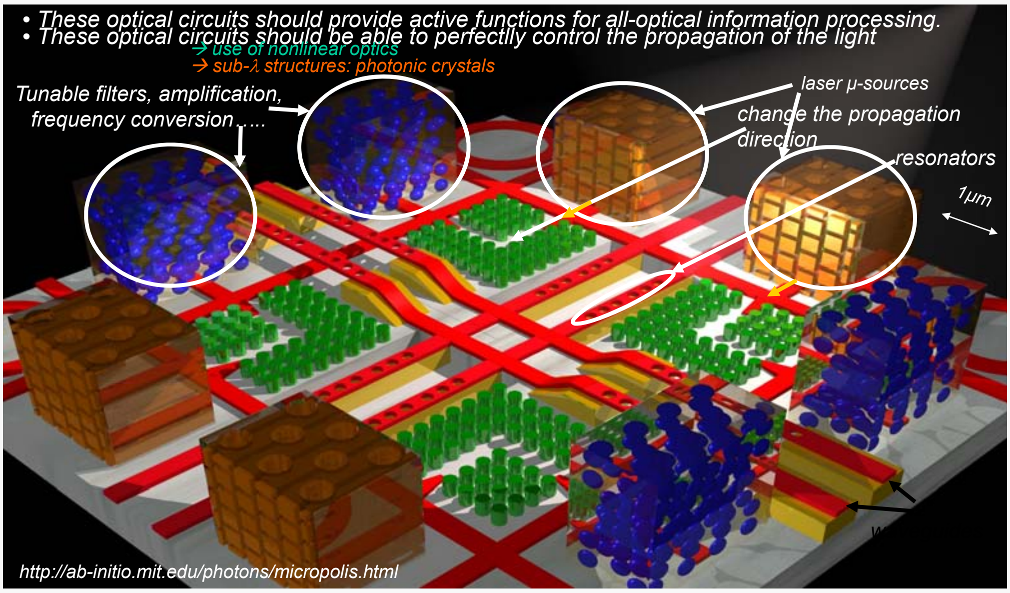
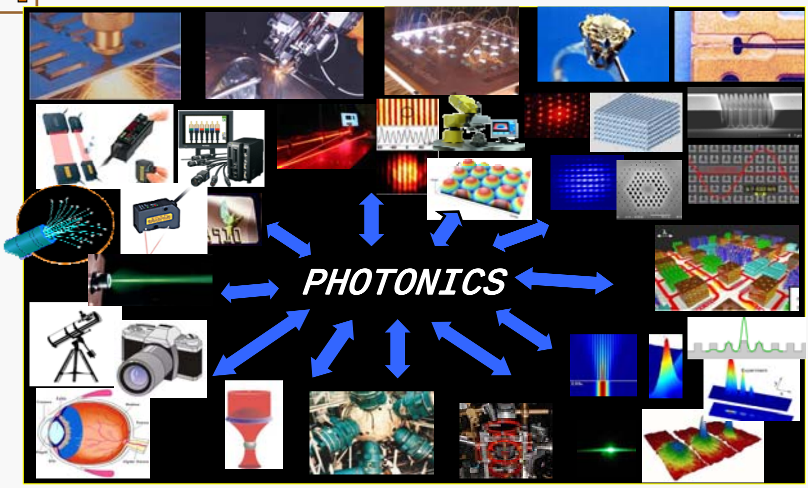


Resum



Futur ...?

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KET: Key Enabling Technologies, for the EU

UB-2010

The European Union (EU) has defined, in 2010, several
“Key Enabling Technologies” (KET)
for sustainable European industry:

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,…)

En parlarem, si és possible, en el 100 aniversari del làser…